This version was reformatted and shortened to 10 pages for presentation before ISART 2008 in Boulder, CO, as "**Deterministic Equations for Computer Approximation of ITU-R P.1546-2 "**. This original draft includes details not included in the presented version, as well as being easier to read.

APPROXIMATION EQUATIONS FOR COMPUTER IMPLEMENTATION OF ITU-R P.1546-2

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January 2008

Abstract:

This paper introduces two sets of equations, the first set empirically derived for two distance ranges, 1 to 50 km and 50 to 1000 km, and one deterministic-based with overlapping range equations, all derived from the data curves in over-land figures in ITU Recommendation P.1546-2. These equations are intended for use in a computer spreadsheet or in a computer software implementation for estimating radio reception signal strength over land, in the 10 MHz to 3GHz range, for a radio path length between 1 and 1000 km. The results of these equations are intended to be highly compatible with the results produced by ITU-R P. 1546-2 and Okimura-Hata for over-land paths at a reliability of 50% of locations, 50% of the time. The line-of-sight deterministic equations have been developed for use in replacing the current line-of-sight calculations utilized in the Longley-Rice Irregular Terrain Model (ITM v. 1.2.2.), in a corrected and completed Irregular Terrain with Obstructions Model (ITWOM) currently under development.

Part I. The Empirical Model:

The designation "empirical" here means that data and/or curves derived from many measurements have been fitted to polynomial equations in order to produce similar results on spreadsheets and in computer calculations. This is done so that it is not necessary to resort to reading and interpolating data points off of a figure or from a database lookup table. In this process, however, we will take into account known radio propagation law and theory to develop the calculations in a manner that will lead to a following derivation of deterministic-based approximation equations.

Concepts and Assumptions:

This work is based on the concept that line-of-sight radio propagation losses can be separated into:

1. Free space dispersion.

2. Multipath loss; primarily considered and computed using two-ray plane wave ground reflection calculations in two physical dimensions, with consideration of wavelet wavefront effects in three physical dimensions.

3. Four Radiative Transfer Engine (RTE) functions: Heat loss due to the passage of radio frequency energy through absorptive vegetation and other clutter atop terrain irregularities (Beer's Law, or RTE I_{ri} startup mode), moderated by RTE scatter and scatter functions Id (a.k.a. I_1 and I_2) and above-canopy-top-long-distance function I_3.

This work is based on the concept that a signal path that is obstructed ceases to follow a line-of-sight model, and must be determined using a diffraction model. A more complete model set, not proposed here, might consider a signal path that is obstructed to be represented by a edge diffraction model, and a signal path that passes very near an obstruction (due to wavefront wavelet interference effects) to be represented by a weighted combination of line-of-sight and grazing diffraction models.

Free Space Dispersion

The classic term "free space loss" is a misnomer. In fact, the classic free space equations depend upon the conservation of energy (Newton's second law), in that they calculate the three dimensional space dispersion of a loss-free spherical radio frequency energy wavefront emitted by a theoretical isotropic point source. The improved free space calculations below will be referred to as Free Space Dispersion (FSD) equations.

Free Space Loss (FSL) and FSD calculations are based on the deterministic concept model of a signal radiating from an isotropic (or, alternately, dipole), antenna located at the center of an empty sphere of a radius r, equal to the path distance, d. The versions of the computation calculate either the radio frequency (RF) voltage field arriving within an area of a size one wavelength square of the inside of the sphere, or the signal power receivable by a dipole antenna at a distance defined as the sphere radius. The well-known equations commonly referred to as the "Free Space Loss" equations, are based on the "free space loss" being the ratio of: the (power received)/(power transmitted):

Starting with the power transmitted, P_t, divided by the area of the inside of the sphere, $4\pi r^2$, with radius, r = radio path distance d:

S, the power per unit area, in units of watts/square meter $= P_t/4\pi d^2$

And then determining the power received, P_r, as the amount of signal intercepted by the receiving antenna's aperture, with the aperture size dependent upon the wavelength of the radio signal:

$$P_r = S\lambda^2/4\pi = P_t \lambda^2 /16\pi^2 d^2$$

The Free Space Power Loss ratio, FSPL, is $= P_r / P_t = (4\pi d/\lambda)^2 = (4\pi df/c)^2$

Where d is in km, f is in MHz, and c is the speed of light. The equation is then split up in a logarithmic conversion:

$$FSPL = 10\log_{10} ((4\pi df/c)^2)$$

$$FSPL = 20\log((4\pi df/c) = 20\log(d) + 20 \log(f) + + 20 \log (4\pi/c)$$

Resulting in the widely used, classic textbook form of this equation:

$$FSPL = 20\log(d) + 20\log(f) +32.44 \text{ dB}$$

Calculation of the FSPL using this equation has an inherent weakness; the separated logarithm functions for d and f are ratios of d/1 and f/1; they fail to calculate in a manner reflecting the real-world phenomena being represented when the values of d or f are less than 1. This is not a problem for f, as the range of P.1546-2 is limited to a minimum of 30 MHz. It is becoming more of a problem for d< 1 km, as interest in radio transmission propagation at shorter ranges increases due to the relatively recent emphasis on cellular, microcellular, and other personal wireless communications systems operating at lower power, and with less range, that traditional broadcast services.

As a corrective step, for short radio paths, the FSPL should be calculated in this form:

$$FSPL = 10\log_{10}((4\pi df/c)^2), \text{ or as}$$

$$FSPL = 20\log_{10}(d) + 20 \log_{10}(f) + 20 \log_{10}(f) – 147.56 \text{ dB}$$

Where: f is in Hz, and d is in meters. This pushes the inherent calculation weakness in the separated logarithmic form down to 1 meter, placing it within the near-field of the antenna, where the equation is unreliable.

For the broadcast scenarios utilized in ITU-R P.1546-2, (P.1546-2) an additional enhancement is necessary. The figures and calculations in P.1546-2 utilize and display a maximum free space loss line that is only correct when the transmitter antenna height is not significantly above the receiver. The additional path

dispersion incurred due to transmitter to receiver height difference path extension is not shown. Significant additional dispersion due to path extension occurs when the height of the transmitting antenna, h_1, significantly exceeds receive terminal height, h_2, and the path distance is short.

To correct this, the flat earth radio path distance, d, in the FSPL equation above, is replaced with a pythegorian two-dimensional vector calculation, $((h_1 - h_2)^2 + d^2)^{1/2}$, of the full path length from the transmit antenna to the receive antenna:

$$FSD = 20\log_{10}((h_1 - h_2)^2 + d^2)^{1/2} + 20\log_{10}(f) - 147.56 \text{ dB}$$

Carrying the square root across the log function results in the Free Space Dispersion (FSD) equation:

$$\text{FSD, Free Space Dispersion} = 10\log_{10}((h_1 - h_2)^2 + d^2) + 20\log_{10}(f) - 147.56 \text{ dB} \quad \text{(xxx)}$$

Where f is in Hz, and the horizontal path length, d, the transmitter height, h_1, and the receive height, h_2, are in meters.

P.1546-2 uses maximum field strength value curves, not received signal curves. These are displayed on the figures as Maximum (free space) lines. They are calculated using:

$$E_{fs} = 106.9 - 20\log(d) \quad \text{dB(uV/m)} \quad \text{where d is in km.}$$

Since the figures start at 1 km, it is not necessary to convert this equation to d in meters. But we will update the equation with the transmitter to receive height path extension addition:

$$E_{fs} = 106.9 - 10\log((h_1 - h_2)/1000)^2 + d^2) \quad \text{dB(uV/m)} \quad \text{[d in km.]} \qquad \text{(xxx)}$$

Since the field strength does not take into account the receive antenna aperture, it is frequency insensitive, and the FSD field strength results are same for all frequencies.

<u>Multipath losses: Plane earth field ray-tracing and wavefront wavelet reflection.</u>

Multipath consideration can be in either two or three physical dimensions. Plane earth field calculations, or two-dimensional ground reflection calculations, are often referred to as two-ray calculations. When expanded in scope from two to three physical dimensions, multipath calculations are computed using multiple ray tracing or wavefront wavelet reflection calculations.

Two-ray calculations start out with the basic concept of a direct, main signal ray, r_0, also described as the "incident plane wave", traveling from the transmitting antenna to the receive antenna. A second set of rays, r_1 and r_2, are traveling in the same plane as r_0. The ray r_1 travels from the transmitter antenna to the earths' surface, where a reflected ray r_2

then proceeds to meet up with the direct ray at the receive antenna. The combination of these two rays is complex; the two signals can theoretically add together to double the RF field arriving at the receive antenna (a 6 dB increase), but only if they arrive at the same time, (i.e. "in phase"); each with an path length (in the case of the reflected signal, due to phase change at the reflection point, the effective path length) equal to a precise multiple of the wavelength of the signal. If they arrive 180 degrees (or π radians) out of phase, they will cancel each other out, creating up to a 25 dB deep null in the received signal.

The angle between ray r_1 and the ground is called the grazing angle, and is normally represented by the Greek symbol (Ψ). If the reflecting medium (the earth) is not a perfect reflector, the grazing angle between the ray leaving the reflection point, r_2 , and the earth, will be perpendicular (90 degrees off of) the angle of the signal absorbed into the ground. However, in Longley-Rice equations, the earth's surface is close enough to a perfect reflector that the grazing angle of ray r_1 is considered to be equal to the grazing angle of ray r_2.

Another factor in the path calculation is the phase of the reflected signal. In horizontal polarization, the phase of the reflected signal reverses (zero degrees becomes 180, or the effective length changes by ½ wavelength) at the reflection point. In vertical polarization, the reflected ray r_2 is in phase with the incoming ray r_1 at a high grazing angle approaching $\pi/2$ radians (90°), but as the path length increases, the grazing angle becomes smaller. At a particular grazing angle the strength of the vertically polarized reflection signal, r_2, drops into a wide, deep null to zero. For a perfectly reflecting medium, this grazing angle is referred to as the "Brewster" angle, and can be determined using the equation: $\Psi_B = \cot^{-1} (\varepsilon_r)^{1/2}$, where for two lossless mediums, $\varepsilon_r = \varepsilon_2 / \varepsilon_1$, and the product of the dielectric constants ε_2 and ε_1 of the two media is a real number.

Slight differences in the reflecting media cause this critical angle to change values for signal strength (the real number) and phase (the imaginary number). For any imperfect reflecting medium, this critical grazing angle is then referred to as the "Pseudo-Brewster angle" (PSB)[1]. For a PSB, the null in the vertically polarized reflection is not as deep as for a Brewster angle. Below the PSB, the vertically polarized reflection signal rapidly changes phase with the angle, from 90 degrees ($\pi/2$ radians) to 180 degrees ($\pi/2$ radians) out of phase.

Ground (or sea) irregularities at the reflection point, and clutter, at and near the reflection point and between the reflection point and a low receiver, can affect the strength, phase, and phase coherence of the received reflected signal.

<u>Reflection coefficient, the PSB and low grazing angles:</u>

With respect to the grazing behavior of scatter and propagation above any rough surface, Dr. Donald Barrick, a radar propagation expert who served from 1972 to 1982 as Chief of the Sea State Studies Division of NOAA's Wave Propagation Laboratory in Boulder, CO., concluded that:[2]

> "Our results show that backscattered power depends on grazing angle to the fourth power; the impedance and admittance are constant as grazing is approached. These relations hold true for both polarizations, for arbitrary surface materials (including perfect conductors), for all frequency/roughness scales, and for a single deterministic roughness profile as well as averages over surface ensembles. …we considered only backscatter rather than arbitrary bistatic scatter, …but the extension to bistatic scatter is obvious: as either the incidence or scattering angle alone approaches grazing, echo power decreases as grazing angle squared.
>
> Although our approach was primarily employed to establish general grazing-limit behavior, our simple angle-independent constants describing backscatter and propagation are useful in their own right; these expressions allow a single numerical evaluation to serve the entire near-grazing region up to the Brewster angle."

Bistatic radar systems, which include but are not limited to passive radar systems, are radar systems where the transmitter and receiver are widely separated. They operate in a like manner to FM and TV broadcasting systems with respect to plane wave multipath considerations; therefore, we can extend Dr. Barrick's conclusions to the case of plane wave reflections. The theory, however, must now change in name from plane wave to wavefront, or wavelet, consideration, as Barrack's conclusions shift the analysis from a two-dimensional plane-wave consideration of a reflection at a spot in a path, to a three-dimensional, Newtonian conservation-of-energy revelation, regarding the consideration of wavelet-based reflections from a large ground area.

To clarify; we are not actually dealing with two rays; that is a two dimensional (plane) model useful for calculation of the strongest, central part of a wavefront. In a more realistic model, we are dealing with a wavefront, and wavelet theory in four dimensions; the three physical dimensions and time. Here Barrick found that a form of Newton's second law, a conservation of energy, applies to radio reflection. The reflection energy at small grazing angles is not entirely lost due to rough surface scattering; for rough but unobstructed surfaces at the reflection point for which there is no ground clutter absorption (such as a rough desert surface) the energy of a narrowband radio signal in the main reflection ray r_1 and r_2 that is lost due to roughness of the surface in a two-dimensional single-ray consideration, is regained in additional reflections from the rough surface in a three-dimensional wavefront reflection area consideration, and therefore, for a ray reflecting off of a surface without significant roughness obstructions or absorbing ground clutter such as vegetation, the strength of the reflected ray will essentially be the same as over a smooth surface.

In short, at low grazing angles, the energy that reflects off in other directions, and is lost due to a rough (but still highly reflective) surface, equals the energy reflected to the receive terminal from other points on the same surface that would have otherwise been directed, in plane waves, toward other receive terminals. The phase coherence, however,

will be affected; there will be a variation in arrival time from these additional reflections that will create variations in phase and realizable signal strength across the bandwidth of wideband signals.

Barrick's equations allow us to ignore the previously considered scattering effect of roughness on plane wave calculations at low grazing angles over nearly smooth or very slightly irregular surfaces, treating these surfaces as smooth earth surfaces with respect to very minor roughness. As the ground clutter layer thickens, or as the underlying terrain surface roughens, absorption losses quickly attenuate the ground reflection, reducing the cancellation effect of the ground reflection. For very short paths through clutter, the absorptive loss of the direct ray where it passes through absorptive clutter approaching the receiver then supplants the multipath loss as the primary cause of line-of-sight losses in addition to the free space loss. For longer cluttered paths, Radiative Transfer I_d functions become the primary determinant of loss.

It is possible for the two-ray cancellation effect to reappear when, at long distances and/or for low transmitter heights, the lengths of the reflected signal path and the direct signal path approach an equal length as both pass approximately equally through the absorptive clutter layer; the signal then receives attenuation from both absorptive and radiative transfer clutter loss, and two-ray cancellation.

Two ray calculation results and the ITU-R P.1546-2:

Two-ray calculation results for horizontally polarized signals, and vertically polarized signals at low grazing angles, over flat, uncluttered, reflective earth, show a "comb" pattern of deep nulls, out to the point where the difference between the direct and reflected ray path effective lengths reduces to ½ of a wavelength. Then the results show a slowly increasing loss with distance that approaches a deep null well past the horizon.

Calculations using a spreadsheet, using the Longley-Rice Irregular Terrain Model (ITM) methodology, show that the two-ray cancellation effects rapidly disappear when the terrain irregularity factor, Δh, exceeds 4 meters. The ITM documentation states that for the continental U.S., a Δh of 90 meters is an average preset value for use when a more accurate determination is not available. Therefore, two-ray effects contribute little loss over average U.S. terrain. The ITU Recommendation P.1546-2, Annex 1, Paragraph 7, states that the minimum value of the representative height of ground cover, or representative clutter height h_2, is 10 m. This does not speak to the roughness of the terrain underlying the ground clutter layer. While Longley-Rice Δh and ITU ground clutter are different parameters, we believe that, from the available information, we have a reasonable expectation that two-ray effects contribute little loss over the average terrain data used to create the Figures in ITU-R P.1546-2 (P.1546-2). In the later calculation of the deterministic model, the average depth of the combined height of the ground clutter and the underlying average terrain roughness is derived from the ITU data.

What little multipath effect remains between 1 and 50 km, was originally considered to exist between the h_1 = 1,200 meter line and the Maximum (free space) line on Figures 1, 9 and 17, from which these models are based. This difference in attenuation value is approximately the same on all three, and therefore does not vary appreciably with frequency. The research by Barrick on radar return values at low grazing angles, indicates that radar return losses follow a fourth-power law; bistatic radar, or one-way loss, would therefore exhibit a relationship to distance that follows the square root of radar return losses, resulting in a relationship to the square of the path distance that, incorporated into an empirical formula combining reflection coefficient and the square of the distance, fits the data well.

Attenuation due to 2-ray multipath = $A_{2R} = R_e d^2$,
wh2e d is in km, and
R_e, the reflection coefficient, is empirically found to be equal to .0016 at 50 km.

$$A_{2R} = .0000016d^2 = (1.6E\text{-}6)d^2, \text{ where d is in meters.} \qquad (1)$$

This formula would be valid from 1 to 50 km in a line-of-sight situation, at all frequencies, for ITU-R P.1546-2. Over a very flat, highly reflective, uncluttered terrain, or a sea path, this may be a valid consideration. In Part II of this paper, regarding the deterministic model, it is determined that there is, in fact, no attenuation from 2-ray multipath effects evident in the data presented on Figures 1, 9 and 17 of P.1546-2.

Absorption losses due to Ground Clutter:

As the ground absorption layer thickens, absorption losses increase, rapidly damping out the two-ray or wavefront reflection losses to near zero as the reflected signal passes twice through the absorptive ground clutter. Significant roughness of the ground also contributes to a many-multiple diffractions to absorption" situation, where the signal is so diffracted that reflection losses from partial reflection off of absorptive or partially transmissive surfaces, and absorption losses due to multiple diffractions terminating in absorbing terrain features, cause the ground reflection to be severely attenuated.

Spreadsheet calculations using the Longley-Rice Irregular Terrain Model (ITM) methodology show that the plane-wave two-ray cancellation effects rapidly disappear when the terrain irregularity factor, Δh, exceeds 4 meters. As Δh increases well beyond 4 meters, and as the related ground clutter layer thickens, absorptive losses due to the path of the direct ray passing through absorptive ground clutter, moderated by Radiative Transfer over and under ground clutter, takes over as the primary cause of line-of-sight attenuation in addition to free space dispersion for the line of sight range.

The absorptive clutter losses, which terminate as conversion to heat, and are therefore true losses, could be referred to as "Clutter losses", or a component of "Clutter" however, this is somewhat confusing, as it does not match the definition of "Clutter" used in P.1546-2. For this empirical set of equations, we make the assumption that for all

practical purposes, the losses documented on Figures 1, 9 and 17 in addition to the free space dispersion, are a form of absorptive attenuation related to the ground clutter. This may include a combination of loss and loss moderation phenomena, the sum of which can be treated as producing an empirically quantifiable result.

On Figure 1, one may imagine this Absorptive Clutter Attenuation (ACA) as being represented by a wedge with four corners, located where the Maximum (free space) and h_1 = 10 lines cross the 1 km and 50 km distance lines. At a point between 45 km and 50 km, this clutter-effect wedge stops increasing in size, and starts to collapse toward a single-value-relative-to-distance line; a reasonable assumption is that this is due to the primary propagation mode transferring from line-of-sight to diffraction mode at the horizon or at an obstacle, and, eventually, to a troposcatter mode.

Note that the h_1 = 10 meter line is, in fact, a 9.35 meter line, as each h_1 line height value, starting at the h_1=1,200 line, is half of the line above; 1200/2 =600, etc., down to the 37.5 meter line. For convenience, below 37.5 meters, where 37.5/2 = 18.75, and 18.75/2 = 9.35, these last two transmitting antenna height values are represented by 20 and 10 on the Figures.

The maximum amount of ACA would occur when both the transmitter and receiver are at a minimum height, represented by the values on the h_1 = 10 meter line. The h_1 = 1,200 line is nearly loss-free from an ACA standpoint. At h_1 = 10 meters, it appears that most, if not all, of the direct radio transmission ray would be at or below the average height of the absorptive clutter layer (ACL).

If plotted on linear paper, the line these values form would be a relatively straight line with a slight curve. We will determine the value of three vertical lines across the wedge, and fit these values to a $y = ad^2 + bd + c$ line.

The difference in value between the Maximum free space line, which is correct for $h_1 = h_2$ = 10 meters, and the h_1 = 10 meters line, is:

106.9 –90 = 16.9 dB @ d=1,
30.25 dB at d= 7 km, and
51.86 dB at d = 40 km.

Solving, at 100 MHz, for $ACA = ad^2 + bd + c$ at $h_1 = h_2$ = 10 m, we get:

$$ACA_{[100MHz,\ d]} = -\ 0.04026d^2 + 2.5471d + 14.39, \text{ where d is in km.} \qquad (1a)$$

Which solves for ACA at a distance d, when $h_1 = h_2$ = 10 m, and has been exponentially derived from P.1546-2.

We also obtain the equivalent values from Figures 9 and 17, and also solve for ACA at 600 and 2,000 MHz:

$$ACA_{[600MHz,\ d]} = -\ 0.0685237d^2 + 3.814856d + 11.65367 \qquad (1b)$$

$$ACA_{[2GHz,\ d]} = -0.0735742d^2 + 4.188594d + 10.03498 \quad (1c)$$

In performing an analysis of these equations, with increasing frequency, we see a slow decrease in the intercept value, and increases in the d^2 and d slope factors. Therefore, there is an apparent frequency relationship between the three equations. We therefore proceed to solve for a frequency relationship between the intercepts of the three equations, in order to produce a single equation that will solve for distance and frequency at $h_1 = h_2 = 10$ meters:

Line formula: $c_{ACA} = af^2 + bf + c$
For 100 MHz, $14.393 = (100^2)a + 100b + c$
For 600 MHz, $11.65 = (600^2)a + 600b + c$
For 2 GHz, $10.035 = (2{,}000^2)a + 2{,}000b + c$

Solving these three equations, we obtain a formula for the zero intercept at all frequencies:

$$c_{ACA} = 15.08 - 0.00707f - (2.27e\text{-}6)f^2 \quad (2a)$$

Solving similarly for the f^2 and f slope factors, a and b:

Line formula: $a_{ACA} = af^2 + bf + c$
For 100 MHz, $-0.04026 = (100^2)a + 100b + c$
For 600 MHz, $-0.0685237 = (600^2)a + 600b + c$
For 2 GHz, $-0.0735742 = (2{,}000^2)a + 2{,}000b + c$

Line formula: $b_{ACA} = af^2 + bf + c$
For 100 MHz, $2.547082 = (100^2)a + 100b + c$
For 600 MHz, $3.81485625 = (600^2)a + 600b + c$
For 2 GHz, $4.18859363 = (2{,}000^2)a + 2{,}000b + c$

And obtain:

$$a_{ACA} = -.03294 - (7.6E\text{-}05)f + (2.79E\text{-}8)f^2 \quad (2b)$$

$$b_{ACA} = 2.272 + 0.003262f - (1.152E\text{-}6)f^2 \quad (2c)$$

Which, summed up, becomes:

$$ACA_{[f,\ d]} = c_{ACA} + b_{ACA}d + a_{ACA}d^2$$

$$ACA_{[f,\ d]} = 15.08\text{-}0.00707f - (2.27e\text{-}6)f^2 + d(2.272 + 0.003262*f - (1.152E\text{-}6)f^2) + d^2(-.03294 - (7.6E\text{-}05)f + (2.79E\text{-}8)f^2)$$

which multiplies out to:

$$ACA_{[f,\,d]} = 15.08-0.00707f -(2.27e-6)f^2 + 2.272d + 0.003262fd$$
$$- (1.152E-6)f^2d \; -.03294d^2 \; - (7.6E-05)*fd^2 \; + (2.79E-8)f^2d^2 \text{ in dB} \qquad (3)$$

Where d is in km and f is in MHz.

This equation calculates the values along the h_1 line for all values of d from 1 to 50 km and for f from 30 to 3000 MHz, where $h_1 = h_2 = 10$ meters, requiring only d in km and f in MHz as input; (the same inputs required for a free space loss computation), in a manner suitable for spreadsheet or computer code implementation.

Transmitter height adjustment:

To solve at a transmitter height, h_1, higher than 10 meters, we find that at 40 km, there is an average, and steady, 6.857 dB decrease in attenuation for each doubling of h_1.
At 1 km, we find an average and steady 2.296 dB decrease in attenuation for each doubling of h_1. To compensate for increased transmitter height, we can then adjust the above result for $ACA_{[f,\,d]}$, calculated at a $h_1 = 10$ (9.35) meters, by multiplying it by $(1 – (\min(\log_{10}(h_{gt}/9.35)/2.11,1)))$ to adjust for a transmitter height, h_{gt}, higher than 10 meters:

$$ACA_{[f,\,d,\,h1]} = ACA_{[f,\,d]} * (1 – (\min(\log_{10}(h_{gt}/9.35)/2.11,1))) \qquad (4)$$

Receive height adjustment:

ITU-R P.1546-2 states that R = 30 m for dense urban, 20 m for urban, and 10 m for rural. To be compatible with the Longley-Rice ITM, we are using 10 meters in all cases; but if one has a higher receive antenna height, the ITU-R P.1546-2 computation can be used for a variation in receive height:

If $h_{gt} < (6.5d + h_{gr})$
$\quad R' = h_{gr}$
Else:
$\quad R' = \max(1, (d* h_{gr} – 15*h_{gt})/(d – 15))$

$$ACA_{[f,\,d,\,h1,\,h2]} = ACA_{[f,\,d,\,h1]} + (3.2 +6.2 \log_{10}(f))*(\log_{10}(h_{gr}/R')$$

If we obtain further information as to the thickness of the ground clutter layer, this is where it would be applied, using:

$ACA_{[total]} = ACA_{[f,\,d,\,h1,\,h2]}$ *(actual ground clutter depth/average ground clutter depth)

Results for Line of Sight Attenuation:

For 1 to 50 km:

$$A_{[total]} = ACA_{[total]} + \text{Free Space Loss} + \text{2-ray cancellation effect} \quad (5)$$

$$A_{[total]} = ACA_{[total]} + FSL + A_{2R} \text{ dB} \quad (6)$$

It has been determined that for land paths in P.1546-2, $A_{2R} = 0$.

With respect to Okimura-Hata results, these equations should provide a good approximation for the entire valid distance range of Okimura-Hata. With respect to ITU-R P.1546-2, the results should provide a very close approximation to the results obtained from Figures 1, 9, and 17, land paths for 50% of time, in the range 1 to 50 km; and also be useable in areas greater than 50 km for paths known to be line-of-sight. In a real-world measurement comparison, these calculations should be valid, given proper consideration of the limitations, averages, and assumptions utilized by the ITU-R P.1546-2 prediction methodology, for the entire actual line-of-sight range; up to the horizon, or the point where the signal path is interrupted by an obstruction.

Beyond Line-of-Sight

At approximately 45 km, the absorptive clutter-related losses reach a peak, as is evident in the change in vertical distance between the h1 = 1200 meter and the h1 = 10 meter lines. The predicted average absorptive clutter loss, which would vary with transmitter height, starts to retract as the average signal path changes with distance, from a line-of-sight path to an obstructed or beyond-the-horizon path. Beyond the line-of-sight path, diffraction and tropospheric scattering are the primary sources of attenuation in addition to free space loss.

Therefore, for distances at and beyond 50 km, we select a new set of key data points and solve for a new set of distance and frequency equations of the form $y = ax^2 + bx + c$. From observation of the h_1=10 meter curves on figures 1, 9 and 17, and data read from these curves, it was determined that choosing to use data at 50 km, 200 km, and 800 km would provide a good fit of an $A_{[d]} = ad^2 + bd + c$ curve to the 50 to 1000 km portion of the h_1= 10 meter curves on the figures. Since the two-ray path losses have been found by Longley and Rice to generally be minimal to the point that the Longley-Rice computer implementations ignore them beyond the line-of-sight range, we here use the vertical difference between the free space loss line and the h_1=10 meter curves to establish our empirical equations to calculate the diffraction and troposcatter losses beyond the line-of-sight range.

The difference in value between the Maximum (free space) line and the h_1 = 10 line, is:

at d = 50 km: 72.52 – 20.25 = 52.27 dB

at d= 200 km: 60.38 dB
at d = 800 km: 101.44 dB

Solving, at 100 MHz, for ACA = $ad^2 + bd + c$ at $h_1 = h_2 = 10$ m, we get:

$$ACA_{[100MHz,\ d\geq 50]} = 0.0000192d^2 + 0.049278d + 49.76, \text{ where d is in km.} \quad (7a)$$

Which solves for ACA at a distance $d \geq 50$ km, when $h_1 = h_2 = 10$ meters.

We also obtain the equivalent values from Figures 9 and 17, and also solve for ACA at 600 and 2,000 MHz:

$$ACA_{[600MHz,\ d\geq 50]} = -0.00002d^2 + 0.094667d + 50.3 \quad (7b)$$

$$ACA_{[2GHz,\ d\geq 50]} = 0.0000169d^2 + 0.058833d + 58.036 \quad (7c)$$

In performing an analysis of these equations, with increasing frequency, we see a slow increase in the intercept value between d = 50 km and 200 km that increases more rapidly as the h_1 curve approaches 800 km. There is a less apparent frequency relationship between the three equations than there was prior to d = 50 km. We therefore proceed to attempt to solve for a frequency relationship between the intercepts of the three equations, in order to produce a single equation that will solve for distance and frequency at $h_1 = h_2 = 10$ meters:

Line formula for d= 50 km: $c_{ACA} = af^2 + bf + c$
For 100 MHz, $49.75822 = (100^2)a + 100b + c$
For 600 MHz, $50.336 = (600^2)a + 600b + c$
For 2000 MHz, $58.036 = (2{,}000^2)a + 2{,}000b + c$

Solving these three equations, we obtain a formula for the zero intercept at all frequencies:

$$c_{ACA} = 49.78 - 0.00045f - (2.29e\text{-}6)*f^2 \quad (8a)$$

Solving similarly for the f^2 and f slope factors, a and b:

Line formula: $a_{ACA} = af^2 + bf + c$
For 100 MHz, $0.0000192 = (100^2)a + 100b + c$
For 600 MHz, $-0.000020 = (600^2)a + 600b + c$
For 2 GHz, $0.0000169 = (2{,}000^2)a + 2{,}000b + c$

Line formula: $b_{ACA} = af^2 + bf + c$
For 100 MHz, $0.049278 = (100^2)a + 100b + c$
For 600 MHz, $0.094667 = (600^2)a + 600b + c$
For 2 GHz, $0.058833 = (2{,}000^2)a + 2{,}000b + c$

And obtain:

$a_{ACA} = 0.0000303 + (1.2e\text{-}7)f + (5.51e\text{-}11)*f^2$ (8b)

$b_{ACA} = .036525 + 0.000134f - (6.1e\text{-}8)*f^2$ (8c)

Which, fitted into a line formula of the form: $y = ax^2 + bx + c$

$ACA_{[f, d]} = c_{ACA} + a_{ACA}d^2 + b_{ACA}d$ in units of dB

$$ACA_{[f, d]} = 49.78 - 0.00045f - (2.29e\text{-}6)*f^2 + d(.036525 + 0.000134f - (6.1e\text{-}8)*f^2) + d^2(0.0000303 + (1.2e\text{-}7)f + (5.51e\text{-}11)*f^2) \text{ dB}$$

Which multiplies out to become:

$$ACA_{[f, d]} = 49.78 - 0.00045f - (2.29e\text{-}6)*f^2 + .036525d + 0.000134fd - (6.1e\text{-}8)*f^2d + 0.0000303d^2 + (1.2e\text{-}7)fd^2 + (5.51e\text{-}11)*f^2d^2 \text{ dB} \quad (9)$$

Where d, the path distance in km, is $\geq$ 50 km., and f is in MHz.

While a crude and long equation, once it is inserted into a spreadsheet cell or computer code, it needs only the same input values, d and f, in the correct units, used for the FSD equation, and produces results closely matching the P.1546-2 Figure 1, 9, and 17 h_1 =10 meter curve results. When modified by the transmitter height adjustment equation, the results closely match the P.1546-2 Figure 1, 9, and 17, h_1 = 20 to 1200 meter curve results.

Transmitter height adjustment at and beyond 50 km:

To solve at a transmitter height, h_1, higher than 10 meters, we find that at 50 km, there is an average, (68 – 17.5)/ 7 = 7.2 dB decrease in attenuation for each doubling of h_1. At 800 km, we find an average 1.57 dB decrease in attenuation for each doubling of h_1. Therefore, we find that we can then adjust the above result for $ACA_{[f, d]}$, calculated at a h_1 = 10 (9.35) meters, by multiplying the change at a distance beyond 50 km, by the same equation used for d = 0 to 50 km, $(\min(\log_{10}(h_{gt}/9.35)/2.11,1))$ and subtracting the result from $ACA_{[f, d]}$, to adjust for a transmitter height, h_{gt}, higher than 10 meters:

$ACA_{[f, d, h1]} = ACA_{[f, d]} - (1-0.000962(d - 50))(39.5)(\min(\log_{10}(h_{gt}/9.35)/2.11,1))$ (4b)

Where d is in km and h_{gt} is in meters, and is not less than 10 meters.

Receive height adjustment:

ITU-R P.1546-2 states that R = 30 m for dense urban, 20 m for urban, and 10 m for rural. To be compatible with the Longley-Rice ITM, we are using 10 meters in all cases; but if one has a high2 receive antenna height, the ITU-R P.1546-2 computation can be used for a variation in receive height:

If $h_{gt} < (6.5d + h_{gr})$

$R' = h_{gr}$

Else:

$R' = \max(1, (d^* h_{gr} - 15^* h_{gt})/(d - 15))$

$$ACA_{[f, d, h1, h2]} = ACA_{[f, d, h1]} + (3.2 + 6.2 \log_{10}(f))^*(\log_{10}(h_{gr}/R')$$

If we obtain further information as to the thickness of the ground clutter layer, this is where it would be applied, using:

$ACA_{[total]} = ACA_{[f, d, h1, h2]}$ *(actual ground clutter depth/average ground clutter depth)

Attenuation Loss Results for Beyond 50 km

So we would then have:

$$A_{[total]} = ACA_{[total]} + \text{Free Space Loss} + \text{2-ray cancellation effect} \quad (5)$$

But since we have determined that the 2-ray cancellation effects are insignificant beyond the horizon or an obstacle, then beyond 50 km this simplifies to:

$$A_{[total]} = ACA_{[total]} + FSL \text{ dB} \quad (6)$$

With respect to ITU-R P.1546-2, the results for the equations for the $\geq$ 50 km range should provide a very close approximation to the results obtained from Figures 1, 9, and 17, land paths for 50% of time, in the range 50 to 1,000 km. Where path conditions are known, the equations for < 50 km should be used up to the horizon or obstacle that ends the line-of-sight path; the $\geq$ 50 km equations should be used at and beyond the horizon or obstacle that ends the line-of-sight path.

Part II. The Deterministic Model:

The designation "deterministic" here means that, to the extent it is practical and possible, we have studied the data and/or curves derived from many measurements, and studied the best-fit empirical equations fitted to this data. We have then developed, taking into account known scientific optical and electromagnetic propagation principles and laws,

and based on scientific models, a derivation of a set of short-form approximation deterministic equations that produce equivalent results to the empirical data. By their nature, these deterministic equations can be expanded and utilized to solve situations not found or anticipated by purely empirical equations.
Note: All references to "log" are to a base 10, or common logarithm, occasionally noted as $\log_{10}$. Natural logarithms will be referred to by "ln".

A path of discovery: developing the deterministic Clutter Absorption Loss equations.

While developing and refining the above empirical equations, a concept and scenario emerged that led to the creation of a deterministic model for clutter absorption. Clutter absorption attenuation occurs along the path of the direct signal from the transmitter to the receiver. For a typical broadcasting scenario, the path starts out from a high transmitting site, and, on a clear day, passes through unobstructed and relatively lossless atmosphere. The receive site is at a relatively low height, 2 to 10 meters above ground level, and the "clutter layer", consisting of a layer of foliage and other absorptive materials atop a smooth or irregular terrain, is taller that the receive antenna height. At a point along the direct signal path, as the transmitted signal approaches the receive site, the signal path enters the clutter layer. While the composition and absorption per meter characteristics of the clutter varies tremendously from case to case, and for a mobile receiver from moment to moment while the receiver is in motion, if the clutter can be considered to be, on the average, relatively homogeneous in absorption per meter and in the height of the clutter layer, then it would be possible to derive not only an average value of clutter attenuation per meter, but an estimate of the average clutter height occurring in the massive amount of test data that was used to create the exponential ITU recommendation and the above exponential model. Ordinary trigonometry and limit calculations can be used, along with the transmitting and receiving antenna heights, and the average terrain height, to determine the distance along the line-of-sight signal path that the signal passes through the absorptive clutter. The clutter absorption function empirically derived above forms a nearly straight line when plotted on a linear graph. What if it is, in fact, a straight-line function, varying with distance, the height of transmit and receive antennas above the average terrain, and frequency; and the slight variation from a straight line is statistical error in the empirical data? The equation might take the form: $A = d * AB$, where AB is the Clutter Absorption coefficient, a function of h_1, h_2, f_{MHz}, and the average clutter layer height above the effective receive height, C_{HR}. C_{HR} is equal to C_H, the average clutter height, less the effective receive height, h2.

Such an equation already exists: Beer's Law. Beer's Law is an extension of the Bouguer Law, which was rediscovered as the Lambert law of absorption. Therefore, Beer's Law is sometimes referred to as the Bouguer-Beer Law, or Beer-Lambert Law. The form of Beer's Law that is the most easily redefined for use in radio propagation is:

$$A = \varepsilon bc$$

where:

A is absorbance, equal to: $\log_{10}$(power in/power out)
b is the path length of the sample
ε is the molar absorbtivity with units of L mol^{-1} cm^{-1}
c is the concentration of the compound in solution expressed in mol L^{-1}

This form is intended for its original purpose, determining the attenuation (absorption) in a ray of light (which exhibits certain aspects of high frequency electromagnetic wave phenomenon) passing through an absorptive liquid medium.

We redefine Beer's Law, and its coefficients, for radio propagation as:

A_{CL} = AB * clp * c, where the function AB = ε, and c = 1.0.

where:

A_{CL} is the attenuation of the signal, = $\log_{10}$(power in/power out), in dB/meter
clp replaces b, defined as the length of the path, in meters, the signal follows through the absorbing medium (ground clutter).
AB is the absorption factor function, defined in attenuation per meter, (dB/meter), and represents ε, where:
ε is the absorbtivity of a theoretical, homogeneous, one-meter depth of statistically average clutter as derived from the figures in ITU-R P.1546-2.
c represents the density of the clutter; we will expect a value of 1.0 for c in this derivation so that c may provide a future external means of adjusting the clutter absorption based on localized clutter data.

First, we determine an equation for the length of the direct propagation path that passes through the clutter, d_{cp}. To calculate the angle from the receive site back toward the transmit site, take the difference in height between the transmitting and receive antennas, divided by the total path distance, to obtain the tangent of the receive site take-off angle, θ_r. For a line-of-sight path, the trigonometric functions of this angle, θ_r, are equal to:

$$\tan \theta_r = (h_1 - h_2)/d = (C_H - h_2)/d_{cp}$$

$$\theta_r = \text{atan}((h_1 - h_2)/d)$$

$$\sin \theta_r = (h_1 - h_2)/r_0 = (C_H - h_2)/clp = C_{HR}/clp$$

$$r_0 = ((h_1 - h_2)^2 + d^2)^{1/2}$$

where

$C_{HR} = (C_H - h_2)$ = clutter height above receive height

C_H	average of combined clutter layer and terrain irregularity height
d	flat earth surface distance between the transmit and receive antennas
h_1	effective height of the transmit antenna
h_2	effective height of the receive antenna
clp	cluttered path length, through clutter layer from entry point to receive antenna
d_{cp}	the portion of d under the clp.
r_0 =	total length of direct signal path ray from transmit to receive antenna.

we then derive:

$$r_0 = (h_1 - h_2) / \sin \theta_r$$

$$clp * (h_1 - h_2) = r_0 * (C_H - h_2) = ((h_1 - h_2)^2 + d^2) * (C_H - h_2)$$

$$clp = (((h_1 - h_2)^2 + d^2) * (C_H - h_2)) / (h_1 - h_2)$$

$$clp = C_{HR} / \sin \theta_r = (C_H - h_2) / \sin \theta_r$$

where

$$\sin \theta_r = (h_1 - h_2) / ((h_1 - h_2)^2 + d^2)^{1/2}$$

Note: flat earth geometry is adequate here; at these distances, the effective earth curvature correction is less that the reading error from the P.1546-2 figures.

From Beer's Law, the clutter attenuation $A_{CL,}$ is equal to the average clutter absorption per meter function, AB, times the clutter path length, clp:

$$A_{CL} = AB * clp = AB * (C_H - h_2) / (\sin \theta_r)$$

Based on an assumption that the average clutter height effectively remains the same at all distances in the ITU Figures, we interpret from Figure 1 of P.1546-2, where we find: f=100 MHz, h_1 = 10 (or, 37.5/4=9.375) meters transmitter height, and h_2 =10 meters (rural) receive height. The statistical reliability is 50% of locations, for 50% of the time. We initially reference the clutter attenuation as being the vertical distance between the h_1 = 10 meter line and the h_1 = 1,200 meter line, and hypothesize that the distance between the h_1 = 1,200 meter line and the FSL line represents the 2-ray multipath losses and other losses.

To test this theory, we determine a set of points across the ITU-R P.1546-2 Figure 1, that have equal receive terminal take-off angles, i.e. where the θ_r is constant. Since clp = C_{HR} / $\sin \theta_{r,}$ and the average clutter height is a constant: if the angle θ_r does not change, the clutter path length, clp, cannot change. The clutter attenuation should then remain the same for each distance where θ_r is held constant. A result showing no change in attenuation per meter across this 19 km portion of path, as its location changes with path

distance, would validate the deterministic theory; or, alternately, would isolate and identify any attenuation due to other causes:

Solving for a held-steady receive take-off angle theta
Figure 1.

sin theta	dist	her	het	1200 line	het line	dB
0.014498	80000	10	1170.0	54.5	54.4	0.1
0.014498	40000	10	590.0	70.25	62	8.25
0.0144985	20000	10	300.0	80	69.5	10.5
0.0144985	10000	10	155.0	86.5	72	14.5
0.0144985	9000	10	140.5	87	73	14
0.0144985	8000	10	126.0	88	74	14
0.0144985	7000	10	111.5	89	74.5	14.5
0.0144985	6000	10	97.0	90.25	76	14.25
0.0144985	5000	10	82.5	92	78	14
0.0144985	4000	10	68.0	94	80	14
0.0144985	3000	10	53.5	96	81.5	14.5
0.0144985	2000	10	39.0	100.5	86	14.5
0.0144985	1000	10	24.5	106	91.5	14.5

First, we note the appearance of a straight, steady attenuation result line from 1 to 10 km, at approximately 14.5 dB, which we will refer to as a “Bouguer” line, for the original discoverer of the scientific concept on which this determination is based. On P.1546-2 Figure 1, if plotted, this line appears to be parallel to, and approximately 15 dB below, the Maximum (free space) line.

We see a counterintuitive <u>reduction</u> in attenuation with distance beyond 10 km. For the test, to hold the sin of θ_r steady, we had to vary the effective transmitter height (h_1) with distance, so the reduction of attenuation due to changes in the average height above the clutter line of the path above the clutter line, a reduction of 4 dB between 10 and 19 km, became evident. This attenuation reduces as the transmitter site height is increased. Since the length of the path through the clp is held steady, this additional effect appears to be varying only with the height of the transmitter, or the length of the path distance.

Therefore, in our test, in addition to the steady clutter loss of 14.5 dB from 1 to 10 km, we find a reduction in loss of 4 dB between 10 km and 20 km that continues to increase with distance; possibly due to an increase in the transmitter height, a change not related to path length change either above or below the clutter line, and not related to the Beer’s law clutter attenuation below the effective clutter line.

As an alternative test, we adjust the spreadsheet by referencing the loss without any consideration of 2-ray or other losses, only free space loss and Beer’s Law loss. To do this, instead of taking the difference between the h_1=1,200 meter line and the

h_1=10 meter line, we take the difference between the Maximum (free space) line as shown on P.1546-2 Figure 1, and the h_1=10 meter line.

Solving for a held-steady receive take-off angle theta
at f = 100 MHz
Figure 2.

sin theta	dist	her	Het	FSL line	het line	dB
0.014498	100000	10	1460.0	66	51	15
0.014498	90000	10	1315.0	67	52	15
0.014498	80000	10	1170.0	69	54	15
0.014498	40000	10	590.0	76	61.5	14.5
0.0144985	20000	10	300.0	80.5	68	12.5
0.0144985	10000	10	155.0	87	72	15
0.0144985	9000	10	140.5	87.5	73	14.5
0.0144985	8000	10	126.0	88.5	74	14.5
0.0144985	7000	10	111.5	89.5	74.5	15
0.0144985	6000	10	97.0	90.75	76	14.75
0.0144985	5000	10	82.5	92.5	78	14.5
0.0144985	4000	10	68.0	94.5	80	14.5
0.0144985	3000	10	53.5	96.5	81.5	15
0.0144985	2000	10	39.0	101	86	15
0.0144985	1000	10	24.5	106.5	91.5	15

Except for a slight aberration at 20 km, the Bouguer line, along which a sliding but fixed-length cluttered path distance, clp, generates a fixed amount of attenuation, now clearly extends from 1 to 100 km! This provides proof that the average clutter height of the measurements used for ITU-R P.1546-2 were, on the average, high enough to practically eliminate all 2-ray plane wave, a.k.a. multipath, reflection effects. From this we can say that the line-of-sight attenuation measured in ITU-R P.1546-2 consists primarily of two components: (1.) Free Space Dispersion, and (2.) Radiative Transfer. We, for purposes of understanding, will consider the three main components of Radiative Transfer Equations as a Beer's Law consideration of cluttered path absorption losses (I_{ri}) muted by Radiative Transfer scatter(I_1) and scatter function(I_2).

Since this proves one of the concepts used to develop the original form of the empirical model in Part I above, to be false, namely, that a small but significant amount of multipath consideration exists, the empirical model provided above has been recalculated to eliminate all current consideration of two-ray multipath effects, as they have proven to be insignificant.

By these tests, the absorptive loss theory presented here for use in developing a deterministic line-of-sight model, namely, attenuation from clutter loss, where the radio path is unobstructed except for passage through, over, and under an absorptive layer of

clutter, computed according to Beer's Law, is validated, in that it is in direct accord with the ITU data.

Solving for the Deterministic Clutter Factor equations:

We now need to quantify our constants and factors, and include a form of Radiative Transfer consideration, for the Beer's Law equation.

The absorption of a single tree at UHF frequencies can exceed 15 dB. Also, if we attempt to calculate AB as a constant at 1 km and at 40 km, at a h_1 = 37.5 meters, the value of AB is orders of magnitude smaller at 40 km than at 1 km. Since AB for a homogenous medium must be a constant, there is a second set of phenomenon at work here; this phenomenon is Radiative Transfer scatter and scatter function.

Our hypothetical simplified framework model for radio signal propagation consists of up to three significant considerations:

For a transmitting antenna at or below the clutter layer, the considerations in addition to FSD are:

1. Absorptive loss of the signal, as it travels vertically (and to some extent, horizontally) up from the antenna to the top of the clutter layer, and back down through the clutter layer to reach the receive antenna.
2. Radiative Transfer scatter and scatter function (surface wave) across the top of the clutter layer.
3. Absorptive loss of the signal that occurs near the start of the cluttered path as the Radiative Transfer scatter and scatter functions build up to swamp out the absorptive loss.

For a transmitting antenna above the clutter layer, the primary considerations in addition to FSD are:

1. Radiative transfer across the top of the clutter layer from where the direct signal path would enter the clutter layer, to the receive antenna.
2. Absorptive loss of the signal, as near the receive antenna, it passes through the clutter layer to reach the receive antenna.
3. Absorptive loss of the signal that occurs near the start of the cluttered path as the radiative transfer function builds up to swamp out the absorptive loss.

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To attempt to start to separate out the Beer's Law absorption factor, AB, from the ITU data, we go to the h_1 = 10 line, where the entire radio signal path is below the clutter canopy line, and clp, the cluttered path distance = d, the flat earth radio path distance. By definition, d_1 the portion of d, the path distance, above which the clp is found, is here also equal to clp, and at h_1 = 10, clp = d = d_1.

$$d_1 = C_{HR}/(\tan \theta_r)$$

On the h_1 = 10 curve, at d=0, $h_1 - h_2 = 0$; clp = 0, and A_{CR} = AB(clp) = 0.
On the h_1 = 10 curve, at d=1000 meters, clp = 1000 meters, and A_{CR} /(clp) $\leq$ AB
At h_1 = 10 (9.375) m., and d= 1 km (1000 meters), A_{CR} = 106.9 – 90 = 16.9 dB, and AB $\geq$ 16.9/1000 = 0.0169 dB/meter: this value has already been reduced by the effect of Radiative Transfer over the first 1000 meters, so we can only say that the constant AB > 0.0169 dB/meter; the loss at 2 km is 100.88 –80.25 = 20.63 dB; less the loss in the first km, the average loss in the second km is only 3.7 dB vs 16.9 dB in the first km; at 4 km, doubling the distance, the loss is 94.86 – 69.5 = 25.36 dB, a 4.7 dB additional loss in 2 km; and an average of 2.4 dB loss in the 3rd and 4th km; so the Radiative Transfer function, f[RT], quickly takes over from direct path propagation as the primary delivery medium of radio frequency field strength at the receive location, even in the first km.

The losses are therefore: A_{CR} = AB(clp) – f[RT] (xxx).

And this general equation includes the considerations for the condition of "at or under the clutter path" mentioned above, as the AB(clp) term includes the entry and exit losses from the transmitter to the top of the clutter layer, and from the top of the clutter layer to the receive antenna.

Even at $h_1 = h_2$, there can be some clutter attenuation loss. Referring to ITU-R P.833-2, Attenuation in Vegetation, Figure 1; note that in this example, the transmitting antenna is the same height as the receive antenna, and $h_1 = h_2$. From the chart, we notice that the moderation of absorptive loss in Radiative Transfer starts at zero at d = 0, where the initial clutter absorptive loss is represented by the straight line on the Excess loss vs. d graph. The loss reduction effect of Radiative Transfer increases with distance, causing the absorptive loss line to bend in a logarithmic manner, reducing to a horizontal line as d increases.

Therefore, for this case, where we can conceptually utilize a homogeneous clutter medium with properties averaged from the sum of the exponential data, it appears that we should be able to utilize the simple exponential function given in ITU-R P.833-2 to approximate all surface wave radiative transfer over clutter in P.1546-2. This function is:

$$Aev = Am [1 - \exp (-d\gamma / Am)]$$

where:

γ , or gamma, the specific attenuation for very short paths, in units of dB/meter. It is, in fact, the same as the absorptive loss factor AB we have used in Beer's Law.

d is the path distance under clp, d_1.

A_m, is the maximum attenuation for one terminal within a specific type and depth of vegetation.

Our analysis of Figure 1, however, does not support the equation given in ITU-R P.833-2, which indicates that the attenuation function reaches a maximum, and therefore ceases

increasing, at a distance. The empirical data on Figure 1, when separated from the FSD, continue to show an increasing attenuation with distance. While the function does follow a logarithmic line, and, at a distance, does approach a horizontal line, it does not achieve it within 1000 km. The use of this equation for a deterministic solution is also limited by the requirement to determine a value for the factor $A_{m.}$

For all cases where the transmitting antenna height, h_1 is not equal to the receive antenna height, h_2, the Radiative Transfer function, f[RT] or RET would vary with the distance d_1, not clp. The distances clp and d_1 are nearly the same at far distance, but near the transmitter, as d, clp and d_1 approach zero, clp approaches the value of C_{HR} as (sin θ_r) approaches 1.0; the function f[RT] approaches 0 as it varies with d_1, which approaches d_1 = (C_{HR} /Infinity) as the (tan θ_r) approaches tan ($\pi/2$) radians, or tan (90°).

Summarizing, At h_1 = 10
At 0 km, $A_{CR[1]}$ = 0, clp = 0, d= 0, and f[RT] = 0
At 1 km, $A_{CR[1]}$ = 16.9, AB > 0.0169 dB/meter
At 2 km, $A_{CR[1]}$ = 20.63
At 4 km, $A_{CR[1]}$ = 25.36

At 2 km, without the surface wave radiative transfer function, (SWRT) i.e. where the clutter layer is so deep that the RET scatter components are minimalized, the attenuation would be at least:

$A_{CR[2]}$ = AB(clp) – f[RT] > .0169 (2,000) – 0 > 33.8 dB.

So in the second km, surface wave radiative transfer is reducing the attenuation by at least:

(33.8 – 20.63) dB / 1 km > 13.17 dB/km

And over the next doubling of distance, reducing the attenuation by at least:

$A_{CR[4]}$ = AB(clp) – f[RT] > .0169(4,000) – 0 > 67.6 dB.
(67.6 – 25.36) dB/ 2 km > 42.24 dB/2 km > 21.12 dB/km

The rate of reduction of the scatter components, including the surface wave of the radiative transfer function, where both the transmitting antenna and receive antenna are below the clutter layer, triples between 1 to 2 km, and 2 to 4 km, a factor of 42.24/13.17 = 3.21. Therefore, we can estimate that the rate of reduction of attenuation for the distance between 0 and 1 km is 13.17/3.21 = 4.1 dB, and therefore the attenuation for the Beer's Law direct ray cluttered path should be at least 16.9 + 16.9/4.1 dB, or > 22.02 dB per kilometer, giving us a new estimate of AB > 22.02/1000, or > 0.02202 dB/meter.

Repeating the above process with AB > .02202 dB/meter, the iteration stabilizes in 10 cycles, with the rate of reduction of 6.2585 dB, resulting in an AB = .019526 dB/meter, and the result is that $A_{CR,}$ in extremely deep, thick clutter where the scatter(I_1) and scatter function (I_2) components of radiative transfer are minimal, and at $h_1 = h_2$, will be:

$A_{CR[Deep\ Clutter]}$ = AB(clp) = .019526(clp) dB = .01953 dB, approximately .02 dB/meter

Which adds up fast; for 1 km, the result would be equal to 19.5 dB below the FSD line, significantly limiting the reception range in deep clutter.

Radiative Transfer

Radiative Transfer, (RTE) as defined in the Generic Model[4], consists of a coherent component, I_{ri}, and an incoherent(diffuse) component I_d. I_d is normally split up and considered as two components, I_1 and I_2. These three major components are:

1. Absorption. This is, plain and simple, the Beer's Law clutter absorption (and associated inseparable scattering loss) we have been considering previously in the discussion. Johnson, Schwering,[3] refers to this as the "first term"; The Generic Model refers to this as the coherent component I_{ri}, defining it as a loss function $e^{-\tau}$ of the "optical density". Here we consider this component in Beer's Law terms of the length of the cluttered path (clp) times the density of the clutter (c, set to 1.0), times the absorption loss rate (AB) of the clutter. It is therefore modeled using a straight-line formula. This absorption function is the base starting function of the RTE. Its loss is first reduced by:

2. Scattering. The Generic Model refers to the two equations that comprise this component, combined, as the component I_1. Johnson, Schwering, refers to this as the "second term." In practice, its effect moderates the absorption loss I_{ri} for a short distance, mid-path, as graphically displayed in Figure 3-18 of the Generic Model. The mathematical model of this term in the Generic model is an exponential term added to a straight line function. The significant part of this term, for the portion of the path where this component controls the results, is primarily contained in the straight line function, so we can approximate this term using a straight line formula.

3. The Scattering Function. The Generic Model refers to this as the non-coherent component I_2; Johnson, Schwering, refers to this as the "third term". In practice, its effect moderates the absorption loss I_{ri}, taking over from I_1 and continuing to the end of all line-of-sight paths. The Generic Model uses an exponential term added to a straight line function to model this component.

Each RTE component controls the loss value during a separate portion of the total path length. The RTE bears a resemblance to a three-stage, variable-leg-length relay foot race; the 1-km distance runner, Beer's Law absorption, starts the race; passing the baton to a 30-meter sprinter, I_1, who then passes the baton to a 10-km runner, I_2. It is therefore necessary to use a MINimum function to separate out the controlling component. The component producing the least loss will therefore be the one "holding the baton" at any given point in the radio path.

Deriving the RTE coefficients from the P.1546-2 data:

At 2 km, where the clutter layer is so deep that I_d (I_1 and I_2) is insignificant, the attenuation would be at least:

$A_{CR[2]}$ = AB(clp) – f[RT] > .0195 (2,000) – 0 > 39 dB.

And in the second km, I_d is reducing the attenuation by at least:

(39 – 20.63) dB / 1 km > 18.4 dB/km

And over the next doubling of distance, reducing the attenuation by at least:

$A_{CR[4]}$ = AB(clp) – f[RT] > .0195(4,000) – 0 > 78.1 dB.
(78.1 – 25) dB/ 2 km > 52.7 dB/ 2km > 26.4 dB/km

A 2.86 times increase for the second doubling of distance.

Therefore, from an analysis of these results, it appears that the a function of the form:

$A_{SWRT} = C_{AB} + b*20\log(d_1 + 1)$ dB, where d is in km, or:

$A_{SWRT} = C_{AB} + b*20\log(d_1/1000 + 1)$ dB, where d is in meters.

Will serve as the form for an initial, interim, simplified RET attenuation (first term)[3] and scatter (second and third term)[3] development equation valid for $d_1 = d \geq 1$ kilometer. At $h_1 = h_2$, C_{AB} should be a constant value, as the RET startup, entry and exit losses should be the same for all d_1 = clp = d. So we should be able to solve for a constant b that will stay approximately the same for all values of h_1 and h_2 when both are below the clutter canopy top, varying only with statistical variation in data, until we reach a point that is level with the top of the clutter layer.

It is expected that C_{AB} will be found to be a function representing the initial absorption attenuation losses, the initial exit loss from the transmitting antenna to the top of the clutter layer, and any final entry loss to the receive antenna. The $b*20\log(d_1 + 1)$ term will represent the I_d loss moderation function for the RET with both terminals below the clutter line, $C_{H.}$ The 1 is added so that the logarithmic function used, a common logarithm, or base 10 function, will properly solve to zero ($20\log_{10}$ of 1/1 is zero dB) when d = 0.

As we increase h_1 to approach the top of the clutter layer, C_{AB} will approach a minimum. These facts we can use to determine the approximate depth of the average clutter layer in P.1546-2.

Solving for the data on each h_1 line starting with 10 meters, and fitting to match the P.1546-2 Figure 1. h_1 = 10 line data, and using d in lieu of d_1, we obtain:

$$A_{SWRT} = C_{AB} + b*20\log(d_1 +1) \text{ dB}$$

At h_1 = 10 meters, $A_{SWRT} = 6.4725 + 1.34795*20\log(d_1 +1)$ dB
At h_1 = 20 meters, $A_{SWRT} = 1.638 + 1.34795*20\log(d_1 +1)$ dB
At h_1= 37.5 meters, $A_{SWRT} = -1.966 + 1.3056*20\log(d_1 +1)$ dB

The negative value of C_{AB} at 37.5 meters, a nonsensical value, indicates that our calculation failed at 37.5 meters because d1 no longer equals d; we have reached and exceeded the top of the average combined terrain roughness and absorptive clutter layer in the P.1546-2 data. Therefore the average terrain and clutter layer canopy top height, C_H, needed to solve for the length of d_1 above the clutter line, lies between 18.375 and 37.5 meters.

We average the multiplication constant for the logarithmic term for h_1 =10 and h_1 = 20, and obtain: 1.34795. Returning to the above calculations, we recalculate A_{SWRT} at 37.5 meters with the averaged logarithmic multiplication constant, for a best fit to the data:

At h_1= 37.5 meters, $A_{SWRT} = -3.049 + 1.34795*20\log(d_1/1000 +1)$ dB

Where d_1, the ground level distance under the clp, is in meters.

Therefore, $C_{AB:}$

1. Reduces from 6.741 dB to 1.638 dB between 10 (9.375) to 20 (18.75) meters.
2. Swings between 1.638 to –3.049, a total difference of 4.687 dB, between 20 (18.75) and 37.5 meters.

$C_{AB,}$ as a below the clutter canopy line function, solves to a near-zero value where the transmitter height equals the average clutter canopy height; so we solve for the zero-crossing point in the below-the-canopy equations above to approximate the average total of the terrain roughness and clutter layer height combined, C_H, and obtain:

$$C_H = 18.75 + 18.75 *1.638/4.687 = 25.30 \text{ meters.}$$

C_{HR}, the portion of C_H above the receive antenna height, h_2 = 10 m., is then:

$$C_{HR} = C_H - h_2 = 25.3 – 10 = 15.3 \text{ meters.}$$

We now have a useable estimate of the average height above ground level of the combined averages of the terrain roughness and ground clutter layer thickness, of C_H = 25.3 meters, and can use the known set of constants to solve for an equation for C_{AB} below the clutter line, and for the constants above it.

This at first appears to be a Beer's Law formula, useable only for $h_1 \leq C_H$. The solution must equal zero at $h_1 = C_H$. This attenuation, $C_{AB,}$ now identified as due to Radiative Transfer launch losses, and a part of I_{ri}, will follow the Beer's Law equation:

$$C_{AB} = AB^* \, clp_{[RTL]}$$

The distance that the signal must traverse through the clutter from the transmit terminal to the top of the clutter layer, clp, must be determined as;

$$clp_{[RTL]} = ((C_H - h_1)^2 + (d_{[RTL]})^2)^{1/2}$$

Where $d_{[RTL]}$ is the ground level distance traversed by the radiative transfer primary ray rising from the transmitter antenna to the clutter layer canopy.

On attempting an iteration to solve with the two data lines provided, $h_1 = 10$ and $h_1 = 20$, solving at $d_{RTL} = 0$, where $clp = (C_H - h_1)$, we find that AB is a function with infinite solutions, such that for each value of AB calculated, there is a primary ray launch angle from the transmitter, $\theta_{e,}$ that solves the equations:

$$C_{AB} = AB^* \, clp_{[RTL]}$$
$$clp_{[RTL]} = (C_H - h_1)/ \sin \theta_e$$
$$(\sin \theta_{e[h1=20]}) = 1.91(\sin \theta_{e[h1=10]})$$
$$AB_{[h1=10]} = .44(\sin \theta_e)$$
$$AB_{[h1=20]} = .23(\sin \theta_e)$$

This indicates that an exponential parabolic solution exists for RTE component I_d. Since we are solving for a value of field strength loss, instead of a value of power received, the curves to solve these equations would match the inverse of the exponential *Sum of Contributions* curves in the Generic Model, Figure 3-18. The inverse of an exponential function is a logarithmic function. It has already been found and shown that a single term of this logarithmic function is adequate to approximate the RTE I_d functions at or below the clutter canopy top, where $clp = d = d_1$.

Which parallels the Weissberger Modified Exponential Decay Model (MED), the COST 235 [COST235, 1996] model, and the ITU model, in that it proposes an exponential mathematical model of loss that rapidly increases from zero over a short distance, and then nearly plateaus with an increasingly smaller increase in loss per km with increasing distance. These three models, however, are empirical models. The RTE is the deterministic model emulated here. This model is attempting to approximate the combined result of the RTE, in a grossly simplified approximation of the RTE model presented in the Generic Model, appropriate to the data that can be derived from the P-1546-2 over-land 50% reliability curves. This simplification is made possible by the homogeneity of the clutter and terrain roughness information present in the P.1546-2 over-land figure curves.

Deriving from the Generic Model, and inverting the exponential functions into decibel logarithmic functions for field strength loss calcuation, the form it would follow would be:

$$A_{RTE} = MIN(I_{ri} , I_d) = MIN(I_{ri} , MIN(I_1, I_2)$$

$$A_{RTE} = MIN((AB*(clp)), MIN((20log(a_1d_1 + c_1)),(20log(a_2d_1 + c_2)]))) \quad dB$$

Our model splits the RTE into three competing terms, the lesser of which at any given location controls the output of the function. The first, I_{ri} term is the straight-line function of the absorptive loss line function(s) following Beer's Law. For the at-or-below canopy computations, it will be split into rising signal clutter absorption loss C_{AB} and Radiative Transfer absorptive launch loss, C_{AB2}. It is reduced by terms two and three, as the amount of the absorptive loss is undermined by the increasingly lessening loss-per-distance-traversed double exponential curve of the I_d clutter scatter and canopy scatter surface wave functions. For the first 250 meters of canopy path distance, the I_{ri} term produces the lowest loss; therefore, the results of the I_d functions do not take significant effect for this distance. Generally speaking, the I_1 function, the second term, then takes control, producing the lowest loss results for a short portion of the clutter canopy distance; at the end of this distance, the I_2 function, the 3rd term, then starts to produce the least loss, and takes final control of the results to the end of the line-of-sight.

For at or below the canopy, it appears that we can use only a single logarithmic term to adequately approximate the RTE I_d function. Above the canopy, it is expected that to calculate the I_d function, it will have to be split into the I_1 and I_2 terms, and both will need to be calculated to adequately approximate the h_1 curves.

It will be necessary to consider both the straight line and exponential components of the I_2 term; but the active portion of the I_1 term, where its losses are less than the I_{ri} and I_2 terms, can be approximated with a straight line function, and will be derived last.

<u>Solving for the RTE terms at or below the clutter canopy line:</u>

Using 2 points to solve for the RTE field strength attenuation losses at or below the clutter canopy line ($A_{RTE-ABC}$), in order to obtain the I_{ri}, or first term, absorptive functions, C_{AB} and C_{AB2}, at or below (ABC) the clutter line:

at h = 10 (9.375) meters, $C_H - h_1 = 15.9277$ meters = $clp_{[RTL10]}$
at h = 20, (18.75) meters, $C_H - h_1 = 6.5527$ meters = $clp_{[RTL20]}$

Iterating for a best fit of C_{AB} along the $h_1 = 10$ and $h_1 = 20$ curves using a log constant of 1.34795 and a $C_H = 25.30$ meters, using: $A_{RTE-ABC} = C_{AB} + 1.34795*20log(d_1 +1)$ dB, where $d_1 = d = clp$, results in:

$AB_{[RTL10]} * clp_{[RTL10]} = C_{AB10}$
$AB_{[RTL10]} = C_{AB10} / clp_{[RTL10]} = 6.4725 / 15.9277 = 0.40637$
$AB_{[RTL20]} = C_{AB20} / clp_{[RTL20]} = 1.638/6.5527 = 0.249973$

Leaving to solve:

$$RTRI1 = c - b*\exp(C_H - h_1)^{-1} \text{ dB/meter}$$

$$0.40637 = c - b*\exp(15.9277)^{-1} \text{ dB/meter}$$
$$0.249973 = c - b*\exp(6.5527)^{-1} \text{ dB/meter}$$

This solves to be:

$$RTRI1 = 2.06943 - 1.56184\exp(C_H - h_1)^{-1} \text{ dB/meter}$$

Since the reduction in the RTRI1 function with an increase in $d_{[RTL]}$ is such that as $d_{[RTL]}$ increases, RTRI1 reduces to match, any change in RTRI1 is then related only to an equivalent change in $(C_H - h_1)$. Since this function is only sensitive to changes in path height, it acts as a vertical vector component of I_{ri}, and will not change with path distance. This results in:

$$C_{AB} = AB* clp_{[RTL]} = RTRI1(C_H - h_1)$$

$$C_{AB} = (C_H - h_1)(2.06943 - 1.56184\exp(C_H - h_1)^{-1}) \text{ dB/meter} \qquad \text{(xxx)}$$

<u>Absorption Loss in the Radiative Transfer Launch Range; the second part of I_{ri}.</u>

In addition to the rise function above, a trans-clutter path absorptive loss function, component I_{ri} of the RTE, which follows Beer's Law, does briefly appear at the beginning of the radio path when the transmitter is below the clutter layer canopy, and is quickly swamped by the rapidly lessening loss of the radiative transfer I_d function. Therefore, while this absorption loss alone would follow the function:

$$C_{AB2} = AB* d = AB* d_1$$

The equation is then modified to include a decay exponent, to reflect the swamping, or bypass increasing with distance, of its effect by the radiative transfer function:

$$C_{AB2} = ce^{bd1}$$

As the rise path shortens, the absorptive path assumes a higher percentage of the total path length, thereby increasing the total absorption; this is accommodated by making the constant c into a function of a straight line, $c = x - a(CH-h_1)$. A best fit to the data is then achieved with:

$$C_{AB2} = ce^{bd1} = (x - a(CH-h_1))e^{bd1} = (17.98 - .84224(CH-h_1))e^{-.61(d1/1000)} \quad \text{(xxx)}$$

Where d, the path length, is in meters.

b, the radiative transfer exponential swamping delay coefficient, is –0.00061

x and a are chosen, using a straight line function, to fit the increase found between the $h_1 = 10$ and $h_1 = 20$ meter curves.

Since this function is sensitive to changes in distance, it acts as a horizontal vector component of $I_{ri.}$ Which we add to the full radiative transfer function approximation equation for below or at C_H:

$$A_{RTE\text{-}ABC} = C_{AB} + C_{AB2} + 1.34795*20\log(d_1 +1) \text{ dB,}$$
(xxx)

where:

$$C_{AB} = (C_H - h_1)(2.06943 -1.56184\exp(C_H - h_1)^{-1}) \text{ dB/meter} \quad \text{(xxx)}$$

and:

$$C_{AB2} = (17.98 - .84224(CH-h_1))e^{-0.00061(d1)} \quad \text{(xxx)}$$

where d_1, C_H and h_1 are in meters.

Which should be used with an "if" statement, as the above equations are valid only for $h_1 \leq C_H$. If $h_1 > C_H$, The equation for C_{AB} disappears, and the equation for C_{AB2} takes a significantly different form.

<u>RTE Above the Clutter Line</u>

Several changes occur in the set of propagation phenomena when the transmitter height rises above the clutter layer while the receiver remains below the clutter layer. The logarithmic form of the term I_d of $A_{RET\text{-}ABC}$, namely $c*20\log(d_1 +1)$, must be split and expanded to the fuller form of:

$$I_d = MIN(I_1, I_2)$$

And the full form will then include:

Attenuation from RET above clutter:

$$A_{RETA} = MIN(I_{ri} ,MIN(I_1, I_2)$$

And would theoretically follow the form of:

$$A_{RETA}= MIN(AB*crp/TC,MIN((c_{I1}*AB*crp+c_1*\exp(1/d_1)),(c_{I1}*AB*crp + c_1*\exp(1/d_1)))$$

In order to match the functional description of the three terms, I_{ri}, I_1 and I_2, given in the Generic Model, section 3.6.4.

Above the clutter canopy, the radio signal will follow a two-ray path: from the transmitter to the clutter canopy, and through the clutter canopy to the receiver. Due to the effect of Snell's law, these two rays will not form a straight line. AB above the canopy will be multiplied by a function relating to T, the transmission coefficient, varying with the angle of incidence of the direct ray into the clutter canopy, according to the Fresnel equations. The angle of incidence, θ_i, the angle of the actual radio path with respect to the vertical (y) axis, will have to be calculated from Snell's Law, using the refractive indices of the atmosphere and the clutter canopy. The C_{AB} rise absorption function disappears above the canopy. The C_{AB2} function equation changes; as it now represents the radiation transfer effect launch losses from a signal arriving above the clutter canopy.

<u>Absorption above the Clutter Canopy</u>

We look primarily to the 1 km data on each h_1 meter curve above the canopy, to determine and verify the equation for C_{ABA} (C_{AB2} above the clutter canopy), as the initial values of these curves represent only Beer's Law absorptive losses. On the h1= 1,200 m. curve, due to the effect of Snell's Law, it is determined below that the actual radio path traversed will not be long enough for the RTE I_d terms to have effect. In the primarily line-of-sight range, all losses will be Beer's Law absorption losses, i.e. RTE I_{ri} or first term losses.

The absorption loss alone follows the function:

$$C_{ABA} = AB^* \, crp/TC$$

Where T is the relative transmission coefficient of the incoming ray as per Snell's Law; a ratio representing the amount of incoming radio signal that will be transmitted through the clutter layer to the receive point. C will represent any other residual transmissive coefficient, including consideration of clutter orientation and reduction in T due to terrain roughness. The term crp represents the actual <u>c</u>luttered <u>r</u>adio <u>p</u>ath length through the clutter as reduced by the effect of Snell's Law.

There are three considerations associated with this coefficient, related to the ratios of the refractive indices and dielectric coefficients of the two mediums, air and clutter layer.

1. The variation in the actual path of the radio signal, from the direct path between the transmitter and the receiver, caused by the difference between the incident angle of the refracted signal vs. a theoretical direct ray between the transmitter and the receiver. This difference causes the actual path refraction point on the clutter canopy to be farther from the transmitter than the theoretical direct ray, and requires a reduction adjustment in the length of clp

(the new value is identified as crp) and d_1. This adjustment reduces the absorptive and radiative transfer losses.

2. The (actual) transmission coefficient, T, is a ratio of the signal arriving at the clutter layer top that is transmitted downward by refraction through the clutter layer to the receive point, relative to the signal arriving from the transmitter. The effect of the application of this coefficient would be to increase the loss.

3. The approach of the reflection coefficient toward 1.0 (and the associated approach of the transmission coefficient to zero) at low grazing angles over rough surfaces, as revealed by Barrick[2]. At great distances from the transmitter site, or for very low transmit height, this would significantly reduce the reception by direct transmission through the canopy, and theoretically minimizes the direct signal absorptive loss components from the calculation at a significant distance from the transmitter, leaving primarily the surface wave I_2 component of the RTE to transfer energy to the receive site.

To solve for T requires the values of the cosine of the incident ($\cos \theta_i$) and transmissive ($\cos \theta_t$) angles. To obtain these in a spreadsheet or in computer code, it is first necessary to iteratively solve, using Snell's law, for the values associated with the actual radio signal path.

<u>The Actual Radio Signal Path</u>

The center of the path of the radio signal does not follow the theoretical straight-line direct path ray from the transmitter, through the clutter canopy, to the receiver. Instead, by Snell's law, the angle of the refracted ray from the clutter canopy to the receiver, with respect to a vertical line, (which we will refer to as the transmissive angle, θ_t), is related to the incident angle, θ_i, of the actual path line between the transmitter and the clutter canopy with respect to a vertical line, by the Snell's law formula:

$$\sin \theta_i / \sin \theta_t = \eta_g / \eta_s \qquad \text{(xxx)}$$

where:

η_g is the refractive index of the ground (clutter)
η_s is the refractive index of the atmosphere at the surface of the clutter canopy layer

The differences this makes in the transmitter take off angle, the receive take off angle, the uncluttered radio path length (urcp) and the cluttered radio path (crp), for what is now a two-ray calculation (here used for refraction, not reflection), can be most efficiently solved on a spreadsheet in a three cycle iteration (or, in code, an iteration repeating until the level of accuracy required is achieved). First, it is necessary to determine the values of θ_i and θ_t; this requires the refractive indicies of air and the clutter canopy.

The refractive indicies of air, ground (clutter), and water

It is necessary to determine the refractive indices, or a reasonable working estimate thereof, for air and for the clutter layer. The refractive index of a vacuum is, by definition, the minimum value of $\eta_v = 1.0$. The refractive index of air is about 1.0003; of water is about 1.33. In field application, microwave ellipsometry can be used to determine the refractive index and thickness of a layer of vegetation over a soil of known refractive index.[5]

The atmospheric radio refractive index η can be computed from N, the radio refractivity:

$$\eta = 1 + N * 10^{-6} \qquad \text{[ITU-R P.453-7, (1)]}$$

In ESSA Technical Report ERL 79-ITS 67,[8] (ITS-67), Longley and Rice stated that the surface refractivity can vary between 240 to 400 N-Units, and that a commonly used value of Ns is 301 N-units.

N_0 is the refractivity of the atmosphere reduced to sea level; N_s, the surface refractivity, is derived from N_0 using the equation:

$$N_s = N_0 \exp(-0.1057\, h_s) \qquad \text{[ITS-67, (2)]}$$

Where the elevation h_s is determined at the base of the lower antenna for line-of-sight paths. Then:

$$\eta_s = 1 + N_s * 10^{-6}$$

Can be adjusted for height of the ground above sea level using:

$$\eta_s = 1 + N_0 * 10^{-6} * \exp(-h_s / h_0) \qquad \text{[ITU-R P.453-7, (8)]}$$

Therefore, for $N_s = 301$, the equivalent, commonly used value of the atmospheric refractive index at ground level is:

$$\eta_s = 1.000301$$

With a commonly found variation range of $\eta_s = 1.000240$ to 1.0004, primarily affected by a combination of relative humidity and ambient temperature.[6] Recent experimental phased array weather radar tests have shown that the refractive index of the atmosphere is most stable, and converges on a value of $\eta_s = 1.00031$, in cold weather. In warm weather, near 38 degrees Centigrade (100° F), a relative humidity (RH) of 0% can result in an $\eta_s = 1.000250$; a RH of 75% produces a $\eta_s = 1.0004$; and a RH of 100% produces a $\eta_s = 1.0005$.

For the reflecting/transmitting surface, for a radio signal, the refractivity of the ground, η_g, is defined as the characteristic impedance of the dielectric:

$$\eta_g = 1 + N_g*10^{-6} = (\mu_r \varepsilon_r)^{1/2}$$

where:

μ_r is the relative permeability, and ε_r is the relative permittivity

Parker and Makarabhiromya[10] found a relatively narrow range of μ_r and ε_r for tropical vegetation ranging from forests to underbrush for VHF frequencies $\leq$ 100 MHz:

$$1.0 < \varepsilon_r < 1.1$$
$$0.8 < \mu_r < 1.1$$

and for HF frequencies;

$$0.9 < \varepsilon_r < 1.2$$
$$0.8 < \mu_r < 1.1$$

These results are suitable for modeling for horizontal polarity. The approximation first considered, is an $\varepsilon_r = 1.05$, and a $\mu_r = 0.95$;

$$\eta_{gc} = (\mu_r\varepsilon_r)^{1/2} = (1.05*0.95)^{1/2} = 0.99875$$

From Snell's Law, the relationship between the refractive indices for ground, η_g, and air, η_a, and the incident incoming angle, θ_i, and incident transmission angle, θ_t, for an air to ground (tropical clutter canopy) refraction point is:

$$\sin(\theta_i)/\sin(\theta_t) = \eta_g / \eta_a = 0.99875/1.0003 = 0.998449,$$

and over land and vegetation, $\sin\theta_i$ is very close to $\sin\theta_t$. However, this difference is significant. If they are equal, it means the indices of refraction are equal, the equivalent of no boundary at all. The cosine terms in the Reflectance equation cancel out, causing the Reflectance coefficient to equal zero and Transmission coefficient to be 1.0; the results expected of no difference in the two mediums. Which raises an interesting side note; since the range of the ground coefficients can swing through 1.0003, can $(\mu_r\varepsilon_r)^{1/2} = \eta_s$? At that point, the Reflectivity near vertical would null out to zero in the associated tropical foliage.

Our target area is more temperate; for P.1546-2, we need to consider foliage and other clutter in the continental Europe and the U.S.; for these areas, a more common range of ε_r used by Tamir[11] [12] is from $1.01 < \varepsilon_r < 1.5$, providing a midrange point of 1.03. Tamir used a conductivity of the plant material value of $10^{-5} \leq \sigma \leq 10^{-3}$, and $\mu_r = 1.0$.

This produces:

$$\eta_g^{\,2} = \varepsilon_r + i60\lambda_0\sigma./1 = 1.03 + i60\lambda_0\sigma$$

With an imaginary component varying with the frequency:

At: 50 MHz, $\eta_g = (1.03 + i0.00073)^{1/2}$

1,300 MHz, $\eta_g = (1.03 + i0.00020)^{1/2}$

For now, it is adequate to approximate using only the real value, $\eta_g = 1.015$.

So: $\sin(\theta_i)/\sin(\theta_t) = \eta_g / \eta_a = 1.015/1.0003 = 1.0147$.

$$\sin(\theta_i) = 1.0147(\sin(\theta_t))$$

Water has a η_{H2O} of 1.33; the signal will refract into water at a steeper angle than into clutter; for water, $\sin\theta_i / \sin\theta_t = \eta_{H2O} / \eta_a = 1.33/1.0003 = 1.3296$.

Incident angles are measured with respect to the vertical, or y-axis. In radio communication, it is more common to work in terms of the grazing angle, the angle between the horizontal (ground, or x axis), and the transmitter, and the ground and the receive point.

The radio path-lengthening effect for air to canopy is minor; it adds 100 meters in 1,000 km. Therefore, it is not necessary, except for high accuracy situations, to revisit the FSD calculation to include the additional path length due to refraction. But the effect of the change in ratio of uncluttered path length to cluttered path length is significant.

<u>Calculation of the actual radio signal path parameters</u>:

Step 1: calculate the earth curvature correction angle for the actual earth radius, $\theta_{\Delta e}$:

$$\theta_{\Delta e} = d/r$$

where: d is the total flat-earth radio path length from transmitter to receiver
r is the actual earth radius: 6,378,137 meters.

Step 2: calculate the earth curvature height; hc: $hc = (CH + r)(1 - \cos(\theta_{\Delta e}))$

Step 3: calculate the equivalent curvature flat distance, dx: $dx = (CH + r)\sin(\theta_{\Delta e})$

Step 4: calculate the un-cluttered radio path w/earth curvature correction; ucrpc:

$$ucrpc = [(h_1 - CH + hc)^2 + (dx)^2]^{1/2}$$

Step 5: calculate the cosine of the flat earth incident angle; $\cos(\theta_I')$:

$$\cos(\theta_i') = (h_1 - CH + hc)/ucrpc$$

Step 6: calculate θ_i': $\theta_i' = \arccos[(h_1 - CH + hc)/ucrpc]$

Step 7: calculate the total incident angle; θ_{ic}: $\theta_{ic} = \theta_i' + \theta_{\Delta e}$

Step 8: calculate the sin of the total incident angle; $\sin(\theta_{ic}) = \sin(\theta_i' + \theta_{\Delta e})$

Step 9: calculate the sin of the transmission angle, θ_{tc} : $\sin \theta_{tc} = (\eta_a / \eta_g)(\sin(\theta_{ic})$

Step 10: calculate θ_{tc} : $\theta_{tc} = \arcsin [(\eta_a / \eta_g)(\sin(\theta_{ic})]$

Step 11: calculate cos θ_{tc}: $\cos(\theta_{tc}) = [1 - \sin^2(\theta_{tc})]^{1/2}$

Step 12: calculate the cluttered radio path with earth correction; crpc:

$$crpc = (CH - h_2)/ \cos(\theta_{tc})$$

Step 13: calculate the sin of the grazing angle Ψ; $\sin \Psi = (\pi/2 - \theta_{ic})$

Step 14: calculate the clutter canopy surface distance; d_{1a}: $d_{1a} = crpc(\sin(\theta_{tc}))/(1 - 1/r)$

Step 15: repeat steps 1 to 13 using a new d' = d (actual value) - d_{1a} until the required accuracy is obtained; for spreadsheet calculation, three iterations are adequate.

<u>The Transmission Coefficient</u>

Again, we will need: $\eta_a = 1.0003$
$\eta_g = 1.015$ for over cluttered land, or 1.33 for water.
$\theta_t = \theta_{rto}$
$\theta_i = \arcsin(1.0147\sin(\theta_t))$

The transmission coefficient, T, is defined as: T = 1- R, where R is the Reflection Coefficient.

While $\eta_g = 1.015$ was used as a starting point, calculation iteration has shows that the optimal value of η_{cc} for the average clutter canopy, for matching the ITU-R P.1546-2 curves to deterministic equations, has proven to be: $\eta_{cc} = 1.0010$

The reflection coefficient, R, calculation is different for horizontal and vertical polarization:

$$R_H = [(\eta_a \cos(\theta_i) - \eta_g \cos(\theta_t))/((\eta_a \cos(\theta_i) + \eta_g \cos(\theta_t))]^2$$
$$R_V = [(\eta_a \cos(\theta_t) - \eta_g \cos(\theta_i))/((\eta_a \cos(\theta_t) + \eta_g \cos(\theta_i))]^2$$

The Transmission coefficient, T, is:

$$T_H = 1- R_H , T_V = 1- R_V$$

The P.1546-2 curves are not separated by polarity, and must be treated as circularly polarized; half of the horizontal polarity result is added to half of the vertical polarity result:

$$T_C = 1- 0.5R_H - 0.5 R_V$$

For an air to clutter canopy interface, a θ_t = 0.69, and a h_1 = 1,200; which describes a receive site near the transmitter site;

cos (θ_t) = .77322, and cos (θ_i) = 0..76548
R_H = 0.000152
R_V = 0.000005
$R = 0.5R_H + 0.5R_V$ = 0.000075
T = 1 – R = 0.99992

Or, for practical purposes, R = 0, T = 1 near the transmitter site.

A higher result is obtained if the calculation also considers the imaginary, or phase, component of ε_r. If the two reflectance indicies are, in fact equal, or nearly so, there is no or minimal reflection, and there is full or nearly full transmission. If the two mediums have the same index of refraction it is equivalent to no boundary at all.

For other selected path lengths at h_1 = 1,200, we obtain:

At h1=1,200		
D	R	T
km		
1	7.85E-05	0.9999
5	0.010598	0.9894
10	0.074045	0.926
40	0.501144	0.4989
50	0.574967	0.425
100	0.757943	0.2421
1000	0.972665	0.0273

With increasing distance, and increasing incident angle, the Reflectance coefficient, R, increases, and the transmission coefficient, T, decreases, reducing the transmission into the canopy and leaving the RTE and forward reflection as the primary propagation mechanisms functioning at far distances.

So we can see that, from Snell's Law, the horizontal polarity and vertical polarity reflectance increases significantly with distance, at slightly different rates. This reduces the percentage of the total radio signal that is transmitted directly into the clutter canopy as the path distance increases, and the receive site grazing angle decreases. This serves to reduce the value of T at a distance, as observed in the P.1546-2 data. Additional detail can be observed on the accompanying electronic spreadsheets.

It also may be possible and necessary to add additional value to the additional transmittance coefficient C, currently set at 1.0, as there may be additional factors, such as the orientation of the components of the clutter, and the effect of terrain roughness on the Reflectance coefficient, to be compensated for. Snell's law, however, goes a long way toward explain the effects documented by Barrick at low grazing angles.[2]

The consideration of the transmissivity coefficient, and the significant change in the length of the cluttered radio path, crp, versus the temporarily considered direct path, clp, is accommodated by modifying our Beer's Law equation for the RTE I_{ri} term:

$$C_{ABA} = AB*crpc/ TC \qquad (xxx)$$

<u>The direct "cluttered path", clp versus the actual "cluttered radio path", crpc:</u>

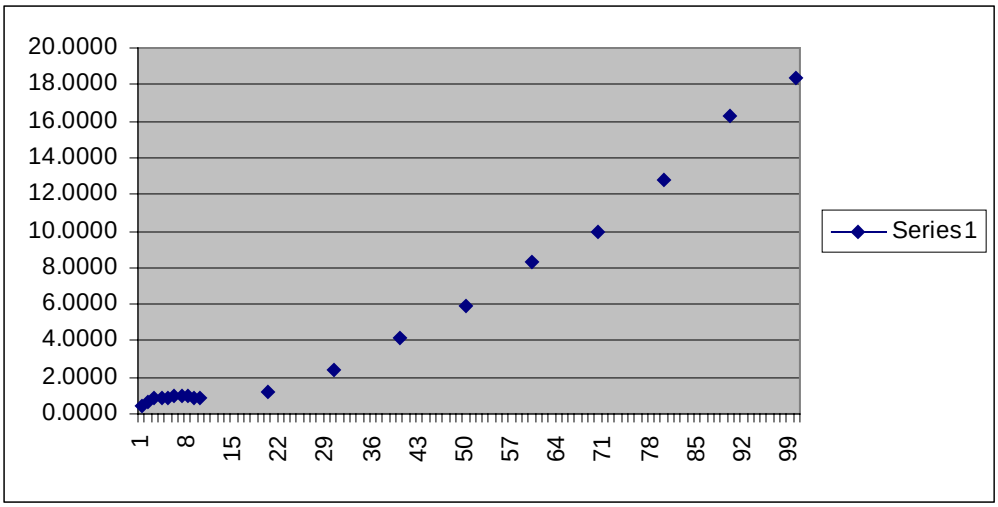
The length of the cluttered radio path, due to the Snell's angle change at the clutter canopy, is very significantly less than the direct ray path from the transmitter to the receiver. As θ_{ic} approaches 1.57 radians, i.e. the transmitter to clutter entry point ray approaches the horizontal, θ_{tc} stabilizes near 1.4004 radians for an air to clutter interface. At d = 80 km, with h_1 = 1,200 m., the portion of the direct ray that would pass through the clutter layer, clp, would be 1,029 meters; but due to angle of the refracted transmission ray, the actual radio path, crpc, has stabilized near 89.9 meters, and will not exceed 90.25 meters at d = 1,000 km! This would tend to explain why minimal re-entry RTE term I_d losses were discernable; the re-entry path is significantly shortened by the effect of Snell's Law.

<u>Absorption Losses above the Clutter Line</u>

We have previously derived an estimate from the P.1546-2 data, for AB in clutter deep enough that radiative transfer does not function, of 0.0195 dB/meter. We continue to use this above the clutter line, but have also added consideration of the Snell's Law refractive transmission coefficient, T, to accommodate the "clutter canopy variable signal splitter" represented by the reflected energy versus the transmitted (into the clutter) energy at the air to canopy top interface. T will vary with the incidence angle of the radio signal.

As a result of the significant shortening of the cluttered radio path by the effect of Snell's Law, the losses on the h_1 = 1,200 m. line of P.1546-2 out to 3 km are all Beer's Law absorption losses, a.k.a. RTE I_{ri} term losses; as the actual length of the canopy top traversed, (d_{1a}), due to the action of Snell's Law, is only 15 to 50 meters; not long enough for the RTE I_d term phenomena to overtake the I_{ri} losses. Study of the curves resulting from plotting the non-FSL losses vs. distance indicate that the Beer' Law absorption losses apply for up to the first 50 meters of clutter canopy path length; from 50 meters to 305 meters, a second set of I_d effects provide the lowest losses; and from 305 meters onward, a third set of loss phenomenon are the controlling function. This can clearly be seen on the following h_1 = 1200 chart, where the initial, climbing I_{ri} loss line gives way to a relatively flat I_d line, which then transitions to a climbing flat curve:

Figure 1; Non-FSL losses in dB (y-axis) vs. d, total radio path distance in km. (x-axis) for h_1 = 1200 meters.



The three distinct sections to the curve suggests that they represent the I_{ri}, $I_{1,}$ and I_2 Radiative Transfer functions; but the Generic Model indicates that the length of path distance that the I_1 function controls is short compared to the I_{ri} function, and could be expected to be less than 15 meters in terms of canopy top (d_{1a}) distance. This would make it difficult to discern in the data used, representing at most a single point. It is now assumed that the relatively flat area in the above chart from d = 3 km to d= 20 km is the combination of the $I_{1,}$ and I_2 functions of the I_d function, and that the rising curve past 305 meters of d_{1a} distance (20 km in the h_1 = 1200 m. chart) represents a third set of Snell's Law-related RTE phenomenon, here referred to as I_3, not quantified in the Generic Model. This I_3 mode continues to the horizon, where the controlling propagation function transitions to a post-horizon diffraction mode. The data has been analyzed, identifying specific phenomenon related to distances and heights, describing them in equations, and subtracting the results to serially uncover layers of data leading to the equations quantifying this I_3 phenomenon.

<u>Approximation equations for the RTE Id (I_1 and $I_{2,}$) functions:</u>

Two equations were derived to match the I_d data in P.1546-2; both apply to situations where the transmitter is above the canopy top, and the canopy top distance (d_{1a}) exceeds 250 meters. The first derives only from the h1 = 1,200 meter line, and are arbitrarily assumed to apply only to h_1 > 1,000 m:

The entire function relates to the canopy top distance, d_{1a}; which forms the primary distance component of a Beer's Law distance times loss/distance construct, with the absorption and dispersion loss term containing a total path distance-related term. The I_d, or combined I_1 & I_2 function approximation for f= 100 MHz, with h_1 at or above 1,000 m. is;

$$I_{1,2[h1>1000m]} = d_{1a}[0.03\exp^{(-.14d)}] - (0.7d - 1)*(h_2/h_1) \qquad \text{(xxx)}$$

The h1 = 1,200 line is missing incorporation of the vertical path length extension loss at locations near the transmitter site. The fact that the approximation equations for the RTE function at the h_1 = 1,200 line also do not match those for all other lines above the clutter line, is additional evidence that the data source and computation of the h_1 = 1,200 line may need review.

For f =100 MHz, and h_1 between 1,000 meters and the canopy top, the I_d equation changes to:

$$I_{1,2[h1>1000m]} = d_{1a}[0.07\exp^{(-.17d)}] - (0.7d - 1)*(h_2/h_1) \qquad \text{(xxx)}$$

<u>Approximation equation for the RTE I3 pre-horizon clutter-top diffraction function:</u>

The I_3 function applies for d1a distances greater than 300 meters up to the past-horizon point where diffraction loss is less, or up to a major path obstruction. The entire function relates to the canopy top distance, d_{1a}; which forms the primary distance component of a Beer's Law construct, with the absorption and dispersion loss terms containing two path distance-driven terms, and an effective transmitter height term. The I_3 approximation for f= 100 MHz, with h_1 above the clutter canopy and h_2 below the canopy, has been discerned by staged subtraction and regression to be:

$$I_3 = d_{1a}\,[0.00055d_{[km]} + \log(d_{[km]})(0.041 - 0.0017(h_1)^{1/2} + 0.019] \qquad \text{(xxx)}$$

The logarithmic form of the RTE terms of $A_{RET\text{-}AC}$ must be redefined and expanded to the fuller form of:

$$I_d = MAX(MIN(I_1,I_2), I_3)$$

And the full form of the sum equation for Attenuation from RET above clutter will be:

$$A_{RET\text{-}AC} = MIN[\, I_{ri}\, ,MAX(MIN(I_1, I_2), I_3)] \qquad \text{(xxx)}$$

For multiple computer calculations, it may be useful to limit the consideration of I_{ri} to a maximum calculation distance of $d_{1a} \leq 60$ meters, and to limit the consideration of $I_{1,2}$ to a maximum calculation distance of $d_{1a} \leq 350$ meters.

<u>At and beyond the horizon; transitioning to beyond-the-horizon diffraction:</u>

Analysis of the remaining data on P.1546-2 Figure 1, produces the following equation for diffraction losses beyond the horizon transition point for f= 100 MHz, consisting of the combination of a distance term, 0.0665d + 48.35, and a relative transmitter height term:

$$A_{DIFF[100MHz]} = 0.0665d + 48.35 - .356(h_1\text{-}h_2)^{1/2}$$

The results of this equation apply where the value produced is less than the RTE I_3 term, or in all cases beyond the horizon, defined as where the combination incident angle above the clutter canopy, θ_{ic}, is greater than 1.59 radians.

Frequency Compensation for other than 100 MHz

Up to this point, we have derived only from Figure 1, with a frequency = 100 MHz. We now turn to an analysis of the change in the functions with frequency, derived from the f = 600 MHz and f = 2,000 MHz over-land figures.

Frequency Compensation for beyond-the-horizon Diffraction

The diffraction function contains frequency compensation requirements. From basic knife edge diffraction theory, we expect the frequency compensation equation for diffraction to follow a form of:

$$A_{freq} = 20\log[(1/\lambda)^{1/2}]$$

Where λ, the wavelength of the frequency, is equal to c/f, c is the speed of light in km/sec and f is the frequency in MHz. Carrying the square root across the logarithmic function, and substituting a constant, a, for the equivalent of 10log(c), we obtain:

$$A_{DIFF}\ \text{Frequency Compensation} = 10\log(f_{MHz}) + a \qquad \text{(xxx)}$$

Incorporating this frequency compensation into the earlier 100 MHz diffraction equation results in:

$$A_{DIFF} = .072d - 0.45(h_1)^{1/2} + 10\log(f_{MHz}) + 27 \qquad \text{(xxx)}$$

This diffraction equation, incorporating height and frequency compensation, proves to be adequate to stand alone to approximate the diffraction attenuation in addition to the FSD, over land, from the horizon or first major pre-horizon obstacle to 1,000 km, for all transmit and receive heights and frequencies within the range of P.1546-2.

Frequency Compensation for the RTE I_3 Function:

For the RTE Id functions I_3, the frequency compensation required swings from slightly negative to positive with distance, with an intercept point controlled by the transmitter height above clutter canopy top. Two equations describe the compensation: a negative compensation term applies prior to the zero intercept point, and a positive compensation term applies after the zero intercept. The frequency compensation equations to be added to the result of the RTE I_3 computation each consists of a frequency and transmitter-

height-controlled gain term multiplied by a distance term based on the distance from the zero intercept:

$$\text{Zero intercept point} = 1.5(h_1 - CH)^{1/2} \text{ meters} \quad \text{(xxx)}$$

$$\text{If } d > 1.5(h_1 - CH)^{1/2}, FCI_{3B} \text{ applies; if not, } FCI_{3A} \text{ applies.} \quad \text{(xxx)}$$

$$FCI_{3A} = [-20((\mathrm{Log}(f_{MHz})-2)/(h_1)^{1/2}]*[(1.5(h_1 - CH)^{1/2} - d_{[km]})/1.5(h_1 - CH)^{1/2}) \quad \text{(xxx)}$$

$$FCI_{3B} = [10.2((\mathrm{Log}(f_{MHz})-2)/(100-1.5(h_1 - CH)^{1/2})]*[d_{[km]} - 1.5(h_1 - CH)^{1/2}] \quad \text{(xxx)}$$

<u>Frequency Compensation for RTE I_d (I_1 and I_2):</u>

For the RTE Id function Id (I_1 and I_2), the height and frequency compensation approximation equation term to add to the result of the RTE computations solves to be:

$$A_{RTEfc} = -((\log(f_{MHz})-2)*(h_2/h_1) \quad \text{(xxx)}$$

<u>Frequency Compensation for the Beer's Law – RTE I_{ri} component</u>

There is no frequency (i.e. color or wavelength) consideration noted in Beer's Law. Therefore, we find, for now, that the Beer's Law absorption function, AB, as used for the RTE I_{ri} function, does not appear to be significantly frequency dependent. No frequency compensation will be included in these approximations for the direct absorption I_{ri} losses.

<u>Transition Points:</u>

To match the P.1546-2 data, the best transition point decision criteria has proven to be:

<u>For above the canopy top level</u>:

If the combined incident angle θ_{ic} is greater than 1.59 radians, beyond-horizon diffraction controls the attenuation.

If the under-canopy top ground distance d_{1a} is greater than 275 meters, and if the combined incident angle θ_{ic} is greater than 1.58 radians, but less than 1.59 radians, then the signal is in a transition at the horizon between I3 and diffraction mode, and the results of the I3 and diffraction modes should be averaged to determine the attenuation.

If the under-canopy top ground distance d_{1a} is greater than 275 meters, and if the combined incident angle θ_{ic} is equal to or less than 1.58 radians, then the I3 mode controls the results.

If the under-canopy top ground distance d_{1a} is less than or equal to 275 meters, and greater than 50 meters, then the I_d (I_1 and I_2) mode controls the results.

If the under-canopy top ground distance d_{1a} is less than or equal to 50 meters, then the I_{ri} mode (Beer's Law direct absorption to RTE function transition) controls the results.

<u>For at or below the canopy top level:</u>

When the transmitter is at or below the canopy top level, the cluttered radio path distance is equal to the path distance d. The results of the equations given for the Iri and Id functions are to be added together; and:

If the path distance d is less than or equal to 6 km., the combined RTE I_{ri} and I_d function results control the resultant attenuation.

If the path distance d is greater than 6 km., and if the combined incident angle θ_{ic} is equal to or less than 1.595 radians, then the lesser of the RTE combined or diffraction mode results determines the horizon transition point and controls the resultant attenuation.

If the path distance d is greater than 6 km., and if the combined incident angle θ_{ic} is greater than 1.595 radians, then the path is beyond the horizon, and diffraction mode results controls the resultant attenuation.

<u>Combining the Results for the Deterministic Approximations Solution:</u>

The last step is to add the Two-Ray Plane wave attenuation, A_{2R}, and the Free Space Dispersion, FSD, to the non-free-space attenuation from RTE or diffraction loss computed above, with frequency compensation included, to obtain the total predicted attenuation:

$$ACA_{[total]} = A(\text{RTE or Diff})_{[+FC\ ]} + A_{2R} + FSD.$$

Where for a ITU-R P.1456-2 land path, $A_{2R} = 0$.

FSD is calculated as in Part I. However, the P.1546-2 figures do not included the additional vertical path loss; we therefore instead use the FSL computation for the current model to match the existing curves, and recommend that the additional vertical path loss be incorporated into the curves for $h_1 > 300$ meters in any future revision of P.1546-2. For the present use, to approximate the results of P.1546-2, the equation then becomes:

$$ACA_{[total]} = A(\text{RTE or Diff})_{[+FC]} + FSL.$$

These deterministic approximations, when assembled on a single line of cells in a computer spreadsheet, calculate the geometry of the actual radio path length through the

clutter, or, by iteration, the radio path lengths above and through the clutter for a transmitter above the clutter canopy based on Snell's Law, and then proceeds to calculate the non-free-space losses.

This process, and the resulting spreadsheet or computer code, requires as input only four input variables in addition to the preset clutter height value of 25.3 meters, to produce a result approximating the results for P.1546-2. These values are: the transmitter height, h_1, in meters; the receiver height h_2, in meters, the total path distance d in kilometers; and the frequency, f, in MHz.

Where a terrain database, or terrain information regarding obstruction location and height is available, a diffraction and/or tropospheric scatter solution, similar to that utilized in the Longley-Rice Irregular Terrain Model, (ITM) or the future Irregular Terrain with Obstructions Model, (ITWOM), scheduled for release in 2008, can be utilized. For compatibility with ITU-R P.1546.2, and, by reference, Okimura-Hata, the line-of-sight deterministic equations here presented will be used to replace the underlying line-of-sight calculations in the ITM model as part of the process of creating the ITWOM model.

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