Propagation Measurement Workshop
Radio Propagation Models
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1–2 PM MDT

Institute for Telecommunication Sciences

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Context

- Spectrum sharing compatibility analyses demand more precise propagation models
- Propagation measurements are needed to refine existing models or develop new ones
- Recent rulemakings have spurred more measurements by government and private sector groups
- Confidence in other groups' measurements would dramatically increase model developers' access to useful data sets
- Data collection and processing techniques need to be well-understood, well-documented, and harmonized. If not, there is a risk of measurement/modeling silos developing

Radio Propagation Models

- Maxwell's curl equations (rationalized MKSA units): $\vec{D} = \varepsilon\vec{E}, \vec{B} = \mu\vec{H}$

$$\mu\frac{\partial\vec{H}}{\partial t} = -\vec{\nabla} \times \vec{E}$$

$$\varepsilon\frac{\partial\vec{E}}{\partial t} + \sigma\vec{E} + \vec{J} = \vec{\nabla} \times \vec{H}$$

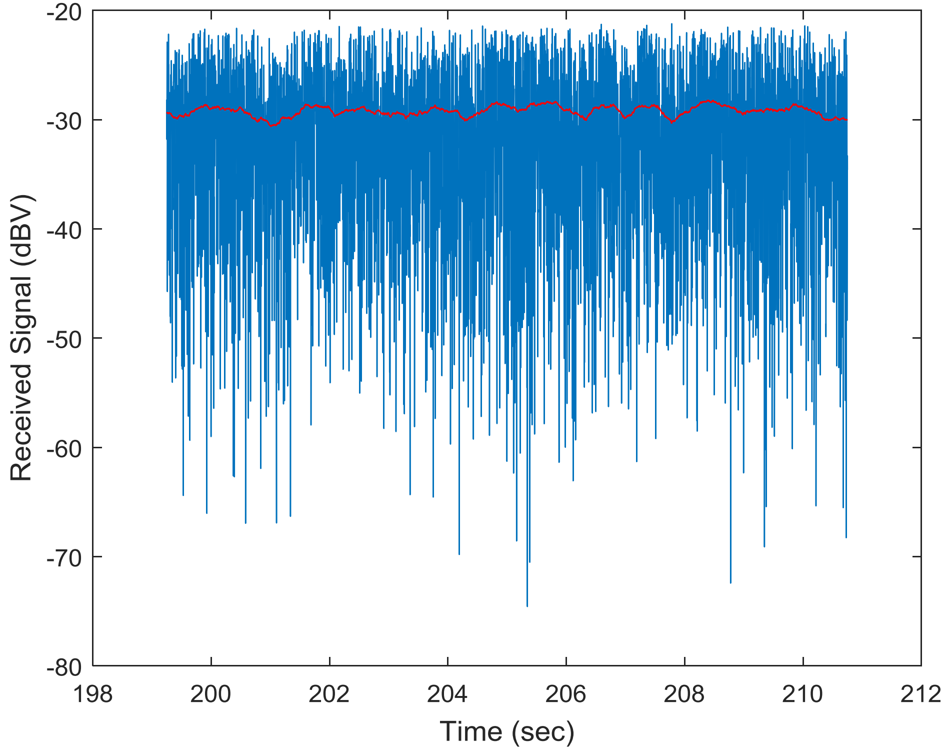
- Can solve for $\vec{E}$ and $\vec{H}$ given initial conditions everywhere and boundary conditions for all times, $t \geq 0$.

Radio Propagation Models

- Numerical solutions to the full wave problem rapidly become computationally inaccessible
  - f = 3.5×10^9 Hz,
  - R $\sim 10^3 - 10^5$m
  - $\lambda \sim 0.1$m
  - $\Delta x, \Delta y, \Delta z \sim 0.1\lambda$
  - $\Delta t \leq \frac{\Delta s}{\sqrt{3}c} \sim \left(10\sqrt{3}f\right)^{-1}$
  - Need to know $\varepsilon, \sigma\ and\ \mu$ to the same level of spatial discretization over the time frames of interest*
- We are forced to fall back to approximate analytic solutions

ε – permittivity, σ – conductivity, μ - permittivity

Slow-fading vs. fast-fading



Radio Propagation Models

- Basic transmission loss (L_b) vs. path loss
  - L_b: Both terminals' hypothetical antennas are isotropic
  - L_b: Both terminals are loss-free
  - L_b: Both terminals' hypothetical antennas are free of polarization and multipath coupling loss
- Free space basic transmission loss, L_{bf} [dB]:

$$L_{bf} = 20\log(2kr)$$
$$k = \frac{2\pi}{\lambda}$$

$$r \approx \sqrt{d^2 + (h_1 - h_2)^2}$$

Euclidean distance between the electrical centers of the terminals. r, λ must be in consistent units and fields must be in the radiation zone

Radio Propagation Models

Empirical models – based on observations and measurements alone

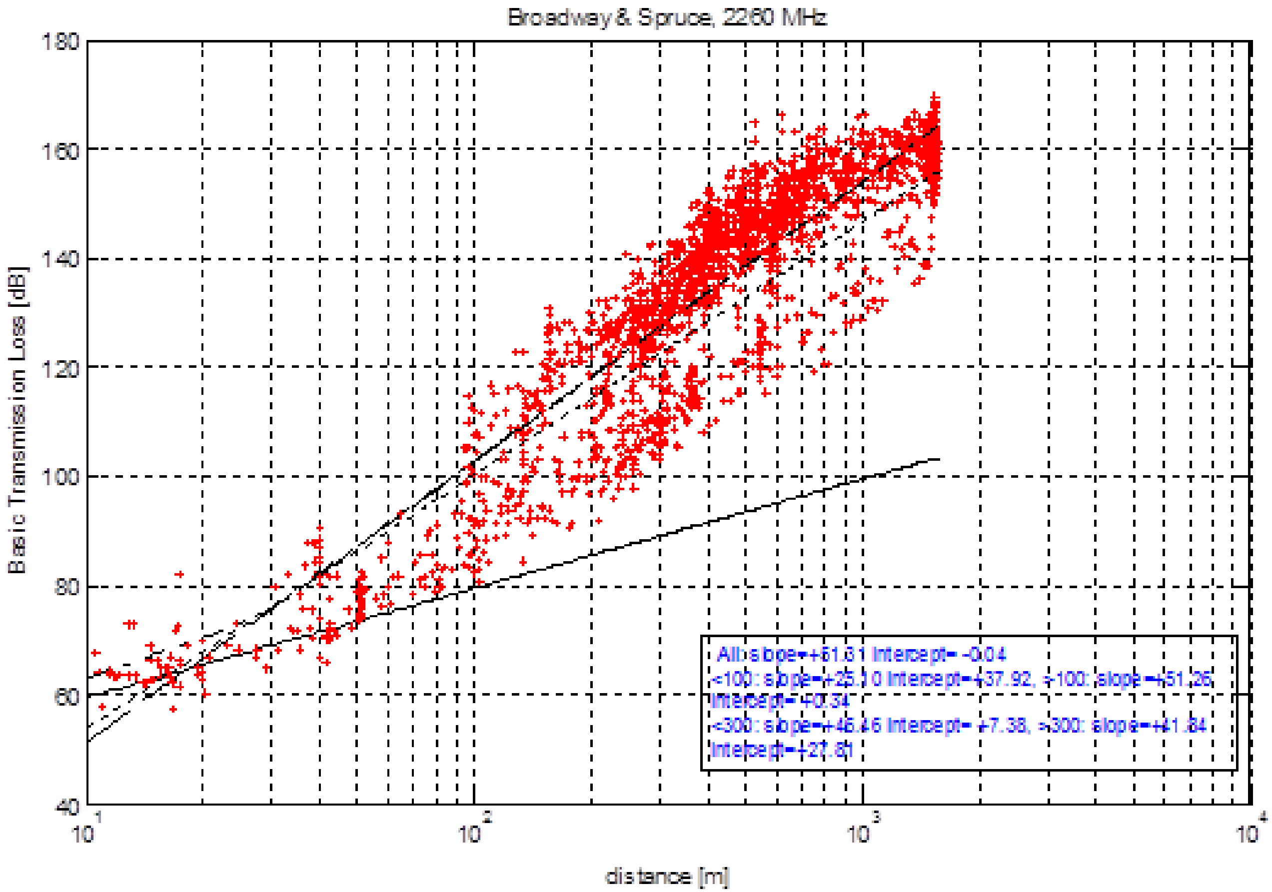
- Okumura-Hata model
- COST-231 Hata model
- Extended Hata model
- Erceg, et al. model
- Recommendation ITU-R P.1411 methods
- Stanford University Interim (SUI) model
- ECC-33 model (fixed wireless systems)
- Recommendation ITU-R P.1546 (superseded Recommendation ITU-R P.370)
- ITM (area mode)
- TIREM's SEM
- IF-77 (site-general/area mode)

Radio Propagation Models

Empirical models – conceptual approach

- Measurements of L_b [dB] are ordered according to environment, frequency, distance and, often, terminal (effective) height (base/T_x)
- A common modeling approach is then to perform a least squares fit to the measurement data vs. $\log d$ (both slope and intercept) – this defines the mean (and, hopefully, the median) L_b
  - More sophisticated dependences may be appropriate (e.g., two slope and a breakpoint's value and distance)
  - Care should be taken to properly account for censored measurements – the most common example being noise-limited measurements
  - Goodness-of-fit tests should applied to this procedure
  - The applicable ranges of all parameters should be carefully and comprehensively defined
    - In particular, the median L_b model should not be extended down to distances where it "predicts" values less than L_{bf}
    - Applicable frequency range, terminal heights' range, environments, etc.

Empirical Model Example



Radio Propagation Models

- Deterministic models – make use of laws governing electromagnetic wave propagation – need real data from propagation environment
  - ITM (point-to-point mode)
  - TIREM
  - CRC Predict
  - COST 231 – Walfisch-Ikegami Model
    - $L_{NLOS} = L_0 + \max\{0, L_{rts} + L_{msd}\}$
  - Recommendations ITU-R P.1812, P.452 and P.2001
  - Ray tracing
  - Parabolic approximation
  - Many others
- All of these models mix determinism with empiricisms

History of ITM

- Numerous background publications found on the ITS Publications web site. A good start is the "A Guide to the Use of the ITS Irregular Terrain Model in Area Prediction Mode", NTIA TR 82-100.
- **"**The ITS model of radio propagation for frequencies between 20 MHz and 20 GHz (the Longley-Rice model) is a general purpose model that can be applied to a large variety of engineering problems. The model, which is based on electromagnetic theory and on statistical analyses of both terrain features and radio measurements, predicts the median attenuation of a radio signal as a function of distance and the variability of the signal in time and in space.**" (NTIA TR 82-100)**
- Validation: cf. Longley and Reasoner (1970)
- See references at end of presentation

Validations

- Used to predict long-term median basic transmission loss over irregular terrain
- Predictions tested against measured data for wide ranges of:
  - Frequency
  - Antenna height
  - Distance
  - Terrain tested is from very smooth plains to rugged mountains
  - Many measurements from all over world
  - Valid for following parameters and ranges:
    - Frequency, 20 to 20,000 MHz
    - Antenna heights: 0.5 to 3,000 m
    - Distance: 1 to 2,000 km
    - Surface refractivity: 250 to 400 N-units
    - Elevation angles to radio horizons should not exceed 12° (~ 0.2 radians)
    - Radio horizon distance should not be less than 1/10 the smooth-earth horizon distance
    - Radio horizon distance should not be more than 3x smooth-earth horizon distance

What does ITM try to capture?
(cf. NTIA TR 82-100, § 6)

- ITM and the Statistics of Radio Propagation Channels
  - Received signal levels are subject to a wide variety of random variations
  - We must employ proper engineering
  - Statistics of random propagation channels are more complex than simple random variables found in elementary probability theory.
- Observed signal levels are greatly stratified
  - Variability from observation to observation
  - Statistics also vary from observation to observation
  - Additional variations are added as:
    - Frequency
    - Distance
    - Antenna heights
    - Environment (i.e., mountains in a continental interior to flat lands in a maritime climate, or from an urban area to a desert)
    - Subtle and important reasons why different sets of observations have different statistics

What is in ITM?

- Atmospheric Effects (empirical)
  - Surface refractivity – surface gradient largely determines radio ray bending
  - Changes in refractive index
  - Changes in amount of turbulence or stratification
- Predictions of attenuation due to terrain features require:
  - Terminal effective antenna heights
  - Ground constants
  - Description of climate – in statistical variabilities
- Calculation using two modes:
  - Area prediction mode (general terrain variations characterized by terrain irregularity parameter, Δh)
  - Point-to-point prediction mode (specific terrain path profiles)

How does ITM work?

- Median reference attenuation value A_{ref} relative to free-space is computed first
- Median basic transmission loss calculated based on free-space path loss and the addition of A_{ref}

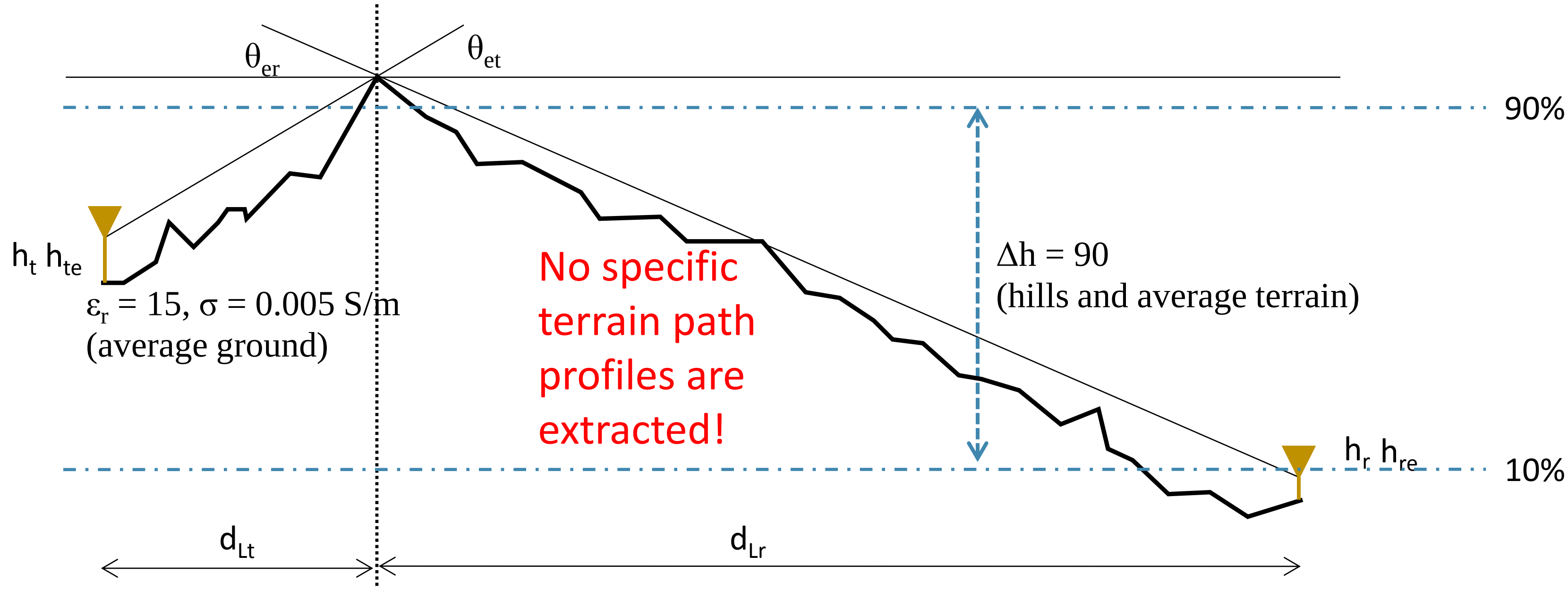
$$L_b = L_{bf} + A_{ref}$$

- Statistics of the variability of the basic transmission loss are computed and added to the median basic transmission loss
  - Variability comes from:
    - Time
    - Location
    - Situation

Irregular Terrain Model (ITM) — 2 Modes

Area Prediction Mode

- **User Input:** Frequency, polarization, terminals' heights above ground (h_t, h_r), siting of terminals, ground electrical properties (ε_r, σ), terrain irregularity parameter (Δh), surface refractivity, mode of variability and radio climate
  - Terminals' effective heights (h_{et}, h_{er}), radio horizon distances (d_{Lt}, d_{Lr}) and elevation angles (θ_{et}, θ_{er}) are then estimated from empirically observed medians

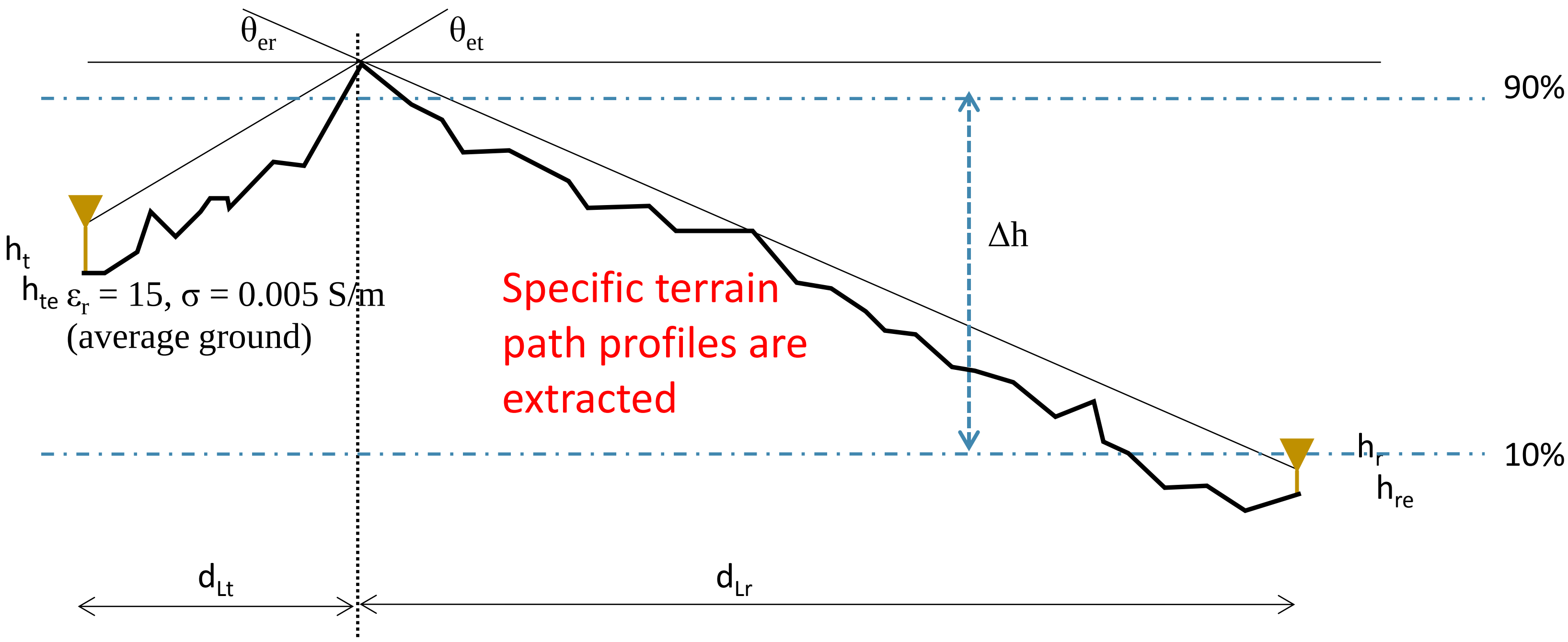


Irregular Terrain Model (ITM) — 2 Modes

Point-to-Point Prediction Mode

- **User Input:** Frequency, polarization, terminals' heights above ground (h_t, h_r), equidistantly spaced terrain profile between terminals, ground electrical properties (ε_r, σ), surface refractivity, mode of variability and radio climate
  - NLOS Path: estimate terrain irregularity parameter (Δh), terminals' effective heights (h_{et}, h_{er}), radio horizon distances (d_{Lt}, d_{Lr}) and elevation angles (θ_{et}, θ_{er}) from the terrain profile
  - LOS Path: estimate terrain irregularity parameter (Δh), and terminals' effective heights (h_{et}, h_{er}) from the terrain profile but use area mode method to determine terminals' radio horizon distances (d_{Lt}, d_{Lr}) and elevation angles (θ_{et}, θ_{er})
    - If path length is greater than the sum of the radio horizon distances (which implies that the path is non-line-of-sight), increase the terminals' effective heights (h_{et}, h_{er}) by an amount that just makes the path line-of-sight and recompute terminals' radio horizon distances (d_{Lt}, d_{Lr})and elevation angles (θ_{et}, θ_{er})

Point-to-point Mode Path Profiles

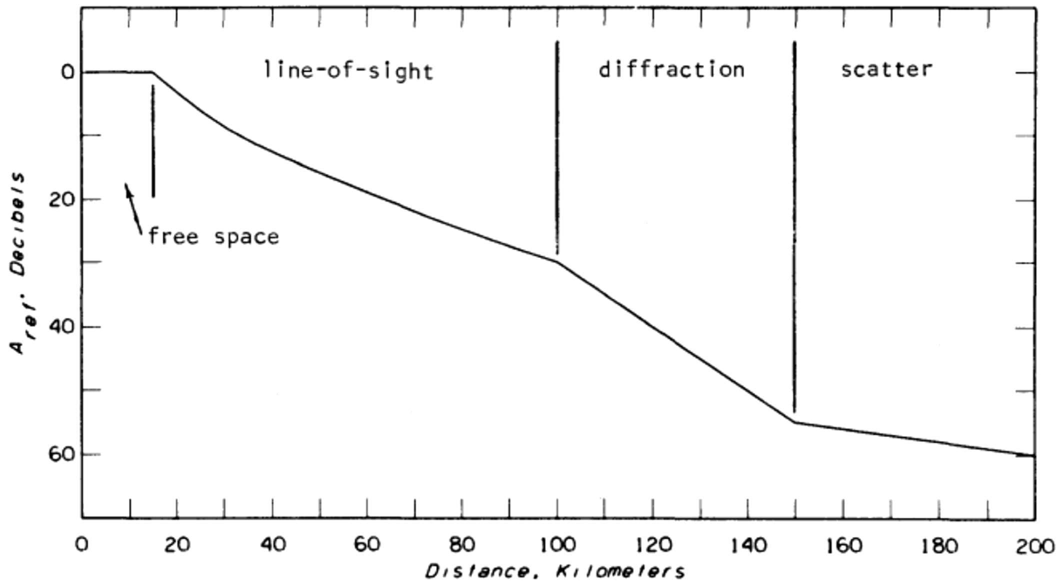


Irregular Terrain Model

- The computed reference attenuation, A_{ref}, Is given by a piecewise, continuous function of distance with continuity imposed at each endpoint

$$A_{ref} = \begin{cases} max\left(0, A_{el} + K_1 d + K_2 \ln\left(\frac{d}{d_{ls}}\right)\right) & \text{for } d \le d_{ls} \\ A_{ed} + m_d d & \text{for } d_{ls} \le d \le d_x \\ A_{es} + m_s d & \text{for } d_x \le d \end{cases}$$

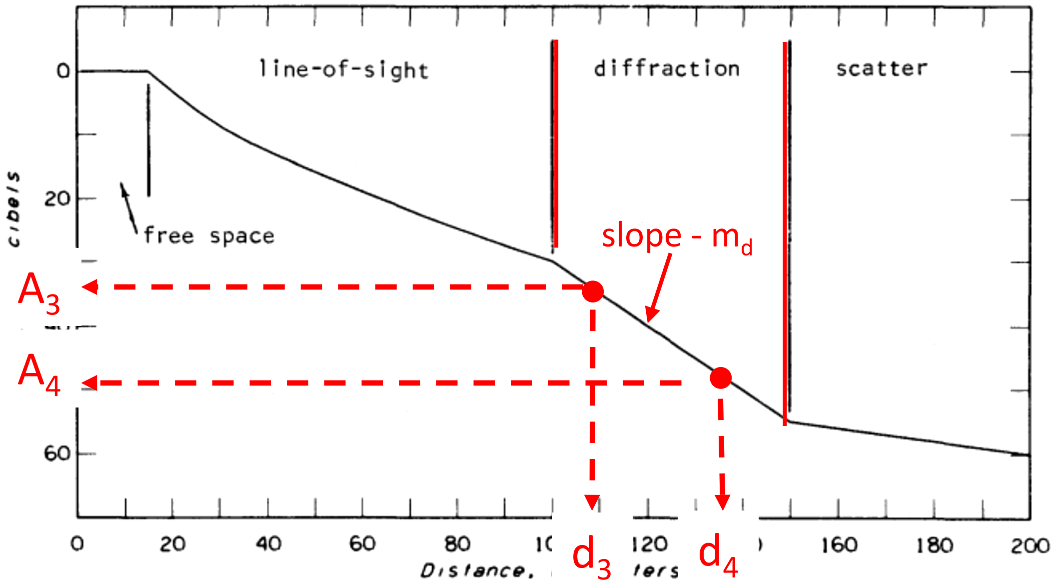
Terminal in line-of-sight range
Terminal in diffraction range
Terminal in scattering range



Computational Steps

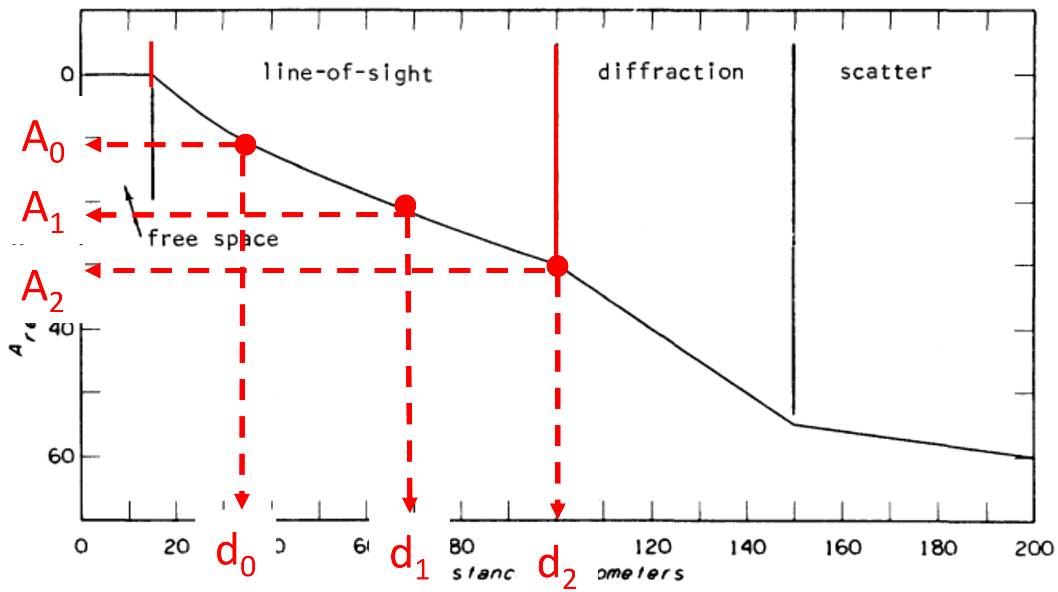
- Evaluate diffraction attenuation function at two distances beyond line-of-sight range to define slope (m_d) and diffraction range attenuation (A_{ed}),

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



Computational Steps

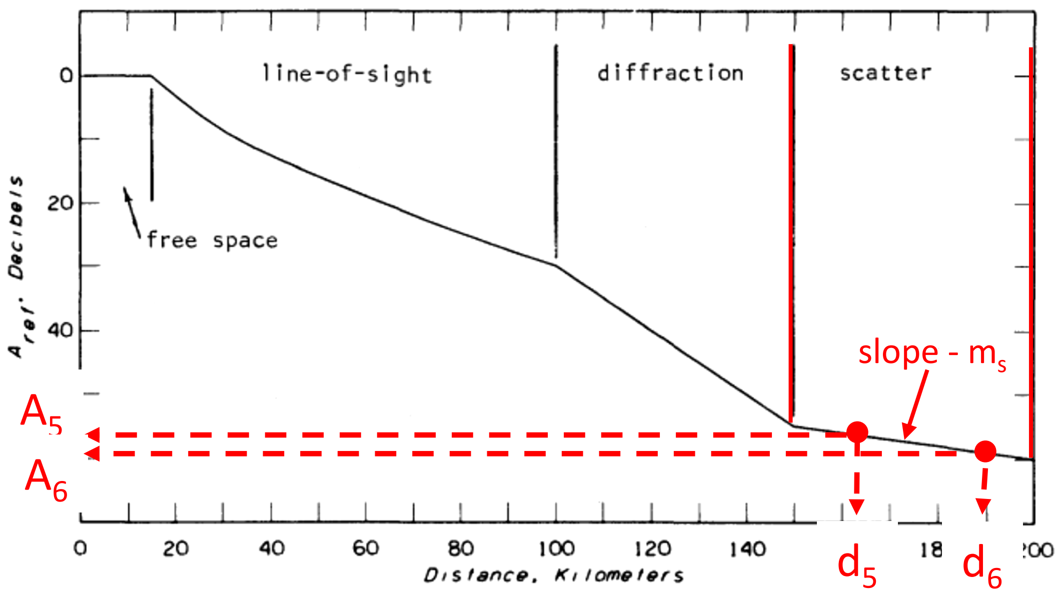
- Ensure continuity at d_2 and compute A_2 based on A_{ed} and m_d, $A_2 = A_{ed} + m_d d_2$
- Evaluate line-of-sight attenuation function at two distances beyond line-of-sight range to eventually determine A_{ref}



Computational Steps

- Finally, evaluate scattering range attenuation function based on two distances to obtain slope and attenuation in scattering range

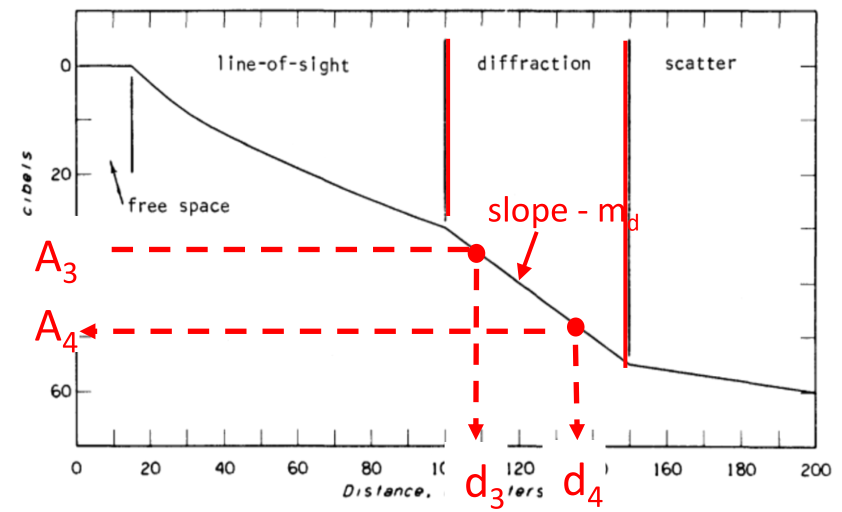
$$m_s = \frac{A_6 - A_5}{D_s} \qquad A_{es} = A_{ed} + (m_d - m_s)d_x$$



Diffraction Range Attenuation Function

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

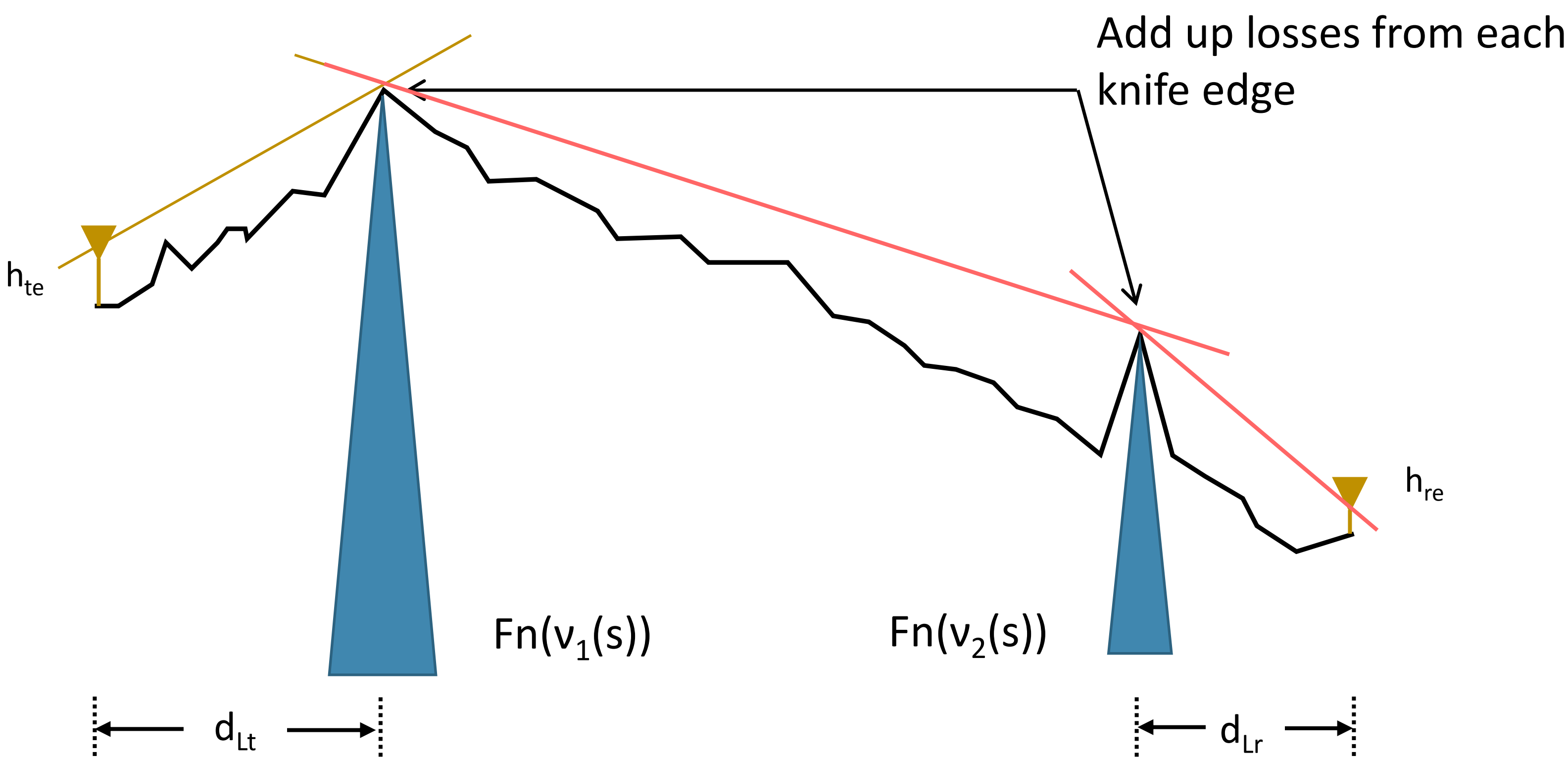
- $A_k(s)$ is the knife-edge diffraction function (physically based)
- $A_r(s)$ is the smooth-earth diffraction function (physically based)
- A_{fo} is a 'clutter' function (empirical)
  - approximately accounts for the median additional diffraction attenuation due to additional knife-edges between the terminals' irregular terrain radio horizons that may obstruct the convex hull between the two irregular terrain radio horizons.
- w(s) is a weighting function (empirical)
  - $w(s) \rightarrow 1, \Delta h \rightarrow 0$
  - $w(s) \rightarrow 0, \Delta h \rightarrow \infty$



Double Knife-edge Diffraction — $A_k(s)$
Epstein-Peterson Model

- Coefficients of the diffraction range ($d_{ls} \leq d \leq d_x$):

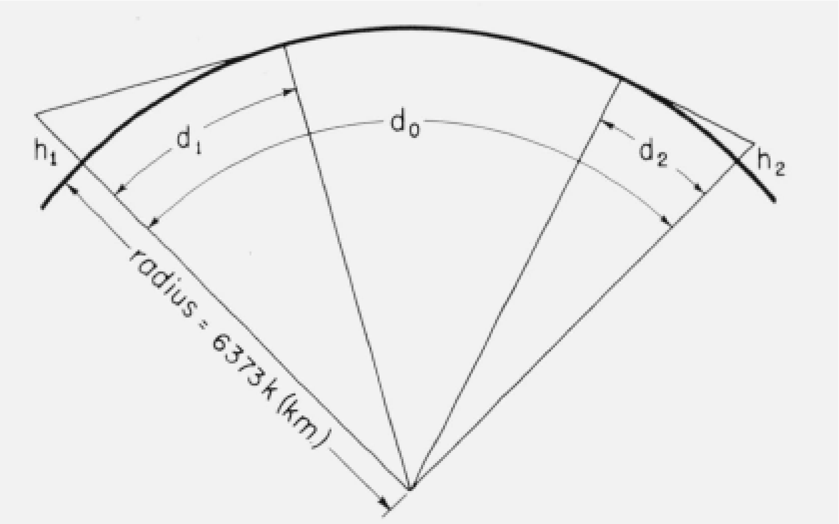
$$A_k(s) = Fn(v_1(s)) + Fn(v_2(s))$$



Smooth Sphere Attenuation – $A_r(s)$

$$A_r(s) = G(x_0) - F(x_1, \mathrm{K}_1) - F(x_2, \mathrm{K}_2) - C_1(\mathrm{K}_0)$$

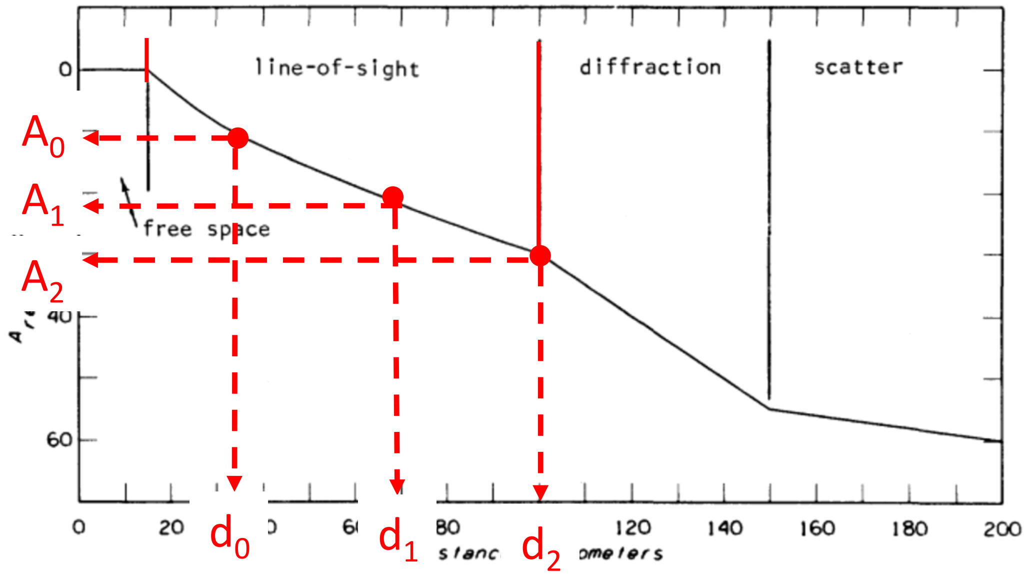
- Based on first term of Van der Pol-Bremmer residue series
- Based on a “three radii” method applied to Vogler’s formulation of the solution of the smooth spherical earth diffraction problem
- x_0, x_1, x_2 are dimensionless functions of distance, frequency, effective earth radius
- K_0, K_1, K_2 are functions of ε, σ, and antenna polarization



Line-of-sight Attenuation Function

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

- $A_d(s)$ is the extrapolated/extended diffraction range attenuation (to maintain piecewise continuity)
- $A_t(s)$ is the two-ray attenuation (physically based)
- w is a weighting function (empirical):
  - $w \to 1, \Delta h \to 0$
  - $w \to 0, \Delta h \to \infty$



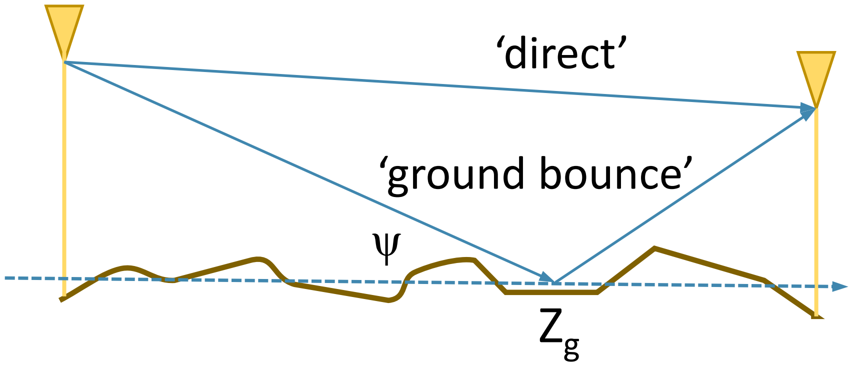
Two-ray Attenuation – $A_t(s)$

$$A_t(s) = -20\log\left|1 + R_e(s)e^{i\delta(s)}\right|$$

$$R_e(s) = \begin{cases} R_e'(s) \text{ for } |R_e'(s)| \geq max\left(0.5, \sqrt{\sin\psi(s)}\right) \\ \dfrac{R_e'(s)}{|R_e'(s)|}\sqrt{\sin\psi(s)} & \text{otherwise} \end{cases}$$

$$\delta(s) = \begin{cases} \delta'(s) \text{ for } \delta'(s) \leq \dfrac{\pi}{2} \\ \pi - \dfrac{\left(\frac{\pi}{2}\right)^2}{\delta'(s)} \text{ otherwise} \end{cases}$$

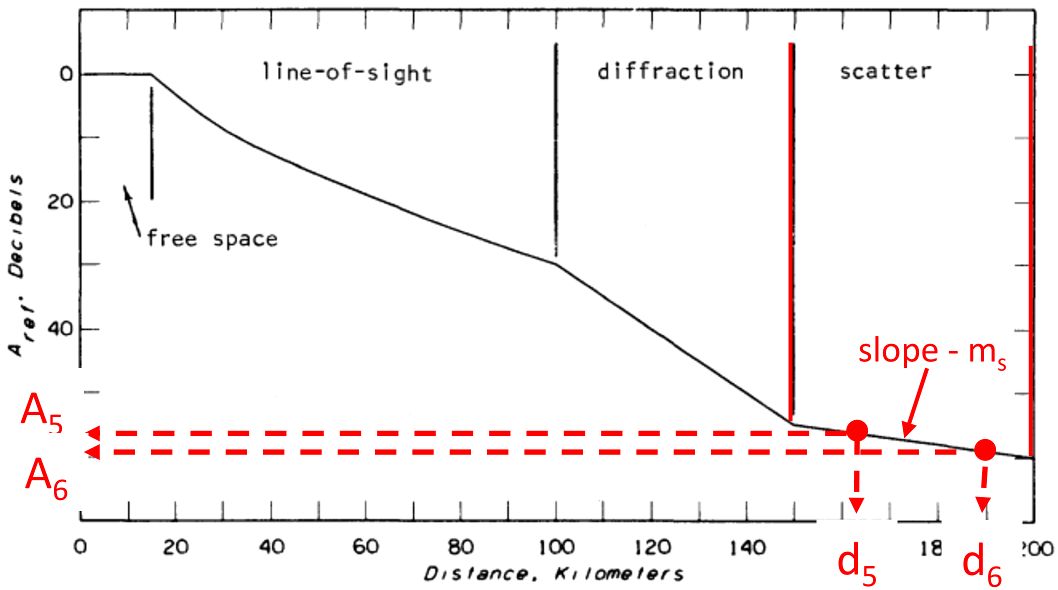
$$R_e'(s) = \frac{\sin\psi(s) - Z_g}{\sin\psi(s) + Z_g} e^{-k\sigma_h(s)\sin\psi(s)}$$



Scattering Range Attenuation Function

$$A_{scat}(s) = 10\log(47.7k\theta^4) + F(\theta s, N_s) + H_0$$

- $F(\theta s, N_s)$ is the attenuation function
- H_0 is the 'frequency gain' function



The Attenuation Function — F(θs, N_s)

$$F(D, N_s) = F(D, 301) - 0.1(N_s - 301)e^{-\frac{D}{4\times10^4}}$$

D = θs

$$F(D,301) = \begin{cases} 133.4 + 0.332 \times 10^{-3}D - 10\log(D) & 0 \le D \le 10^4 \\ 104.6 + 0.212 \times 10^{-3}D - 2.5\log(D) & 10^4 \le D \le 7 \times 10^4 \\ 71.8 + 0.157 \times 10^{-3}D + 5\log(D) & \text{otherwise} \end{cases}$$

Frequency Gain Function

$$H_0 = H_{00}(r_1, r_2, \eta_s) + \Delta H_0(s_s, q, \eta_s)$$

- If antennas sufficiently high, ground reflected energy doubles power incident on scatterers visible to both antennas and doubles power scattered to receiver
- As frequency decreases, effective antenna heights in terms of λ becomes smaller, ground-reflected energy tends to cancel direct-ray energy
- H_0 is a an estimate of the corresponding transmission loss

Variability and Quantiles

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

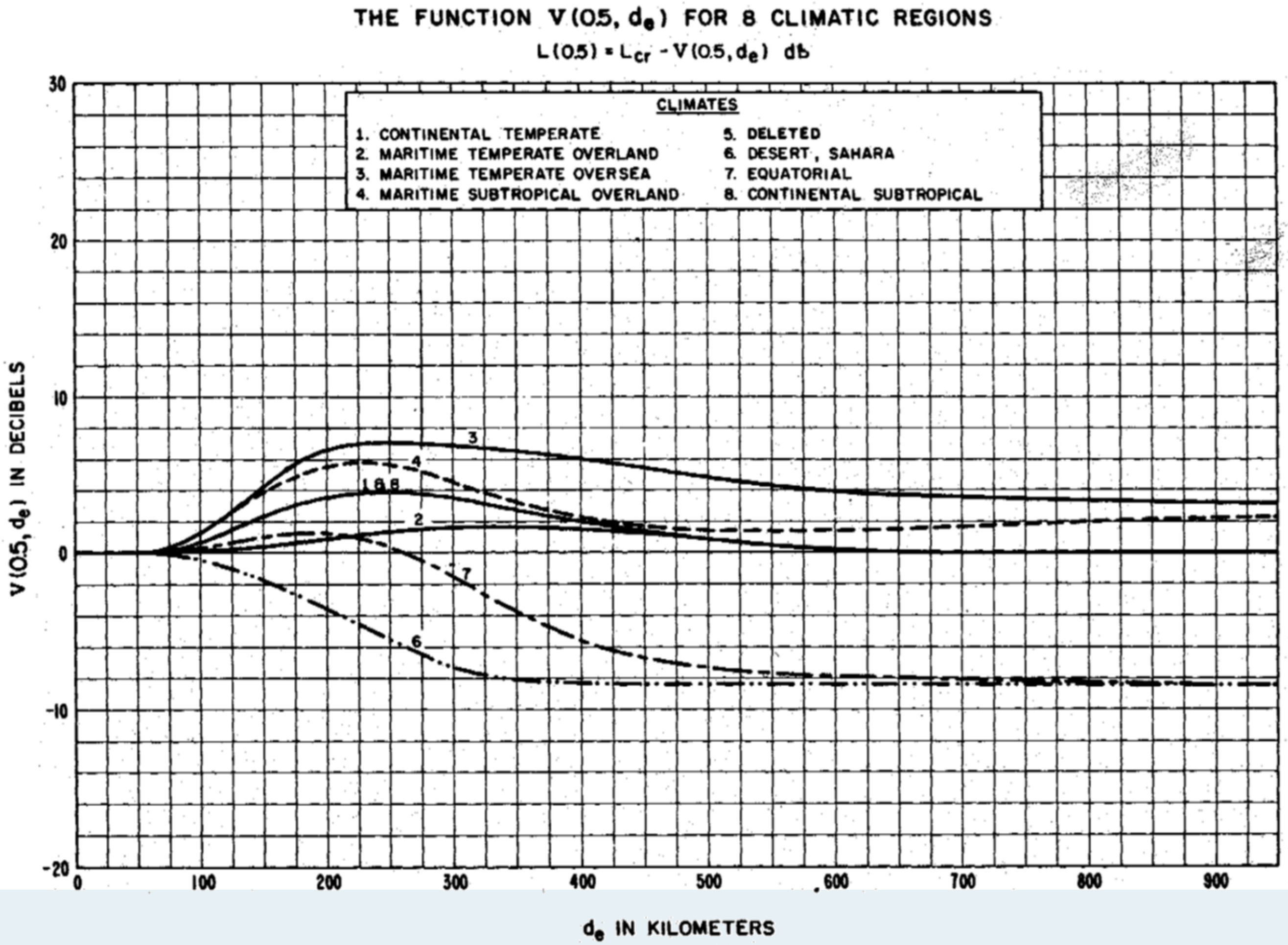
- $\mathbf{Y_T}$ is the time deviation
- $\mathbf{Y_L}$ is the location deviation
- $\mathbf{Y_S}$ is the situation deviation
- V_{med} is the all-year median adjustment

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

- Uses quantiles of observations: Y = z(q)σ
  - Values not exceeded for a certain fraction of times, locations, situations

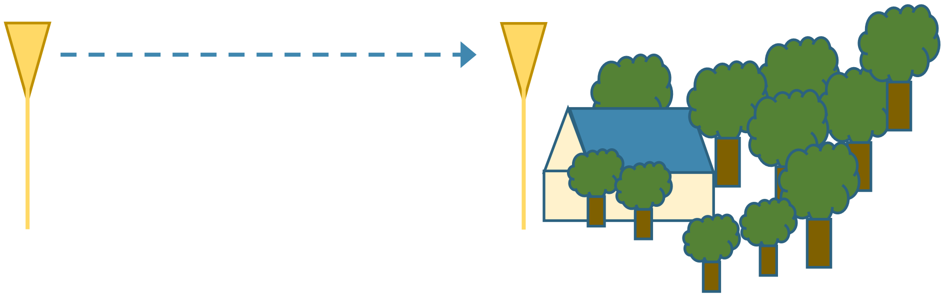
Irregular Terrain Model

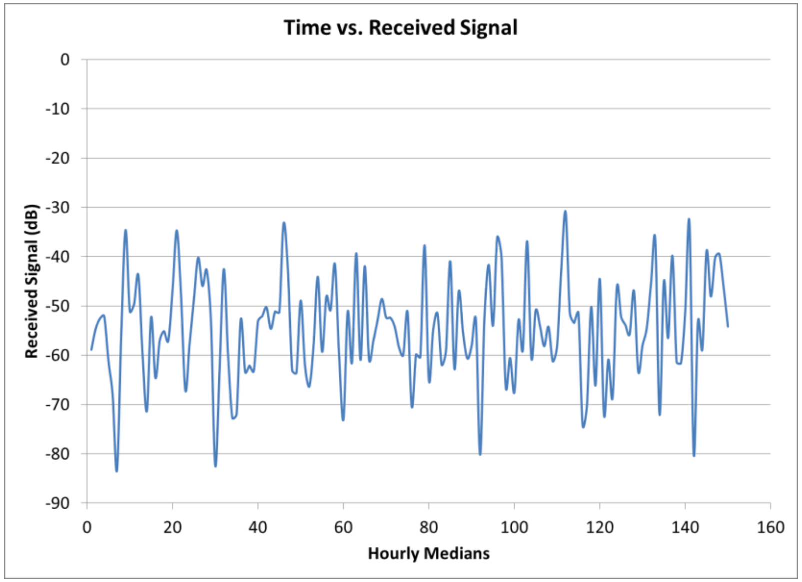
- All year median adjustment, V_{med}:



Time Variability, Y_T

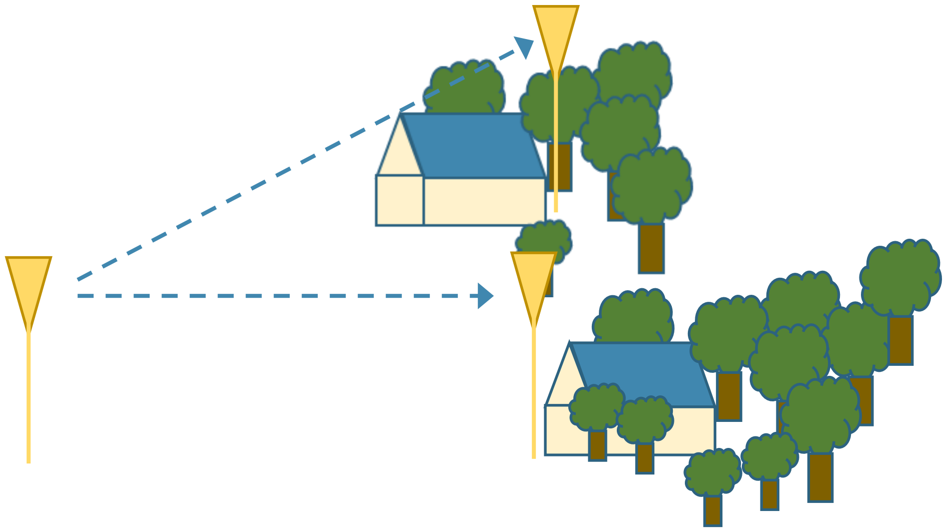
- Choose fixed link
- Record measurements of hourly median received signal for 2-3 years
- Resulting statistics will describe the time variability of this path
- Tries to understand the long-term variability in the atmosphere, climate
- Does not capture short-term variability due to multipath fading
- We would say, “On this path for 95% of the time the attenuation did not exceed X dB”

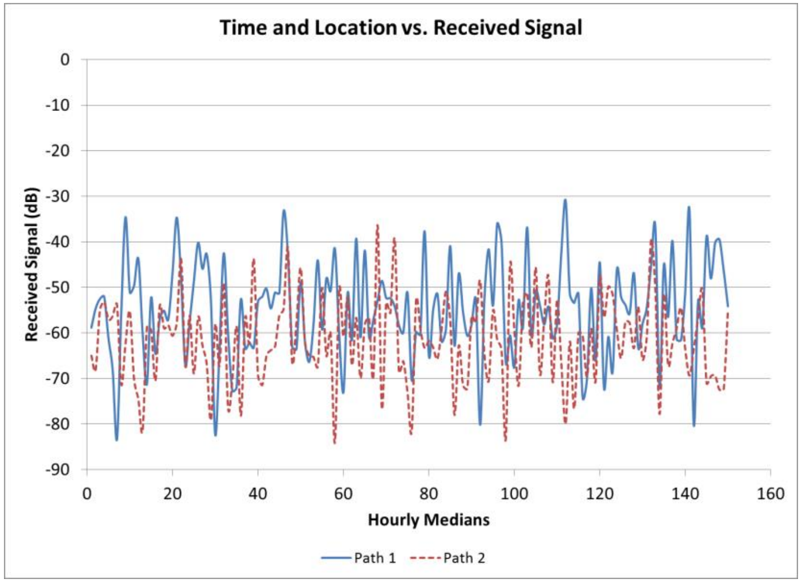




Location variability, Y_L

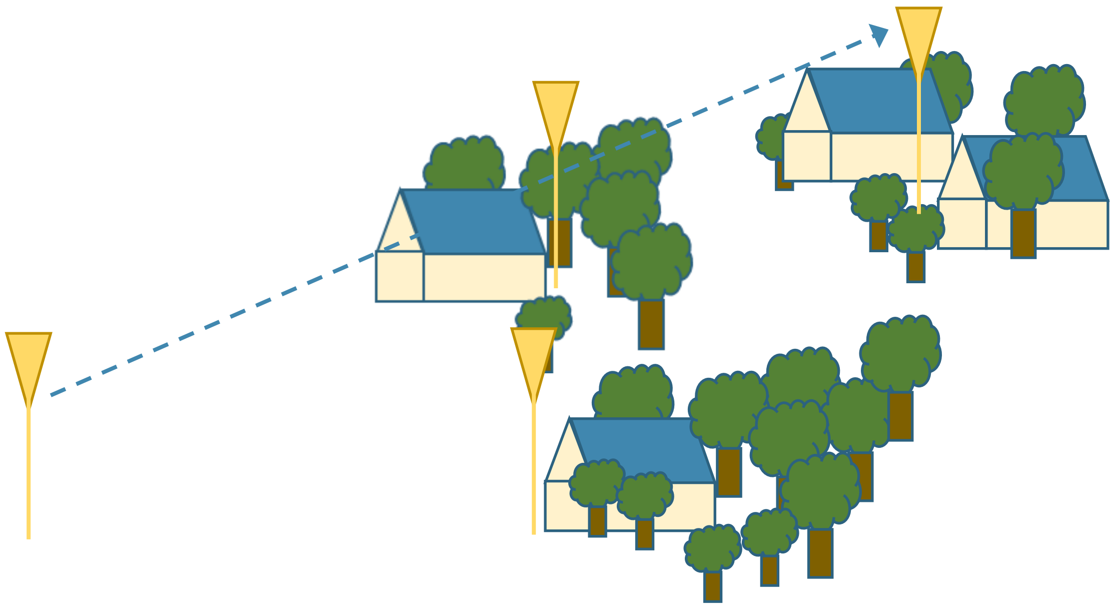
- Choose second path
- Keep environmental parameters as nearly constant as reasonable
- Restrict measurements to single area of earth
- "Path-to-path" variability
- We would say, "In this situation, there will be 70% of the path locations where the attenuation does not exceed X dB for at least 95% of the time"





Situation variability, Y_S

- Change operations from one area to another similar area
- Collection of all paths and times
- Assume we have specified system, environmental, and deployment in sufficient detail
- Use first and second situation to “predict” the observations from another situation
- We say, “In 90% of like situations there will be at least 70% of the locations where the attenuation will not exceed X dB for at least 95% of the time.”



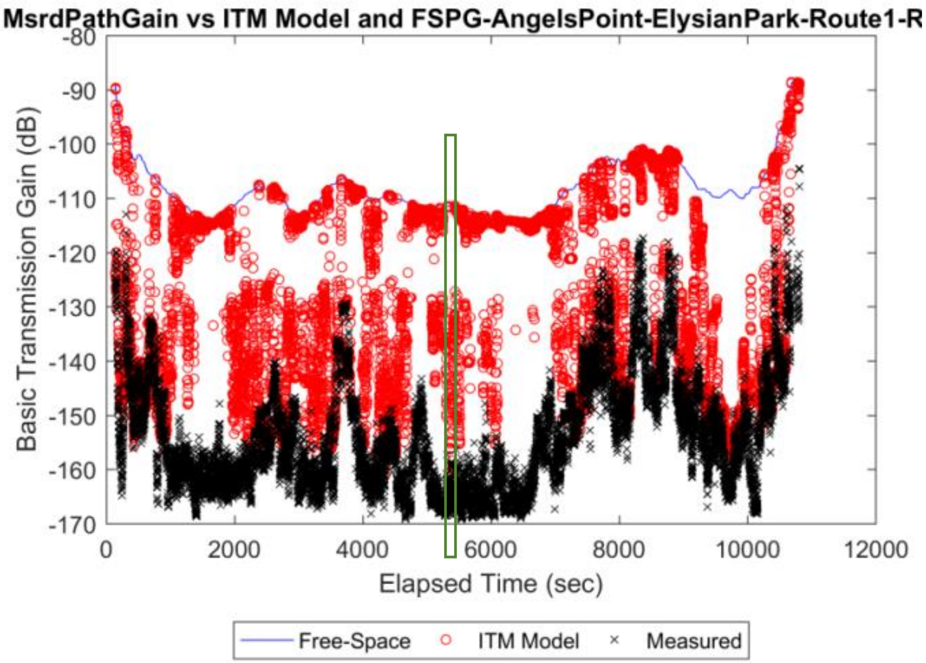
Reliability and Confidence

- Reliability is associated with the term “adequate service”
  - For an individual receiver, reliability is associated with a fraction of time
  - For a broadcaster, reliability is associated with both fraction of time and location
- Confidence is associated with a large number of engineering systems
  - Using the same confidence level a certain fraction of decisions will be correct
- Modes of Variability
  - Broadcast mode – reliability measures time/location variability, confidence measures situation variability
  - Individual mode – reliability measures time variability, confidence measures location/situation variability
  - Mobile mode – reliability measures time/location variability, confidence measures situation variability
  - Single message mode – confidence measures time/location/situation variability

Los Angeles – Example Run

Inputs:

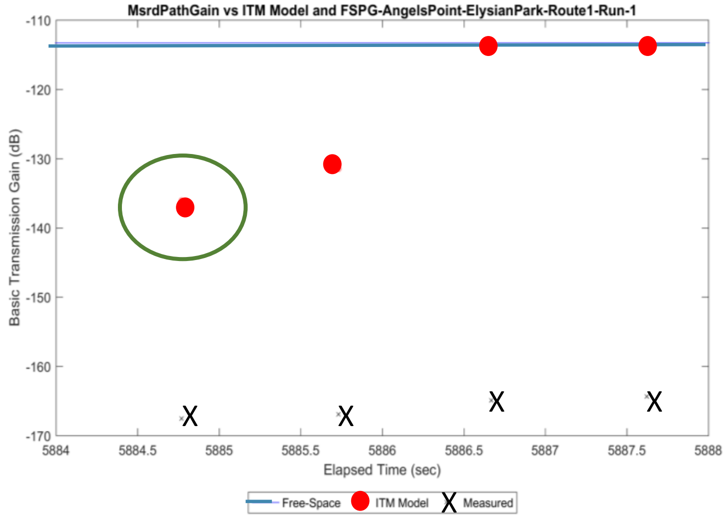
- h_t = 15.2
- h_r = 3.0
- POL = 1; (Vertical polarization)
- ε_r = 15, σ = 0.005 S/m (Average Ground)
- KLIM = 5; Continental Temperate
- Quantiles for reliability (R) and confidence (C):
  - Q_R = 10%, Q_C = 50%,
  - Q_R = 50 %, Q_C = 50%
  - Q_R = 90%, Q_C = 50%

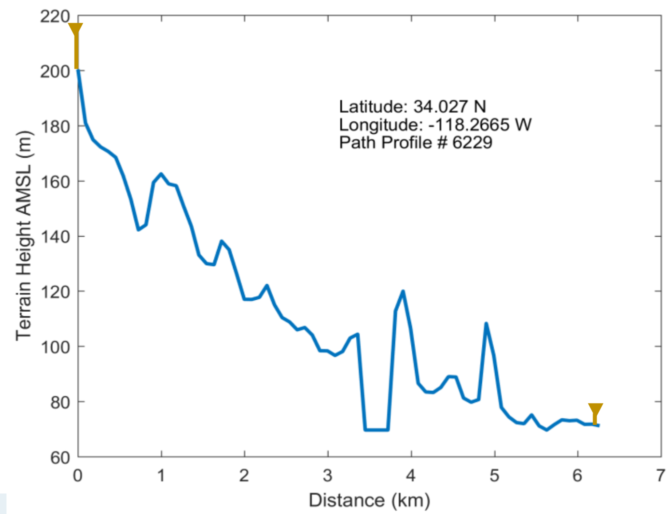


Los Angeles Example

Outputs at time ~= 5884.7 sec :

- DIST = 6262.7 m (distance between terminals-d)
- HE(1) = 44.5 m, HE(2) = 4.6 m (h_{et}, h_{er})
- THE(1) + THE(2) ($\theta_{et} + \theta_{er}$) = 0.0028 rad
- DL(1) = 4901.3 m, DL(2) = 1361.5 m (radio horizon distances, d_{l1}, d_{l2})
- DH = 97.2 m (terrain irregularity parameter, Δh)
- A_{ed} = 24.5, m_d =
- A_{el} = 19.6
- A_{es} = 0
- A_{ref} = 22.7;
- Median = FSPL + A_{ref} = 136.1 dB
- $Q_{R=10}$, $Q_{C=50}$= 126.3,
- $Q_{R=50}$, $Q_{C=50}$=136.1 dB,
- $Q_{R=90}$, $Q_{C=50}$=145.8 dB

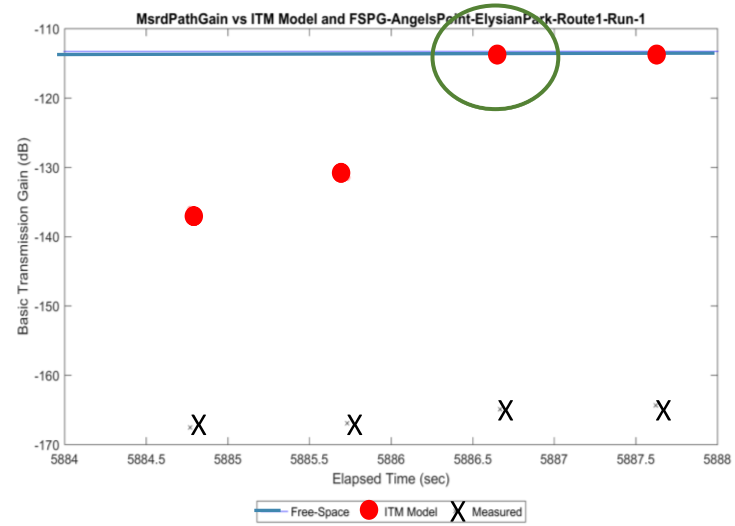


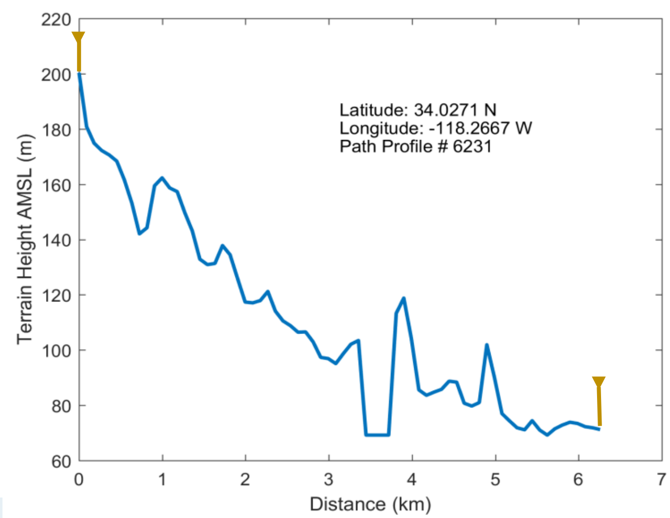


Los Angeles Example

Outputs at time ~= 5886.7 sec:

- DIST = 6258.3 m (distance between terminals-d)
- HE(1) = 54.5 m, HE(2) = 17.8 m (h_{et}, h_{er})
- THE(1) + THE(2) ($\theta_{et} + \theta_{er}$) = -0.005 rad
- DL(1) = 27708 m, DL(2) = 14744 m (radio horizon distances, d_{l1}, d_{l2})
- DH = 97.8 m (terrain irregularity parameter, Δh)
- $A_{ed} = -2.6$
- $A_{el} = -3.31$
- $A_{es} = 0$
- $A_{ref} = 0$;
- Median = FSPL + A_{ref} = 113.3 dB
- $Q_{R=10}$, $Q_{C=50}$= 110.3,
- $Q_{R=50}$, $Q_{C=50}$= 113.3 dB,
- $Q_{R=90}$, $Q_{C=50}$=123.7 dB





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Acronym Definitions

- COST – COopération européenne dans le domaine de la recherche Scientifique et Technique
- CRC – Communications Research Centre
- dB – decibels
- ECC – Electronic Communication Committee
- IF-77 – ITS/FAA 1977
- ITM – Irregular Terrain Model
- ITS – Institute for Telecommunication Sciences

Acronym Definitions

- ITU-R – International Telecommunications Union Radiocommunication Sector
- LOS – Line-of-sight
- MKSA – meter-kilogram-second-ampere
- NLOS – Non-line-of-sight
- SUI – Stanford University Interim
- TIREM – Terrain Integrated Rough Earth Model
- S/m – Siemens per meter
- SEM – Smooth Earth Model

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ITM Use in 3.5 GHz Analysis

"In the aggregate interference analysis, it was recognized that interference predictions arising from sources in a small cell deployment in heavy traffic areas would be required to account for radio propagation in man-made and naturally cluttered environments, as well as other impediments to propagation, such as terrain obstructions. An extensive review was performed of existing propagation models. In general, it was found that most of the existing propagation models were used for predicting signal strength and propagation path loss in built-up urban/suburban areas where there are numerous man-made building structures. Typically these propagation models are based on measurements with a high antenna (e.g., base station) and a lower antenna (e.g., mobile station) immersed in clutter. Propagation models based on this methodology (i.e., using the mean/median of measurements at given distances between the two terminals) tend to underestimate interference for the small percentages of time/locations, which must be considered for interference calculations. It was understood that accurate interference and propagation models should be developed and tuned based on real field measurement results. *However, given limitations on time and resources and after consideration of possible alternative models and the aggressive schedule of the work, a compromise approach was adopted as the way forward. This compromise was to revisit the Okumura et al. basic median attenuation curves, with the intention of extending Hata's empirical formulae in both distance and frequency ranges, and then apply the "Urban Factor" approach suggested by Longley, a method referred to as the extended Hata model.* A brief description of this approach is provided below." (NTIA TR 15-517)