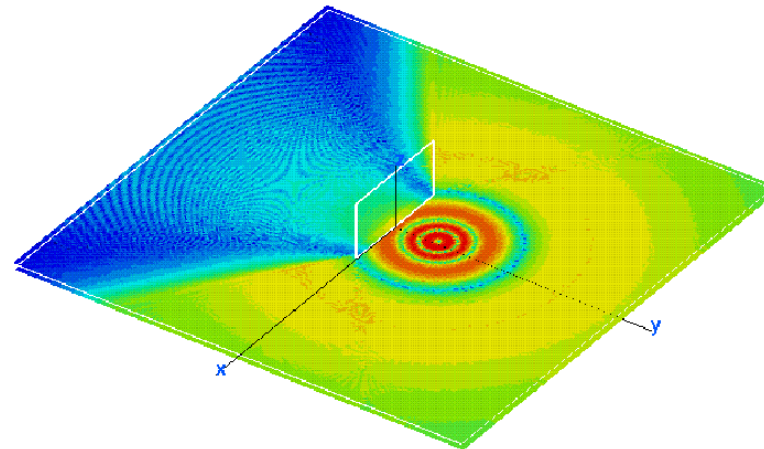


EC3630 Radiowave Propagation

**GEOMETRICAL OPTICS AND THE GEOMETRICAL
THEORY OF DIFFRACTION**

by Professor David Jenn



(version 1.6.3)

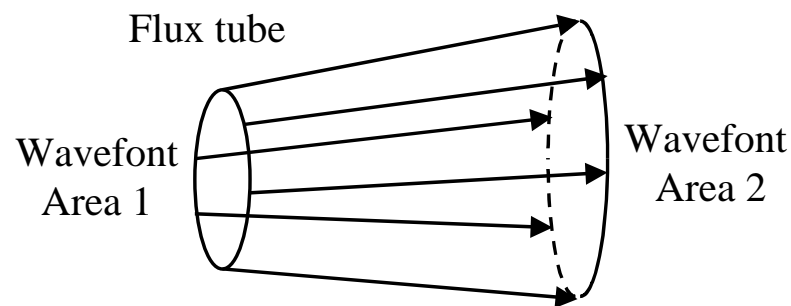
Geometrical Optics (1)

Geometrical optics (GO) refers to the simple ray tracing techniques that have been used for centuries at optical frequencies. The basic postulates of GO are:

1. Wavefronts are locally plane and waves are TEM
2. The wave direction is specified by the normal to the equiphase planes (“rays”)
3. Rays travel in straight lines in a homogeneous medium
4. Polarization is constant along a ray in an isotropic medium
5. Power in a flux tube (“bundle of rays”) is conserved

$$\iint_{\text{Area 1}} \vec{W} \cdot d\vec{s} = \iint_{\text{Area 2}} \vec{W} \cdot d\vec{s}$$

6. Reflection and refraction obey Snell’s law



7. The reflected field is linearly related to the incident field at the reflection point by a reflection coefficient

Geometrical Optics (2)

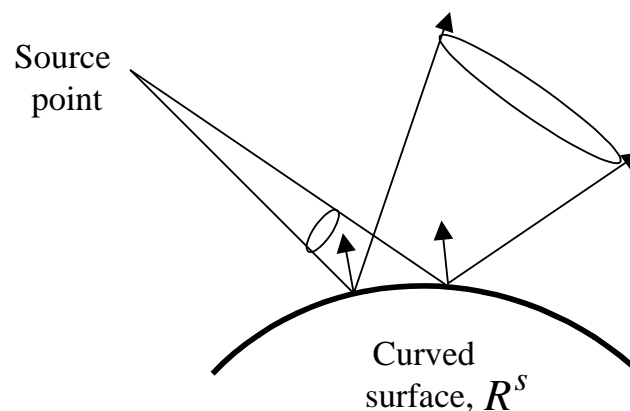
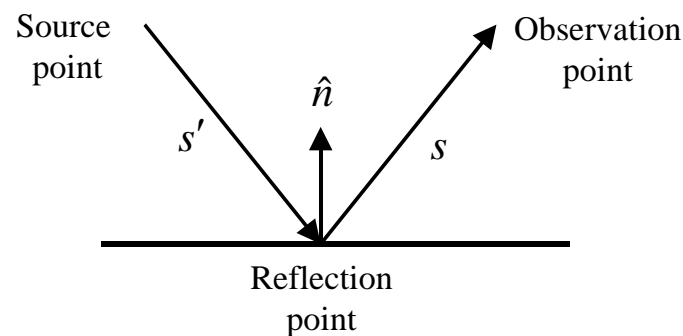
We have already used GO for the simple case of a plane wave reflected from an infinite flat boundary between two dielectrics.

For example, for perpendicular polarization:

$$E_{r\perp}(s) = \Gamma_{\perp} E_{i\perp}(s') e^{-jks}$$

where s' is the distance from the source to the reflection point and s the distance from the reflection point to the observation point. This has the general form of postulate 7.

The curvature of the reflected wavefront determines how the power spreads as a function of distance and direction. It depends on the curvature of both the incident wavefront, R^i , and reflecting surface, R^s .



Geometrical Optics (3)

A doubly curved surface (or wavefront) is defined by two principal radii of curvature in two orthogonal planes: R_1^s, R_2^s for a surface or R_1^i, R_2^i for the incident wavefront. The reflected wavefront curvature (R_1^r, R_2^r) can be computed by first finding the focal lengths in the principal planes. When the principal planes of the incident wavefront and surface can be aligned, then

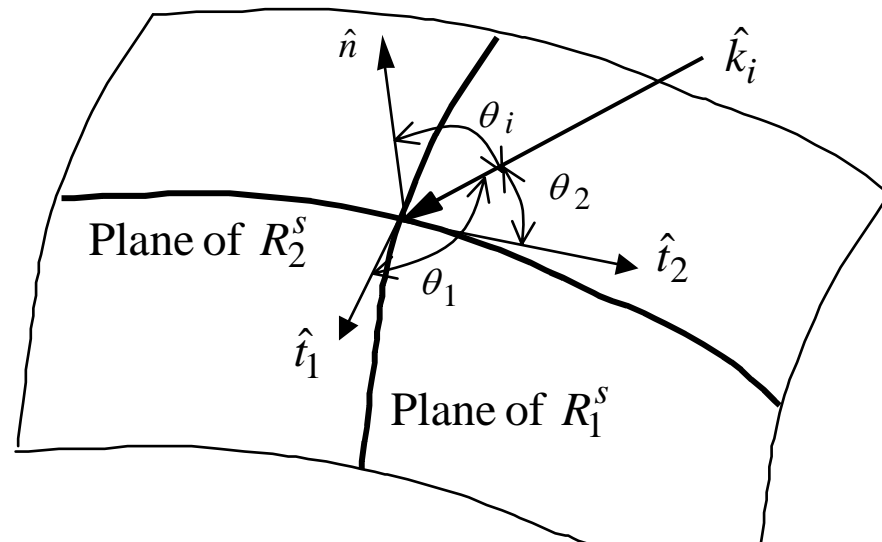
$$\frac{1}{f_{1,2}} = \frac{1}{\cos \theta_i} \left[\frac{\sin^2 \theta_2}{R_1^s} + \frac{\sin^2 \theta_1}{R_2^s} \right] \pm \left[\frac{1}{\cos^2 \theta_i} \left(\frac{\sin^2 \theta_2}{R_1^s} + \frac{\sin^2 \theta_1}{R_2^s} \right)^2 - \frac{4}{R_1^s R_2^s} \right]^{1/2}$$

where

$$\frac{1}{R_{1,2}^r} = \frac{1}{2} \left[\frac{1}{R_1^i} + \frac{1}{R_2^i} \right] + \frac{1}{f_{1,2}}$$

\hat{t}_1, \hat{t}_2 = unit vectors tangent to the surface in the two principal planes

\hat{n} = surface normal at the reflection point



Geometrical Optics (4)

For an arbitrary angle of incidence and polarization, the field is decomposed into parallel and perpendicular components. The reflected field can be cast in matrix form as:

$$\begin{bmatrix} E_{r\perp}(s) \\ E_{r\parallel}(s) \end{bmatrix} = \begin{bmatrix} \Gamma_{\perp\perp} & \Gamma_{\perp\parallel} \\ \Gamma_{\parallel\perp} & \Gamma_{\parallel\parallel} \end{bmatrix} \begin{bmatrix} E_{i\perp}(s') \\ E_{i\parallel}(s') \end{bmatrix} \underbrace{\sqrt{\frac{R_1^r R_2^r}{(R_1^r + s)(R_2^r + s)}}}_{A(s), \text{ Spreading Factor}} e^{-jks} e^{j\phi_c}$$

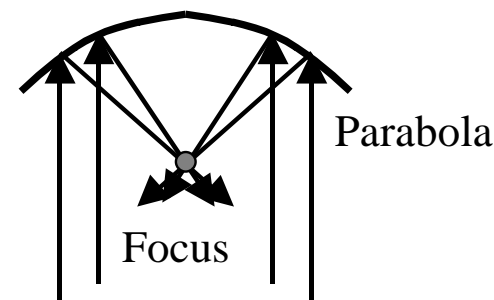
where:

ϕ_c = phase change when the path traverses a caustic (a point at which the cross section of the flux tube is zero)

Γ_{pq} = reflection coefficient for p polarized reflected wave, q polarized incident wave

Disadvantages of GO:

1. Does not predict the field in shadows
2. Cannot handle backscatter from flat or singly curved surfaces (R_1^s or $R_2^s = \infty$)



Example of a caustic: the focus of a parabola. All reflected rays pass through the focus. The cross section of a tube of reflected rays is zero

Geometrical Optics (5)

Example: A plane wave is normally incident on a conducting doubly curved surface.

Normal incidence $\theta_i = 0^\circ \rightarrow \cos \theta_i = 1$ and $\theta_1 = \theta_2 = 90^\circ \rightarrow \sin \theta_1 = \sin \theta_2 = 1$

$$\frac{1}{f_{1,2}} = \frac{1}{1} \left[\frac{1}{R_1^s} + \frac{1}{R_2^s} \right] \pm \left[\left(\frac{1}{R_1^s} + \frac{1}{R_2^s} \right)^2 - \frac{4}{R_1^s R_2^s} \right]^{1/2}$$

If the surface is a sphere of radius a , then $R_1^s = R_2^s = a$ and $f_1 = f_2 = a/2$. For a plane wave $R_1^i = R_2^i = \infty$ so that

$$\frac{1}{R_{1,2}^r} = \frac{1}{2} \left[\frac{1}{R_1^i} + \frac{1}{R_2^i} \right] + \frac{1}{f_{1,2}} = \frac{2}{a} \rightarrow A(s) = \sqrt{\frac{(a/2)^2}{s^2}} = \frac{a}{2s}$$

where in the denominator it was assumed that $R_1^r, R_2^r \ll s$. For a PEC, $\Gamma = -1$, and the reflected field is

$$E_r = -\frac{E_i a}{2} \left(\frac{e^{-jks}}{s} \right)$$

i.e., a spherical wave.

Geometrical Theory of Diffraction (1)

The geometrical theory of diffraction (GTD) was devised to eliminate many of the problems associated with GO. The strongest diffracted fields arise from edges, but ones of lesser strength originate from point discontinuities (tips and corners). The total field at an observation point P is decomposed into GO and diffracted components

$$\vec{E}_r(P) = \vec{E}_{GO}(P) + \vec{E}_{GTD}(P)$$

The behavior of the diffracted field is based on the following postulates of GTD:

1. Wavefronts are locally plane and waves are TEM.
2. Diffracted rays emerge radially from an edge.
3. Rays travel in straight lines in a homogeneous medium
4. Polarization is constant along a ray in an isotropic medium
5. The diffracted field strength is inversely proportional to the cross sectional area of the flux tube
6. The diffracted field is linearly related to the incident field at the diffraction point by a diffraction coefficient

Geometrical Theory of Diffraction (2)

Define a local ray fixed coordinate system: the z axis is along the edge; the x axis lies on the face and points inward.

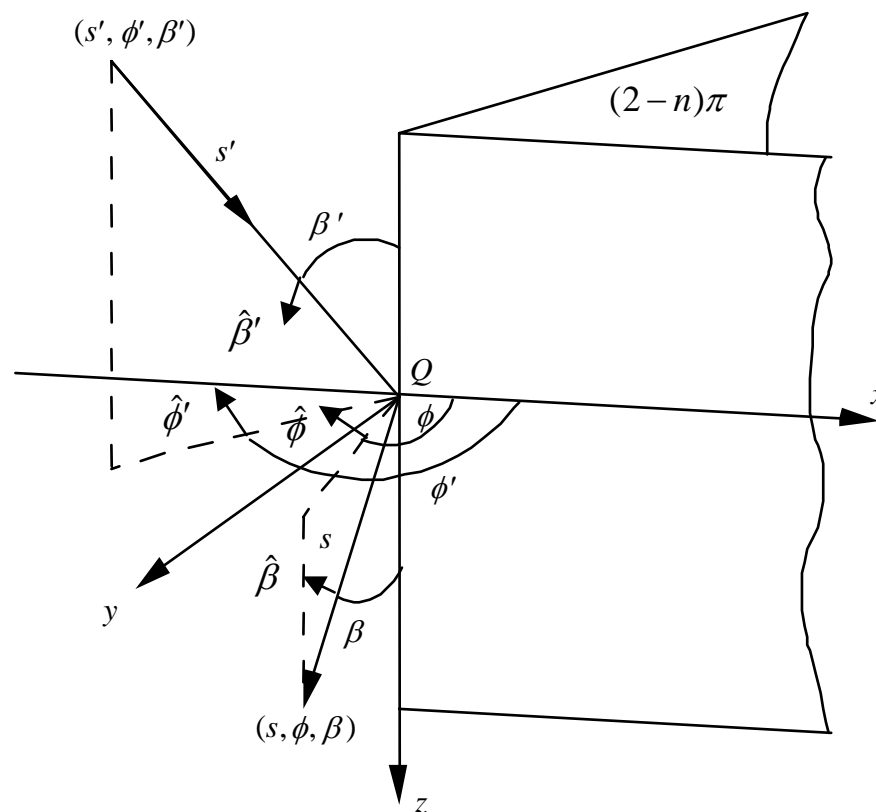
The internal wedge angle is $(2 - n)\pi$, where n is not necessarily an integer. A knife edge is the case of $n = 2$.

Primed quantities are associated with the source point; unprimed quantities with the observation point. Variable unit vectors are tangent in the direction of increase (like spherical unit vectors)

Diffacted rays lie on a cone of half angle $\beta = \beta'$ (the *Keller cone*)

The matrix form of the diffracted field is

$$\begin{bmatrix} E_{d\beta}(s) \\ E_{d\phi}(s) \end{bmatrix} = \begin{bmatrix} D_s & 0 \\ 0 & -D_h \end{bmatrix} \begin{bmatrix} E_{i\beta'}(s') \\ E_{i\phi'}(s') \end{bmatrix} A(s, s') e^{-jks}$$



Geometrical Theory of Diffraction (3)

The diffraction coefficients, D_s and D_h ¹, are determined by an appropriate “canonical” problem (i.e., a fundamental related problem whose solution is known).

The scattered field from an infinite wedge was solved by Sommerfeld. The infinitely long edge can represent a finite length edge if the diffraction point is not near the end.

The diffraction coefficient can be “backed out” of Sommerfeld’s exact solution because we know the GO field and the form of the GTD field from the postulates

$$\underbrace{\vec{E}_r(P)}_{\substack{\text{known} \\ \text{from} \\ \text{Sommerfeld}}} = \underbrace{\vec{E}_{GO}(P)}_{\substack{\text{can be} \\ \text{found}}} + D \underbrace{\vec{E}_i(Q)A(s, s')e^{-jks}}_{\text{known}}$$

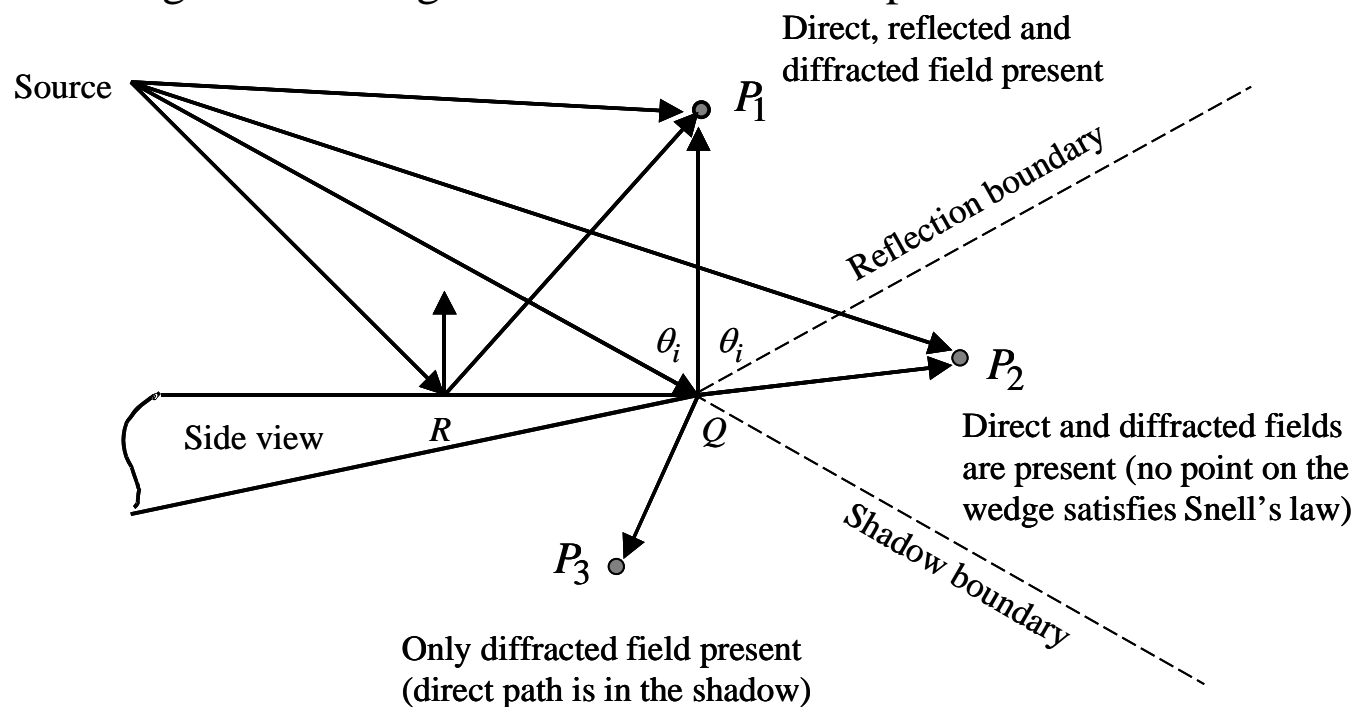
The basic expressions for the diffraction coefficients of a knife edge are simple (they contain only trig functions), however they have singularities at the shadow and reflection boundaries.

More complicated expressions have been derived that are well behaved everywhere. The most common is the uniform theory of diffraction (UTD). (See Stutzman and Thiele.)

¹ This notation is borrowed from optics: s = soft or parallel polarization; h = hard or perpendicular polarization. The reference plane is the plane defined by the edge and the incident ray (for incident polarization) or diffracted ray (for diffracted polarization).

Geometrical Theory of Diffraction (4)

Example: scattering from a wedge for three observation points



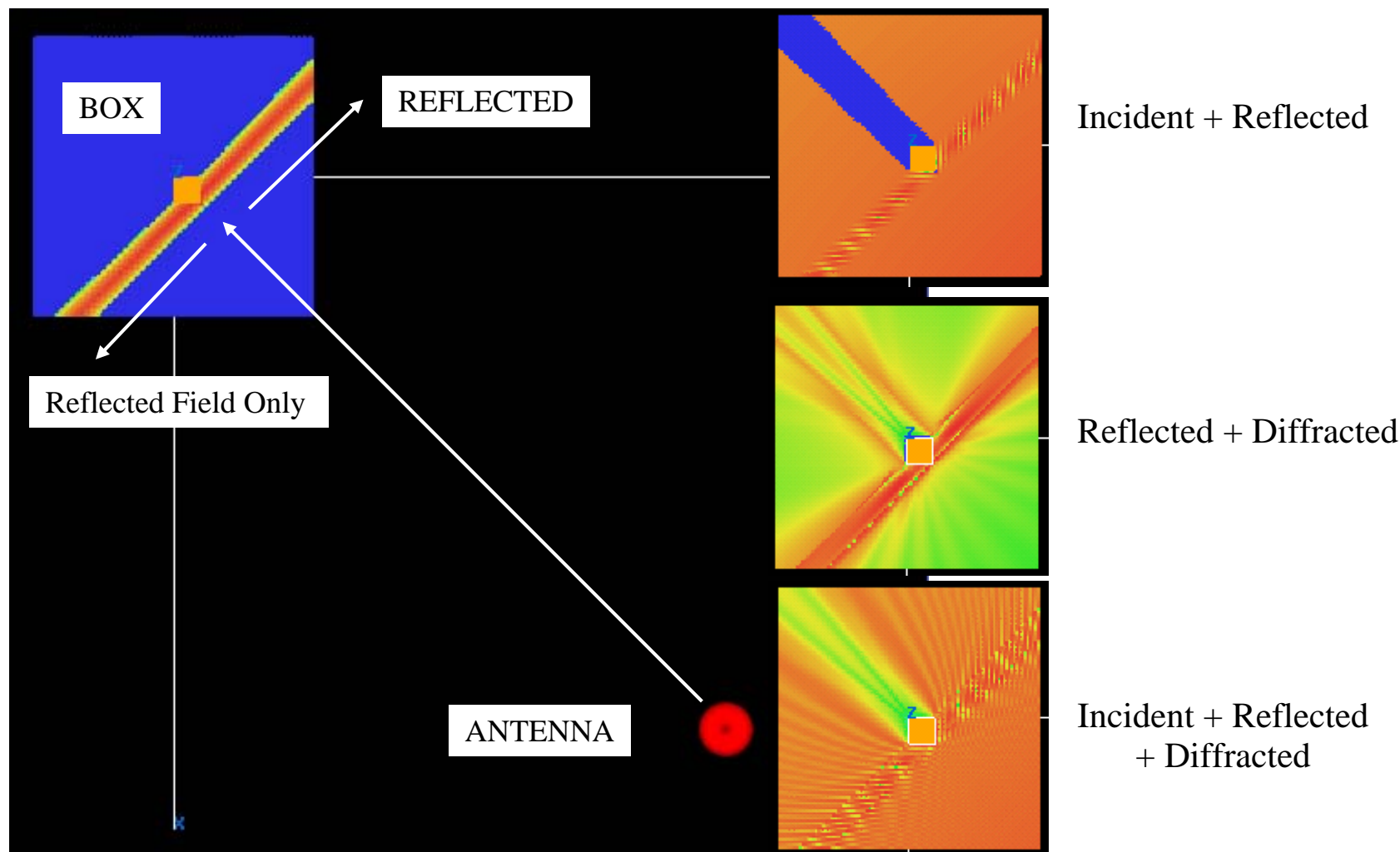
GO and GTD rays can “mix” (reflected rays can subsequently be diffracted, etc.):

- reflected – reflected (multiple reflection)
- reflected – diffracted and diffracted – reflected
- diffracted – diffracted (multiple diffraction)

An accurate (converged) solution must include all significant contributions.

Example: Fields Scattered From a Box

$f=1$ GHz, -100 dBm (blue) to -35 dBm (red), 0 dBm Tx power , 1 m PEC cube



Wave Matrices For Layered Media (1)

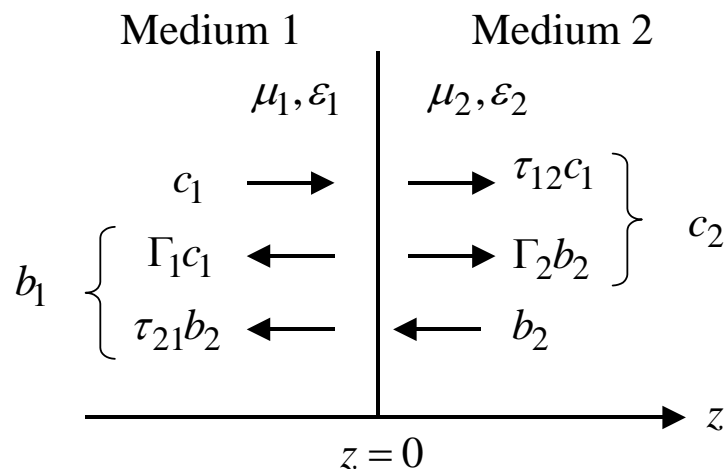
For multilayered (stratified) media, a matrix formulation can be used to determine the net transmitted and reflected fields. The figure below shows incident and reflected waves at the boundary between two media. The positive z traveling waves are denoted c and the negative z traveling waves b . We allow for waves incident from both sides simultaneously.

Thus,

$$b_1 = \Gamma_1 c_1 + \tau_{21} b_2$$

$$c_2 = \Gamma_2 b_2 + \tau_{12} c_1$$

where Γ and τ are the appropriate Fresnel reflection and transmission coefficients.



Rearranging the two equations:

$$b_1 = \left(\tau_{21} - \frac{\Gamma_1 \Gamma_2}{\tau_{12}} \right) b_2 + \frac{\Gamma_1}{\tau_{12}} c_2$$

$$c_1 = \frac{c_2}{\tau_{12}} - \frac{\Gamma_2 b_2}{\tau_{12}}$$

which can be written in matrix form:

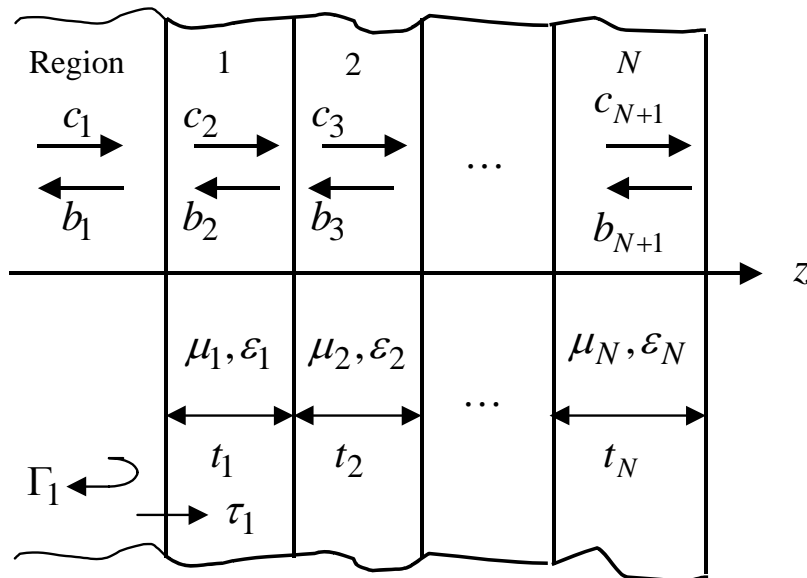
$$\begin{bmatrix} c_1 \\ b_1 \end{bmatrix} = \frac{1}{\tau_{12}} \begin{bmatrix} 1 & -\Gamma_2 \\ \Gamma_1 & \tau_{12} \tau_{21} - \Gamma_1 \Gamma_2 \end{bmatrix} \begin{bmatrix} c_2 \\ b_2 \end{bmatrix}$$

This is called the wave transmission matrix. It relates the forward and backward propagating waves on the two sides of the boundary.

Wave Matrices For Layered Media (2)

As defined, c and b are the waves incident on the boundary, $z = 0$. At some other location, $z = z_1$ the forward traveling wave becomes $c_1 e^{-j\beta z_1}$ and the backward wave becomes $b_1 e^{j\beta z_1}$. For a plane wave incident from free space onto N layers of different material (μ_n, ϵ_n) and thickness (t_n) , the wave matrices can be cascaded

$$\begin{bmatrix} c_1 \\ b_1 \end{bmatrix} = \prod_{n=1}^N \frac{1}{\tau_n} \begin{bmatrix} e^{j\Phi_n} & \Gamma_n e^{-j\Phi_n} \\ \Gamma_n e^{j\Phi_n} & e^{-j\Phi_n} \end{bmatrix} \begin{bmatrix} c_{N+1} \\ b_{N+1} \end{bmatrix} \equiv \begin{bmatrix} A_{11} & A_{12} \\ A_{21} & A_{22} \end{bmatrix} \begin{bmatrix} c_{N+1} \\ b_{N+1} \end{bmatrix}$$



where, for normal incidence $\Phi_n = \beta_n t_n$ is the electrical length of layer n . If the last layer extends to $z \rightarrow \infty$ then $b_{N+1} = 0$. We can arbitrarily set $\Phi_N = 0$ if the transmission phase is not of interest.

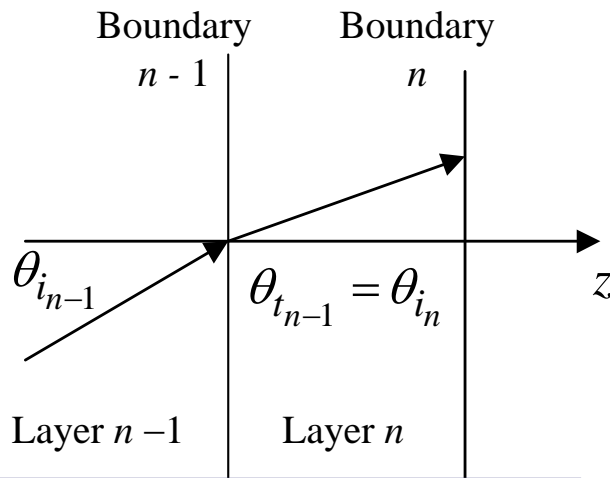
The overall transmission coefficient of the layers (i.e., the transmission into layer N when $b_{N+1} = 0$) is $c_{N+1} / c_1 = 1 / A_{11}$. The overall reflection coefficient is $b_1 / c_1 = A_{21} / A_{11}$.

Wave Matrices For Layered Media (3)

If the incidence angle in region 1 is not normal, then Φ_n must be determined by taking into account the refraction in all of the previous $n - 1$ layers. The transmission angle for layer n becomes the incidence angle for layer $n + 1$ and they are related by Snell's law:

$$\beta_o \sin \theta_i = \beta_1 \sin \theta_{i_1} = \beta_2 \sin \theta_{i_2} = \dots = \beta_{N-1} \sin \theta_{i_{N-1}}.$$

Oblique incidence and loss can be handled by modifying the transmission and reflection formulas as listed below, where θ_i is the incidence angle at the first boundary:



$$\Phi_n = \beta_o t_n \left(\epsilon_{r_n} \mu_{r_n} - \sin^2 \theta_i \right)^{1/2}$$

$$\Gamma_n = \frac{Z_n - Z_{n-1}}{Z_n + Z_{n-1}}, \quad \tau_n = 1 + \Gamma_n$$

$$\frac{Z_n}{Z_o} = \frac{\sqrt{\epsilon_{r_n} \mu_{r_n} - \sin^2 \theta_i}}{\epsilon_{r_n} \cos \theta_i}, \quad (\text{parallel polarization})$$

$$\frac{Z_n}{Z_o} = \frac{\mu_{r_n} \cos \theta_i}{\sqrt{\epsilon_{r_n} \mu_{r_n} - \sin^2 \theta_i}}, \quad (\text{perpendicular polarization})$$

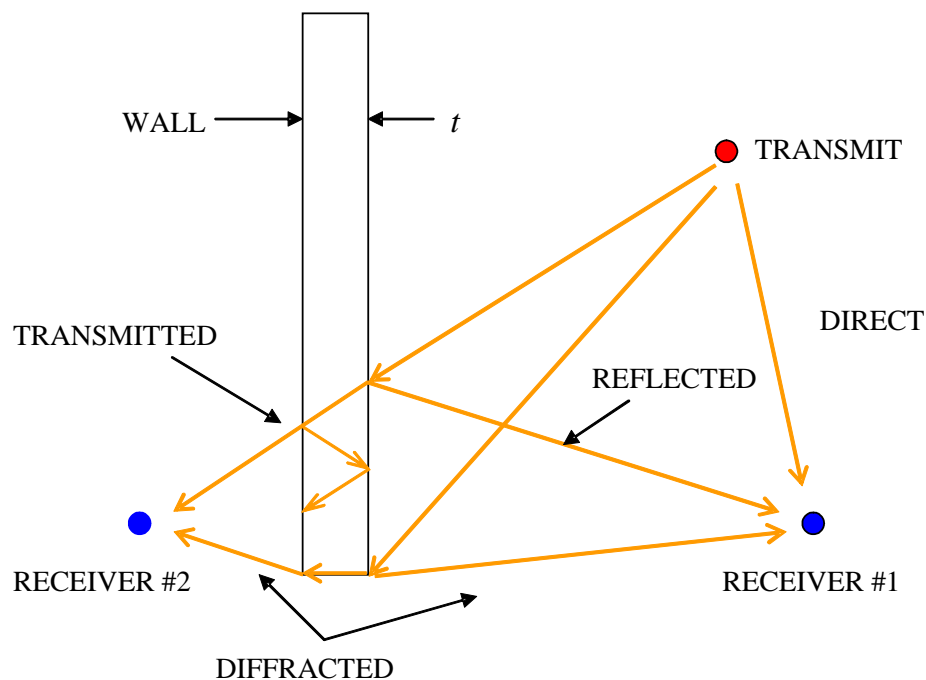
For lossy materials: $\epsilon_{r_n} \rightarrow \epsilon_{r_n} - j \frac{\sigma_n}{\omega \epsilon_o}$

Indoor and Urban Propagation Modeling (1)

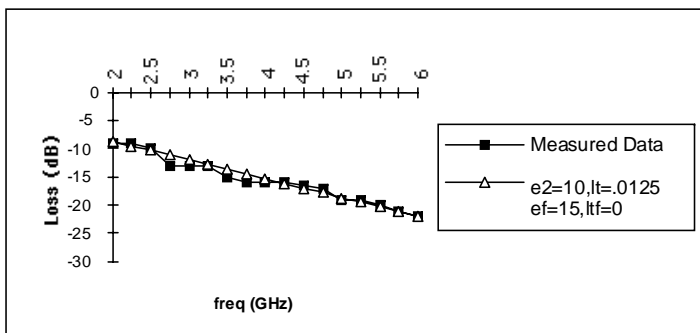
- An important application for which the use of GO and GTD are well suited, is the modeling of propagation for wireless systems in buildings and urban environments.
- Applications include
 1. wireless local area networks (WLANs)
 2. mobile communications systems
 3. cellular phones
 4. command, control, and data links for UAVs flying in cities
 5. high power microwaves (both attack and protect)
 6. GPS performance in urban environments
- These systems generally operate at frequencies above 900 MHz (some European wireless systems operate at frequencies as low as 400 MHz). High frequency methods are applicable in this range.
- Computational electromagnetics (CEM) codes are used to predict the propagation of electromagnetic (EM) waves indoors and in urban environments.

Indoor and Urban Propagation Modeling (2)

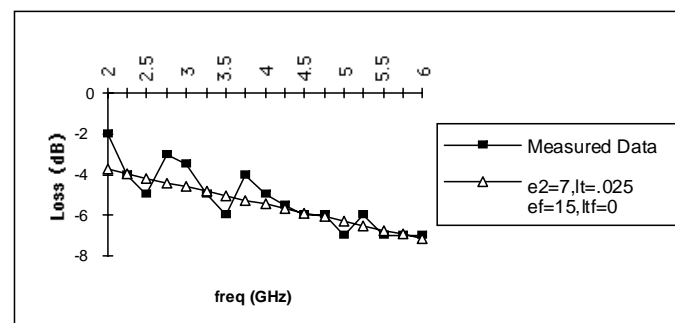
- Scattering properties of common building materials are determined by their permittivity, permeability, and conductivity
- Sources of loss (attenuation) inside of walls:
 1. absorption (energy dissipated inside of material)
 2. cancellation by reflection
- Propagation and interaction with materials is decomposed into
 1. transmission
 2. reflection
 3. diffraction from discontinuities
- Usually we do not know exactly what is inside of a wall (plumbing, wiring, duct work, insulation, etc.)



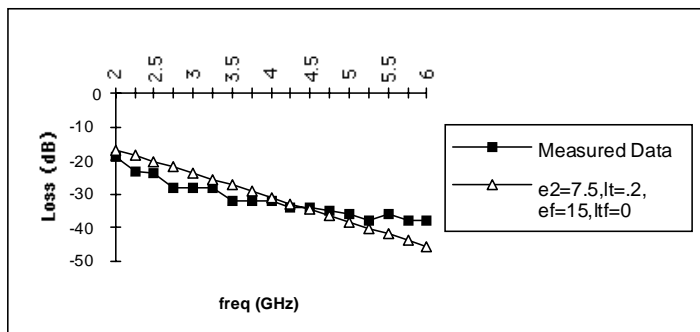
Propagation Loss Through Walls



Loss through a 10 inch concrete wall



Loss through a 1.75 inch wood doors



Loss through 1.75 inch metal doors



Measurement of propagation through building walls

Propagation Loss Through Windows

Closed blinds



Insertion loss about 10 dB

Window tinting film



Insertion loss about 20 dB

WLAN Antennas (Omnidirectional)

- Ceiling mount



- Desktop mount diversity antennas

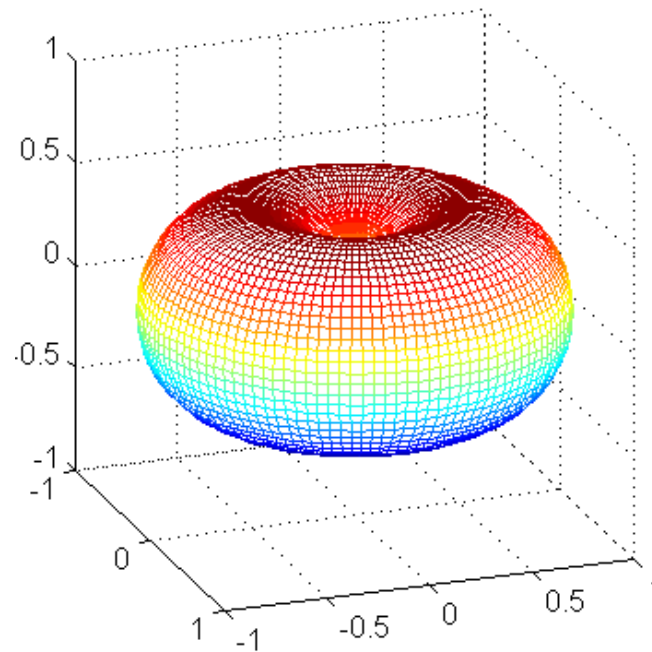


Spatial diversity



Polarization diversity

- Spatial radiation distribution of a vertical dipole antenna

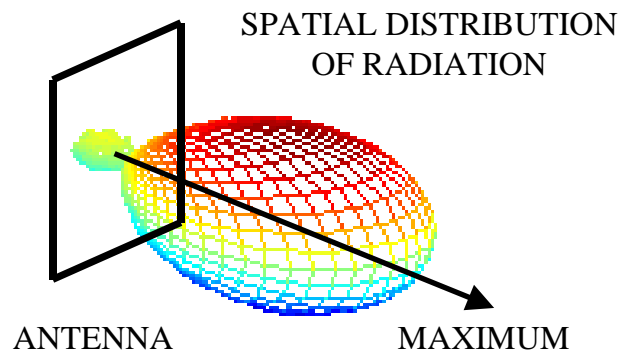


WLAN Directional Antennas

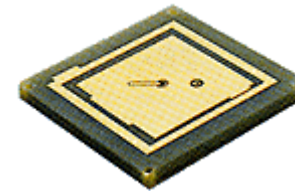
Microstrip patch antenna
(typically mounted on a wall)



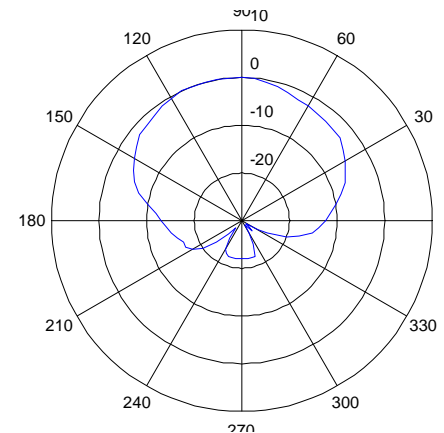
Radiation pattern (power measured as a function of angle at constant radius)



Radome cover removed



Typical antenna pattern
(top view)



Urbana Wireless Toolset

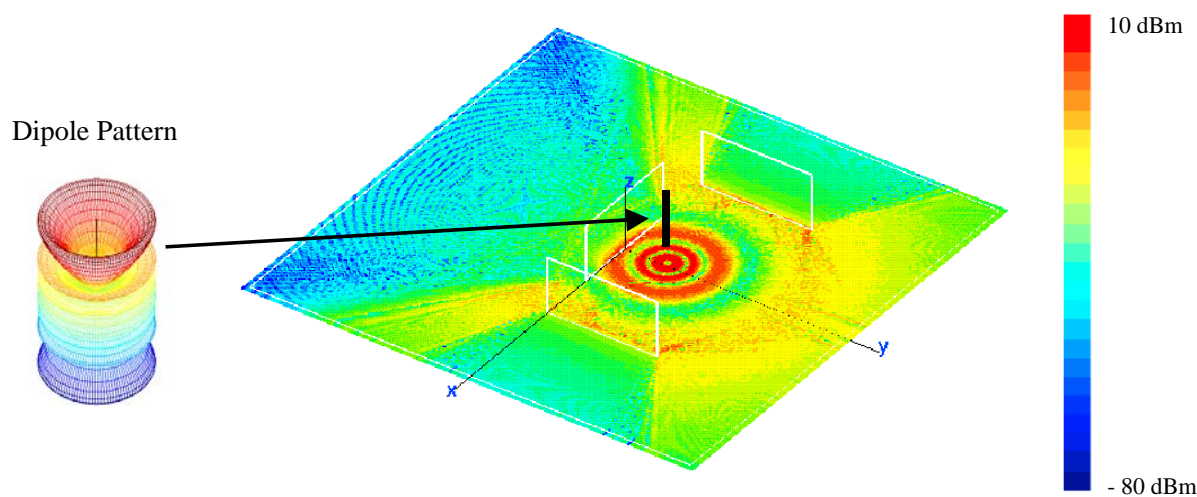
- Components
 1. *XCell*: geometry builder and visualizer; antenna placement; observation point definition
 2. *Cifer*: utilities, translators, geometry manipulation
 3. *Urbana*: electromagnetic solvers

- Features:
 1. Interfaces with computer aided design (CAD) software
 2. Reflections by geometrical optics (GO) or “shooting and bouncing rays” (SBR)
 3. Diffraction by geometrical theory of diffraction (GTD) or physical theory of diffraction (PTD)
 4. Surface and edge curvature can be modeled
 5. Complex materials (dielectrics, conductors, magnetic material)

- The SGI and Windows version (Windows version in the Microwave Lab)

Simple Three Wall Example

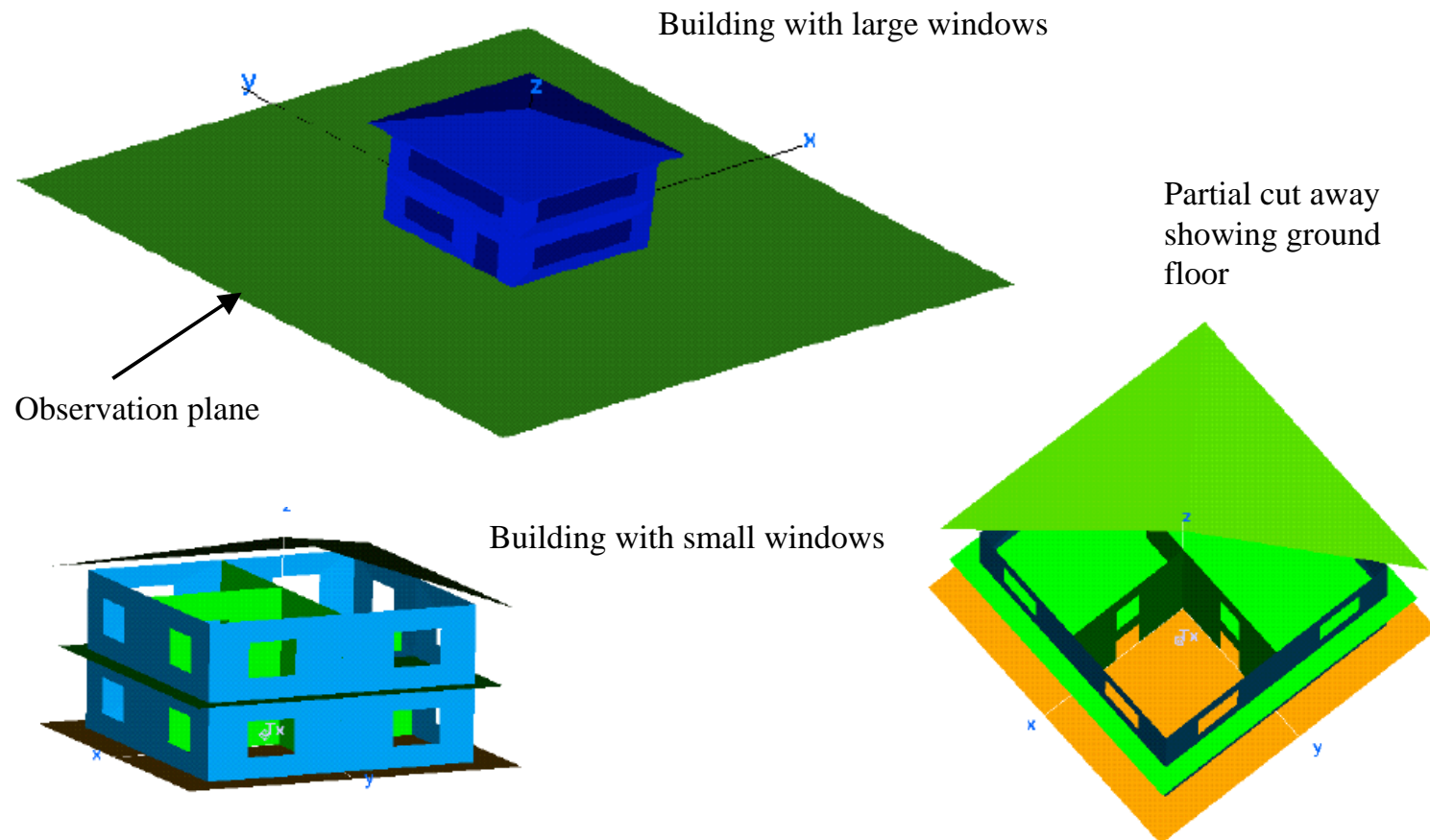
- Dipole behind walls (edges shown white)
- 1 watt transmit power; plastic walls are 25m by 50m; 8 wavelength dipole antenna



- Propagation features can be identified:
 - > dipole radiation rings (red)
 - > multipath from ground and wall surfaces (red speckle)
 - > propagation through gaps
 - > “shadows” behind walls (shadow boundaries from wall edges)
 - > diffraction from wall edges (blue arcs)

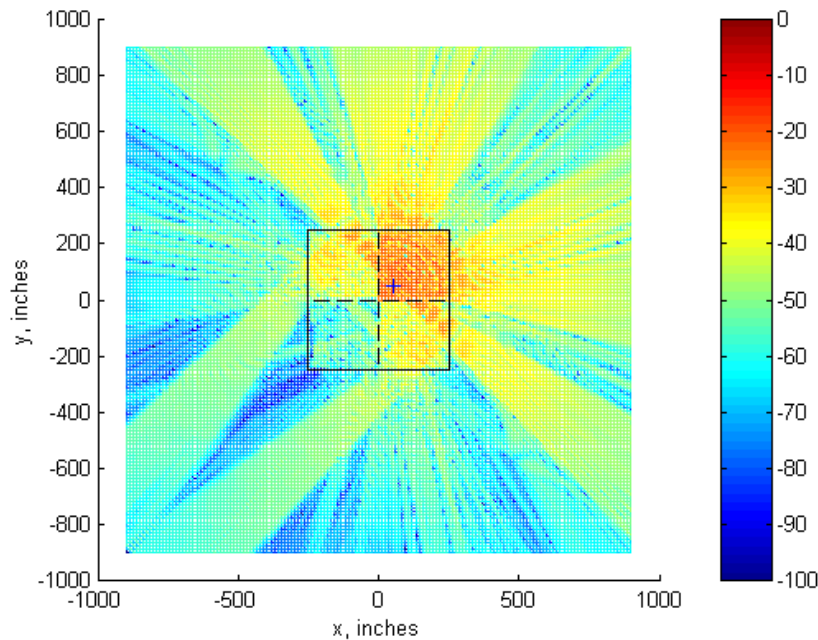
Two Story Building

Two story building: 40 feet on a side. Observation plane is 150 feet on a side.

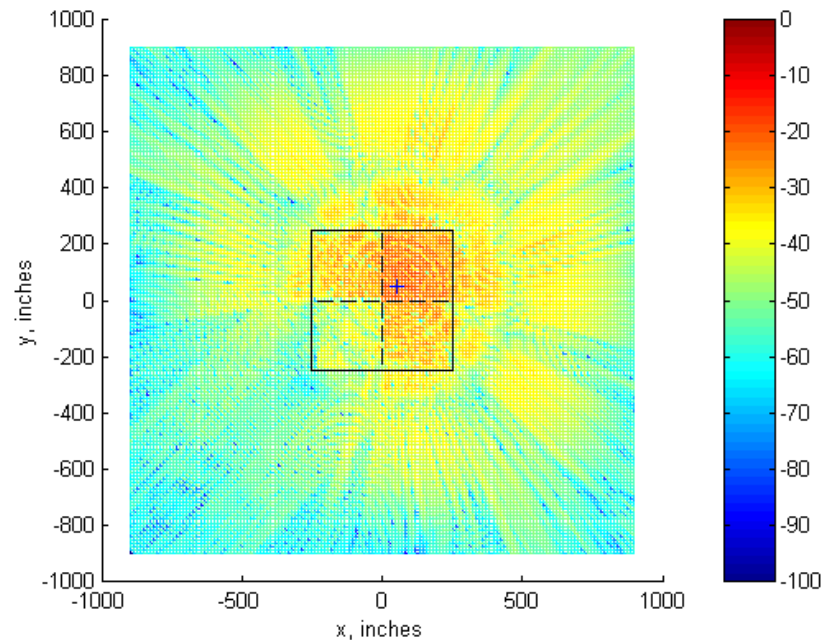


Wall Materials

Metal composite walls



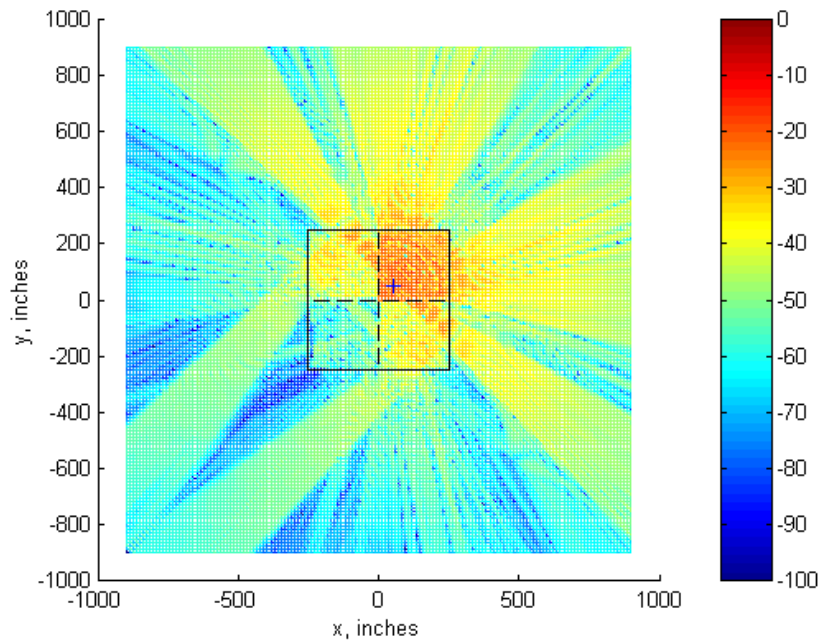
Wood walls



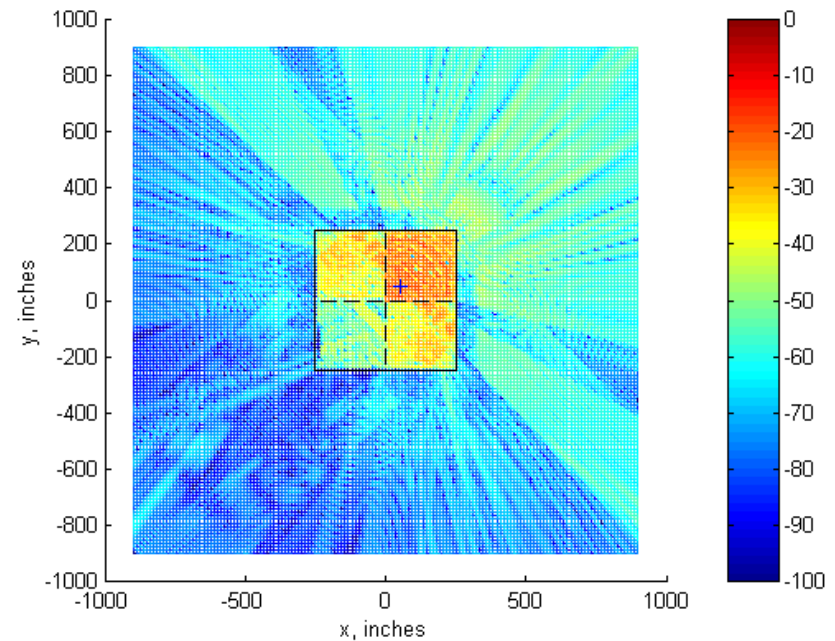
- Propagation through windows dominates for metal buildings
- Many transmissions and reflections diffuse the signal for the wood building
- Receive antenna is 5 feet above ground

Window Materials

Standard glass windows



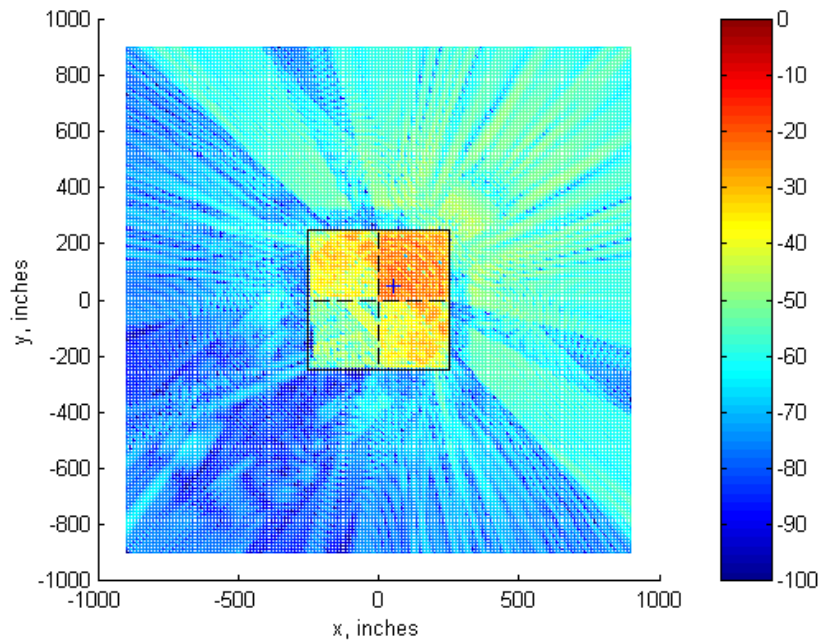
Tinted windows



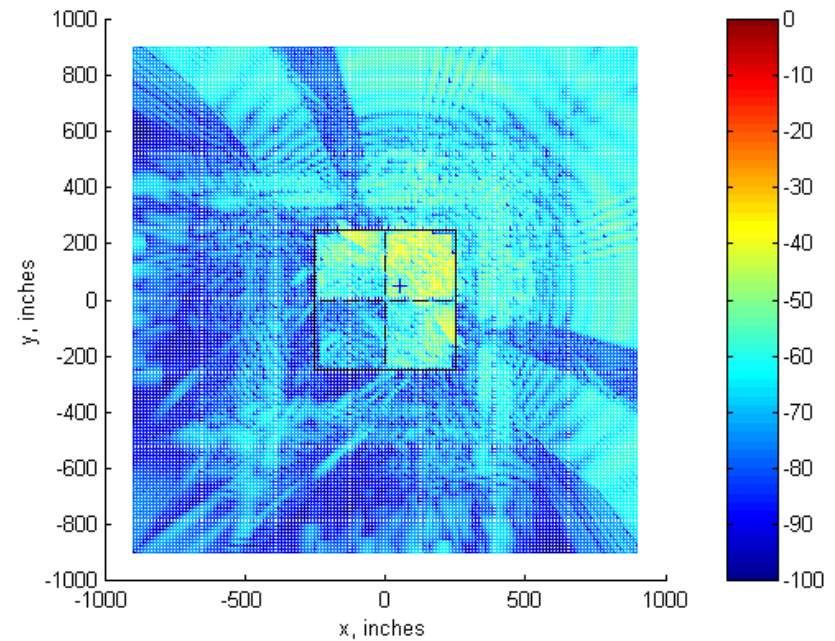
- There is a direct line of sight above the window sill from inside the building
- Receive antenna is 5 feet above ground

Antenna Location

Access point on 1st floor



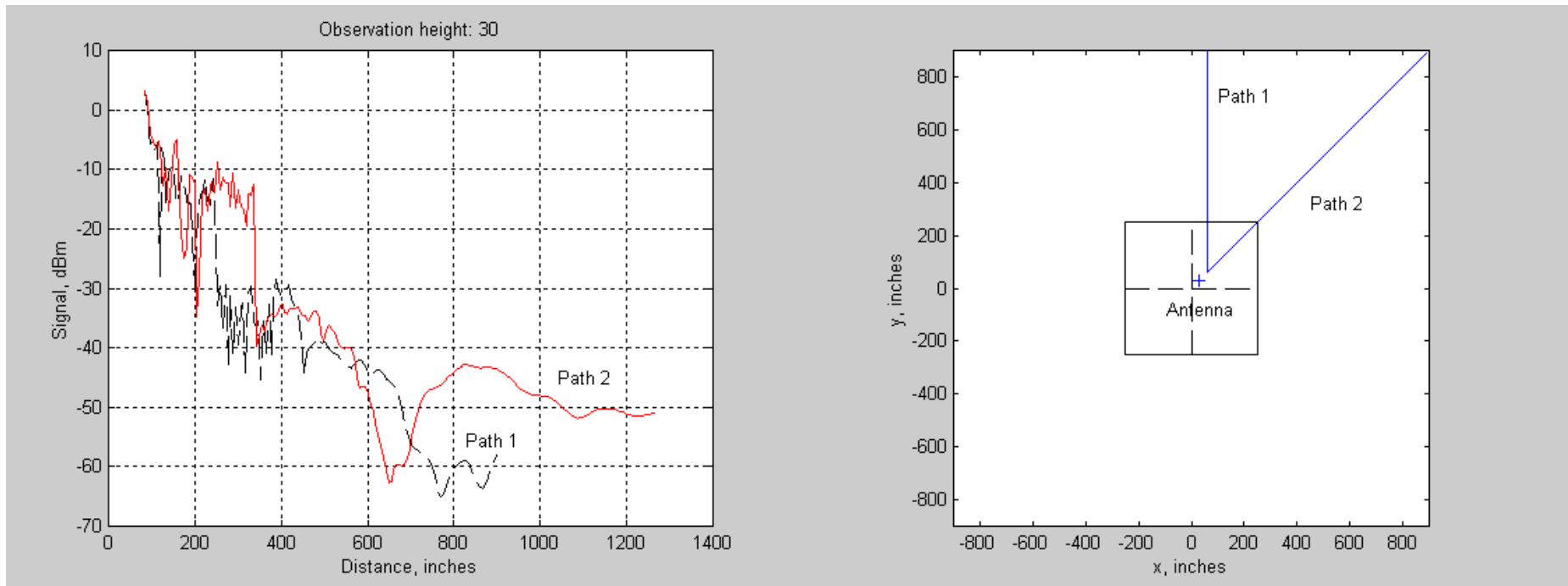
Access point on 2nd floor



- Detection is reduced by moving the access point to second floor
- Results in reduced signal levels inside on first floor
- Receive antenna is 5 feet above ground

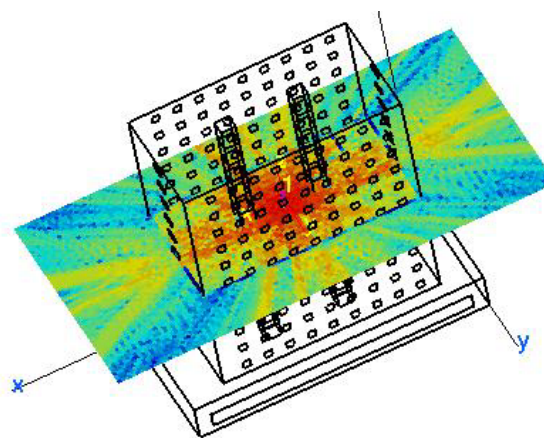
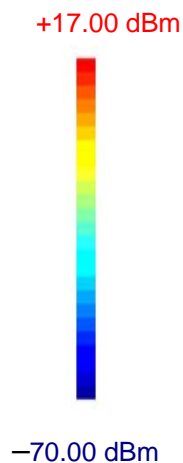
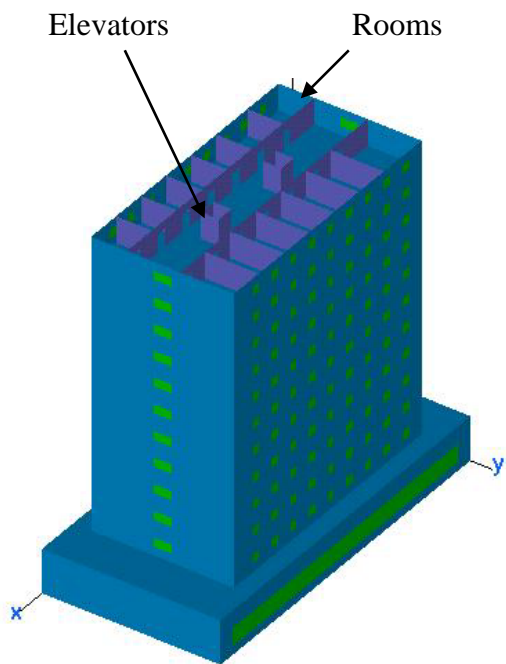
Field Along a Line Path Through a Wall

- Metal composite walls, standard glass
- 10 to 20 dB drop through the wall

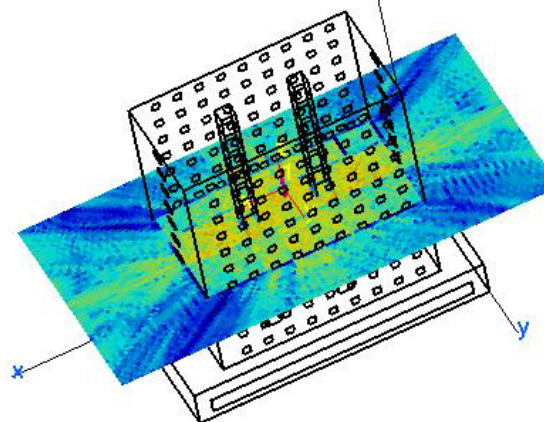


High Rise Buildings

- Building with open windows
- Vertical dipole
- 1 W transmitter on the seventh floor
- $f=2.4$ GHz



Signal contours on the 7th floor

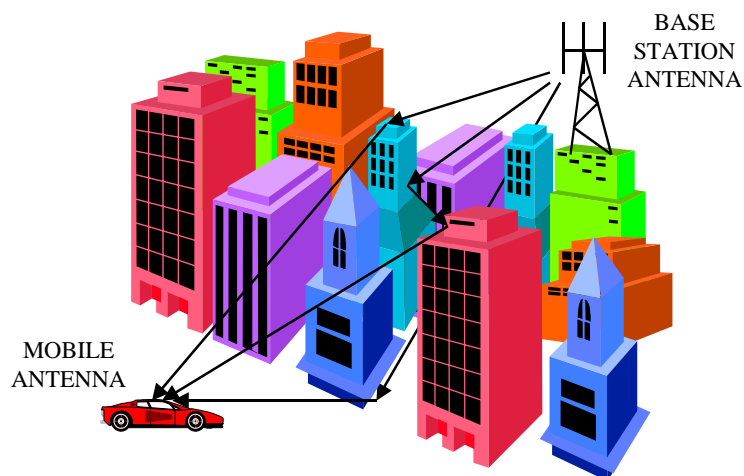


Signal contours on the 6th floor

Urban Propagation (1)

Urban propagation is a unique and relatively new area of study. It is important in the design of cellular and mobile communication systems. A complete theoretical treatment of propagation in an urban environment is practically intractable. Many combinations of propagation mechanisms are possible, each with different paths. The details of the environment change from city to city and from block to block within a city. Statistical models are very effective in predicting propagation in this situation.

In an urban or suburban environment there is rarely a direct path between the transmitting and receiving antennas. However there usually are multiple reflection and diffraction paths between a transmitter and receiver.

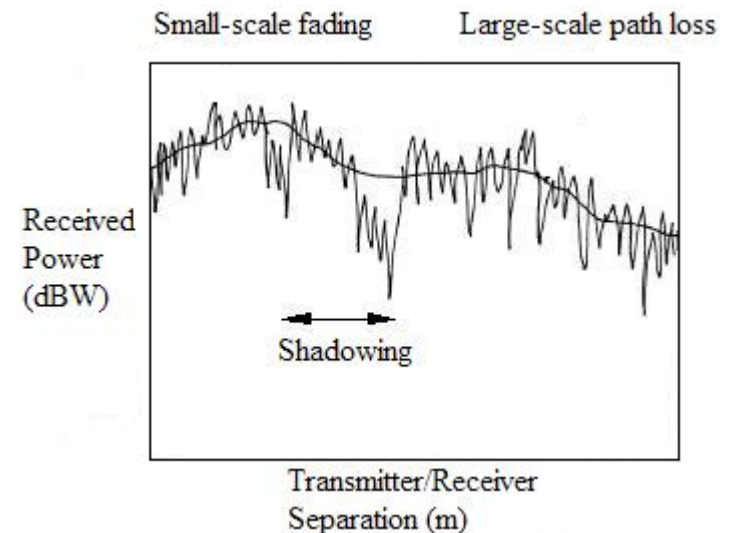


- Reflections from objects close to the mobile antenna will cause multiple signals to add and cancel as the mobile unit moves. Almost complete cancellation can occur resulting in “deep fades.” These small-scale (on the order of tens of wavelengths) variations in the signal are predicted by Rayleigh statistics.

Urban Propagation (2)

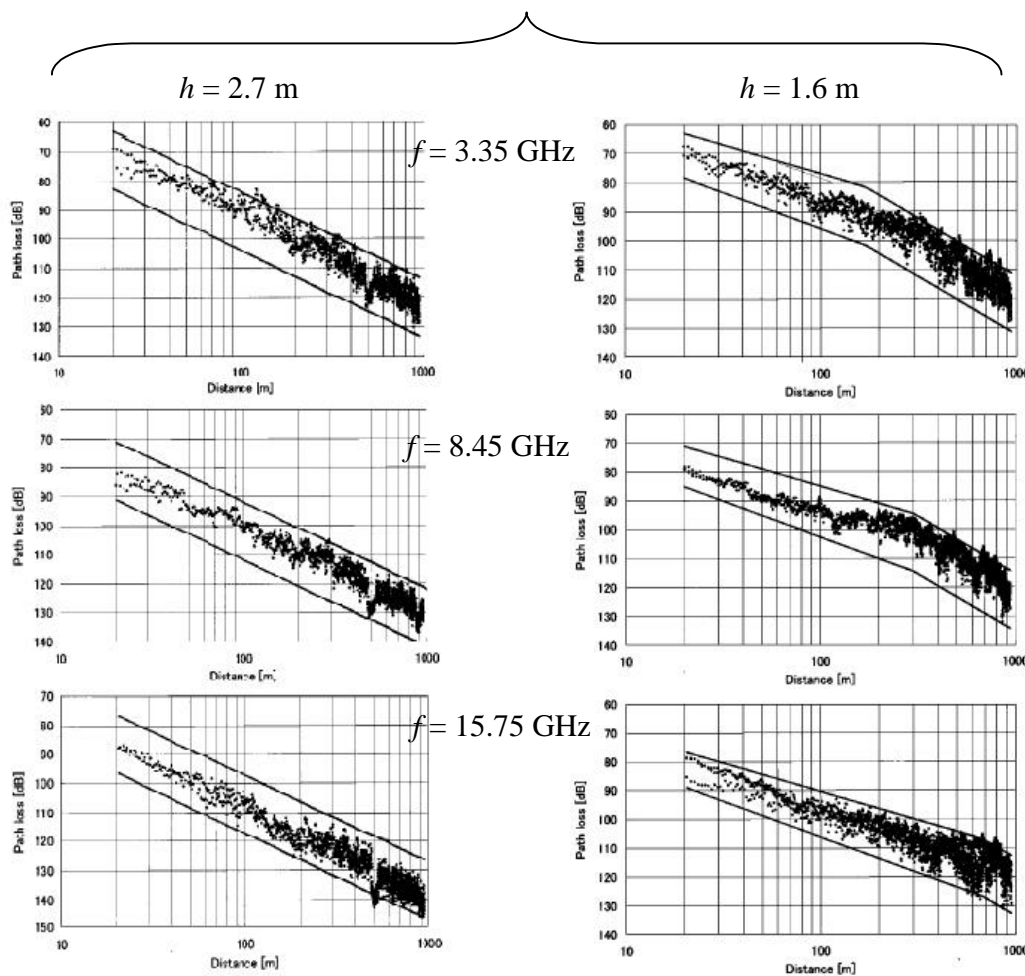
- On a larger scale (hundreds to thousands of wavelengths) the signal behavior, when measured in dB, has been found to be normally distributed (hence referred to a lognormal distribution). The genesis of the lognormal variation is the multiplicative nature of shadowing and diffraction of signals along rooftops and undulating terrain.
- The Hata model is used most often for predicting path loss in various types of urban conditions. It is a set of empirically derived formulas that include correction factors for antenna heights and terrain.
- Free space path loss is the $1/r^2$ spreading loss in signal between two isotropic antennas. From the Friis equation, with $G_t = G_r = 4\pi A_e / \lambda^2 = 1$

$$L_s = \frac{P_r}{P_t} = \frac{(1)(1)\lambda^2}{(4\pi r)^2} = \left(\frac{1}{2kr}\right)^2$$



Measured City Data

Two different antenna heights



Measured data in an urban environment

Three different frequencies

From Masui, "Microwave Path Loss Modeling in Urban LOS Environments," *IEEE Journ. on Selected Areas in Comms.*, Vol 20, No. 6, Aug. 2002.

Urban Propagation Models

- Theoretical Models: The Walfisch Model (Diffracting Screens Model), the COST 231 Model (The COST-WI Model) and the Longley-Rice Model (ITS Irregular Terrain Model).

Longley-Rice Model Parameter Ranges		
Parameters	Min	Max
Frequency	200 MHz	20 GHz
Range	1 km	2000 km
Antenna Heights	0.5 m	3 km
Polarization	Horizontal and Vertical	

- Empirical Models: The London model of Ibrahim and Parsons, the Tokyo model of Okumura, and the Hata model

Okumura Model Parameter Ranges		
Parameters	Min	Max
Frequency	150 MHz	1920 MHz
Range	1 km	100 km
Antenna Heights	30 m	1000 m
Polarization	Horizontal and Vertical	

Hata Model Parameter Ranges		
Parameters	Min	Max
Frequency	100 MHz	1.5 GHz
Range	1 km	20 km
Mobile Ant. Heights	1 m	10 m
Antenna Heights	30 m	200 m

Ibrahim-Parsons Model Parameter Ranges		
Parameters	Min	Max
Frequency	150 MHz	1 GHz
Range	0 m	10 km
Mobile Ant. Heights	0 m	3 m
Antenna Heights	30 m	300 m
Urbanization Factor	0-100	

Hata Model

Hata model parameters²: d = transmit/receive distance ($1 \leq d \leq 20$ km)
 f = frequency in MHz ($100 \leq f \leq 1500$ MHz)
 h_b = base antenna height ($30 \leq h_b \leq 200$ m)
 h_m = mobile antenna height ($1 \leq h_m \leq 10$ m)

The median path loss is

$$L_{\text{med}} = 69.55 + 26.16 \log(f) - 13.82 \log(h_b) + [44.9 - 6.55 \log(h_b)] \log(d) + a(h_m)$$

In a medium city: $a(h_m) = [0.7 - 1.1 \log(f)] h_m + 1.56 \log(f) - 0.8$

In a large city: $a(h_m) = \begin{cases} 1.1 - 8.29 \log^2(1.54 h_m), & f \leq 200 \text{ MHz} \\ 4.97 - 3.2 \log^2(11.75 h_m), & f \geq 400 \text{ MHz} \end{cases}$

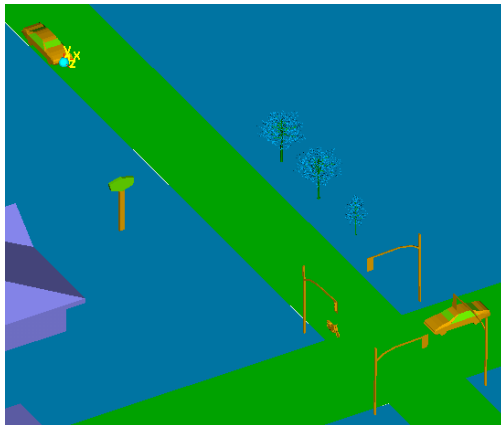
Correction factors: $L_{\text{cor}} = \begin{cases} -2 \log^2(f/28) - 5.4, & \text{suburban areas} \\ -4.78 \log^2(f) + 18.33 \log(f) - 40.94, & \text{open areas} \end{cases}$

The total path loss is: $L_s = L_{\text{med}} - L_{\text{cor}}$

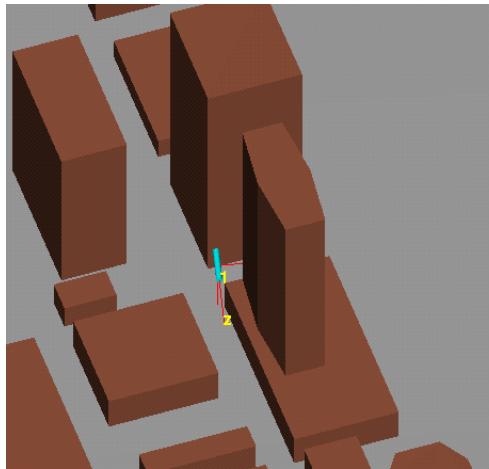
²Note: Modified formulas have been derived to extend the range of all parameters.

Urban Propagation Simulation

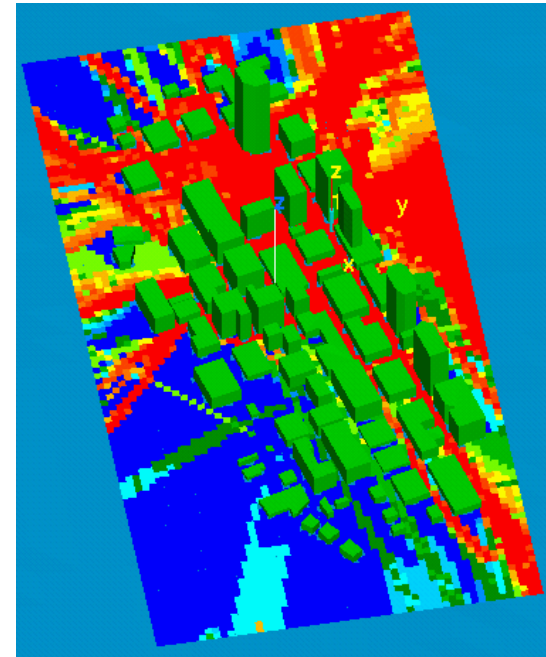
- Examples of urban propagation models and field distributions from ray tracing



Suburban model with buildings and roads



Transmitter antenna in urban location

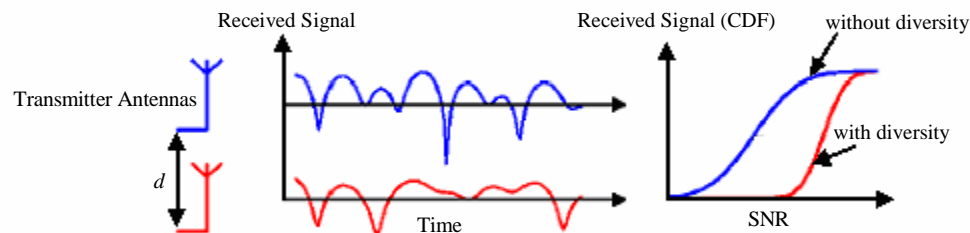


Signal strength distribution

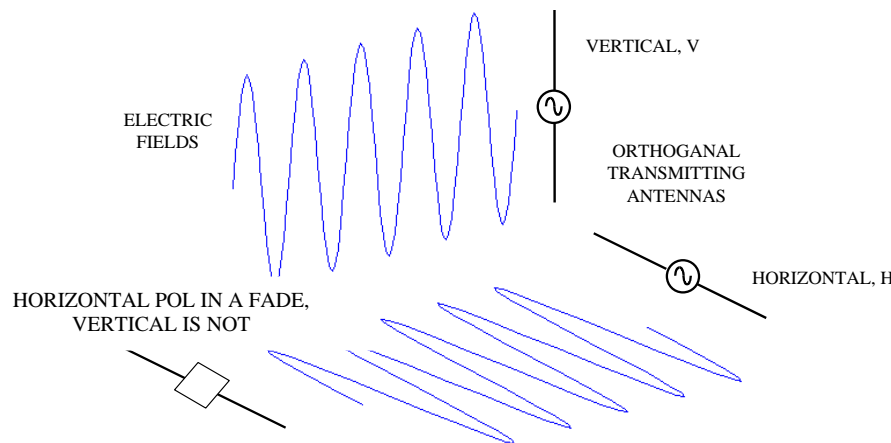
From SAIC's *Urbana Wireless Toolkit*

Diversity Techniques to Combat Fading

1. Spatial diversity: receive and/or transmit using two sufficiently separated (spatially uncorrelated) antennas
2. Frequency diversity: use multiple frequencies sufficiently spaced so that both do not suffer fading simultaneously
3. Polarization diversity: use two orthogonal polarizations simultaneously
4. Angle diversity: use multiple paths (different directions) in an urban environment

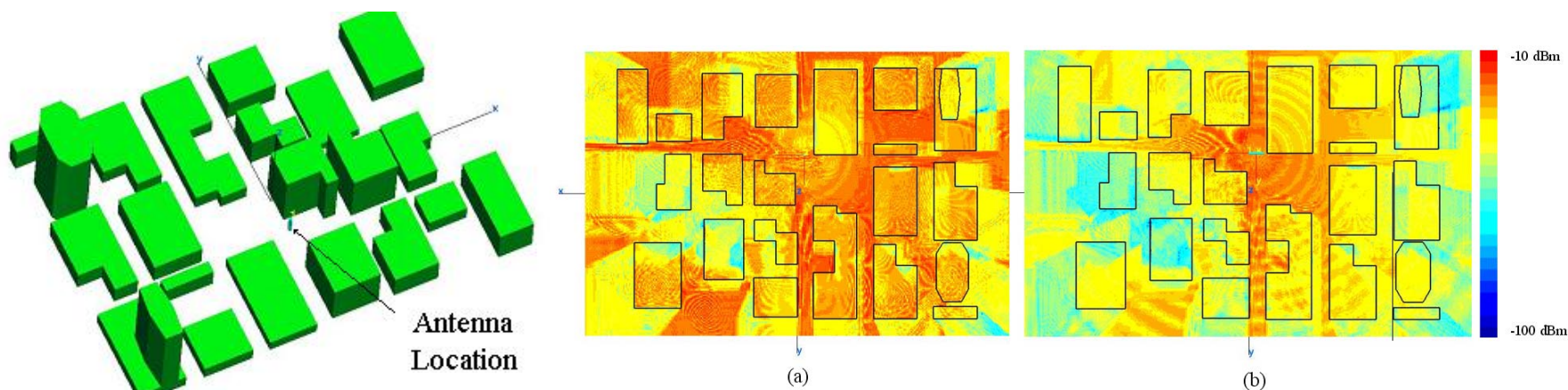


Spatial diversity

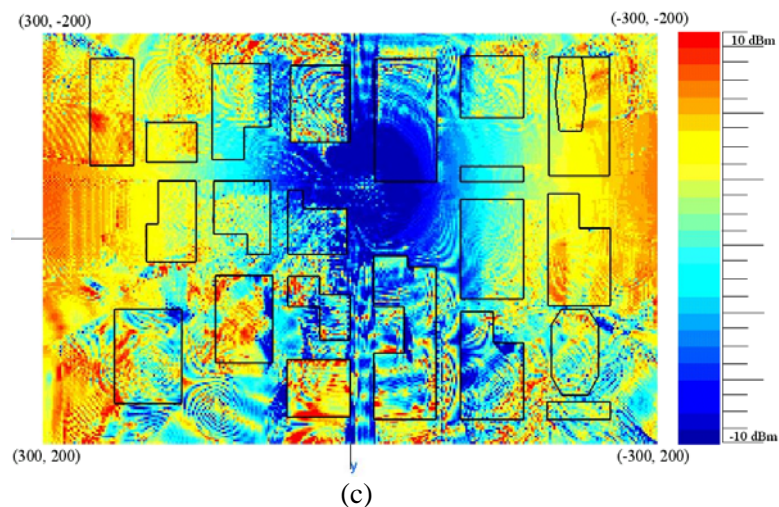


Polarization diversity

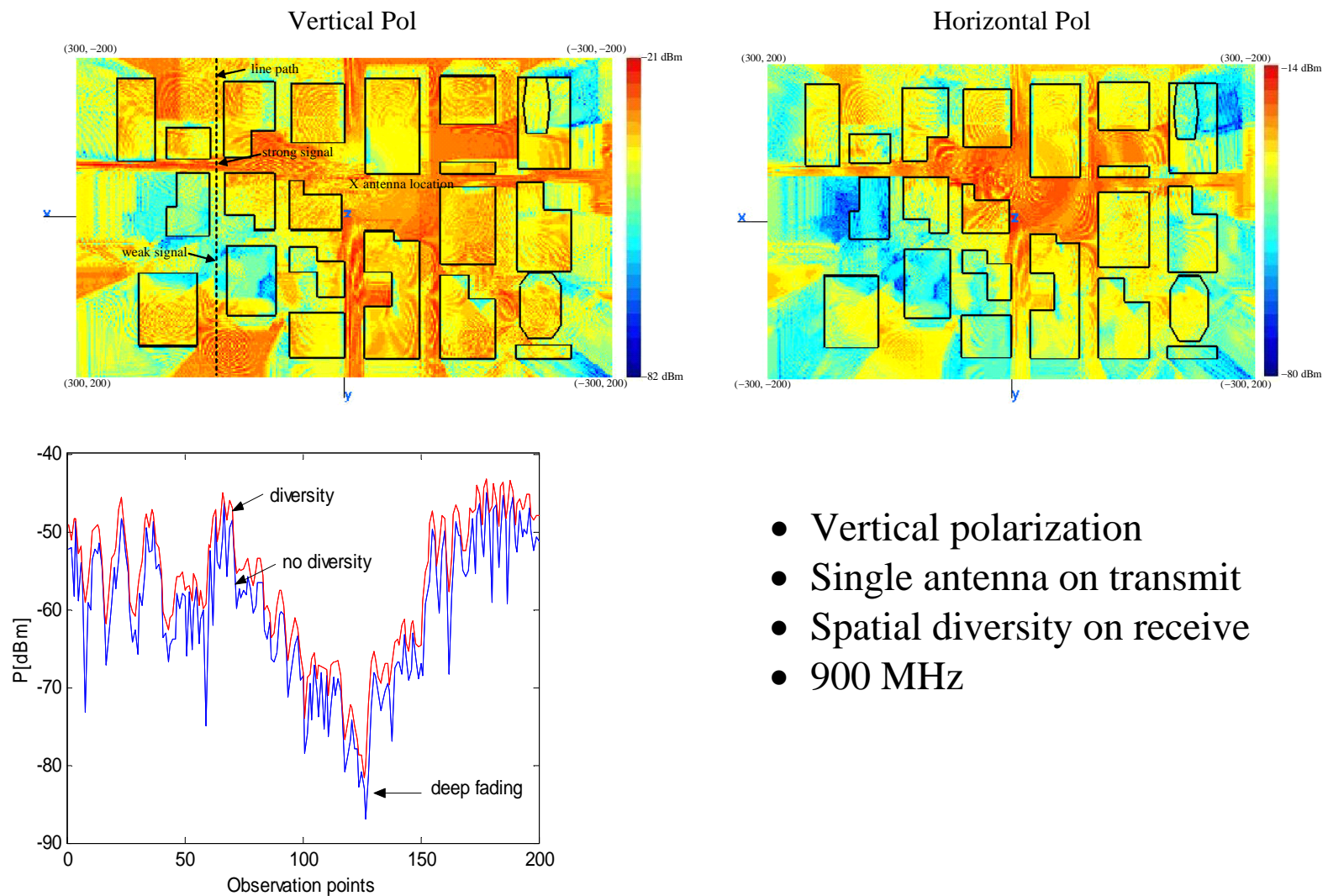
Polarization Diversity



Polarization comparison for 900 MHz (a) vertical and (b) horizontal (c) difference

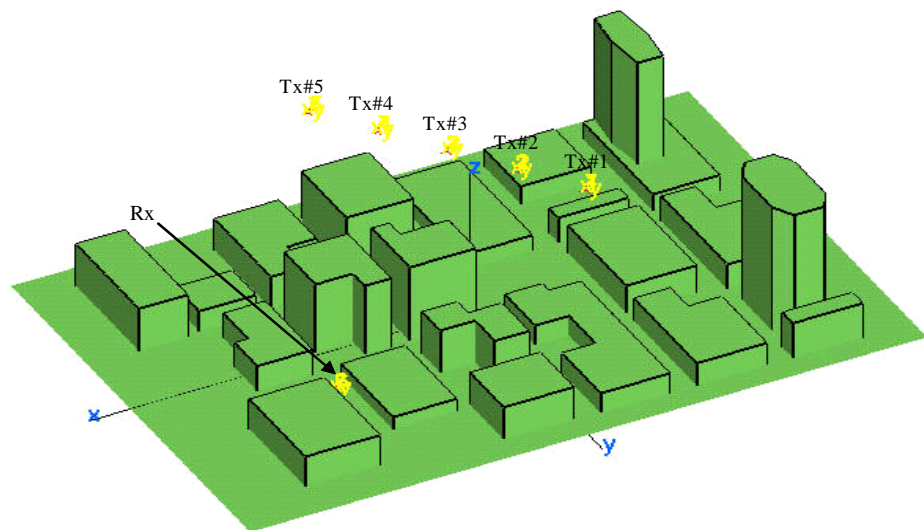


Spatial Diversity



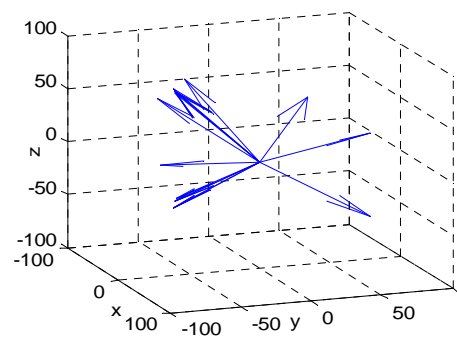
- Vertical polarization
- Single antenna on transmit
- Spatial diversity on receive
- 900 MHz

Angle Diversity

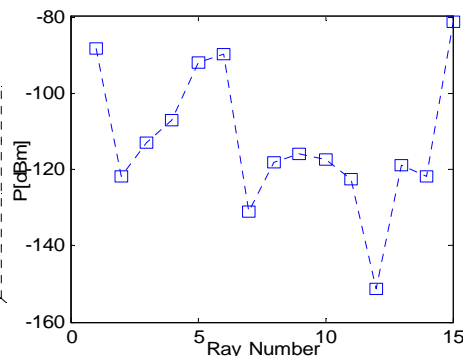


- Transmitter along a flight path at locations #1 through #5
- Dipole receiver at location (145 m, 52 m, 1.5 m)
- Signal arrival at Rx when transmitting from Tx #3 shown below

Arriving rays



Power (dBm)



Angle of arrival for each ray

