Path-Specific Propagation Models for Subgroup 3K-1

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Introduction and Background

- Six Path-Specific Models were proposed for study
  - Each has a somewhat different rationale but a "common" goal
  - Each is intended to optimize the radio propagation prediction on most paths
  - The optimal model will choose the "best" parts of each model

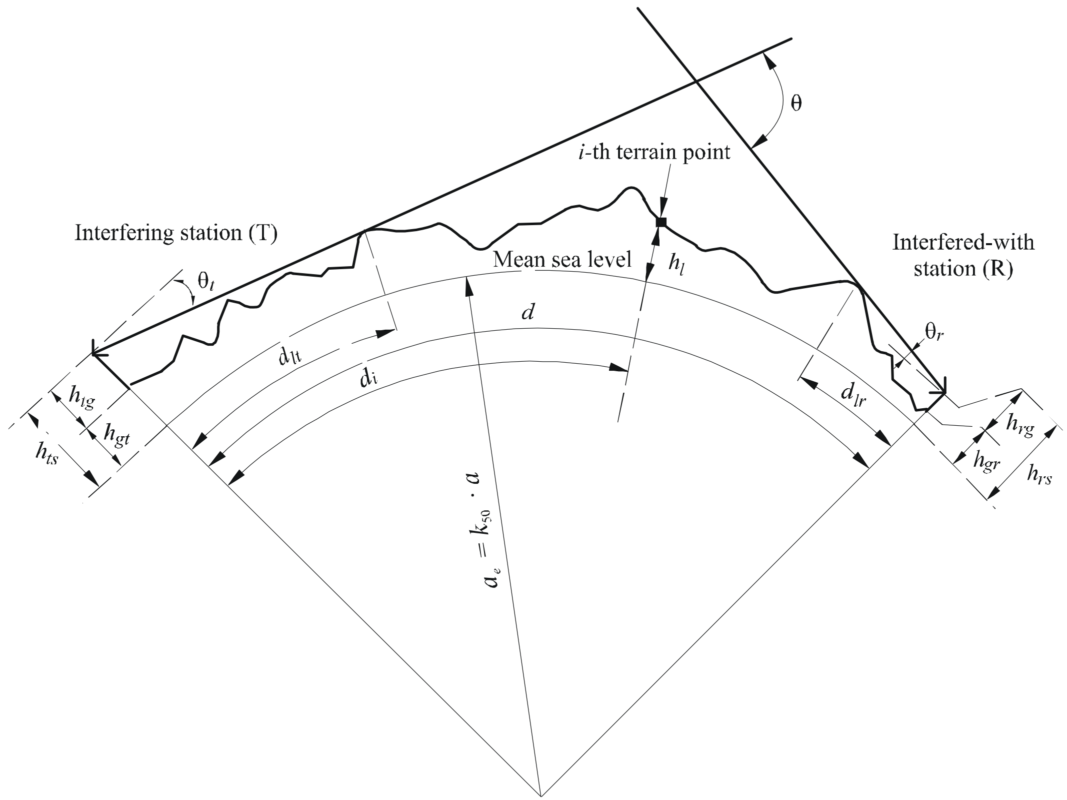
Rec. ITU-R P.452

- Clear Air Propagation Mechanisms
  - *line-of-sight* (including signal enhancements due to multipath and focusing effects);
  - *diffraction* (embracing smooth-earth, irregular terrain and sub-path cases);
  - *tropospheric scatter*;
  - *anomalous propagation* (ducting and layer reflection/refraction);
  - *height-gain variation in clutter* (where relevant).

Rec. ITU-R P.452

FIGURE 14

Example of a (trans-horizon) path profile



Note 1 – The value of θ_t as drawn will be negative.

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Rec. ITU-R P.452

- Line-of-Sight

  $L_{b0}(p) = 92.5 + 20 \log(fd) + E_s(p) + A_g$ dB

  where:

  $E_s(p)$: correction for multipath and focusing effects:

  $E_s(p) = 2.6\ (1 - e^{-d/10})\log(p/50)$ dB

  A_g : total gaseous absorption (dB):

  $A_g = [\gamma_o + \gamma_w(\rho)]d$

  where:

  γ_o, $\gamma_w(\rho)$: specific attenuation due to dry air and water vapor, respectively, and are found from the equations in Recommendation ITU-R P.676

  ρ : water vapor density:

  $\rho = 7.5 + 2.5\omega$ g/m^3

  ω : fraction of the total path over water.

Rec. ITU-R P.452

- Diffraction

$$L_d(p) = L_d(50\%) + F_i(p)[L_d(\beta_0) - L_d(50\%)]$$

$$F_i(p) = \frac{I\left(\frac{p}{100}\right)}{I\left(\frac{\beta_0}{100}\right)}$$

$$L_{bd}(p) = 92.5 + 20\log(f \cdot d) + L_d(p) + E_{sd}(p) + A_g$$

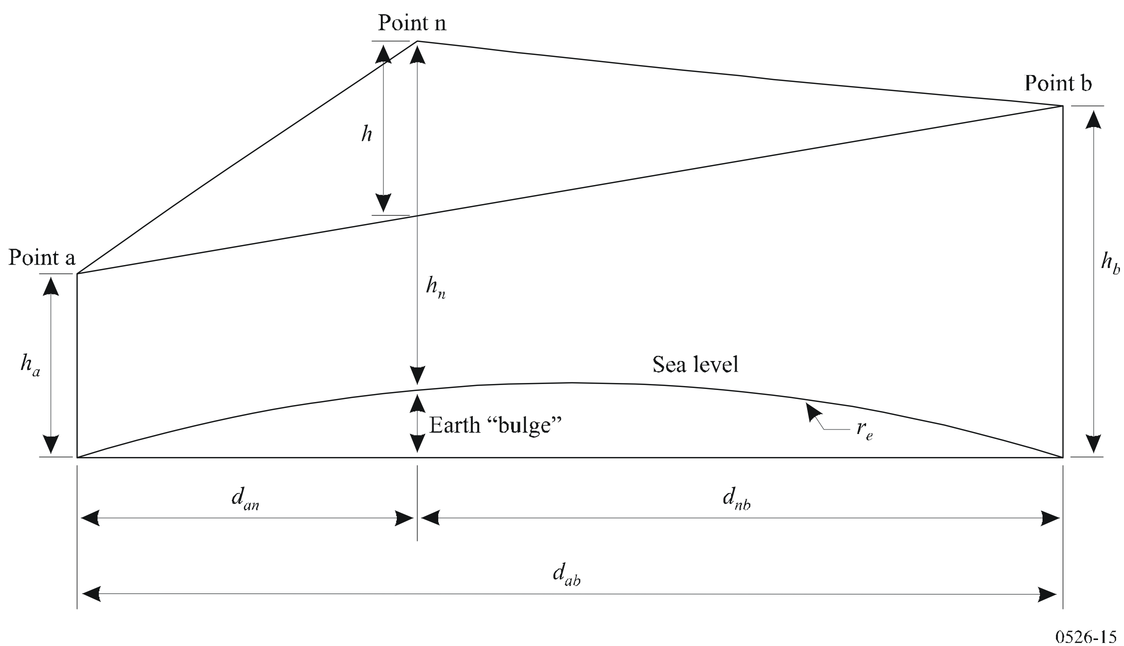
$$E_{sd}(p) = 2.6(1 - e^{-(d_{lt}+d_{lr})/10})\log(\frac{p}{50})$$

Rec. ITU-R P.452

- Obstacle Height Above the Straight Line Between the Ends of the Path

FIGURE 15

Geometry for a single edge



Rec. ITU-R P.452

- Cascaded Knife Edge Diffraction (Deygout Construction)

$$\nu_p = \max(\nu_n),\ n = 1,\ldots,npfl\ \ (\nu_p < 0 \Rightarrow \text{los path})$$

$$\nu_n = h\sqrt{\frac{2d_{ab}}{\lambda d_{an} d_{nb}}}\ \text{where}\ h = h_n + \frac{d_{an} d_{nb}}{2a_e} - \frac{\left(h_a d_{nb} + h_b d_{an}\right)}{d_{ab}}$$

$$\text{if}\ \nu_p > -0.78\ \text{then also find}$$

$$\nu_t = \max(\nu_i),\ i = 1,\ldots,p\ \text{and}\ \nu_r = \max(\nu_j),\ j = p,\ldots,npfl$$

$$L_d = J(\nu_p) + \left(1 - e^{-\frac{J(\nu_p)}{6}}\right) \cdot \left(J(\nu_t) + J(\nu_r) + 10 + 0.04d\right)$$

$$\text{where}\ J(\nu) = 6.9 + 20\log\left(\sqrt{(\nu - 0.1)^2 + 1} + \nu - 0.1\right)\ (\nu > -0.78)$$

Rec. ITU-R P.452

- Tropospheric Scatter

$$L_{bs}(p) = 190 + L_f + 20\log d + 0.573\theta - 0.15N_0 + L_c + A_g - 10.1\left(\log\left(\frac{50}{p}\right)\right)^{0.7}$$

$$L_f = 25\log f - 2.5\left(\log\left(\frac{f}{2}\right)\right)^2$$

$$L_c = 0.051 \cdot e^{0.055(G_t + G_r)}$$

$$\theta = \frac{10^3 d}{a_e} + \theta_t + \theta_r$$

Rec. ITU-R P.452

- Anomalous Propagation (Ducting & Layer Reflection/Refraction)

$$L_{ba}(p) = A_f + A_d(p) + A_g$$

$$A_f = 102.45 + 20\log(f(d_{lt} + d_{lr})) + A_{st} + A_{sr} + A_{ct} + A_{cr}$$

$$A_d(p) = 5 \cdot 10^{-5} a_e f^{1/3} \theta' + A(p)$$

$$\theta' = \frac{10^3 d}{a_e} + \min(\theta_t, 0.1 d_{lt}) + \min(\theta_r, 0.1 d_{lr})$$

$$A(p) = -12 + (1.2 + 3.7 \cdot 10^{-3} d)\log(\frac{p}{\beta}) + 12(\frac{p}{\beta})^{\Gamma}$$

$$\beta = \beta_0 \cdot (\text{path geometry correction}) \cdot (\text{terrain roughness correction})$$

$$\Gamma = \Gamma(\log(\beta), d)$$

Rec. ITU-R P.452

- Anomalous Propagation (Ducting & Layer Reflection/Refraction)

$$A_{st,sr} = 20\log\left[1 + 0.361\theta''_{t,r}\sqrt{f \cdot d_{lt,lr}}\right] + 0.264\theta''_{t,r} f^{\frac{1}{3}}$$

$$if$$

$$\theta''_{t,r} = \theta_{t,r} - 0.1 d_{lt,lr} > 0$$

$$otherwise$$

$$A_{st,sr} = 0$$

$$A_{ct,cr} \text{ are over-sea surface ducting corrections}$$

Rec. ITU-R P.452

- Height Gain Variation in Clutter

d_k: distance (km) from nominal clutter point to the antenna
h : antenna height (m) above local ground level
h_a: nominal clutter height (m) above local ground level.

$$A_h = 10.25 e^{-d_k} \left(1 - \tanh\left(6 \left[\frac{h}{h_a} - 0.625 \right] \right) \right) - 0.33$$

Rec. ITU-R P.452

TABLE 6

Nominal clutter heights and distances

Clutter (ground-cover) category	Nominal height, h_a (m)	Nominal distance, d_k (km)
High crop fields Park land Irregularly spaced sparse trees Orchard (regularly spaced) Sparse houses	4	0.1
Village centre	5	0.07
Deciduous trees (irregularly spaced) Deciduous trees (regularly spaced) Mixed tree forest	15	0.05
Coniferous trees (irregularly spaced) Coniferous trees (regularly spaced)	20	0.05
Tropical rain forest	20	0.03
Suburban	9	0.025
Dense suburban	12	0.02
Urban	20	0.02
Dense urban	25	0.02
Industrial zone	20	0.05

Rec. ITU-R P.452-12

- The Overall Prediction
  - Line-of-Sight

$$L_b(p) = L_{b0}(p) + A_{ht} + A_{hr}$$

  - Line-of-Sight with sub-path diffraction

$$L_b(p) = L_{b0}(p) + L_{ds}(p) + A_{ht} + A_{hr}$$

Rec. ITU-R P.452-12

- The Overall Prediction
  - Trans-horizon

$$F_k(d) = 1 - 0.5 \cdot \left(1 + \tanh\left(1.5\frac{(d-20)}{20}\right)\right), F_j(\theta) = 1 - 0.5 \cdot \left(1 + \tanh\left(2.4\frac{(\theta - 0.3)}{0.3}\right)\right)$$

$$L_{bam}(p) = \left[2.5\ln\left(e^{\frac{L_{ba}(p)}{2.5}} + e^{\frac{L_{b0}(p)}{2.5}}\right) \cdot \left(1 - F_k(d)\right) + L_{bd}(p) \cdot F_k(d)\right] \cdot \left(1 - F_j(\theta)\right)$$
$$+ \left[L_{bd}(50\%) \cdot \left(1 - F_i(p)\right) + L_{b0}(\beta_0) \cdot F_i(p)\right] \cdot F_j(\theta)$$

$$L_b(p) = -5.0 \cdot \log\left(10^{-0.2 L_{bs}(p)} + 10^{-0.2 L_{bam}(p)} + 10^{-0.2 L_{bd}(p)}\right) + A_{ht} + A_{hr}$$

CHINESE METHOD(1)

- Median field strength based on ITU-R Recs. P.452, 526 and time/location variability based on ITU-R Rec. P.1546
- Median basic transmission loss is sum of free-space basic transmission loss and median attenuation relative to free space
- Three path types: LOS with first Fresnel zone clearance, LOS with sub-path diffraction, transhorizon path (diffraction and troposcatter)
- Clutter loss includes those for transmitting and receiving stations

CHINESE METHOD(2)

Field strength for *T%* time and *L%* location

$E(T,L) = E(50,50) + \Delta E_t(T) + \Delta E_l(L)$

$\Delta E_t(T)$, $\Delta E_l(L)$: *variations for time, location*

Median field strength *E(50,50)*

$E(50,50) = ERP - L_b(50,50) + 20 \log f + 109.4$

$L_b(50,50)$: median basic transmission loss

ERP: effective radiated power (dBW)

f: frequency (MHz)

Median basic transmission loss $L_b(50,50)$

$L_b(50,50) = L_{bf} + A(50,50)$

$A(50,50)$: median attenuation (dB) relative to free space

$L_{bf;}$: free space basic transmission loss (dB)

CHINESE METHOD(3)

LOS path with first Fresnel zone clearance

$$L_b(50,50) = L_{bf} + A_{cldt} + A_{cldr}$$

A_{cldt}, A_{cldr} : additional clutter losses due to diffraction

LOS path with sub-path diffraction

$$L_b(50,50) = L_{bf} + A_{cldt} + A_{cldr} + A_d\ (50,50)$$

A_d (50,50): median sub-path diffraction loss (P.526)

Trans-horizon path

$$L_b(50,50) = -10 \log \{10^{-0.1L_{bd}(50,50)} + 10^{-0.1L_{bs}(50,50)}\}$$

L_{bd}: median basic transmission loss due to trans-horizon diffraction

L_{bs}: median basic transmission loss due to troposcatter

CHINESE METHOD(4)

Median basic transmission loss due to trans-horizon diffraction

$L_{bd}(50,50) = L_{bf} + A_{cldt} + A_{cldr} + A_{dt}\,(50,50)$

A_{dt} for spherical earth, 3.1.1.2 in ITU-R P.526-8

for irregular earth, 4.4.2 in ITU-R P.526-8

Median basic transmission loss due to troposcatter

$L_{bs}(50,50) = L_{bso}\,(50,50) + A_{cls}$

L_{bso} (50,50): median basic transmission loss due to troposcatter without clutter based from Eq.15 in ITU-R P.452-12

A_{cls}: clutter loss due to scatter

CHINESE METHOD(5)

Location Variability

$$\Delta E_l(L) = Q_i(L/100)\ \sigma_L(f)$$

$Q_i(x)$: the inverse complementary cumulative normal distribution

σ_L: the standard deviation

Time variability

$$\Delta E_t(T) = E(T) - E(50)$$

$E(T)$: field strength for T% time

Based on ITU-R P.1546 tabulated field strengths and relevant ITU-R P.453 climatic data files

Corrections for receiving antenna heights and clearance angle not done

PSPROGCN-1

- FUNCTION E50 (F,ERP,NPL,HTG,HRG,N,HI,DI,NGC,HGC,ALON1,ALAT1, ALON2,ALAT2)

  for calculation of the median field strength
- FUNCTION DETT (F,T,HTG,N,HI,DI,GNC,ALON1,ALAT1,ALON2,ALAT2)

  for calculation of the variation with time
- FUNCTION ETQ (F,ERP,NPL,HTG,HRG,N,HI,DI,NGC,HGC,ALON1,ALAT1, ALON2,ALAT2,T,Q)

  for calculating of field strength for any time and location percentages

PSPROGCN-1

- FILES DNZ.TXT,NO.TXT,IDN.TXT AND FST.TXT files

  for basic climatic and field strength data
- MAIN PROGRAM

  for opening the basic climatic and field strength data files and the measurement data files, reading and processing the data, calculating field strength and comparing it with measured field strength, and putting the results into the output data file

PSPROGCN-1

Input Parameters

- frequency
- effective radiated power
- polarization
- antenna heights above ground level
- distance from transmitting/base station, terrain height amsl, ground cover type and its height at the ith terrain point on the path profile
- latitude and longitude of transmitting/base station
- latitude and longitude of receiving/mobile station
- percentage of time

EBU METHOD(1)
Propagation Mechanisms

- Free space
- Diffraction loss (irregular terrain and sub-path
- Tropospheric scatter
- Anomalous propagation (ducting)
- Height variation in ground cover
- Building penetration

EBU METHOD(2) Basic Input Data

Parameter	Description
f	Frequency (MHz)
p	Required time percentage(s) for which the basic transmission loss is not exceeded
φ_t φ_r	Latitude of transmitter and receiver (degrees)
ψ_t ψ_r	Longitude of transmitter and receiver (degrees)
h_{tg} h_{rg}	Transmitter and receiver antenna center height above ground level (m)
h_{ts} h_{rs}	Transmitter and receiver antenna center height above mean sea level (m)
G_t G_r	Transmitter and receiver antenna gain in the direction of horizon along great circle path

EBU METHOD(3) Radiometeorological data

- ΔN (N-units/km), average radio-refractive index lapse rate through the lowest 1 km of the atmosphere (world map of average annual ΔN in Rec. p.452)
- β_0 (%),time percentage for which refractive index lapse-rates exceeding 100 N-units/km expected in the first 100 m
- N_0 (N-units), the sea-level surface refractivity (world map of annual N_0 in Rec. p.452)

EBU METHOD(4)
Parameters derived from path profile analysis

Path type	Parameter	Description
Transhorizon	d	Great-circle path distance in km
Transhorizon	d_{lt} d_{lr}	Distance from transmit and receive antennas to their respective horizons in km
Transhorizon	θ_t θ_r	Transmit and receive horizon elevation angles
Transhorizon	θ	Path angular distance
All	h_{ts} h_{rs}	Antenna center height above mean sea level

EBU METHOD(5)
Path classifications and propagation models

LOS with first Fresnel zone clearance

- Free space basic transmission loss
- Relative ground cover and receiving antenna height loss
- Building penetration loss (where appropriate)

EBU METHOD(6)
Path classifications and propagation models

LOS with sub-path diffraction

- Free space basic transmission loss
- Diffraction
- Relative ground cover and receiving antenna height loss
- Building penetration loss (where appropriate)

EBU METHOD(7)
Path classifications and propagation models

Trans-horizon

- Free space basic transmission loss
- Diffraction
- Troposcatter
- Ducting
- Relative ground cover and receiving antenna height loss
- Building penetration loss (where appropriate)

EBU METHOD(7.1)

Electric field strength for 1 kW e.r.p

$E_b = 139 - L_b + 20 \log f$ dBμV/m

L_b is basic transmission loss in dB

Free space basic transmission loss

$Lbf = 32.4 + 20 \log f + 20 \log d$ dB

Diffraction loss

Based on ITU-R P.452 and P.526

Assumes a horizontal exclusion zone of the principal obstacle to avoid over-estimating loss

EBU METHOD (8)

Line-of-sight

Field Strength $E_b = 106.9 - 20 \log d - (A_{hr} + A_{bl})$ dB

A_{hr} : additional ground cover and receiving antenna height loss

A_{bl} : additional losses due to building penetration

Line-of-sight with sub-path diffraction

Field Strength $E_b = 106.9 - 20 \log d - (L_d + A_{hr} + A_{bl})$ dB

L_d : sub-path diffraction loss for p% of time

L

EBU METHOD (9)

Trans-horizon

$E_b = 10 \log(10^{Ed/10} + 10^{Es/10} + 10^{Ea/10}) – (A_{hr} + A_{bl})$

$E_d = 106.9 – 20 \log d – L_d$

L_d: diffraction loss for p% of time

$E_s = 106.9 – 20 \log d – L_s$

L_s : troposcatter loss for p% of time

E_a: field strength resulting from ducting

SWISS STUDY

- Comparison of predicted results with measured data in Alpine region
- Three diffraction modeling techniques: Bullington, Epstein-Peterson and Deygout methods and Longley-Rice model used
- Terrain profile from DBSG5 and Shuttle Radar Topography Mission (SRTM) data
- Bullington method gives consistently optimistic results with relatively small errors, other methods overestimate path loss with larger errors

Irregular Terrain Model (ITM)

- Computed Reference Attenuation (Attenuation Relative to Free Space)

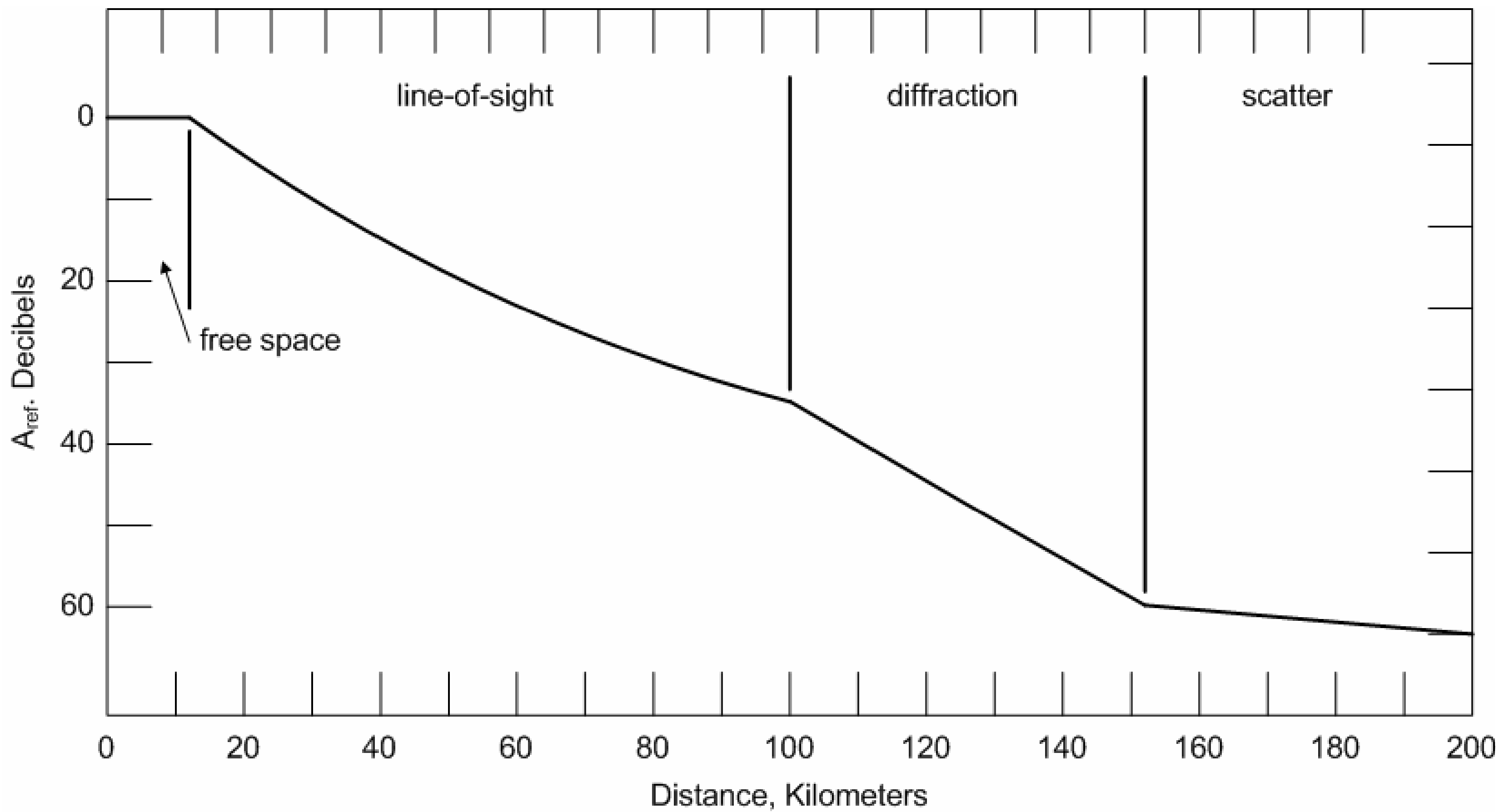
$$A_{ref} = \max(0, a_{el} + a_{k1} d + a_{k2} \ln\left(\frac{d}{d_{ls}}\right)) \text{ for } d \le d_{ls}$$

$$= A_{ed} + m_d d \qquad \text{for } d_{ls} < d \le d_x$$

$$= A_{es} + m_s d \qquad \text{for } d > d_x$$

$$A_{ref} \text{ is continuous at } d = d_{ls}, d_x$$

Irregular Terrain Model (ITM)



Irregular Terrain Model (ITM)

- Time, Location and Situation Variabilities; Attenuation not exceeded for p_T (percentage Time), p_L (percentage Locations) and p_S (percentage Situations), $A(p_T,p_L,p_S)$:

$$A(z_T, z_L, z_S) \equiv A(z(q_T), z(q_L), z(q_S)) = A\left(z\left(\frac{p_T}{100}\right), z\left(\frac{p_L}{100}\right), z\left(\frac{p_S}{100}\right)\right)$$

where $z(q) = Q^{-1}(q)$ and $q = Q(z) = \frac{1}{\sqrt{2\pi}} \int_z^{\infty} e^{-t^2} dt$

then using $X(q) = X_0 + z(q) \cdot \sigma$ where X_0 is the mean and σ is the standard deviation

$$A' = A_{ref} - V_{med} - Y_T - Y_L - Y_S$$

$$A(z_T, z_L, z_S) = A' \qquad \text{if } A' \geq 0$$

$$= A' \frac{29 - A'}{29 - 10 \cdot A'} \quad \text{if } A' < 0$$

Irregular Terrain Model (ITM)

- Coefficients for the Diffraction Range

$$X_{ae} = \left(\frac{2\pi}{\lambda a_e^2}\right)^{-\frac{1}{3}} = a_e\left(\frac{\lambda}{2\pi a_e}\right)^{\frac{1}{3}}$$

$$d_3 = \max\left(d_{ls}, d_{lt} + d_{lr} + 1.3787\, X_{ae}\right)$$

$$d_4 = d_3 + 2.7574\, X_{ae}$$

$$A_3 = A_{diff}(d_3)$$

$$A_4 = A_{diff}(d_4)$$

$$m_d = \frac{A_4 - A_3}{d_4 - d_3}, A_{ed} = A_3 - m_d d_3$$

Irregular Terrain Model (ITM)

- The function $A_{diff}(s)$

$$\text{weighting factor } w = \frac{1}{1+0.1\sqrt{Q}}$$

$$Q = \min\left(\frac{\Delta h(s)}{\lambda}, 10^3\right)\cdot\left(\frac{h_{et}h_{er}+10}{h_{gt}h_{gr}+10}\right)^{\frac{1}{2}} + \frac{d_{lt}+d_{lr}+a_e\cdot\theta_e}{s}$$

$$\Delta h(s) = \left(1-0.8e^{-\frac{s}{5\times 10^4}}\right)\cdot\Delta h,\ \theta_e = \max\left(\theta_t+\theta_r, -\frac{d_{lt}+d_{lr}}{a_e}\right)$$

$$\alpha = 4.77\times 10^{-4}\,m^{-2},\ \sigma(s) = 0.78\cdot\Delta h(s)\cdot e^{-\left(\frac{\Delta h(s)}{16}\right)^{\frac{1}{4}}}$$

$$A_{fo} = \min\left(15, 5\log(1+\alpha k h_{gt} h_{gr}\sigma_h(d_{ls}))\right)$$

$$A_{diff}(s) = (1-w)\cdot A_k + w\cdot A_r + A_{fo}$$

Irregular Terrain Model (ITM)

- The function $A_{diff}(s)$, continued

$$\theta = \theta_e + \frac{s}{a_e}, d_l = d_{lt} + d_{lr}, \nu_{t,r} = \frac{\theta}{2}\left(\frac{2}{\lambda}\cdot\frac{d_{lt,lr}\cdot(s-d_l)}{(s-d_l+d_{lt,lr})}\right)^{\frac{1}{2}}$$

$$A_k = Fn(\nu_t) + Fn(\nu_r), \text{ where } Fn(\nu) = 20\log\left|\frac{1}{\sqrt{2i}}\int_{\nu}^{\infty} e^{i\pi\frac{u^2}{2}}du\right|$$

$$\gamma_0 = \frac{\theta}{s-d_l}, \gamma_{t,r} = \frac{2h_{et,er}}{d_{lt,lr}^2}, \alpha_{0,t,r} = \left(\frac{k}{\gamma_{0,t,r}^2}\right)^{\frac{1}{3}}, K_{0,t,r} = \frac{1}{i\alpha_{0,t,r}Z_g}$$

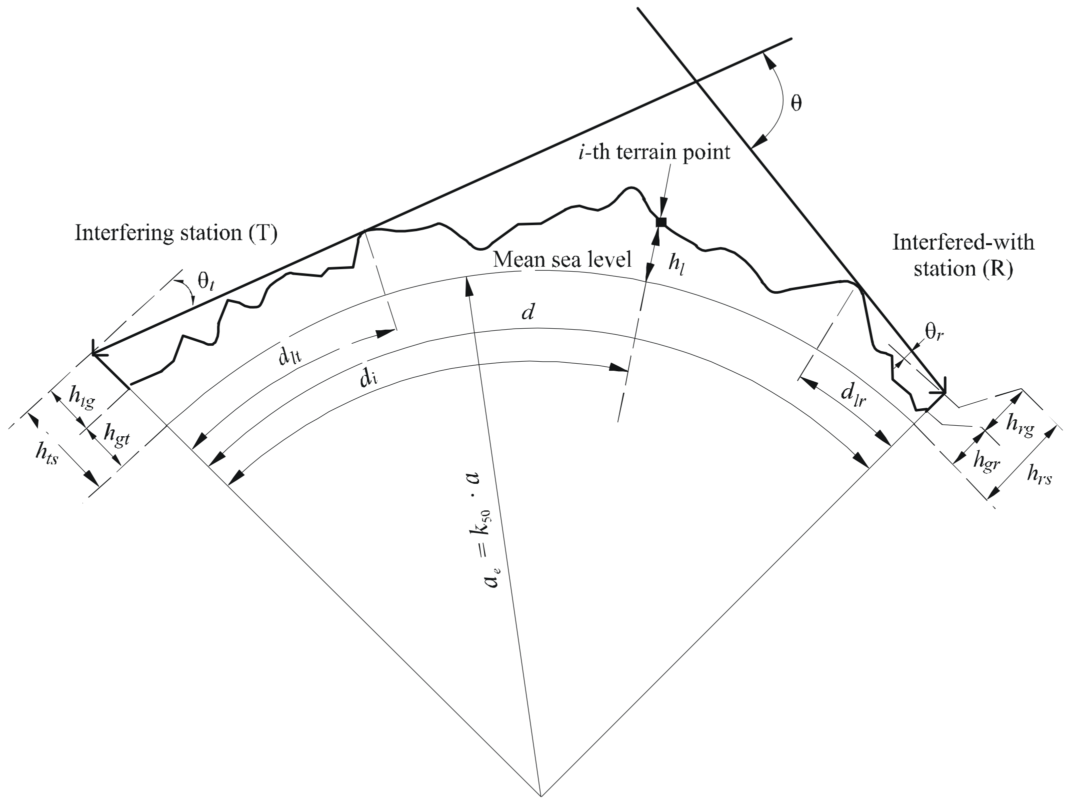
$$x_{t,r} = 151.03\cdot B(K_{t,r})\alpha_{t,r}\gamma_{t,r}d_{lt,lr}, x_0 = 151.03\cdot B(K_0)\alpha_0\theta + x_t + x_r$$

$$A_r = G(x_0) - F(x_t, K_t) - F(x_r, K_r) - C_1(K_0)$$

Irregular Terrain Model (ITM)

FIGURE 14

Example of a (trans-horizon) path profile



Note 1 – The value of θ_t as drawn will be negative.

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Irregular Terrain Model (ITM)

- Coefficients for the Line-of-Sight Range, A_{el}, a_{k1}, a_{k2}:

$$d_2 = d_{ls},\ A_2 = A_{ed} + m_d d_2$$

$$if\ (A_{ed} \geq 0)\ then$$

$$d_0 = \min\left(\frac{d_l}{2}, 1.908 k h_{et} h_{er}\right),\ d_1 = \frac{3d_0 + d_l}{4},\ A_0 = A_{los}(d_0),\ A_1 = A_{los}(d_1)$$

$$a'_{k2} = \max\left(0, \frac{(d_2 - d_0)\cdot(A_1 - A_0) - (d_1 - d_0)\cdot(A_2 - A_0)}{(d_2 - d_0)\cdot\ln\left(\frac{d_1}{d_0}\right) - (d_1 - d_0)\cdot\ln\left(\frac{d_2}{d_0}\right)}\right)$$

$$a'_{k1} = \frac{A_2 - A_0 - a'_{k2}\ln\left(\frac{d_2}{d_0}\right)}{d_2 - d_0}$$

$$if\ (a'_{k1} \geq 0)\ a_{k1} = a'_{k1},\ a_{k2} = a'_{k2}$$

$$else$$

$$a''_{k2} = \frac{A_2 - A_0}{\ln\left(\frac{d_2}{d_0}\right)}$$

$$if\ (a''_{k2} \geq 0)\ a_{k1} = 0,\ a_{k2} = a''_{k2}$$

$$else\ a_{k1} = m_d,\ a_{k2} = 0$$

$$else$$

Irregular Terrain Model (ITM)

- Coefficients of the Line-of-Sight Range, continued:

$$d_0 = 1.908 k h_{et} h_{er},\ d_1 = \max\left(\frac{-A_{ed}}{m_d}, \frac{d_l}{4}\right)$$

$$if\ (d_0 < d_1)\ A_0 = A_{los}(d_0),\ A_1 = A_{los}(d_1),\ evaluate\ a'_{k2}$$

$$if\ (a'_{k2} > 0)\ evaluate\ a'_{k1} \text{ and proceed as described above}$$

$$elseif\ (d_1 < d_0\ or\ a'_{k2} = 0)\ A_1 = A_{los}(d_1),\ a''_{k1} = \frac{A_2 - A_1}{d_2 - d_1},\ a_{k1} = a''_{k1},\ a_{k2} = 0$$

$$else\ a_{k1} = m_d,\ a_{k2} = 0$$

$$endif$$

$$endif$$

$$A_{el} = A_2 - a_{k1} d_2$$

Irregular Terrain Model (ITM)

- The function $A_{los}(s)$

$$\text{weighting factor } w = \frac{1}{1 + \dfrac{4.77 \times 10^{1} k \Delta h}{\max\left(10^{4}, d_{ls}\right)}}$$

$$A_{los} = (1 - w) A_d + w A_t$$

$$A_d = A_{ed} + m_d s, \; A_t = -20 \log\left|1 + R_e e^{i\delta}\right|$$

Irregular Terrain Model (ITM)

- The function $A_{los}(s)$, continued

$$R_e' = \frac{\sin\psi - Z_g}{\sin\psi + Z_g} \cdot e^{-k\sigma_h(s)\sin\psi}, \sin\psi = \frac{h_{et} + h_{er}}{\sqrt{s^2 + (h_{et} + h_{er})^2}}$$

$$Z_g = \sqrt{\varepsilon_r' - 1} \text{ for horizontal polarization}$$

$$Z_g = \frac{\sqrt{\varepsilon_r' - 1}}{\varepsilon_r'} \text{ for vertical polarization}$$

$$\varepsilon_r' = \varepsilon_r + i\frac{Z_0\sigma}{k}$$

$$if\left(|R_e'| \geq \max\left(0.5, \sqrt{\sin\psi}\right)\right) R_e = R_e', else\, R_e = \frac{R_e'}{|R_e'|} \cdot \sqrt{\sin\psi}$$

$$\delta' = \frac{2kh_{et}h_{er}}{s}$$

$$if\left(\delta' \leq \frac{\pi}{2}\right)\delta = \delta', else\, \delta = \pi - \frac{\pi^2}{4\delta'}$$

Irregular Terrain Model (ITM)

- Coefficients of the (Tropo)Scatter Range

$$d_5 = d_l + 2\times10^5, d_6 = d_5 + 2\times10^5$$

$$A_5 = A_{scat}(d_5), A_6 = A_{scat}(d_6)$$

$$m_s = \frac{A_6 - A_5}{2\times10^5}$$

$$A_{es} = A_{ed} + (m_d - m_s)d_x, \text{ where}$$

$$d_x = \max\left(d_{ls}, d_l + X_{ae}\cdot\log(4.77\times10^1 k), \frac{A_5 - A_{ed} - m_s d_5}{m_d - m_s} \right)$$

Irregular Terrain Model (ITM)

- The function A_{scat}(s)

$$\theta = \theta_e + \frac{s}{a_e}, \theta^{'} = \theta_t + \theta_r + \frac{s}{a_e}, r_{t,r} = 2k\theta^{'} h_{et,er}$$

$$if\,(r_t \,\&\, r_r \geq 0.2) A_{scat}(s) = 10\log\left(4.77\times 10^{1} k\theta^{4}\right) + F\left(\theta s, N_s\right) + H_0$$

where

$F(\theta s, N_s)$ is related to the Attenuation Function (TN101 - V1, Section 9.1)

H_0 is the Frequency Gain Function (TN101 - V1, Section 9.2)

Irregular Terrain Model (ITM)

- The Attenuation Function, $F(\theta s, N_s)$

$$F(\theta s, N_s) = F(\theta s, 301) - 0.1 \cdot (N_s - 301) \cdot e^{-\frac{\theta s}{4\times 10^4}}$$

$$if\ (\theta s \le 10^4)$$

$$F(\theta s, 301) = 133.4 + 3.32 \times 10^{-4}\theta s - 4.343\ \ln(\theta s)$$

$$if\ (10^4 < \theta s \le 7\times 10^4)$$

$$F(\theta s, 301) = 104.6 + 2.12 \times 10^{-4}\theta s - 1.086\ \ln(\theta s)$$

$$if\ (7\times 10^4 < \theta s)$$

$$F(\theta s, 301) = 71.8 + 1.57 \times 10^{-4}\theta s + 2.171\ \ln(\theta s)$$

Irregular Terrain Model (ITM)

- The Frequency Gain Function, H_o:

$$d_s = s - d_{lt} - d_{lr}, S_s = \frac{d_{lt} + \frac{d_s}{2}}{d_{lr} + \frac{d_s}{2}} = \frac{s + (d_{lt} - d_{lr})}{s - (d_{lt} - d_{lr})}, z_0 = \frac{S_s s \theta'}{(1 + S_s)^2} = \frac{(s - (d_{lt} - d_{lr}))(s + (d_{lt} - d_{lr}))\theta'}{4s}$$

$$\eta_s = \frac{z_0}{Z_0}\left[1 + \left(3.1\times10^{-2} - N_s 2.32\times10^{-3} + N_s^2 5.67\times10^{-6}\right)e^{-\left(\frac{z_0}{Z_1}\right)^6}\right] \text{with } Z_0 = 1.756\times10^3 \text{ and } Z_1 = 8\times10^3$$

$$H_{0,i}(r_{t,r}) = 10\log\left(1 + B_i \cdot r_{t,r}^{-2} + A_i \cdot r_{t,r}^{-4}\right) \text{for } i = 1,\ldots,5 \text{ and let } i_\eta = \text{int}(\eta_s), 1 \le i_\eta \le 5, Q = \eta_s - i_\eta, Q \equiv 0 \text{ for } \eta_s > 5 \text{ or } \eta_s < 1$$

$$H_0(r_{t,r}) = (1 - Q)\cdot H_{0,i_\eta}(r_{t,r}) + Q \cdot H_{0,i_\eta+1}(r_{t,r})$$

$$H_0 = \frac{H_0(r_t) + H_0(r_r)}{2} + \Delta H_0$$

$$\text{where } \Delta H_0 = 6(0.6 - \log\eta_s)\log S_s \log\left(\frac{r_r}{S_s r_t}\right) \text{subject to some restrictions (see TN101-V1, Section 9.2)}$$

Irregular Terrain Model (ITM)

- Time, Location and Situation Variabilities; Attenuation not exceeded for p_T (percentage Time), p_L (percentage Locations) and p_S (percentage Situations), $A(p_T,p_L,p_S)$:

$$A(z_T, z_L, z_S) \equiv A(z(q_T), z(q_L), z(q_S)) = A\left(z\left(\frac{p_T}{100}\right), z\left(\frac{p_L}{100}\right), z\left(\frac{p_S}{100}\right)\right)$$

where $z(q) = Q^{-1}(q)$ and $q = Q(z) = \dfrac{1}{\sqrt{2\pi}} \displaystyle\int_z^{\infty} e^{-t^2} dt$

then using $X(q) = X_0 + z(q) \cdot \sigma$ where X_0 is the mean and σ is the standard deviation

$$A' = A_{ref} - V_{med} - Y_T - Y_L - Y_S$$

$$A(z_T, z_L, z_S) = A' \qquad \text{if } A' \geq 0$$

$$= A' \frac{29 - A'}{29 - 10 \cdot A'} \text{ if } A' < 0$$

Irregular Terrain Model (ITM)

- The Effective Distance for Variabilities, d_e:

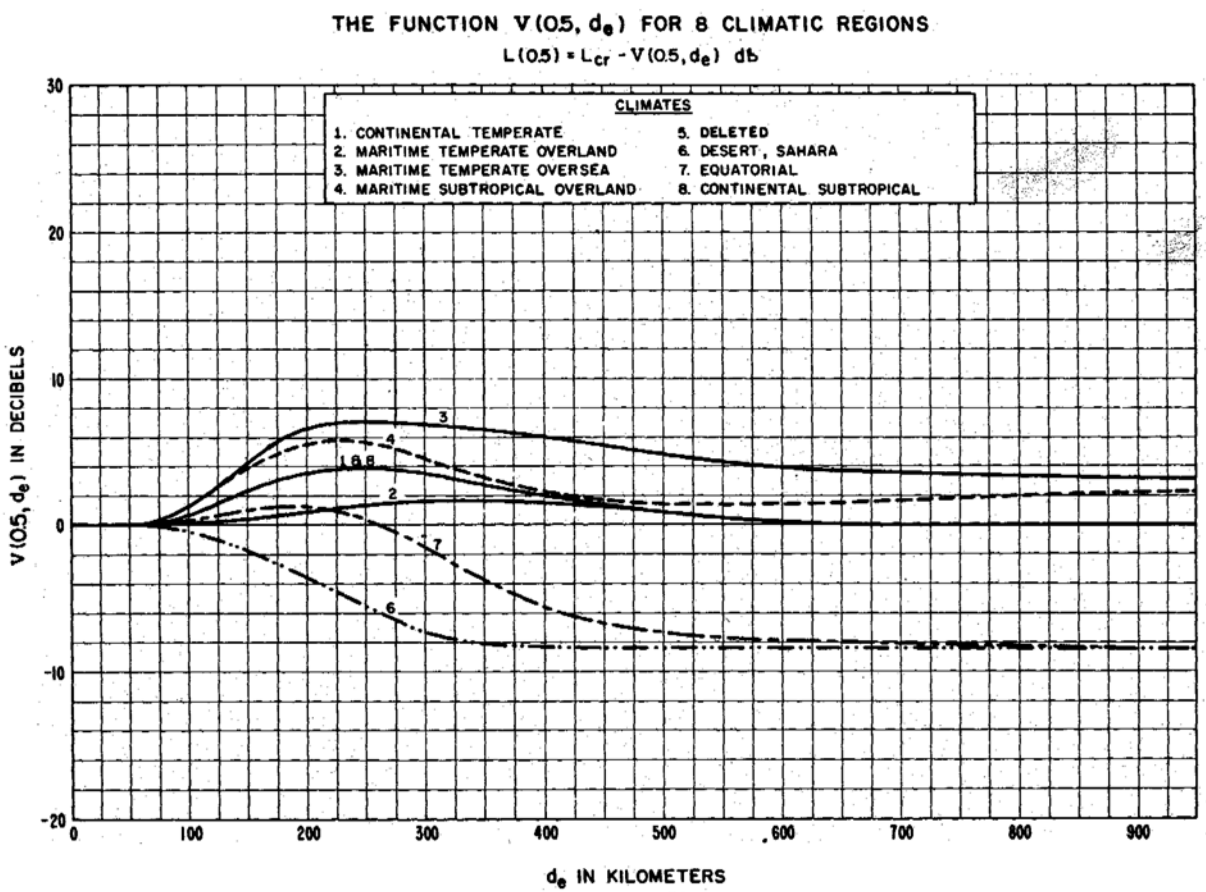
$$d_{ex} = \sqrt{2a_1 h_{et}} + \sqrt{2a_1 h_{er}} + a_1 \cdot \left(kD_1\right)^{-\frac{1}{3}}, a_1 = 9\times10^6, D_1 = 1.266\times10^6$$

$$d_e = 1.3\times10^5 \frac{d}{d_{ex}} \qquad \text{for } d \le d_{ex}$$

$$= 1.3\times10^5 + d - d_{ex} \text{ for } d > d_{ex}$$

Irregular Terrain Model (ITM)

- Time Variability, $V_{med}(d_e,clim)$:



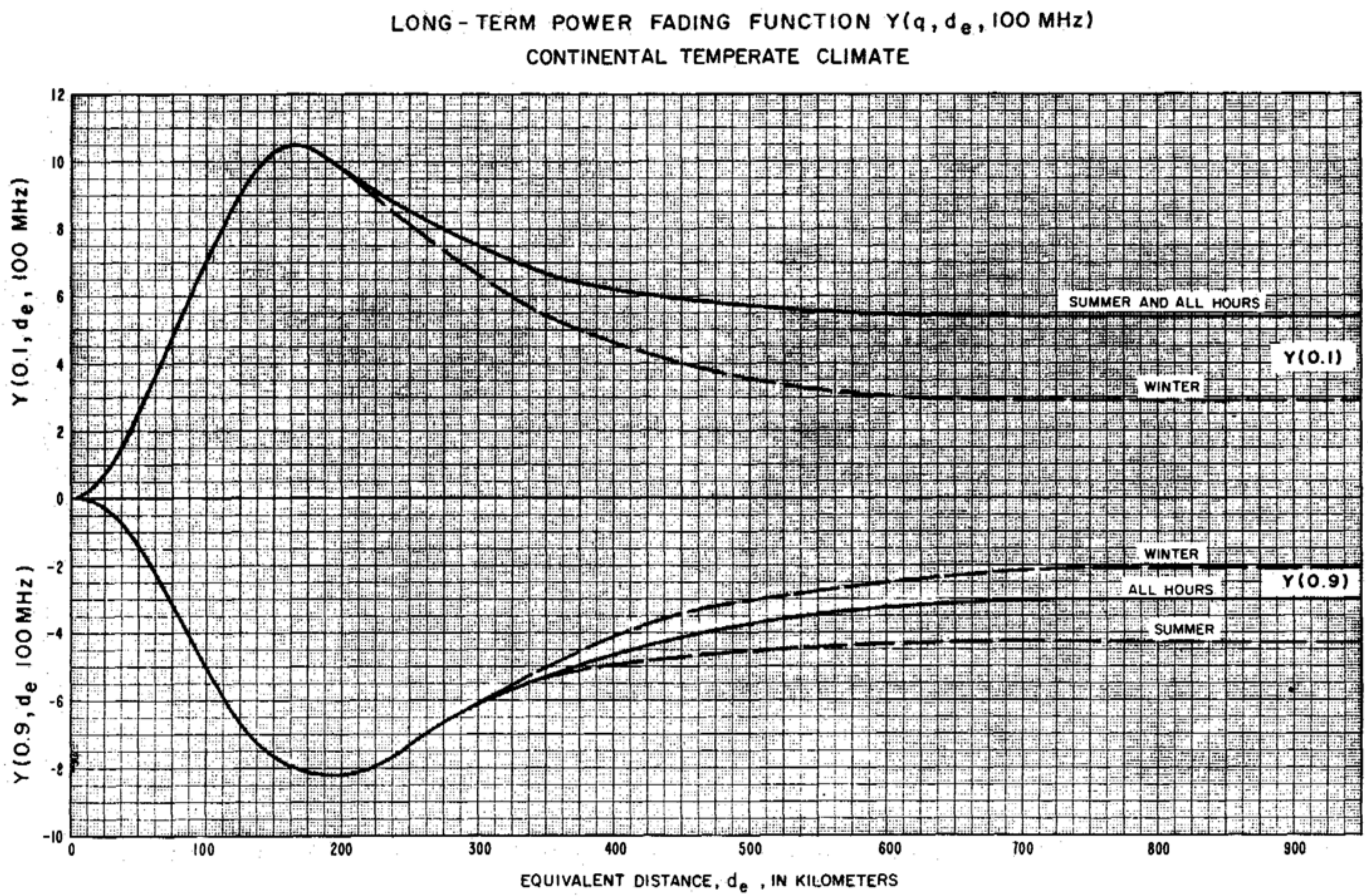
Irregular Terrain Model (ITM)

- Time Variability, the deviation Y_T:

$$
\begin{aligned}
Y_T &= z_T \sigma_{T_-} && \text{for } z_T \le 0 \\
&= z_T \sigma_{T_+} && \text{for } 0 \le z_T \le z_D \\
&= z_D \sigma_{T_+} + (z_T - z_D)\sigma_{TD} && \text{for } z_D \le z_T
\end{aligned}
$$

$$
\sigma_{T_\pm} = \sigma_{T_\pm}(d_e, \text{clim}),\ z_D = z_D(\text{clim}),\ \sigma_{\text{TD}} = C_D(\text{clim})\sigma_{T_+}
$$

Irregular Terrain Model (ITM)



Irregular Terrain Model (ITM)

- Location and Situation Variability, the deviations Y_L and Y_S:

$$Y_L = z_L \sigma_L, \sigma_L = \frac{10k\Delta h(d)}{k\Delta h(d) + 13}$$

$$Y_S = z_S \left(\sigma_S^2 + \frac{Y_T^2}{7.8 + z_S^2} + \frac{Y_L^2}{24 + z_S^2} \right)^{\frac{1}{2}}, \sigma_S = 5 + 3e^{-\frac{d_e}{10^5}}$$

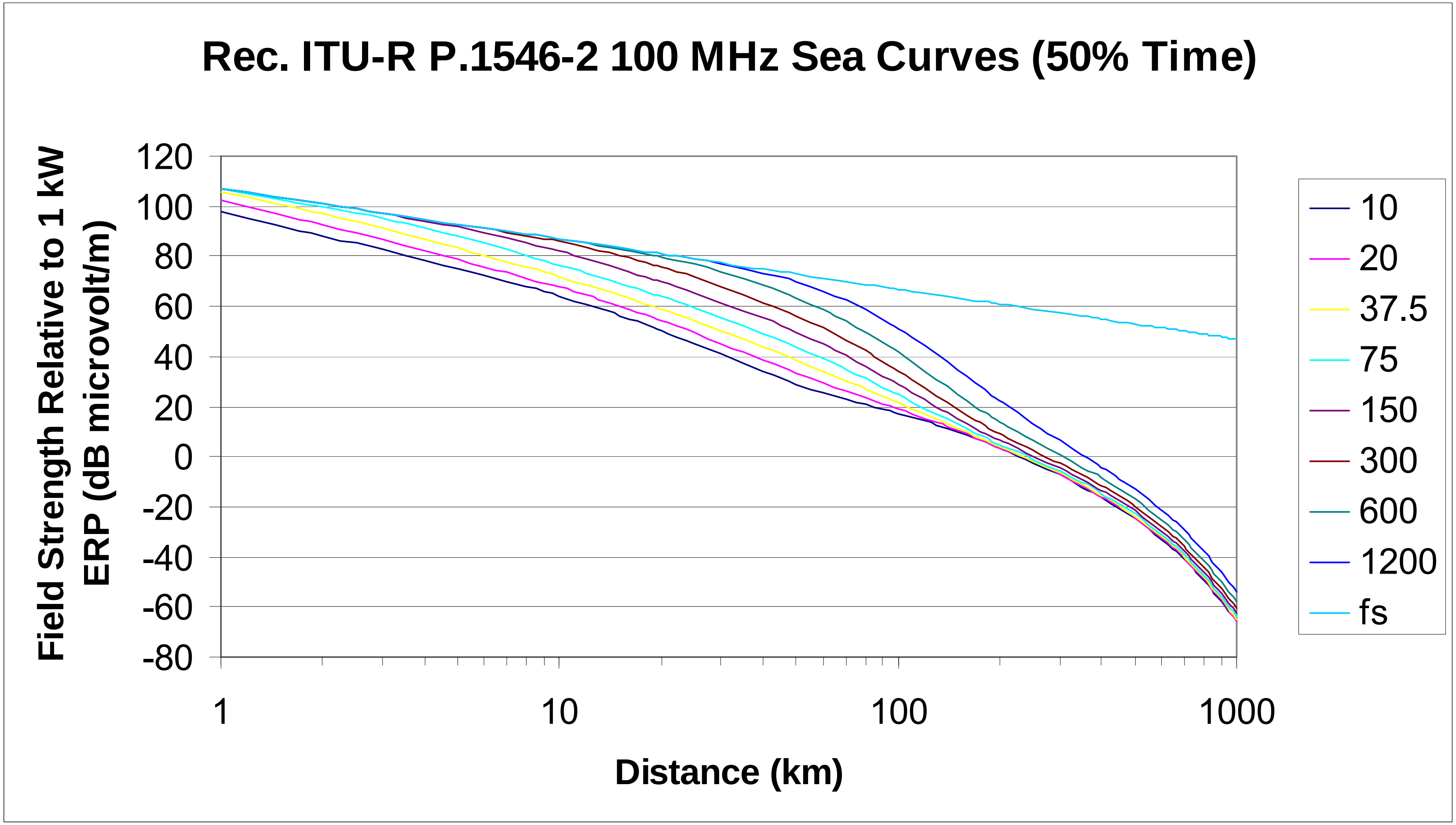
SSMD or the NTIA Model

- SSMD (or the NTIA Model) is a Hybrid Combination of Site-Specific and Site-General Approaches with "Similarities" to the ITM Approach
  - Sea Curves of Rec. ITU-R P.1546 (50% Time) for Propagation over a Smooth Spherical Earth
  - Irregular Terrain Diffraction Using the Deygout Three-Edge Construction of Rec. ITU-R P.526 (Minus the Smooth Sphere Contribution): r_e @ 50% Time
    - Combine These Using ITM's "Diffraction Range"-like Weights
  - Troposcatter Using Rec. ITU-R P.452 When This Yields Less Attenuation Than the Above
  - Use the Rec. ITU-R P.1546 Land Curve Differences to obtain Time Percentages between 50% and 1%

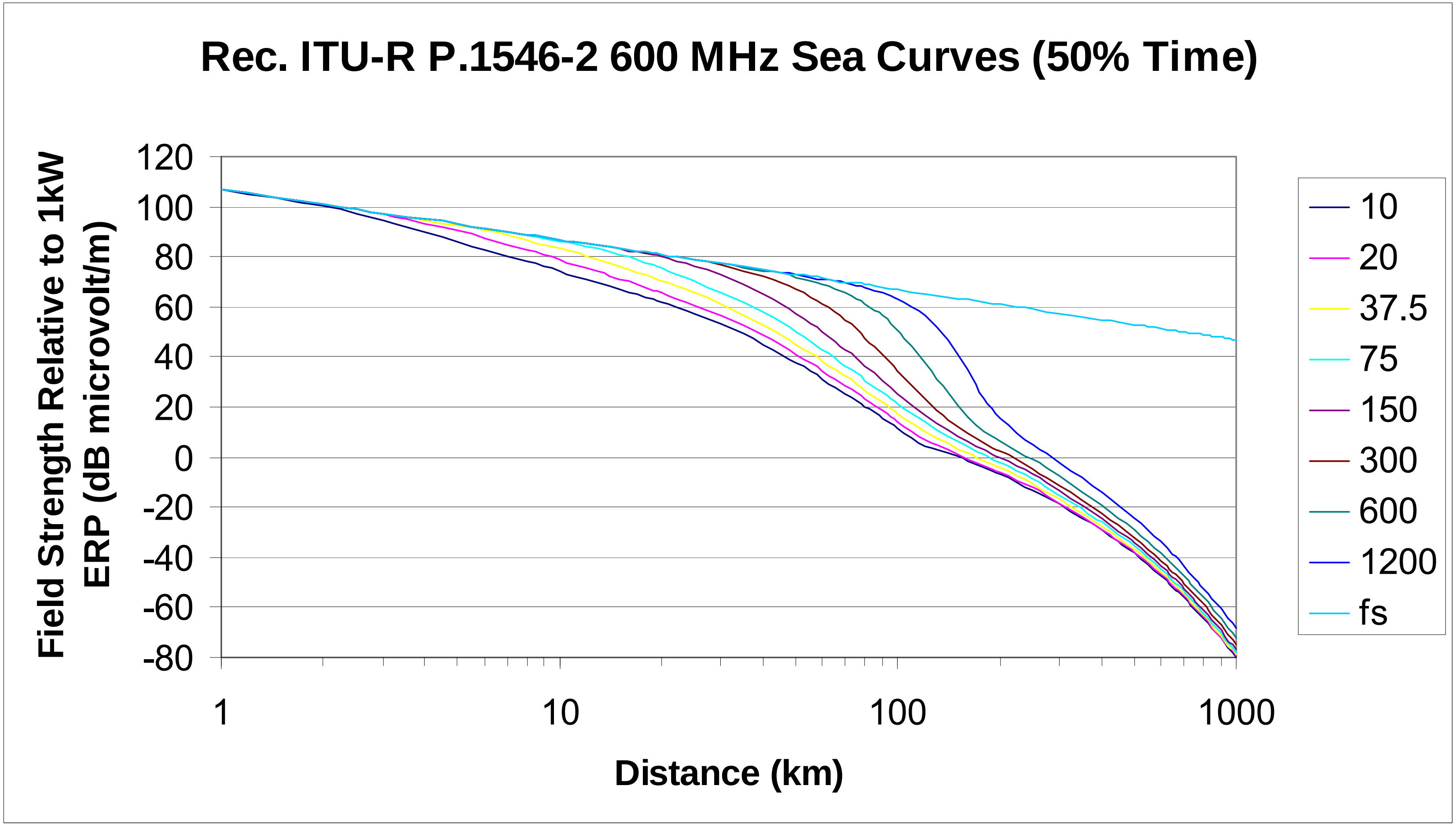
SSMD or the NTIA Model

- Sea Curves from Rec. ITU-R P.1546
  - Interpolate for Required Value of Distance, then Interpolate/Extrapolate for Required Values of h_1 and f
  - h_1 Computed Using Terrain Heights from 2 – 15 km Distances from This Designated Terminal (but Always Greater Than or Equal to 1 m), however use the UK's method of extrapolation for $0 \leq h_1 \leq 10$ m.
  - Include the h_2 Correction When This Terminal's Height Above Ground Is Not Equal to 10 m

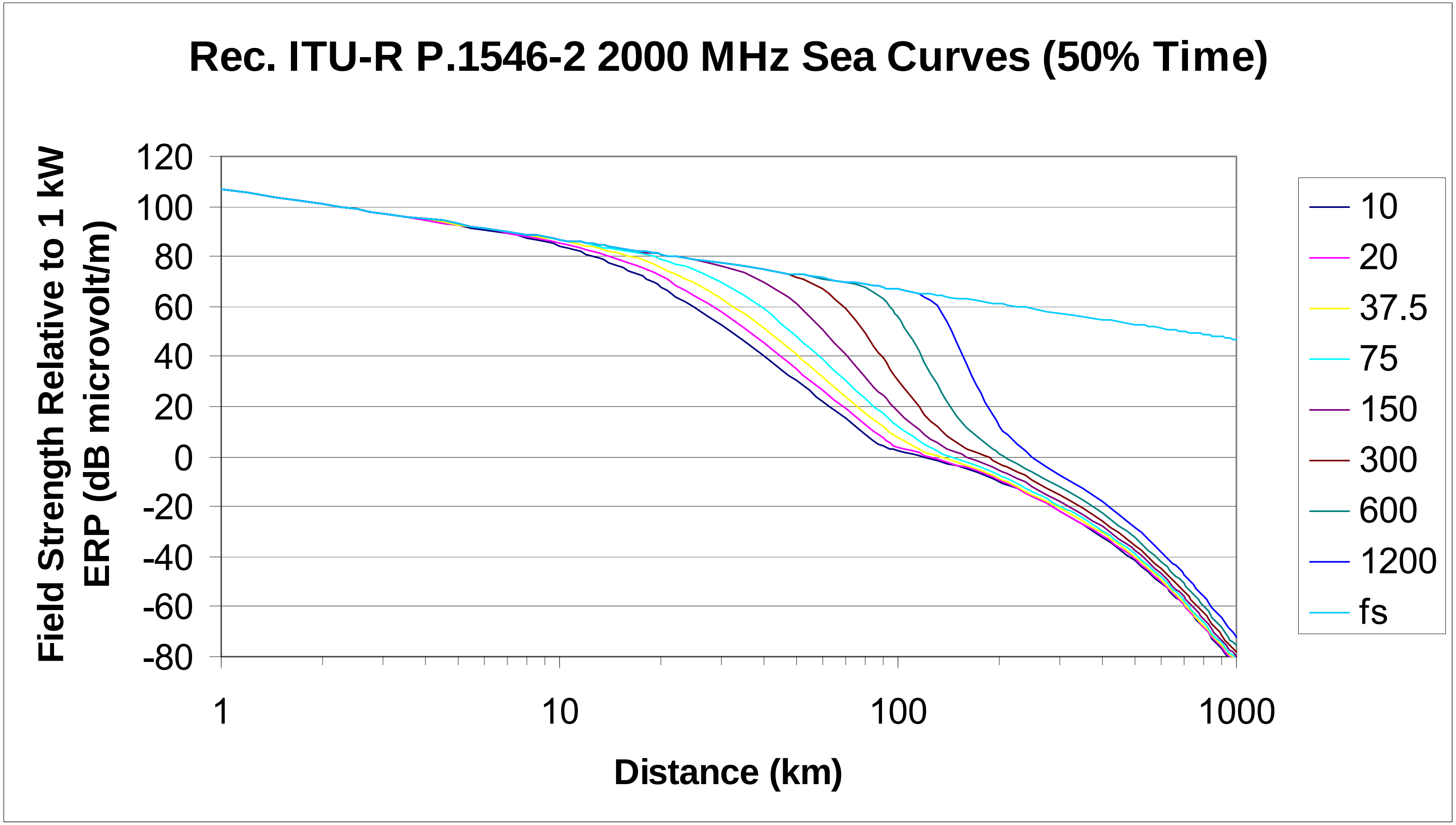
SSMD or the NTIA Model/Sea Curves



SSMD or the NTIA Model/Sea Curves



SSMD or the NTIA Model/Sea Curves



SSMD or the NTIA Model

- The Smooth Sphere Contribution, A_r’
  - Under line-of-sight conditions this should yield a direct ray-reflected ray model for a “smooth” earth
  - Under line-of-sight without first Fresnel zone clearance this should yield sub-path diffraction
  - This latter method should blend smoothly into smooth sphere diffraction

$$A_r' = E_{fs}(d) - E_{P.1546,s}(d, h_1, f, 50\%)$$

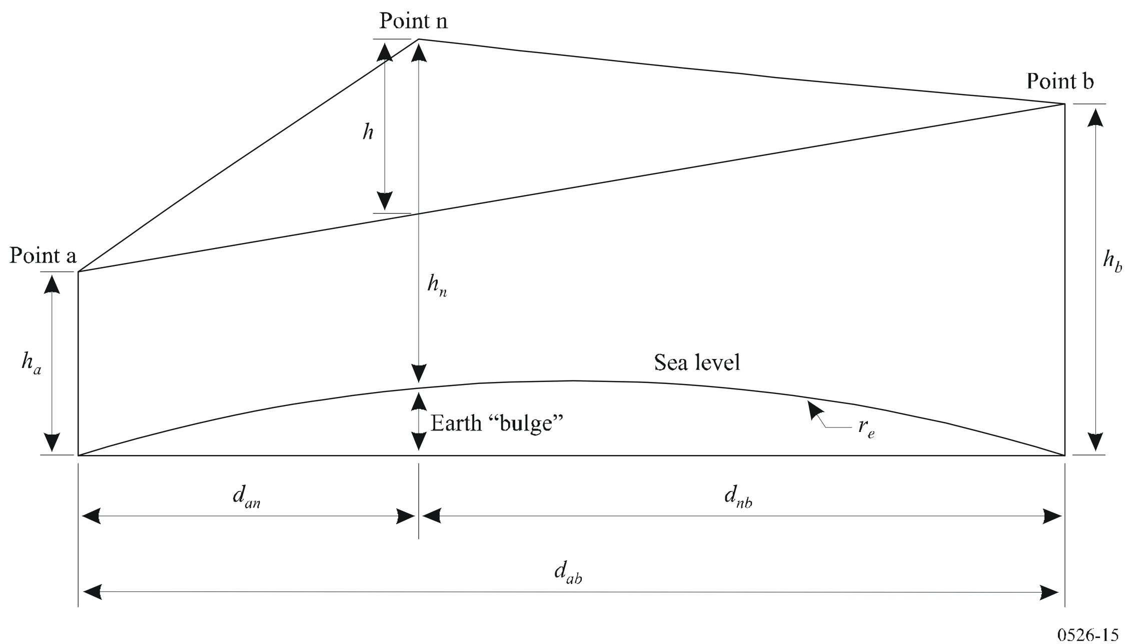
$$E_{fs}(d) = 106.9 - 20\log(d)$$

SSMD or the NTIA Model/Diffraction

Geometry for Deygout Construction

FIGURE 15

Geometry for a single edge



SSMD or the NTIA Model/Diffraction

- Cascaded Knife Edge Diffraction (Deygout Construction)

$$\nu_p = \max(\nu_n), n = 1,\ldots, npfl \ (\nu_p < 0 \Rightarrow \text{los path})$$

$$\nu_n = h\sqrt{\frac{2d_{ab}}{\lambda d_{an} d_{nb}}} \text{ where } h = h_n + \frac{d_{an} d_{nb}}{2a_e} - \frac{\left(h_a d_{nb} + h_b d_{an}\right)}{d_{ab}}$$

$$\text{if } \nu_p > -0.78 \text{ then also find}$$

$$\nu_t = \max(\nu_i), i = 1,\ldots, p \text{ and } \nu_r = \max(\nu_j), j = p,\ldots, npfl$$

$$L_d = J(\nu_p) + \left(1 - e^{-\frac{J(\nu_p)}{6}}\right) \cdot \left(J(\nu_t) + J(\nu_r) + 10 + 0.04d\right)$$

$$\text{where } J(\nu) = 6.9 + 20\log\left(\sqrt{(\nu - 0.1)^2 + 1} + \nu - 0.1\right) (\nu > -0.78)$$

$$\text{repeat this procedure with } h_n = 0, n = 1,\ldots, npfl \text{ and set the result to } L_{d_0}$$

$$\text{return } A_k' = L_d - L_{d_0}$$

SSMD or the NTIA Model

- The Weighted Combination of Smooth Sphere and Cascaded Knife Edge Diffraction, Comparison to Troposcatter and the Final Prediction

$$\text{weighting factor } w = \frac{1}{1 + 0.039\sqrt{Q}}$$

$$Q = \min\left(\frac{\Delta h(d)}{\lambda}, 10^3\right) \cdot \left(\frac{h_{et}h_{er} + 10}{h_{gt}h_{gr} + 10}\right)^{\frac{1}{2}} + \frac{d_{lt} + d_{lr} + a_e \cdot \theta_e}{d}$$

$$\Delta h(d) = \left(1 - 0.8e^{-\frac{d}{50}}\right) \cdot \Delta h, \theta_e = \max\left(\theta_t + \theta_r, -\frac{d_{lt} + d_{lr}}{a_e}\right)$$

$$A'_{diff}(d) = (2 - w) \cdot A'_k + w \cdot A'_r$$

$$A_{50} = \min\left(A'_{diff}(d), E_{fs}(d) - E_{tropo,50}(d)\right)$$

$$A_p = A_{50} + \left(E_{P.1546,l}(d, h_1, f, p) - E_{P.1546,l}(d, h_1, f, 50\%)\right)$$

Comparisons of the Path-Specific Models' Features

- Terrain (possibly Irregular Terrain) Diffraction Mechanisms
- Line-of-Sight Mechanisms
- Troposcatter Mechanisms
- Anomalous Propagation Mechanisms
- Land Use–Land Clutter/Site-Shielding Mechanisms
- Building Entry Loss Mechanisms
- Radiometeorological Parameters and Time, Location (and Situation) Variabilities
- Blending the Mechanisms (i.e., predicting enhancements at low time percentages)

Comparison of the Models' Features

- Terrain Diffraction Mechanisms
  - the Rec. ITU-R P.452, the Chinese and EBU Models each use the Deygout 3 knife-edge construction as found in Rec. ITU-R P.526
    - the EBU Model restricts the location of the subsidiary edges
    - the Chinese Model uses smooth sphere diffraction for "flat" paths
    - Some differences in how the time variability is treated, Chinese Model uses P.1546, while the others blend to reach the desired time percentage
  - the SSMD/NTIA Model uses the Deygout 3 knife-edge construction with the "smooth earth" contribution removed plus smooth sphere diffraction from the P.1546 Sea Curves
    - median only until the Rec. ITU-R P.1546 land curves are factored in
  - the Swiss Model advocates the Bullington Method
    - median only
  - the ITS' ITM uses "double knife-edge" plus smooth sphere diffraction attenuation plus an additional clutter correction, A_{fo}, to account for obstructions between the radio horizons
    - median only, until the time, location and situation variabilities are factored in

Comparison of the Models' Features (cont'd)

- Line-of-Sight Mechanisms
  - the ranges at which these mechanisms take place differ between the models
    - ITM appears to be much different from the Rec. ITU-R P.452 based models in this regard
  - All models use free space loss as the "dominant" mechanism with first Fresnel zone clearance
    - Rec. ITU-R P.452 includes multipath enhancements for time percentages less than 50%
  - Most models account for loss of first Fresnel zone clearance via sub-path diffraction
  - ITM includes the ground reflection contribution
    - the other models do not explicitly do so, other than a nominal contribution in SSMD/NTIA

Comparison of the Models' Features (cont'd)

- Troposcatter Mechanisms
  - These give rise to signal enhancements at (generally) small time percentages
  - The ITU-R P.452/Chinese/EBU Model is designed to blend smoothly with the other signal enhancement mechanisms
  - The ITM mechanism is designed to match with empirical and physical models of the expected phenomena.
  - The SSMD/NTIA uses the absolute prediction of the ITU-R P.452 Model to predict troposcatter losses

Comparison of the Models' Features (cont'd)

- Anomalous Propagation Mechanisms
  - Explicitly treated through Rec. ITU-R P.452 (not including the Chinese Model) based models
  - Treated through the variabilities in ITM and P.1546 variability based models
- Land-Use/Land-Clutter/Site-Shielding Losses
  - each model's formulation is different
  - Chinese and EBU's Models for LU-LC losses have frequency dependence
- Building Entry Loss
  - A feature of the EBU Model only, but this could be adopted by the other models

Comparison of the Models' Features (cont'd)

- Radiometeorological Parameters and Time, Location and Situation Variabilities
  - P.452, the Chinese and EBU models take global maps of radiometeorological parameters into account to assess effects of time variability into account
  - ITM uses the radio climate to assess time variability, but requires user specification of the radio climate
  - all of the models take time variability into account
    - each assumes that the time variability is normally distributed
  - some models (P.452, Chinese and EBU) take the time percentage, p%, explicitly into account in the computation of all propagation mechanisms while others combine the variabilities after computation of an overall mean/median
- Location and Situation Variabilities are an open question: only ITM considers situation variability

Comparison of the Models' Features (cont'd)

- Blending the Different Mechanisms
  - ITM method: forces continuity at the "break points", requires a continuously increasing attenuation with path distance
  - Rec. ITU-R P.452 method:
    - blend via antilog-log combining process plus other mechanisms

i.e., $A = b \cdot a^{\left(\frac{\ln_a(A_1)}{b} + \ldots + \frac{\ln_a(A_n)}{b}\right)}$