Karlsruhe Institute of Technology

Chapter 2:
Radio Wave Propagation Fundamentals

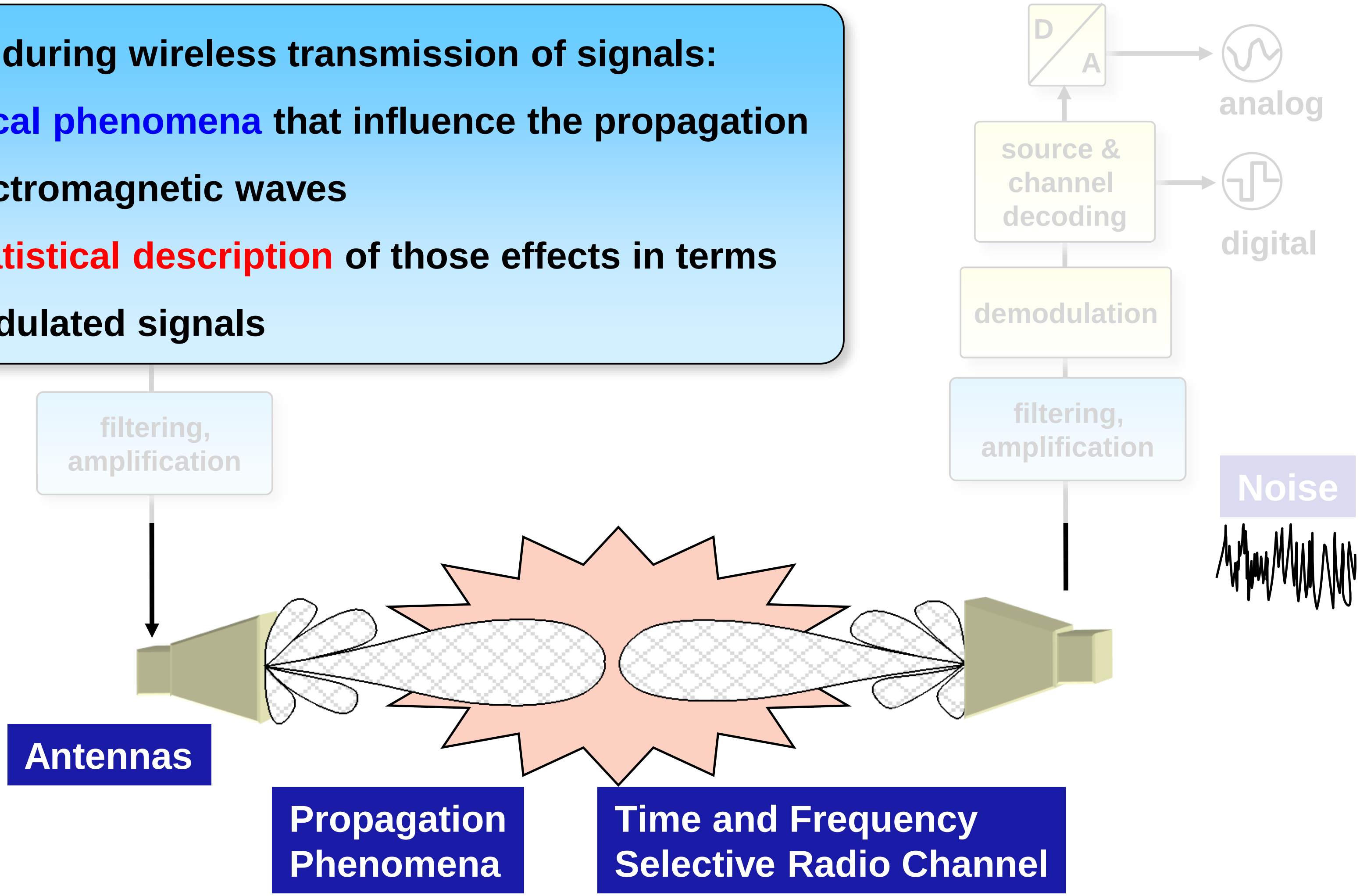
M.Sc. Sevda Abadpour
Dr.-Ing. Marwan Younis

INSTITUTE OF RADIO FREQUENCY ENGINEERING AND ELECTRONICS

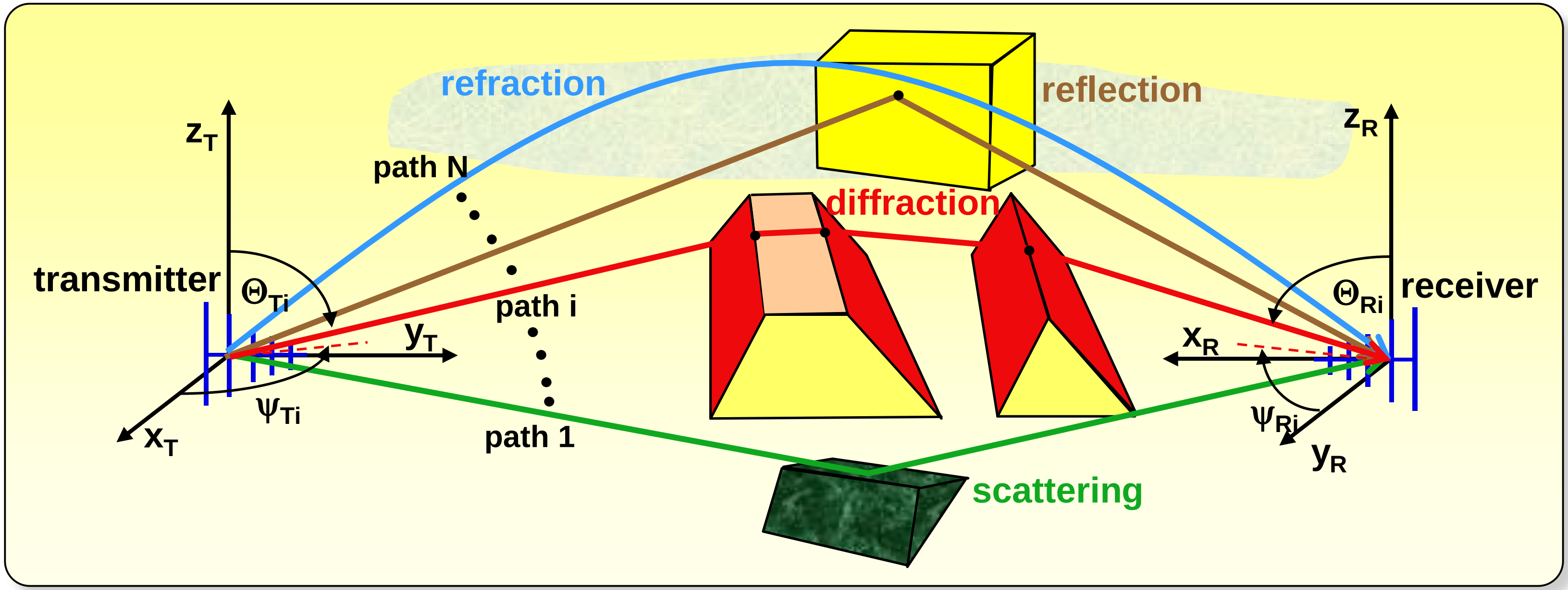
Scope of the (Today‘s) Lecture

Effects during wireless transmission of signals:

- **physical phenomena that influence the propagation of electromagnetic waves**
- **no statistical description of those effects in terms of modulated signals**



Propagation Phenomena



free space propagation:
- line of sight
- no multipath

reflection:
- plane wave reflection
- Fresnel coefficients

scattering:
- rough surface scattering
- volume scattering

diffraction:
- knife edge diffraction

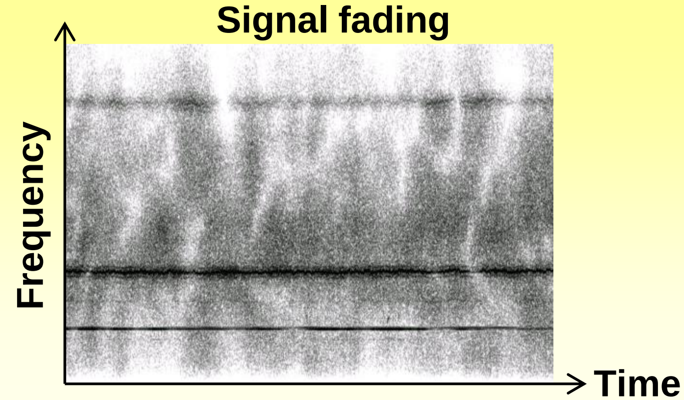
refraction in the troposphere:
- not considered

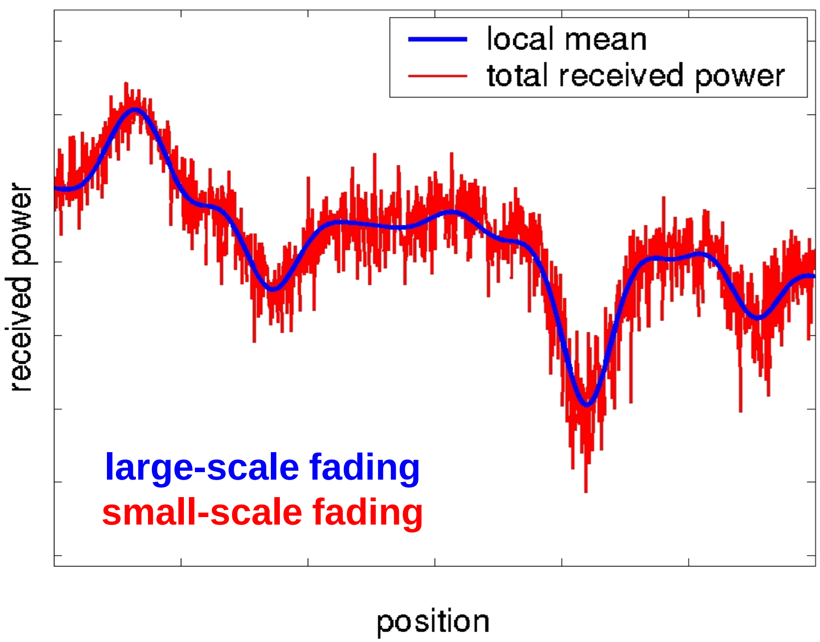
In general multipath propagation leads to fading at the receiver site

The Received Signal

Fading is a deviation of the attenuation that a signal experiences over certain propagation media.

It may vary with time, position and/or frequency





Classification of fading:

- ***large-scale fading*** **(gradual change in local average of signal level)**
- ***small-scale fading*** **(rapid variations due to random multipath signals)**

Propagation Models

Karlsruhe Institute of Technology

Propagation models (PM) are being used to predict:

- **average signal strength at a given distance from the transmitter**
- **variability of the signal strength in close spatial proximity to a particular location**

PM can be divided into:

- ***large-scale* models**

***(mean signal strength for large transmitter receiver* separation)**

- ***small-scale* models**

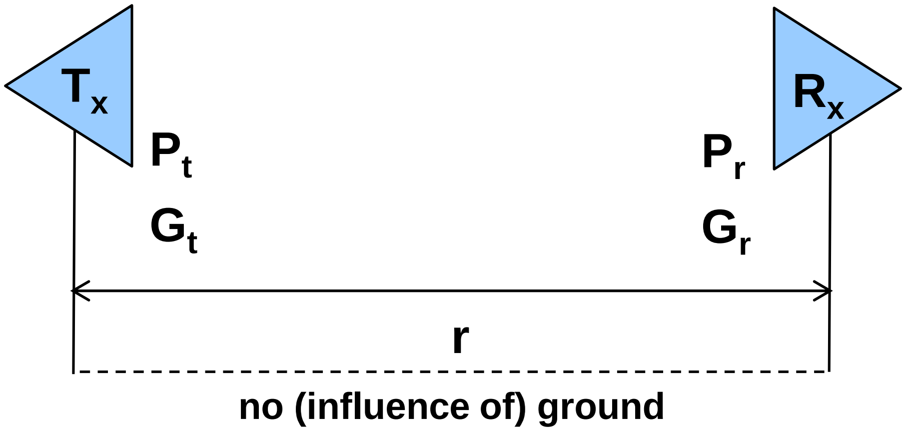
***(rapid fluctuations of the received* signal over very short travel distances)**

Severe multipath conditions in urban areas (*small-scale fading*)

Large-Scale Propagation

Free Space Propagation

Free Space Propagation



Assumptions:

- **unobstructed line of sight (LOS)**
- **no multipath propagation**

Received power:

$$P_R = A_{eR} \cdot S_R$$

Power density at Rx site:

$$S_R = \frac{P_T G_T}{4\pi r^2}$$

Antenna effective area:

$$A_{eR} = \frac{\lambda^2}{4\pi} G_R$$

Friis free space equation:

$$P_R = \frac{\lambda^2}{4\pi} G_R \cdot \frac{P_T G_T}{4\pi r^2} = \left(\frac{\lambda}{4\pi r}\right)^2 G_R G_T P_T \propto \frac{1}{r^2}$$

Received Power and Path Loss

Using: $$(P_R)^{dBm} = 10\log\left(\frac{P_R}{1mW}\right)$$

$$(P_R)^{dBm} = P_T^{dBm} + G_R^{dBi} + G_T^{dBi} - 20\log\left(\frac{4\pi d}{\lambda}\right)$$

Assumptions:

- **polarization matched receiving antenna**
- **conjugate complex impedance matching of the receiver**

Path loss:

$$(P_L) = \frac{P_T}{P_R} \Rightarrow (P_L)^{dB} = 20\log\left(\frac{4\pi d}{\lambda}\right) - G_R^{dBi} - G_T^{dBi}$$

Isotropic path loss (no antenna gains):

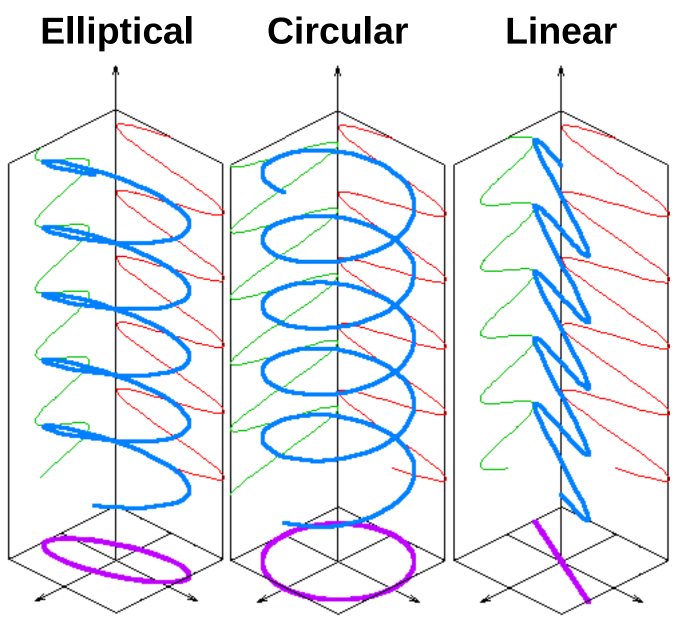
$$(P_L)^{dB} = 20\log\left(\frac{4\pi d}{\lambda}\right)$$

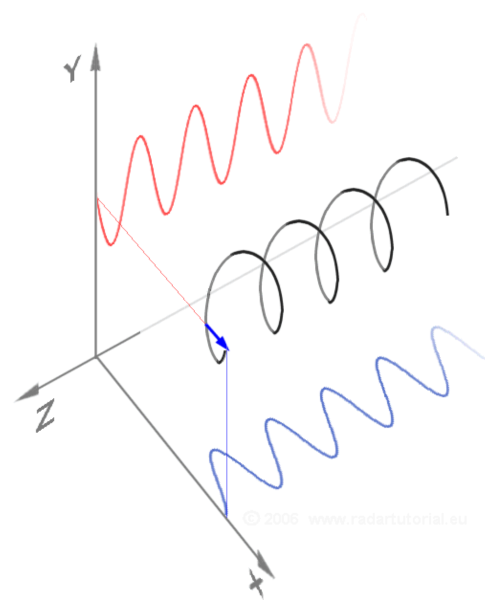
Polarization

Orientation of Field Vectors and Reference Planes

Polarization of the EM Waves

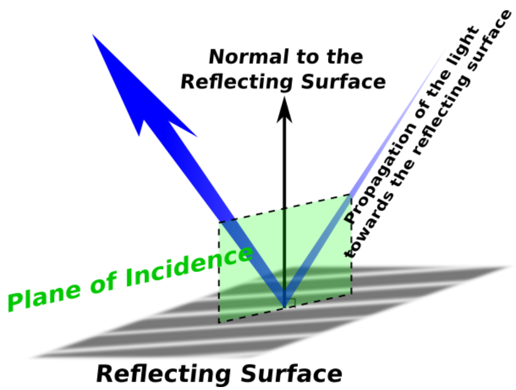
Every elliptically polarized EM wave can be decomposed into a horizontal and a vertical component.

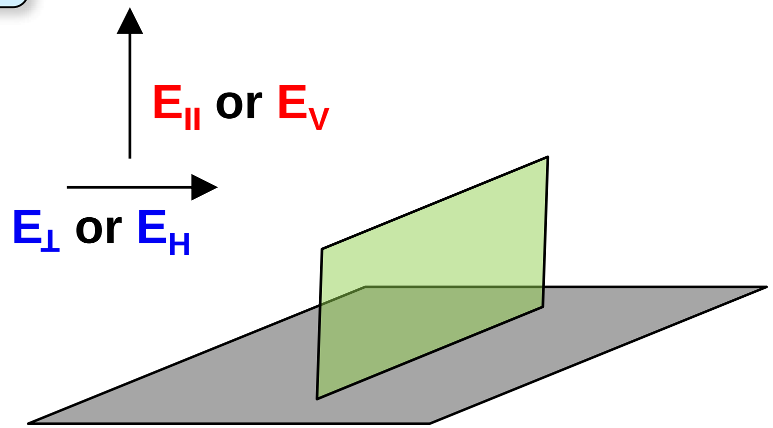




Polarization: II, ⊥, V or H?

Plane of incidence: formed by the **normal vector** to the reflecting surface and **Poynting vector** of the incidence wave





Polarization (E-field vector) with respect to the plane of incidence:

- parallel (II)
- perpendicular (⊥)

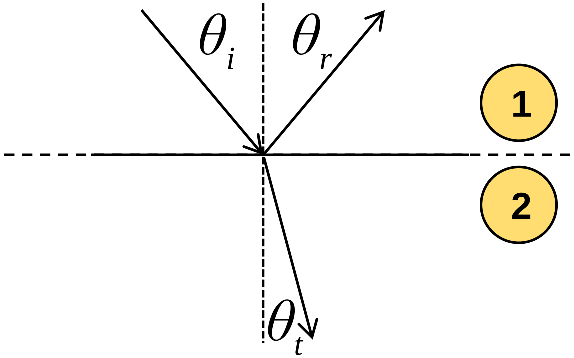
Polarization (E-field vector) with respect to the earth coordinates:

- vertical (V)
- horizontal (H)

Reflection and Transmission

Dielectric Boundary

Snell's Law of Reflection



- **surface large compared to the wave length**
- **smooth surface (otherwise scattering)**
- **three angles: - incidence**
  - reflection
  - transmission / refraction

- **Relation between angles through Fermat's principle (principle of least time):**

- "the rays of light (EM-waves) traverse the path of stationary optical length"

- **This results in* Snell's laws:**

- "ratio of the sines of the angles of incidence and refraction is equivalent to the opposite ratio of the indices of refraction"

- "the incidence and reflection angles are equal and they are in the same plane"

$$\frac{\sin(\theta_i)}{\sin(\theta_t)} = \frac{n_2}{n_1} \qquad n_x = \sqrt{\varepsilon_{r,x} \cdot \mu_{r,x}} \qquad \theta_i = \theta_r$$

****full derivation in Arthur Schuster: "An Introduction to the Theory of Optics"***

Which Part is Transmitted / Reflected?

Derivation procedure:

- ***Definition of the electric field strength of the incident wave***
- ***Reflected and transmitted field strengths***
- ***Faraday's law of induction***
- ***Boundary conditions at the border between two dielectric media***
- ***Decomposition of the incident waves on parallel and normal components***

Fresnel Reflection & Transmission Coefficients

$$R_{\|} = \frac{\eta_1 \cos\Theta_i - \eta_2 \cos\Theta_t}{\eta_1 \cos\Theta_i + \eta_2 \cos\Theta_t} = \frac{E_r}{E_i}$$

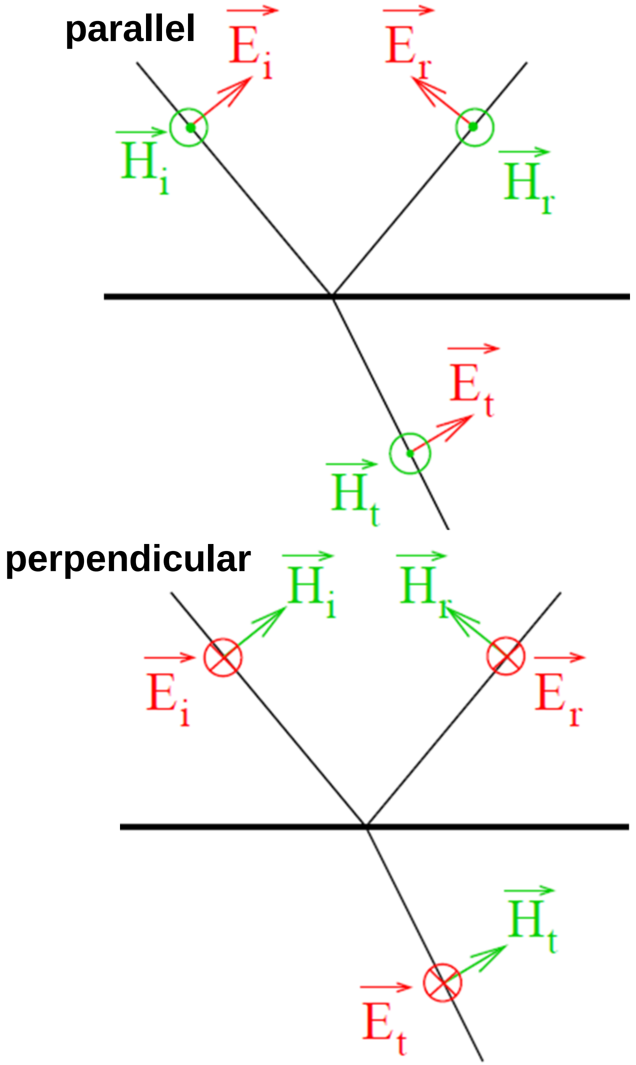
$$T_{\|} = \frac{2\eta_2 \cos\Theta_i}{\eta_1 \cos\Theta_i + \eta_2 \cos\Theta_t} = \frac{E_t}{E_i}$$

$$R_{\perp} = \frac{\eta_2 \cos\Theta_i - \eta_1 \cos\Theta_t}{\eta_2 \cos\Theta_i + \eta_1 \cos\Theta_t} = \frac{E_r}{E_i}$$

$$T_{\perp} = \frac{2\eta_2 \cos\Theta_i}{\eta_2 \cos\Theta_i + \eta_1 \cos\Theta_t} = \frac{E_t}{E_i}$$

where: $\eta = \sqrt{\frac{j\omega\mu}{\sigma + j\omega\epsilon}}$

Fresnel coefficients are frequency dependent and in general complex



Institute of Radio Frequency Engineering and Electronics

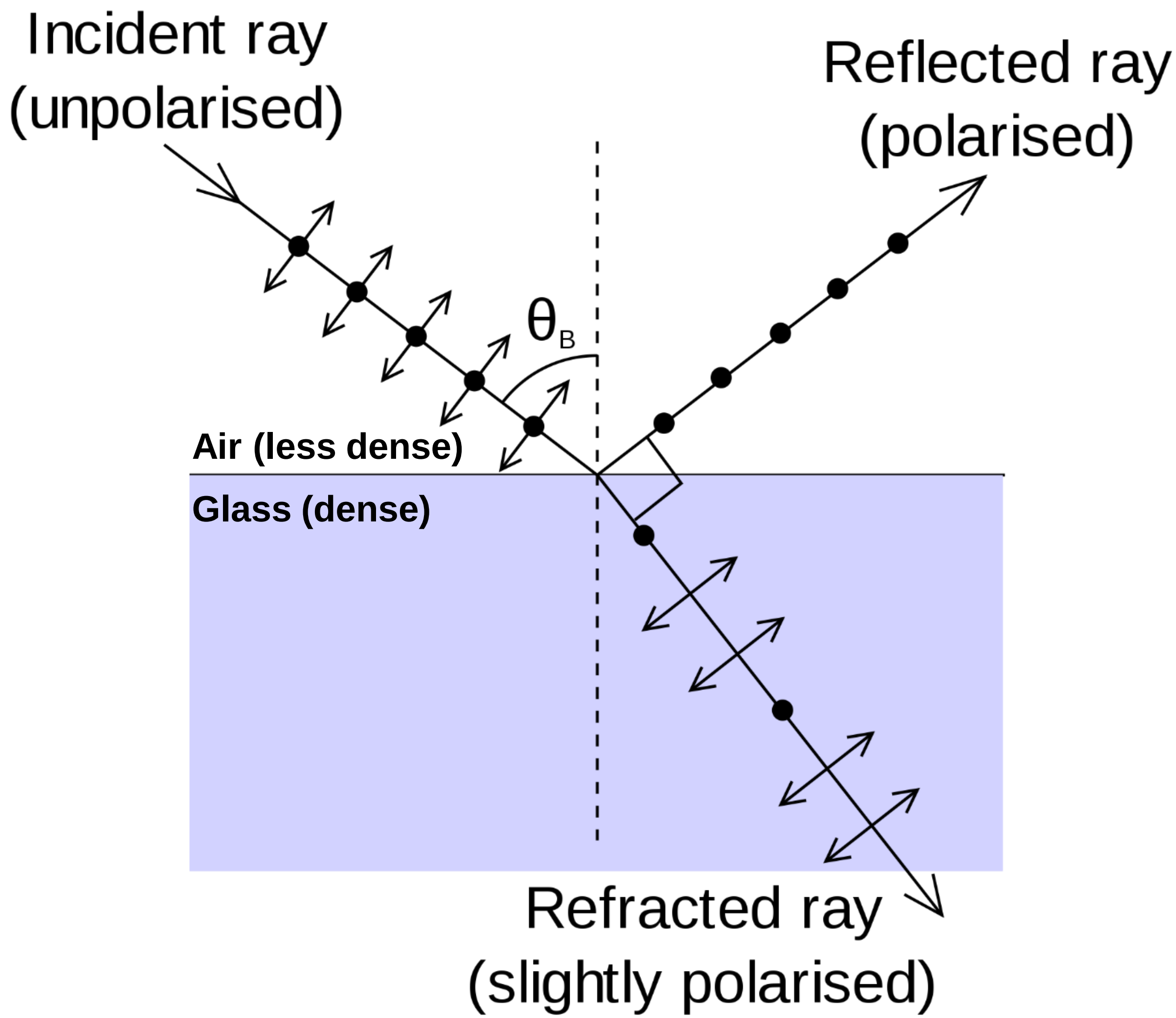
Brewster‘s Angle (I)

Angle, where no reflection occurs is Brewster’s Angle:

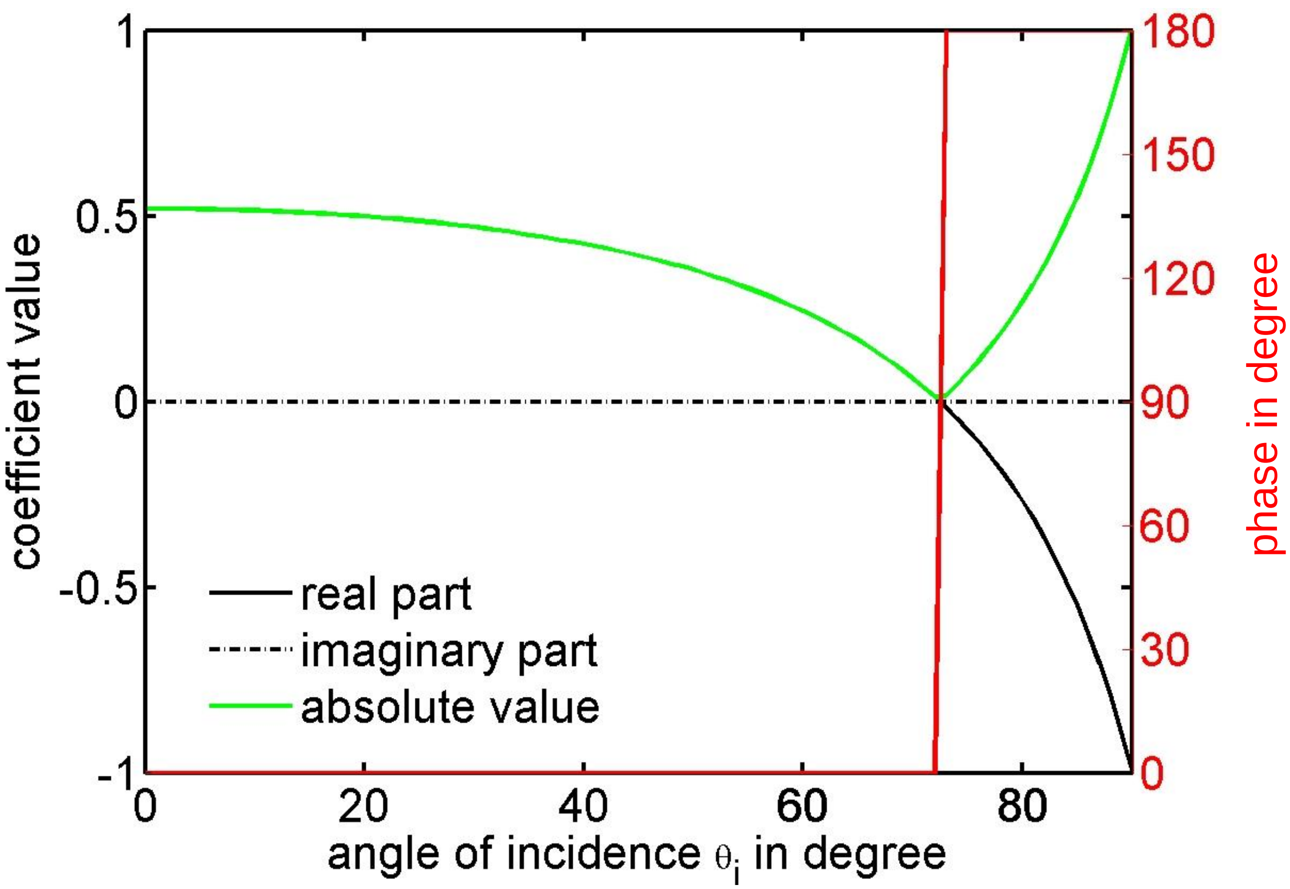
- **exists only for parallel (II / V) polarization**
- **calculation by comparing the reflection coefficient to zero**
- **calculation by using “physical limitations”**

$$R_{||} = \frac{\eta_1 \cos\Theta_i - \eta_2 \cos\Theta_t}{\eta_1 \cos\Theta_i + \eta_2 \cos\Theta_t} \stackrel{!}{=} 0$$

Brewster‘s Angle (II)



Brewster‘s Angle (III)

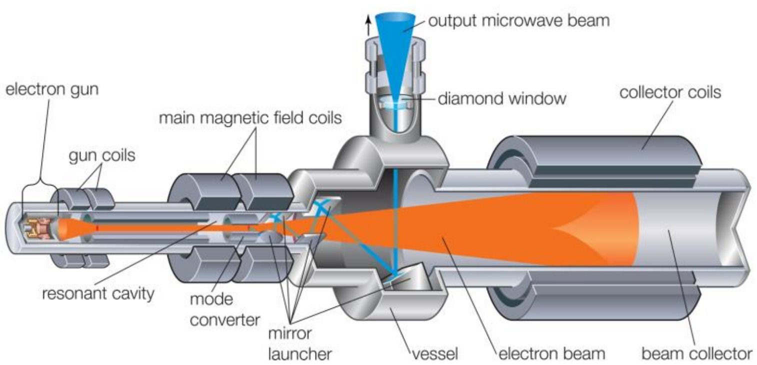


Brewster‘s Angle (IV)

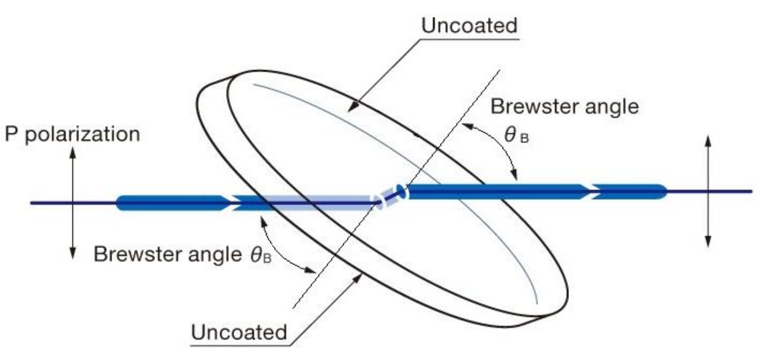
Operation principle of Brewster window:

- **used for windows in optical or quasi optical systems**
- **window with normal incidence → reflection loses at window**
- **window tilted at Brewster’s angle → no reflection loses at window**

Microwave gyrotron



Brewster window



Total Internal Reflection (I)

When does the total internal reflection appears?

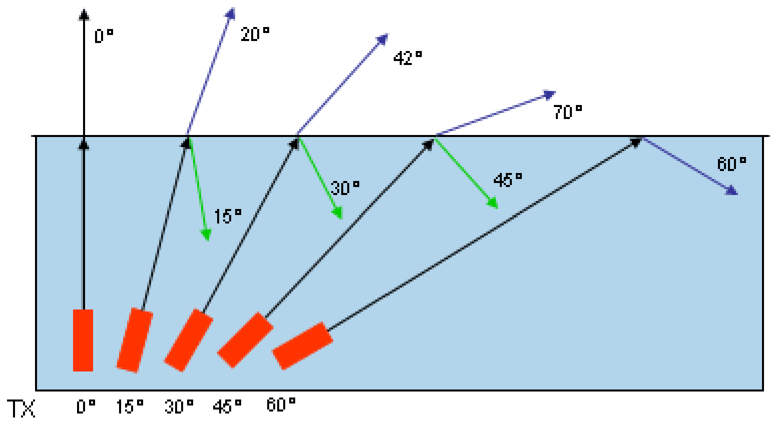
- **a ray must strike the medium's boundary at an angle larger than the critical angle**
- **calculation by comparing the transmission angle to 90 degree**

$$n_i \sin\theta_i = n_t \sin\theta_t \Big|_{\theta_t = 90^\circ}$$

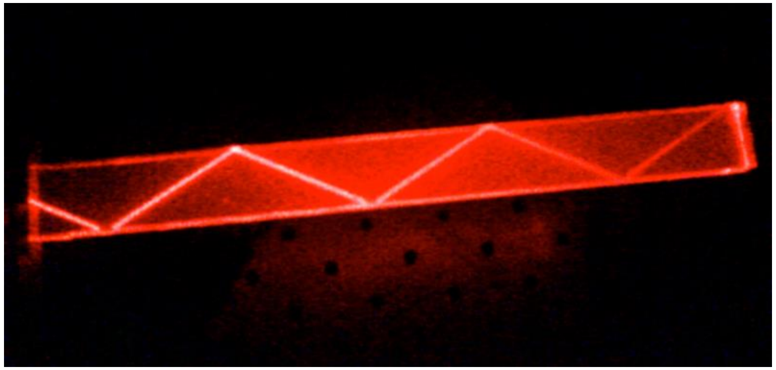
$$\theta_c = \arcsin\left(\frac{n_t}{n_i}\right)$$

critical angle exists only for $n_t < n_i$

Increasing the incidence angle



Total reflection of red laser light in PMMA

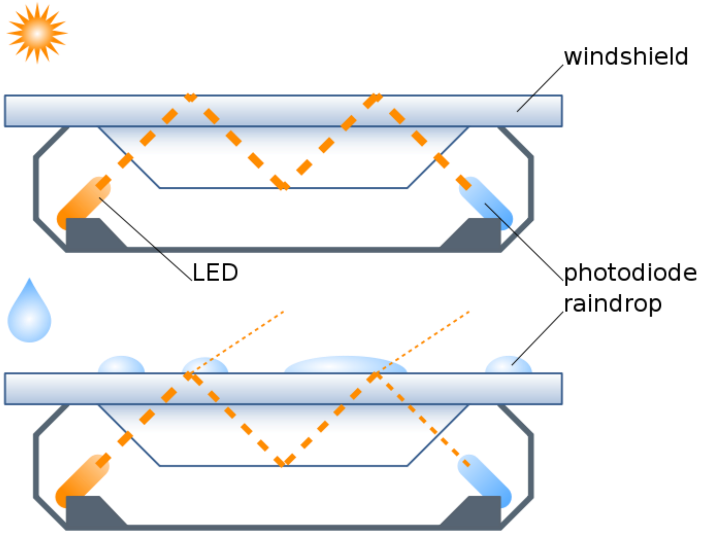


Total Internal Reflection (II)

Operation principle of rain sensors:

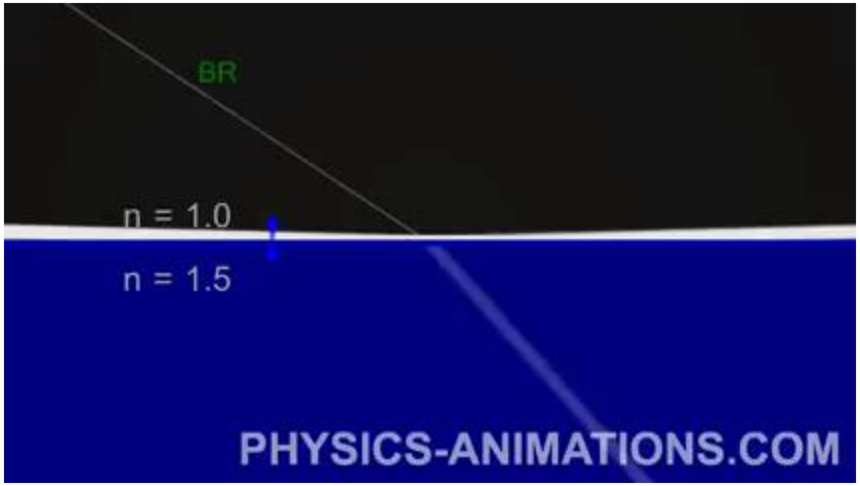
- **IR-beam projected on the glass-air interface at a specific angle**
- **total inner reflection in dry conditions**
- **partial transmission to the second medium if windshield is wet**
- **reduced receive power triggers the sensor**

Rain sensor in the rear view mirror

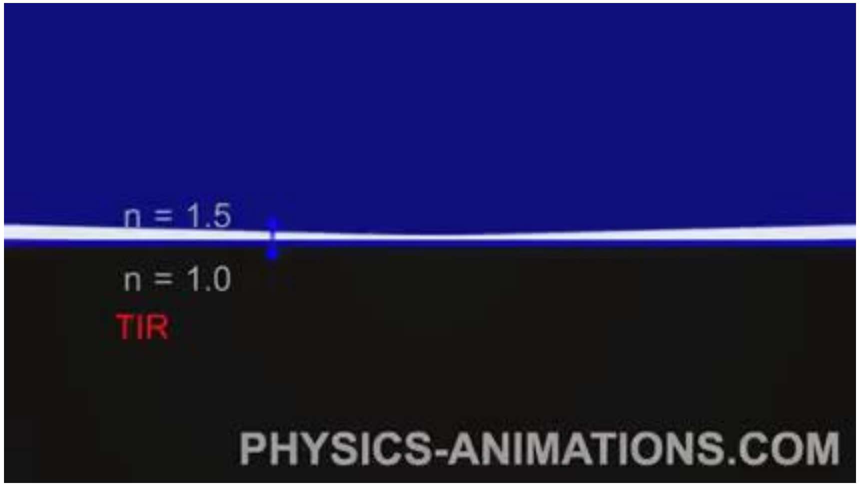


Visualization Parallel Pol – E-Field

Parallel Pol – Air to Glass

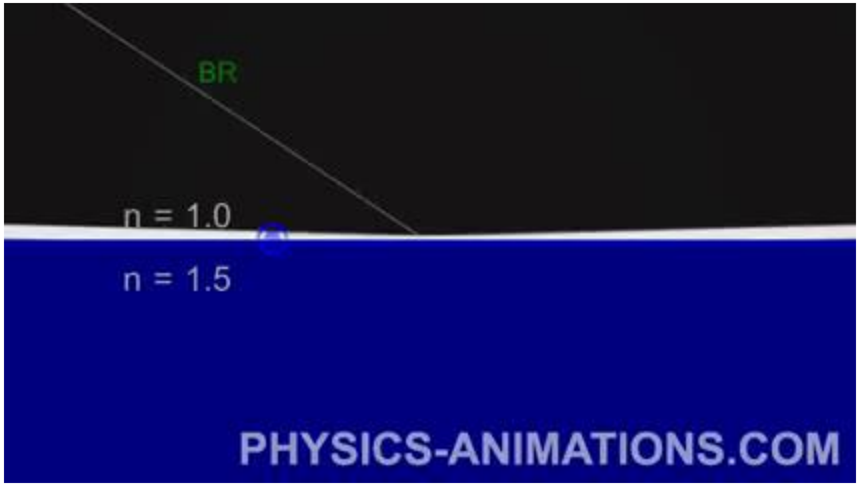


Parallel Pol – Glass to Air

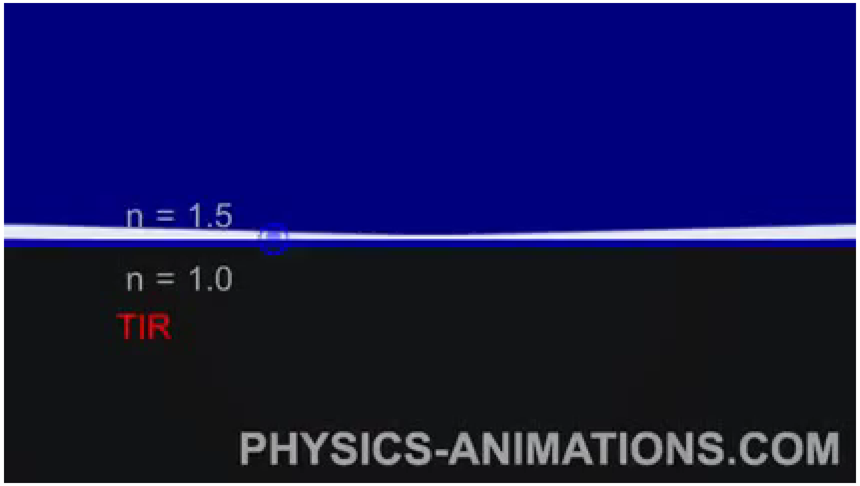


Visualization Perpendicular Pol – E-Field

Perpendicular Pol – Air to Glass



Perpendicular Pol – Glass to Air



Reflection and (no) Transmission

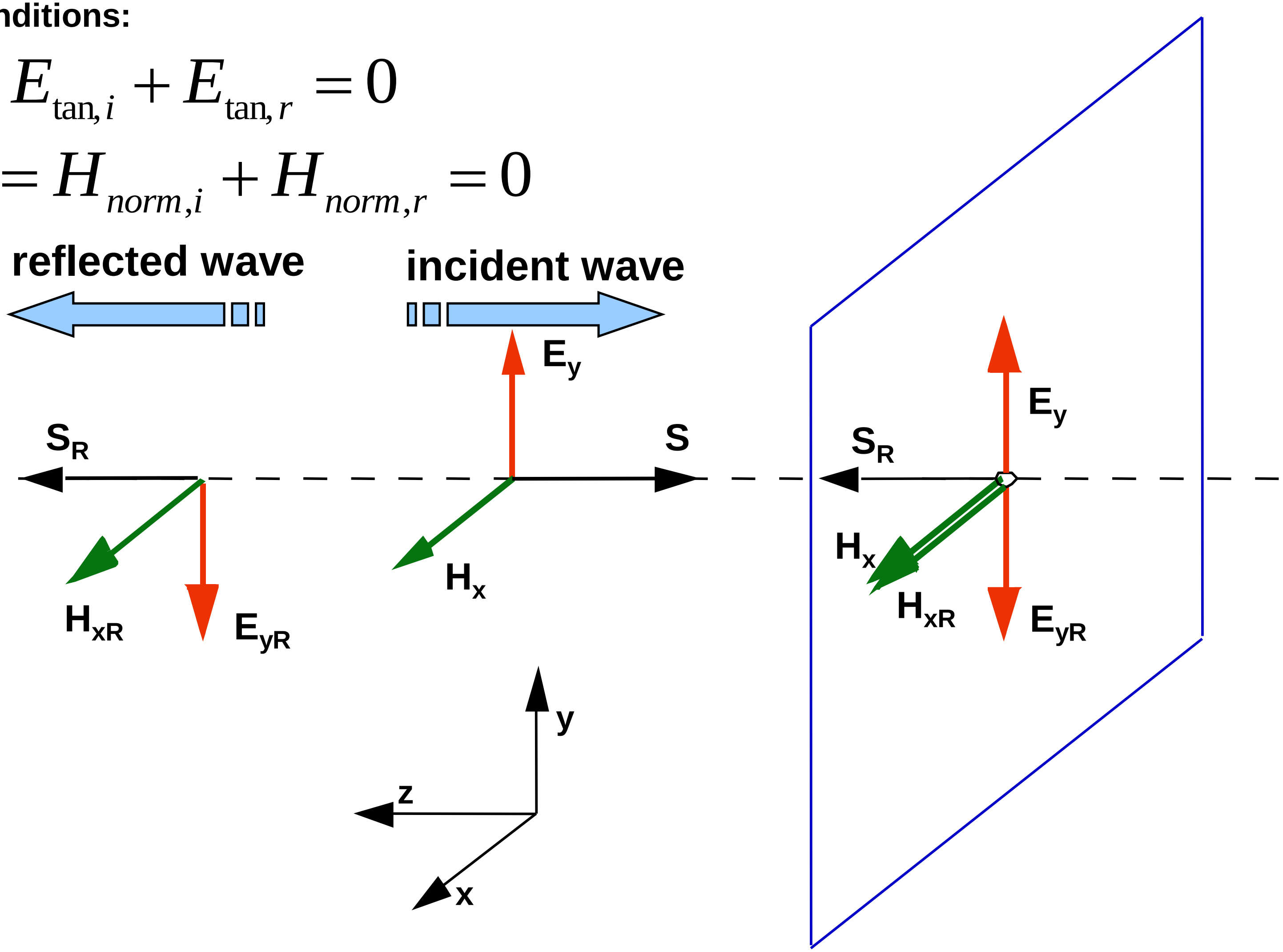
Perfect Electric Conductor (PEC)

Orthogonal PEC Reflection

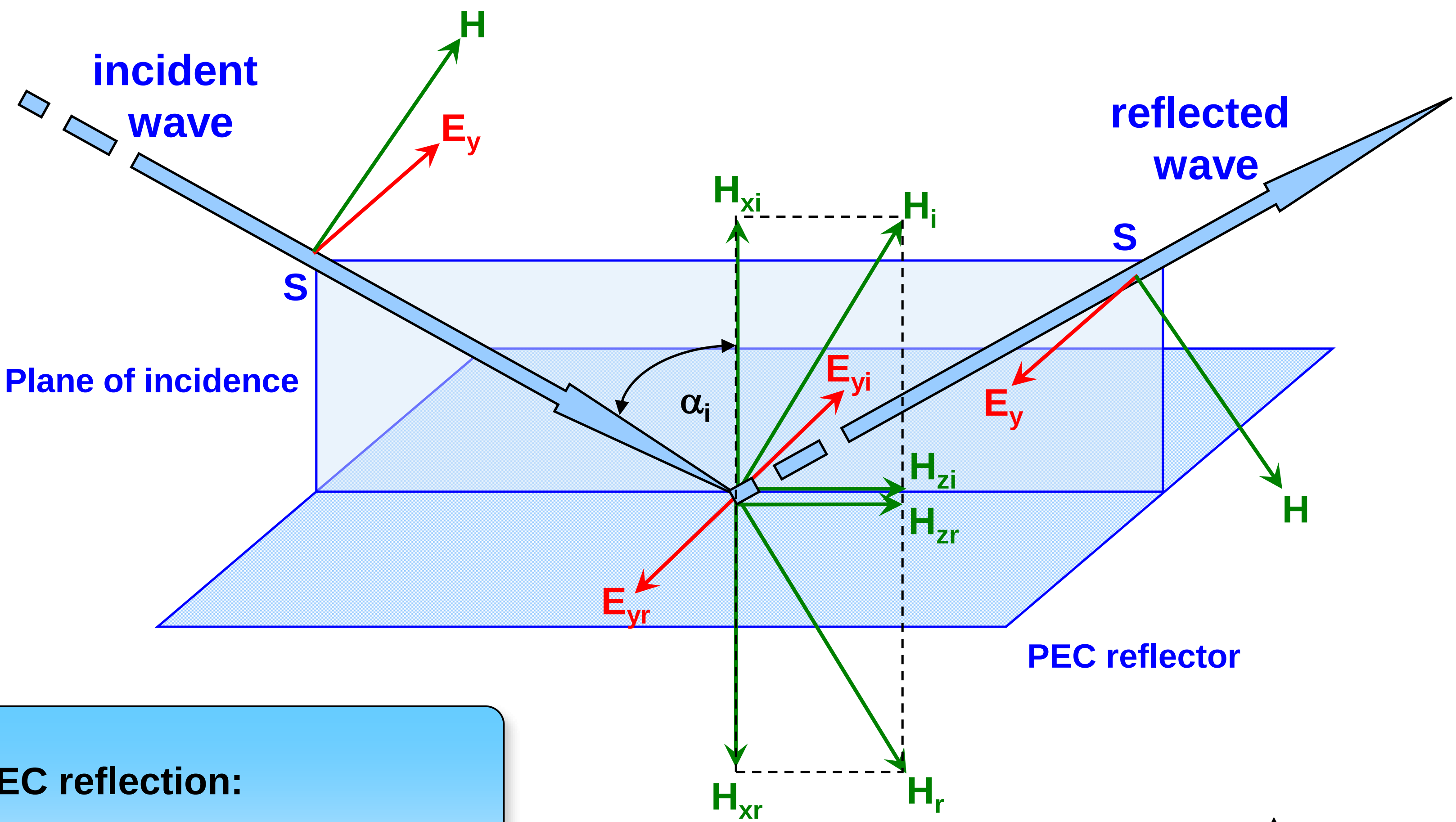
Boundary conditions:

$$\sum E_{\tan} = E_{\tan,i} + E_{\tan,r} = 0$$

$$\sum H_{norm} = H_{norm,i} + H_{norm,r} = 0$$



PEC Reflection, Orthogonal Polarization



PEC reflection:

- R_{II} = +1
- $R_{\perp}$ = -1 (to ensure E_{tan} = 0)

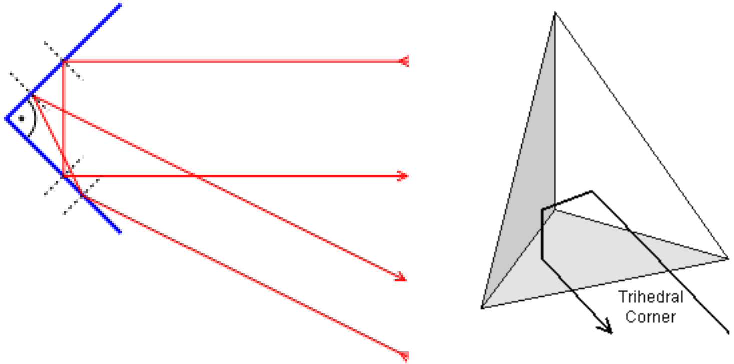
$$\alpha_i = \alpha_r$$

PEC Reflection: Applications

Radar calibration with metallic:

- **dihedral**
- **trihedral (corner reflector)**

Reflection in the direction of incidence:



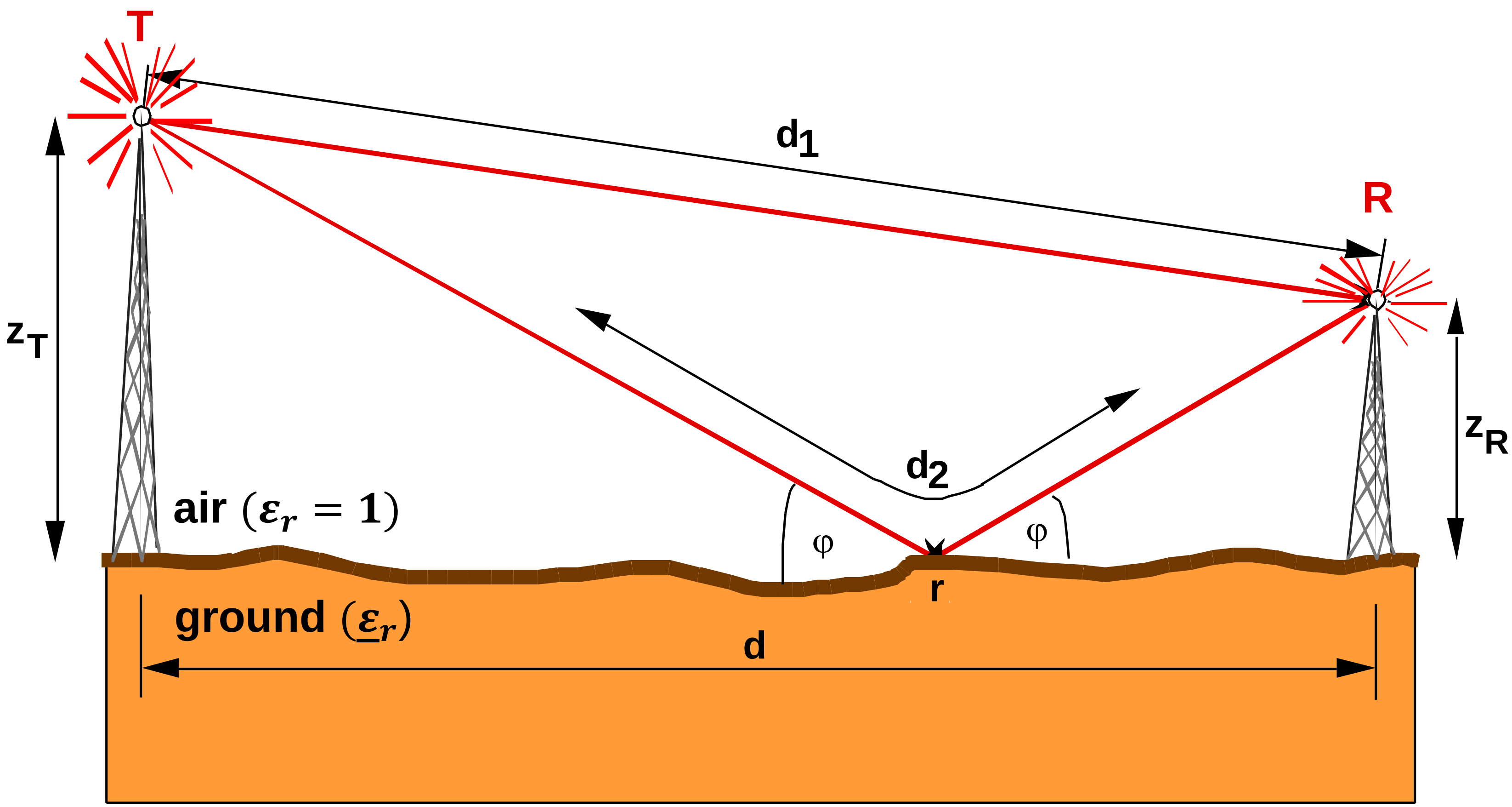
Satellite radar calibration

Radar image with corner reflectors

Buoy with dihedral

Two-Ray Propagation Model

Geometry

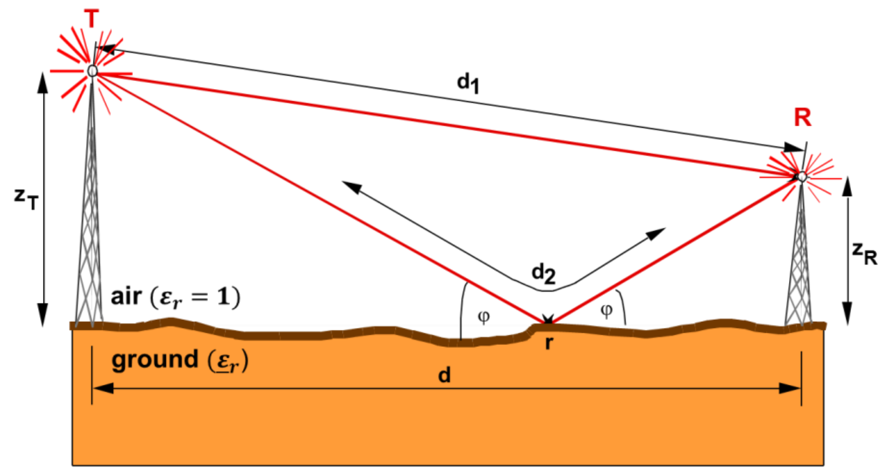


Two-Ray model is based on geometrical optics and predicts large-scale fading

Assumptions

Assumptions in two-ray model:

- ground is PEC
- d >> z_T,z_R



$$P_{R\perp,\|} = \left(\frac{\lambda_0}{4\pi d}\right)^2 G_R G_T P_T \cdot \begin{cases} 4\cos^2\left(\frac{k_0 z_T z_R}{d}\right) & \text{for } \| \\ 4\sin^2\left(\frac{k_0 z_T z_R}{d}\right) & \text{for } \perp \end{cases}$$

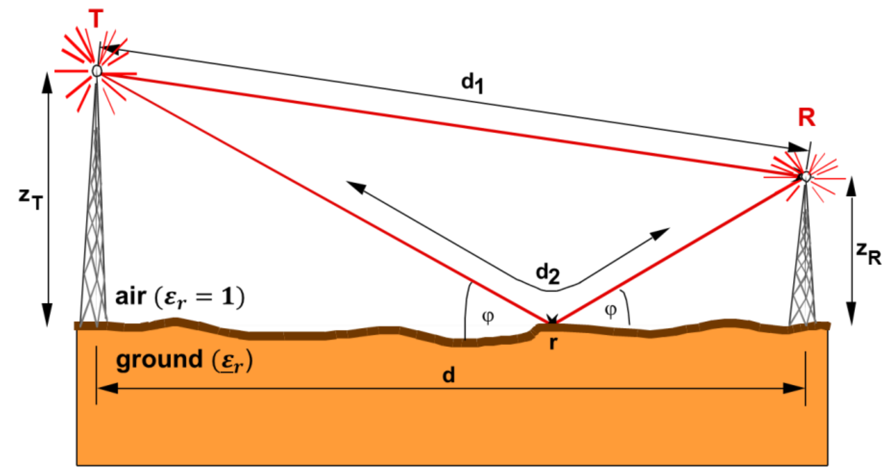
Observations:

- the received power P_R oscillates like a $\sin^2$ or $\cos^2$ with distance
- the minimum value of P_R is 0
- the maximum value of P_R is $4 \cdot P_{R,freespace}$ (+ 6 dB)

Large Distances

Conditions:

- $d \gg k_0 z_T z_R$
- $\cos^2 x \rightarrow 1$
- $\sin^2 x \rightarrow x^2$



$$P_{R\perp,\parallel} = \begin{cases} 4\left(\frac{\lambda_0}{4\pi d}\right)^2 G_R G_T P_T & \text{for } \parallel \\ 4\left(\frac{\lambda_0}{4\pi d}\right)^2 G_R G_T P_T \cdot \left(\frac{k_0 z_T z_R}{d}\right)^2 = P_T G_T G_R \frac{(z_R z_T)^2}{d^4} & \text{for } \perp \end{cases}$$

Observations:

- parallel pol: 20 dB / decade, perpendicular pol: 40 dB / decade
- perpendicular pol: independent on frequency
- perpendicular pol: antenna height gain (double z_T or z_R → quadruple P_R)

Institute of Radio Frequency Engineering and Electronics

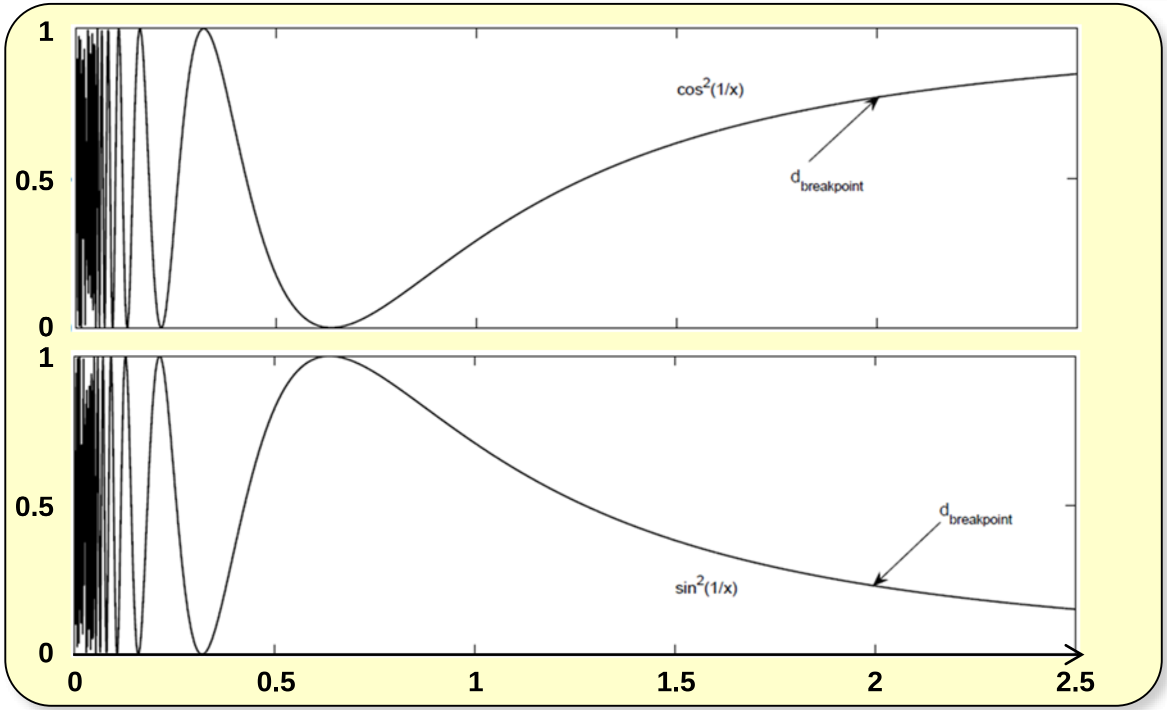
Breakpoint

Definition:

The breakpoint is the distance where the argument of the $\sin^2$ and $\cos^2$ terms equals 0.5

$$\Rightarrow \frac{k z_R z_T}{d} \leq \frac{1}{2}$$

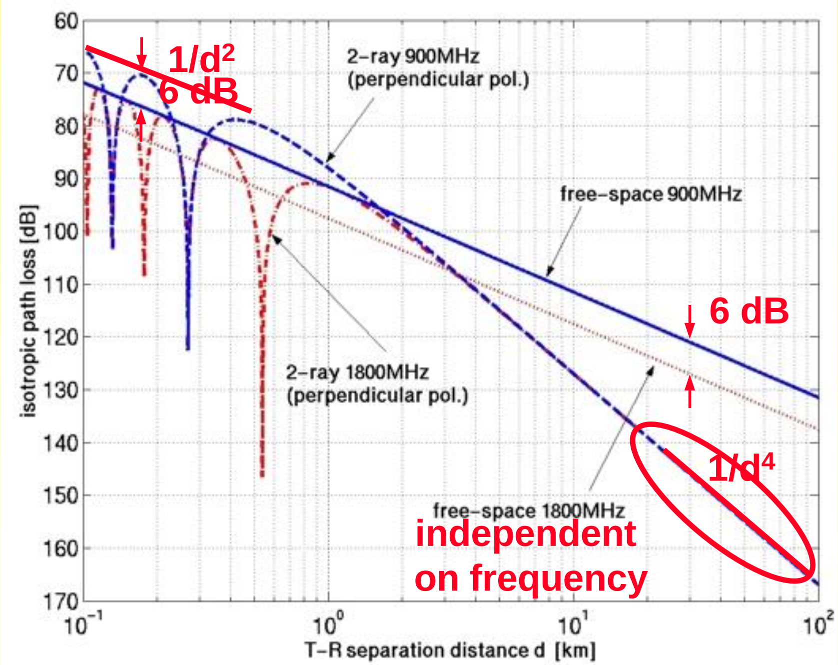
$$d_{\text{breakpoint}} = 2k_0 z_T z_R = \frac{4\pi z_T z_R}{\lambda}$$



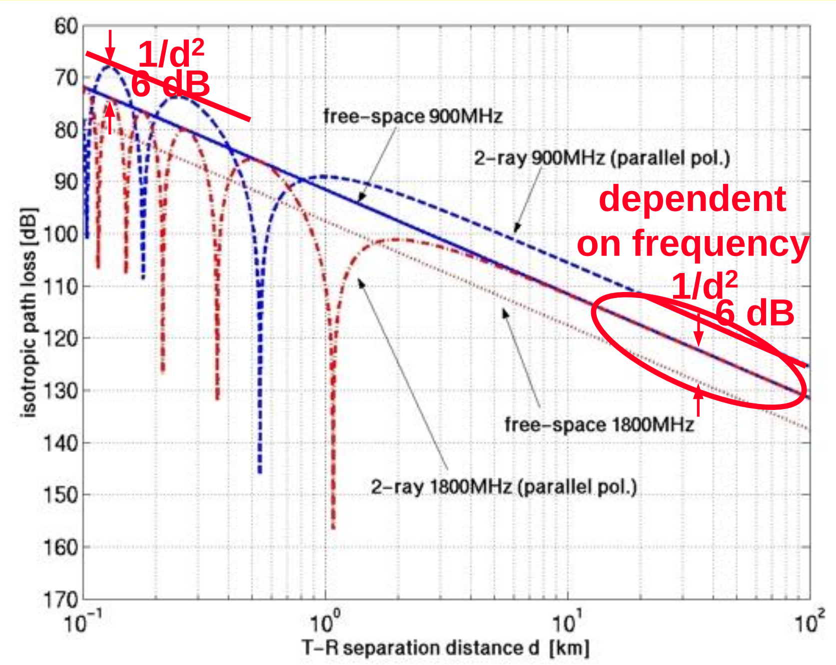
Beyond the breakpoint there are no oscillations!

Polarization Dependence

perpendicular polarization



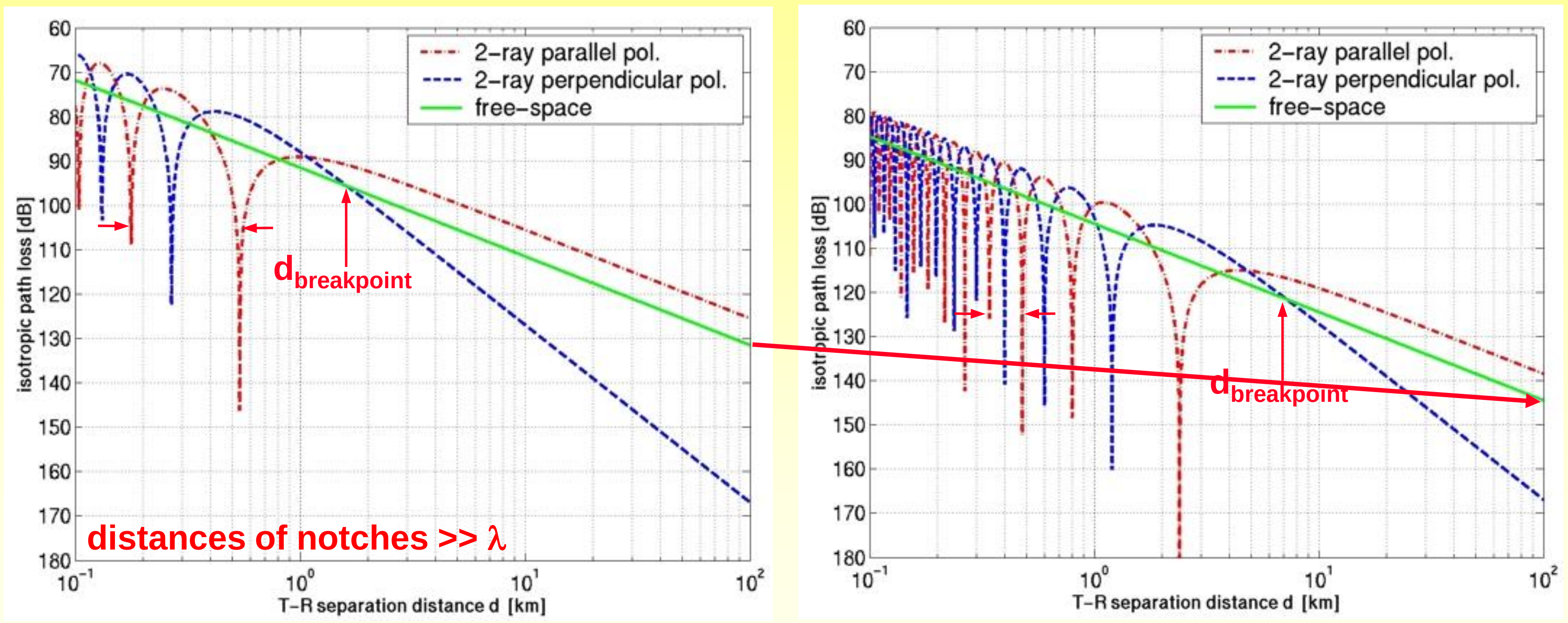
parallel polarization



$$P_{R\perp,\parallel} = \begin{cases} 4\left(\frac{\lambda_0}{4\pi d}\right)^2 G_R G_T P_T \ (\parallel \text{ polarization}) \propto \frac{1}{d^2} \\ 4\left(\frac{\lambda_0}{4\pi d}\right)^2 G_R G_T P_T \cdot \left(\frac{k_0 z_T z_R}{d}\right)^2 = P_T G_T G_R \frac{(z_R z_T)^2}{d^4} \quad \text{for } \perp \end{cases}$$

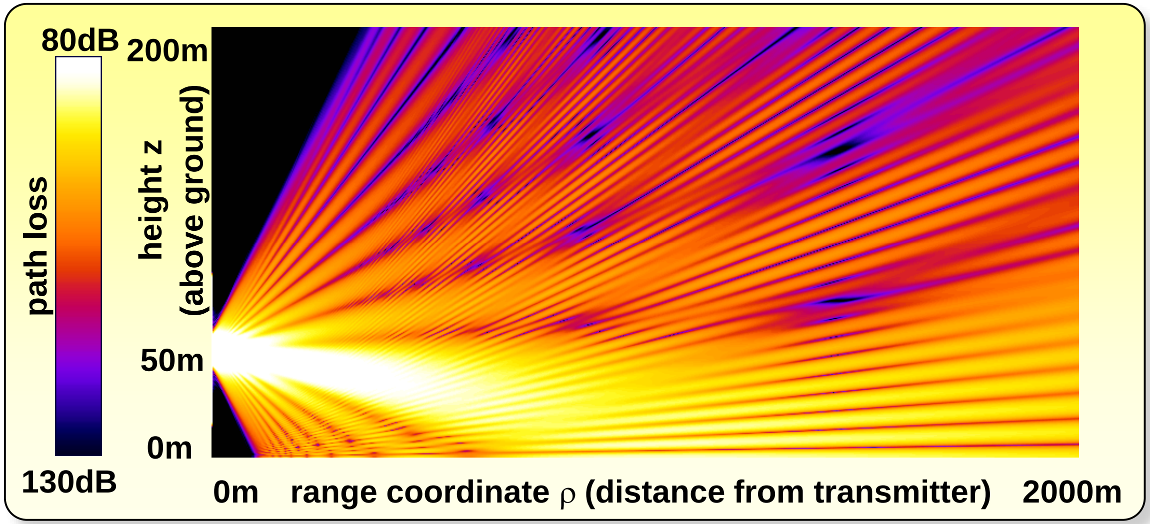
Frequency Dependence

f = 900 MHz | **f = 4 GHz**

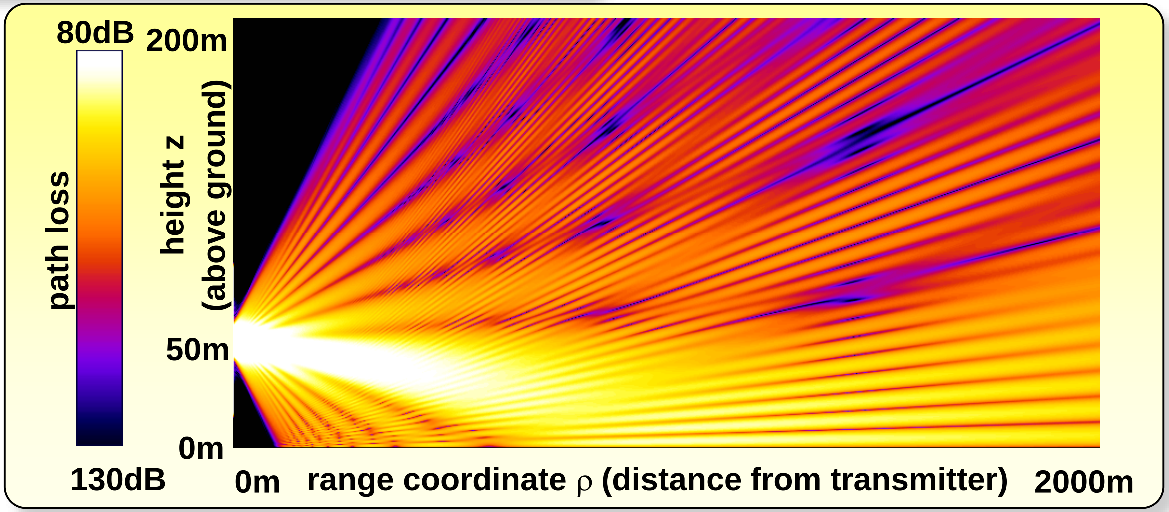


$$d_{\text{breakpoint}} = 2k_0 z_T z_R = \frac{4\pi z_T z_R}{\lambda}$$

Path Loss Prediction



vertical (parallel) polarization



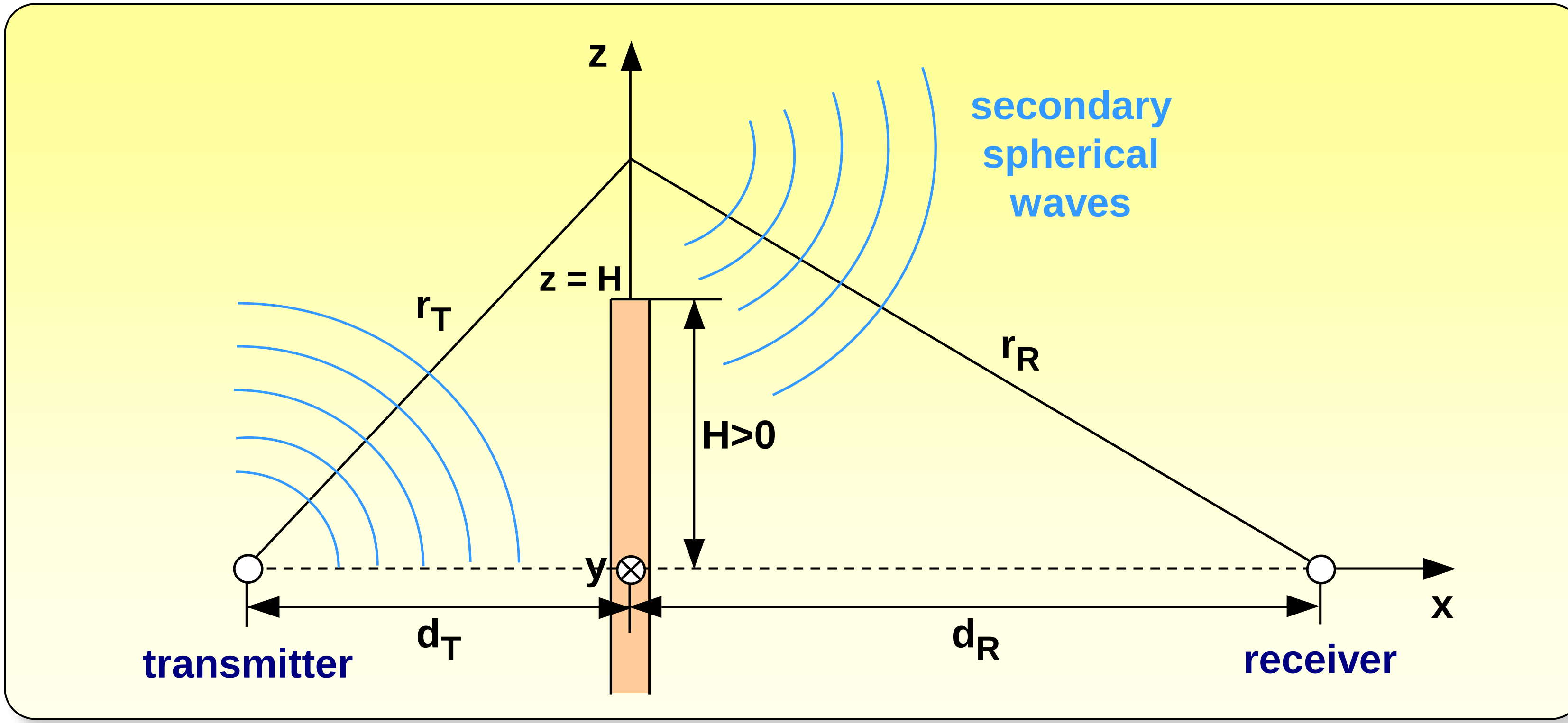
horizontal (perpendicular) polarization

Institute of Radio Frequency Engineering and Electronics

Diffraction

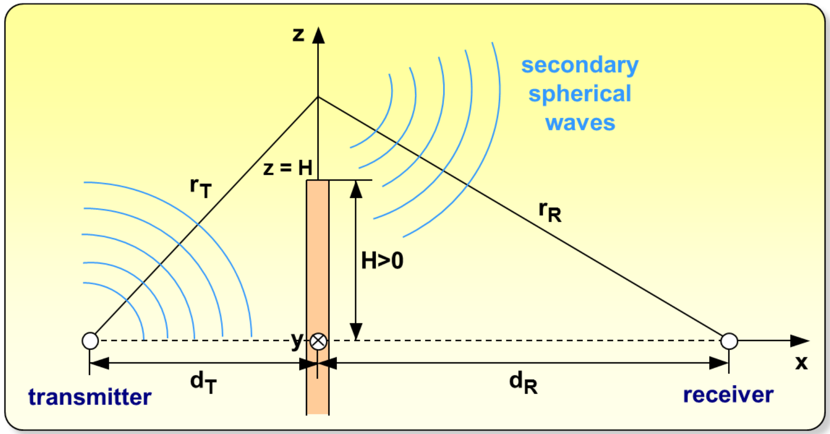
Diffraction on Absorbing Half-Plates

Knife Edge Diffraction: Geometry



- obstacle: semi-infinite, infinitely thin, absorbing plate
- calculate behavior behind the plate: *Huygens' principle*
- wave propagation behind the plate: sum of secondary waves

Knife Edge Diffraction: Model



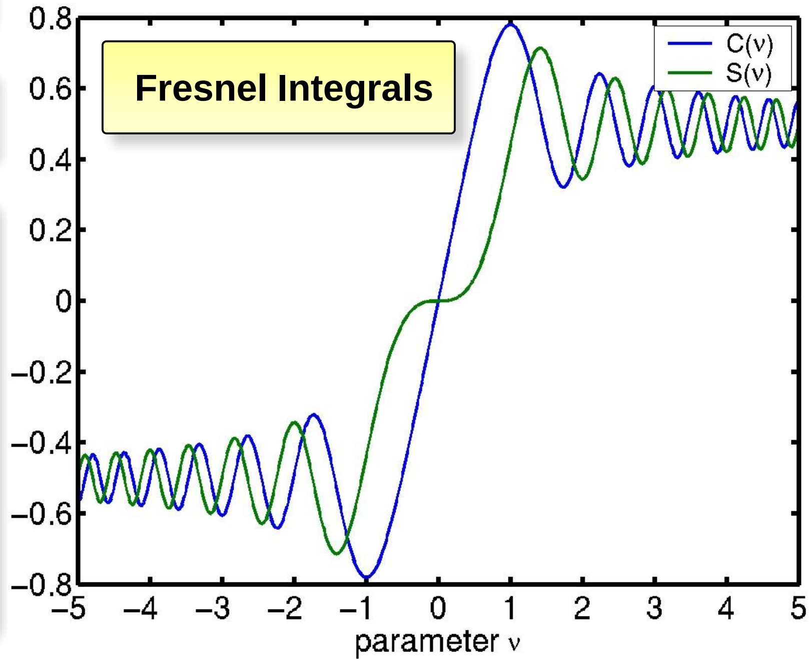
Assumptions in knife edge model:

- **cylindrical waves (2D problem)**
- **T_x and R_x at same height**
- **$|H| << d_T, d_R$**

Field-strength relative to free space (no obstacle):

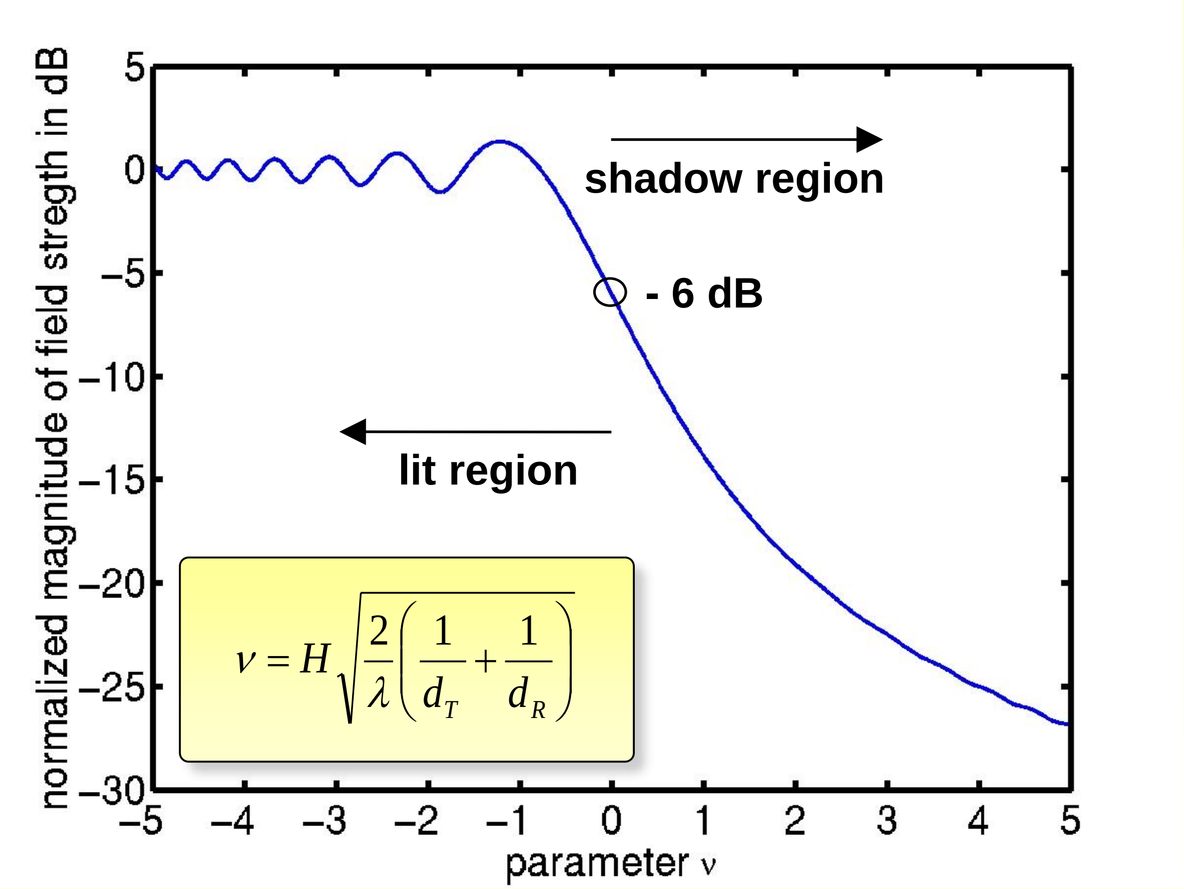
$$\left|\frac{\underline{E}}{\underline{E}_{H\to-\infty}}\right| = \frac{1}{\sqrt{2}}\sqrt{\left(\frac{1}{2}-C(\nu)\right)^2+\left(\frac{1}{2}-S(\nu)\right)^2}$$

$$\nu = H\sqrt{\frac{2}{\lambda}\left(\frac{1}{d_T}+\frac{1}{d_R}\right)}$$



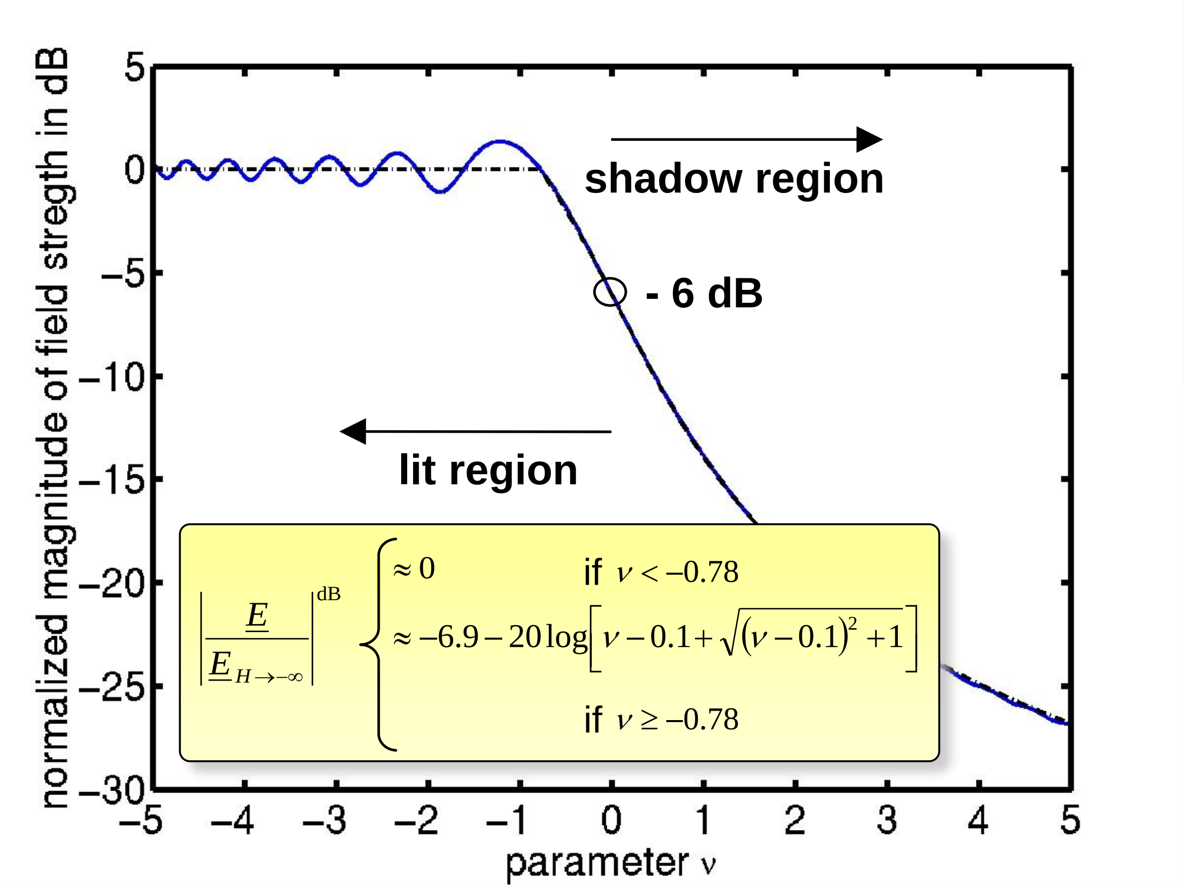
Institute of Radio Frequency Engineering and Electronics

Knife Edge Diffraction: Electric Field (I)



$$\nu = H\sqrt{\frac{2}{\lambda}\left(\frac{1}{d_T}+\frac{1}{d_R}\right)}$$

Knife Edge Diffraction: Electric Field (II)

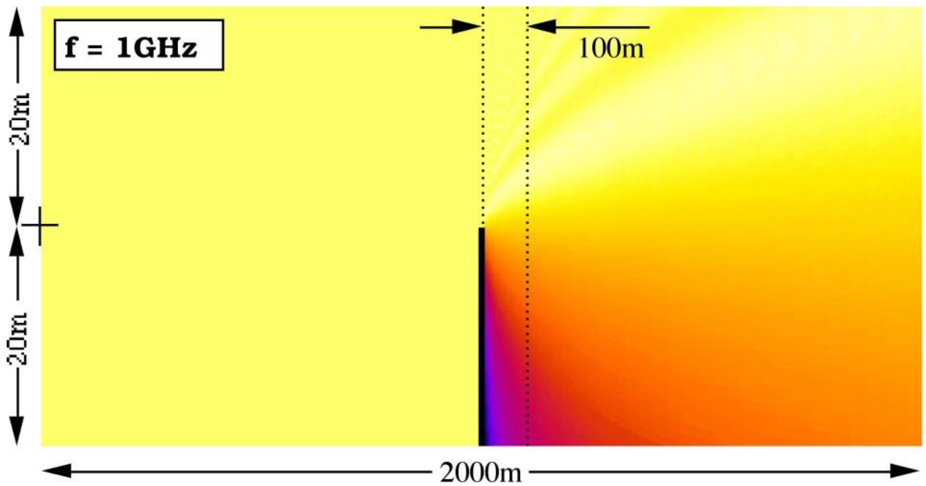


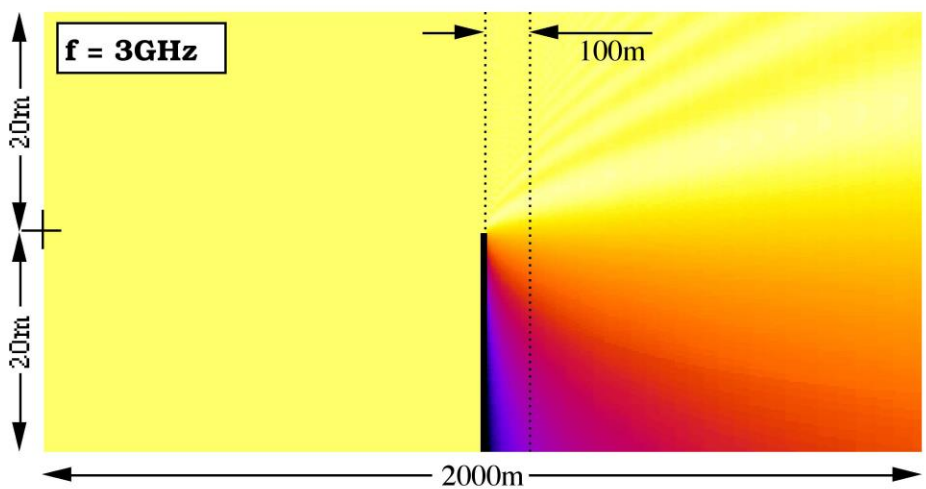
$$\left|\frac{\underline{E}}{\underline{E}_{H\to-\infty}}\right|^{\mathrm{dB}} \begin{cases} \approx 0 & \text{if } \nu < -0.78 \\ \approx -6.9 - 20\log\left[\nu - 0.1 + \sqrt{(\nu-0.1)^2 + 1}\right] & \text{if } \nu \geq -0.78 \end{cases}$$

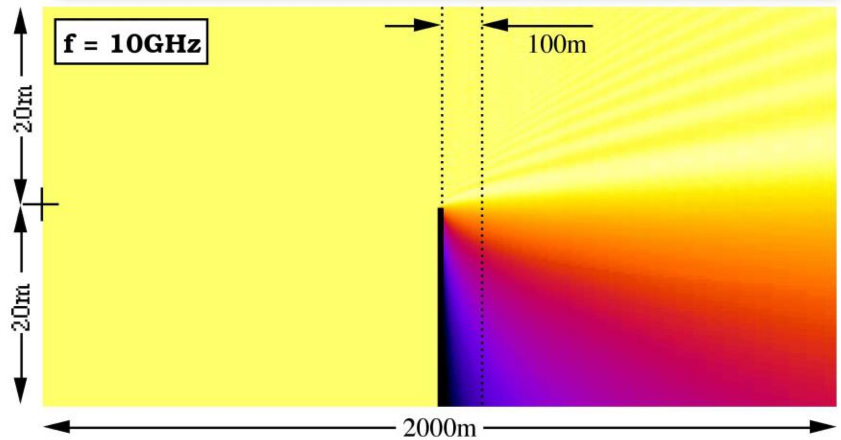
Institute of Radio Frequency Engineering and Electronics

Knife Edge Diffraction: Frequency Dependence (I)

- field strength normalized to free space level
- isotropic Tx antenna
- semi-infinite, absorbing plate
- *f* = 1 GHz, 3 GHz, 10 GHz



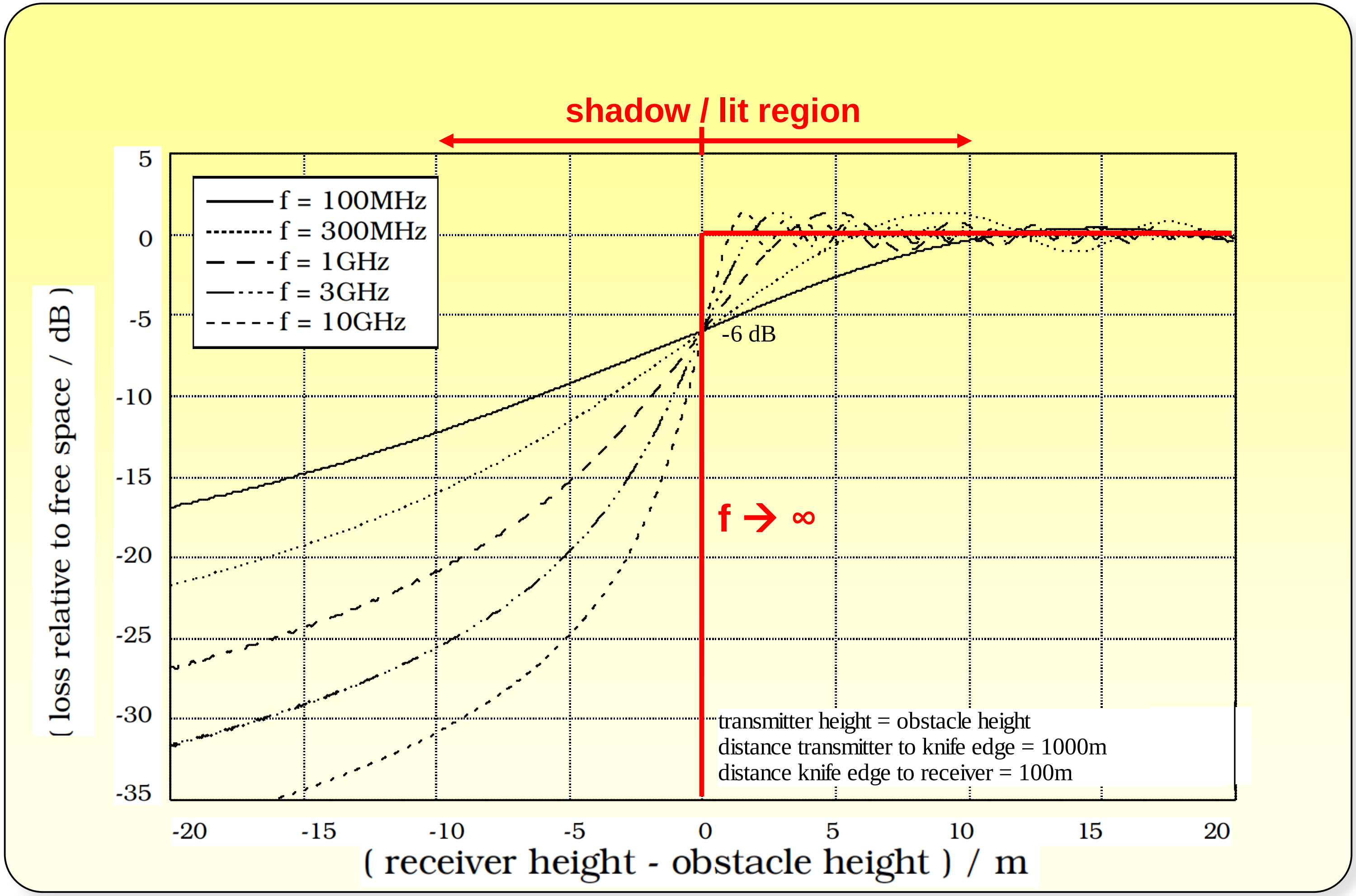




diffraction loss increases with frequency

$$\propto \sqrt{f} \quad \textbf{for} \quad \nu >> 1$$

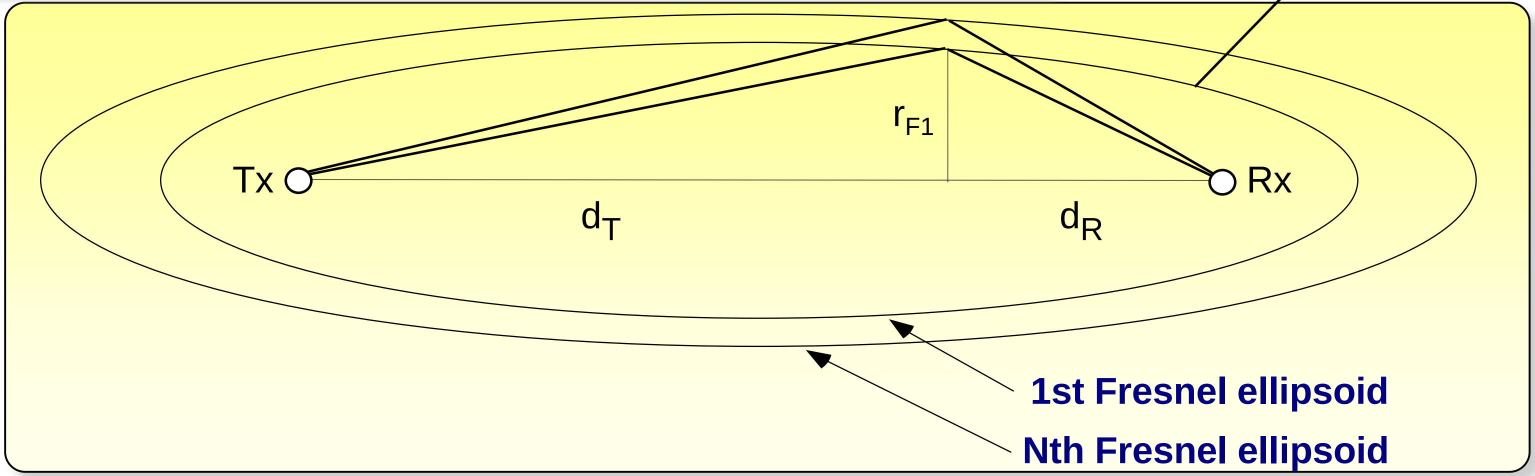
Knife Edge Diffraction: Frequency Dependence (II)



Fresnel Ellipsoids

N^th Fresnel zone is bounded by an ellipsoid, where the Tx-Rx-path is N half wavelengths longer than the direct Tx-Rx-path $d_T + d_R$ between Tx and Rx

$$d_{FN} = d_T + d_R + N \cdot \lambda/2$$



$$\sqrt{d_T^2 + R_{FN}^2} + \sqrt{d_R^2 + R_{FN}^2} - d_T - d_R \overset{\sqrt{1+x^2}\approx 1+\frac{1}{2}x^2}{\approx} \frac{1}{2}\left(\frac{1}{d_T} + \frac{1}{d_R}\right) R_{FN}^2 \overset{!}{=} \frac{N\lambda}{2}$$

$$\Rightarrow R_{FN} = \sqrt{N\lambda \frac{d_T d_R}{d_T + d_R}}$$

Radius of N^th Fresnel ellipsoid

When to Neglect the Knife Edge Diffraction?

Relate Fresnel radius R_{FN} with diffraction parameter ν:

$$R_{FN} = \sqrt{N\lambda \frac{d_T d_R}{d_T + d_R}}$$

$$\frac{d_T d_R}{d_T + d_R} = \left(\frac{R_{FN}}{\sqrt{N\lambda}}\right)^2$$

$$\nu = H\sqrt{\frac{2}{\lambda}\left(\frac{1}{d_T} + \frac{1}{d_R}\right)} = H\sqrt{\frac{2}{\lambda}\left(\frac{d_T d_R}{d_T + d_R}\right)^{-1}}$$

$$\nu = \frac{H}{R_{FN}}\sqrt{2N}$$

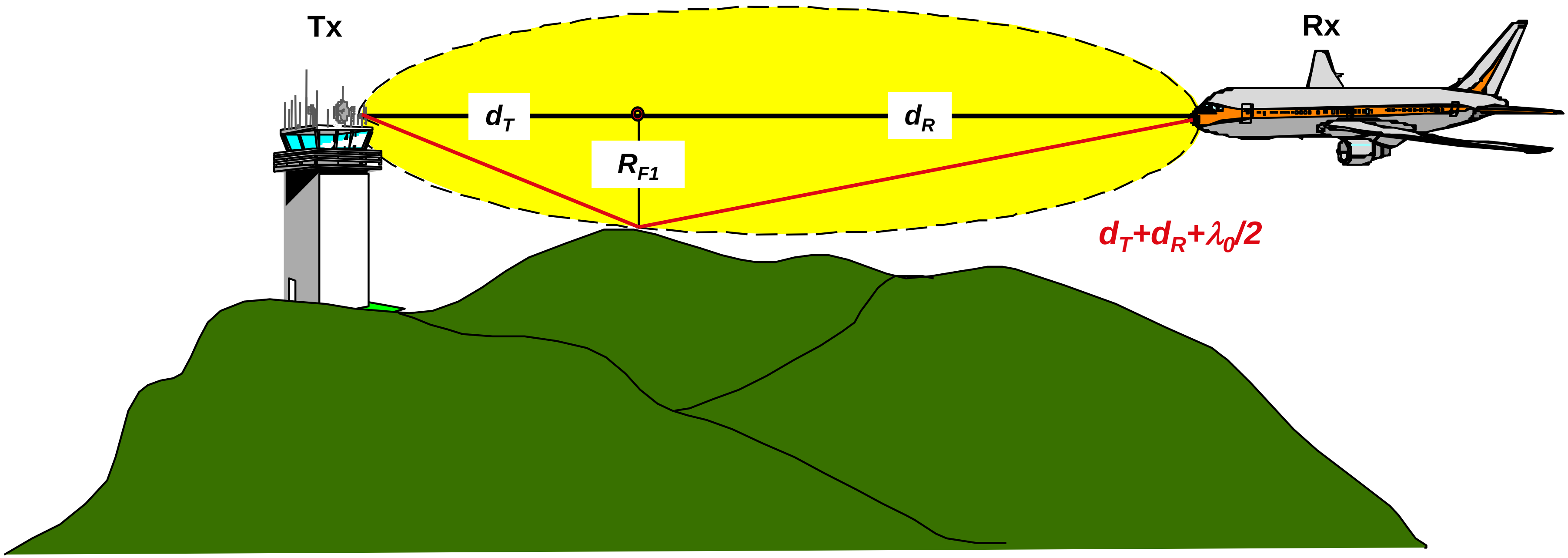
If the knife edge does not extend into 1st Fresnel zone, then the error compared to free space propagation is less than 1.1 dB:

$$-H > R_{F1}$$

$$\nu < -\sqrt{2}$$

If the knife edge does not extend into the 1st Fresnel zone, then knife edge diffraction can be neglected

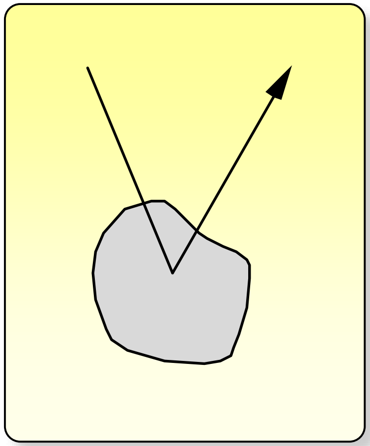
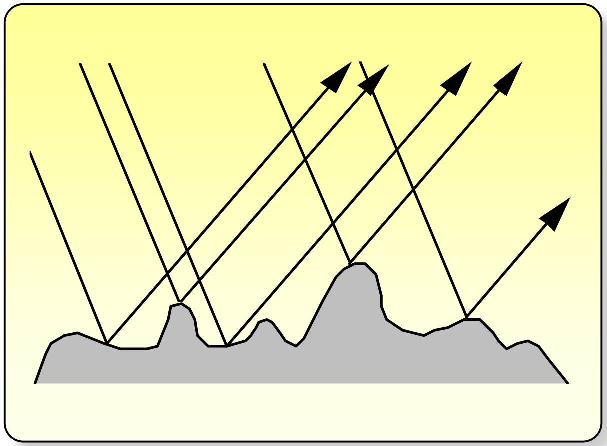
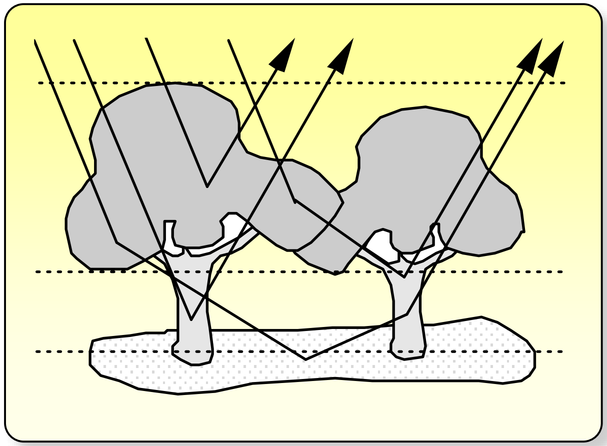
Fresnel Ellipsoids: Example



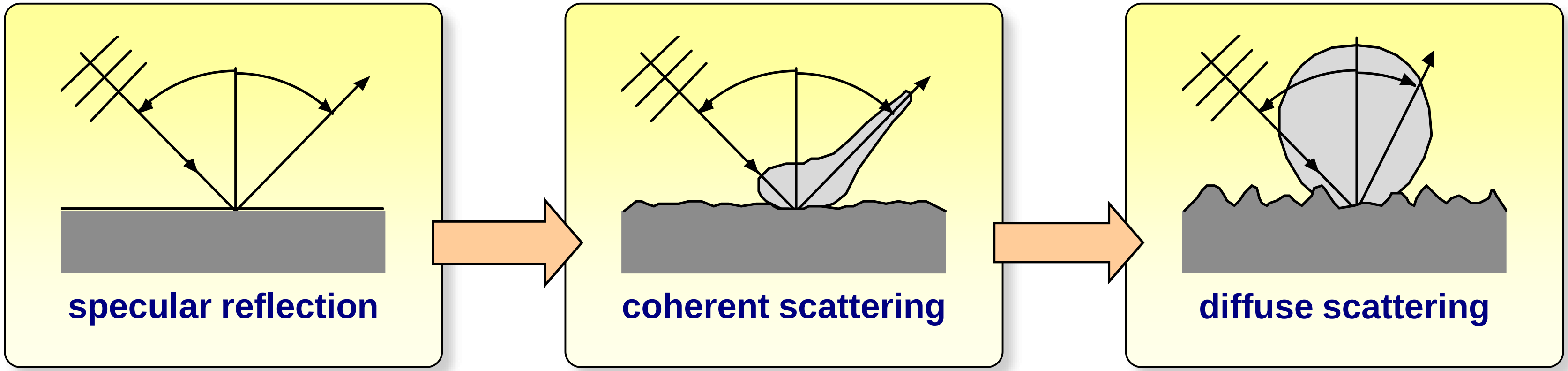
Scattering

Scattering of Incident Energy on Rough Surfaces

Different Types of Scattering

point scattering	distributed scattering	
		
Simple targets (plate, sphere, cylinder, etc.)	rough surface scattering	volume scattering

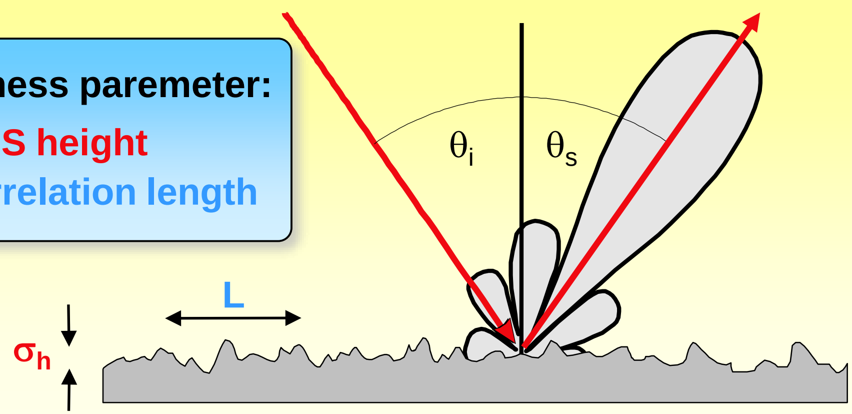
From Specular Reflection to Incoherent Scattering



Roughness paremeter:

σ_h: RMS height

L: correlation length



Roughness criteria:

Rayleigh: $$\sigma_h \le \frac{\lambda_0}{8\cos\theta_i}$$

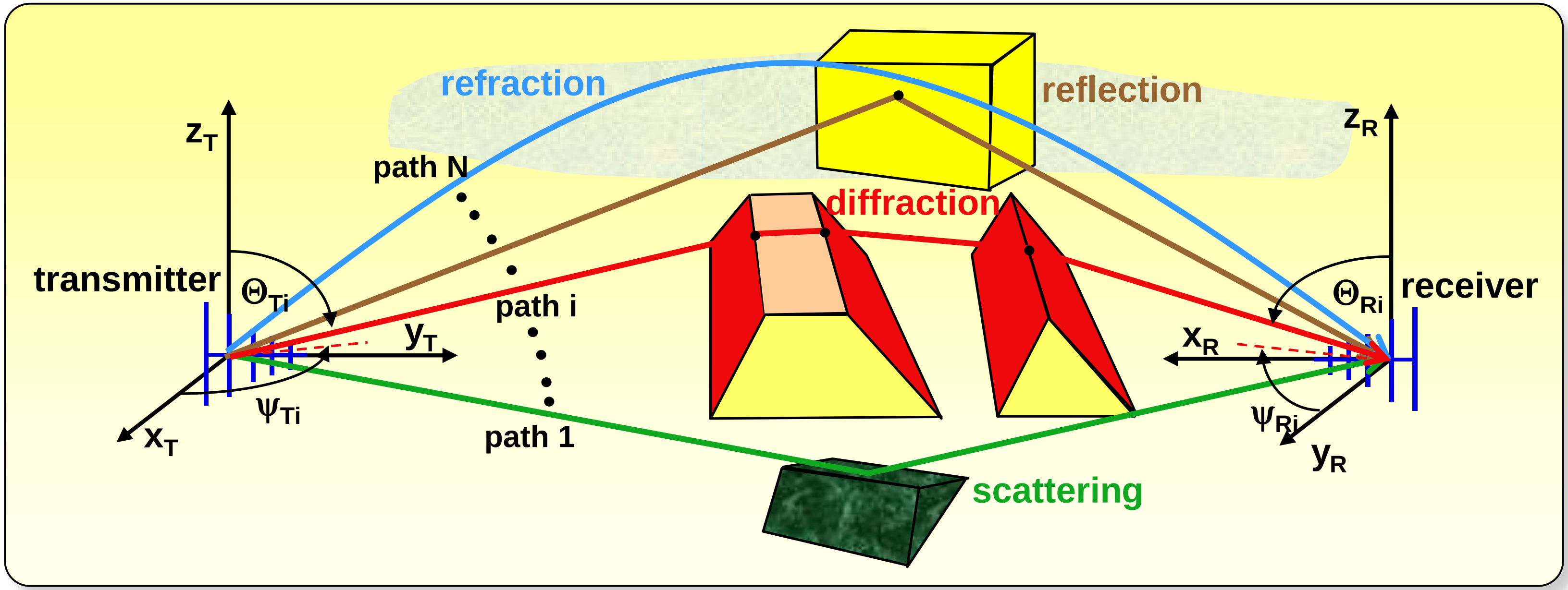
Fraunhofer: $$\sigma_h \le \frac{\lambda_0}{32\cos\theta_i}$$

Institute of Radio Frequency Engineering and Electronics

Multipath Propagation

Combination of all Wave Propagation Effects

Propagation Phenomena



free space propagation:
- line of sight
- no multipath

reflection:
- plane wave reflection
- Fresnel coefficients

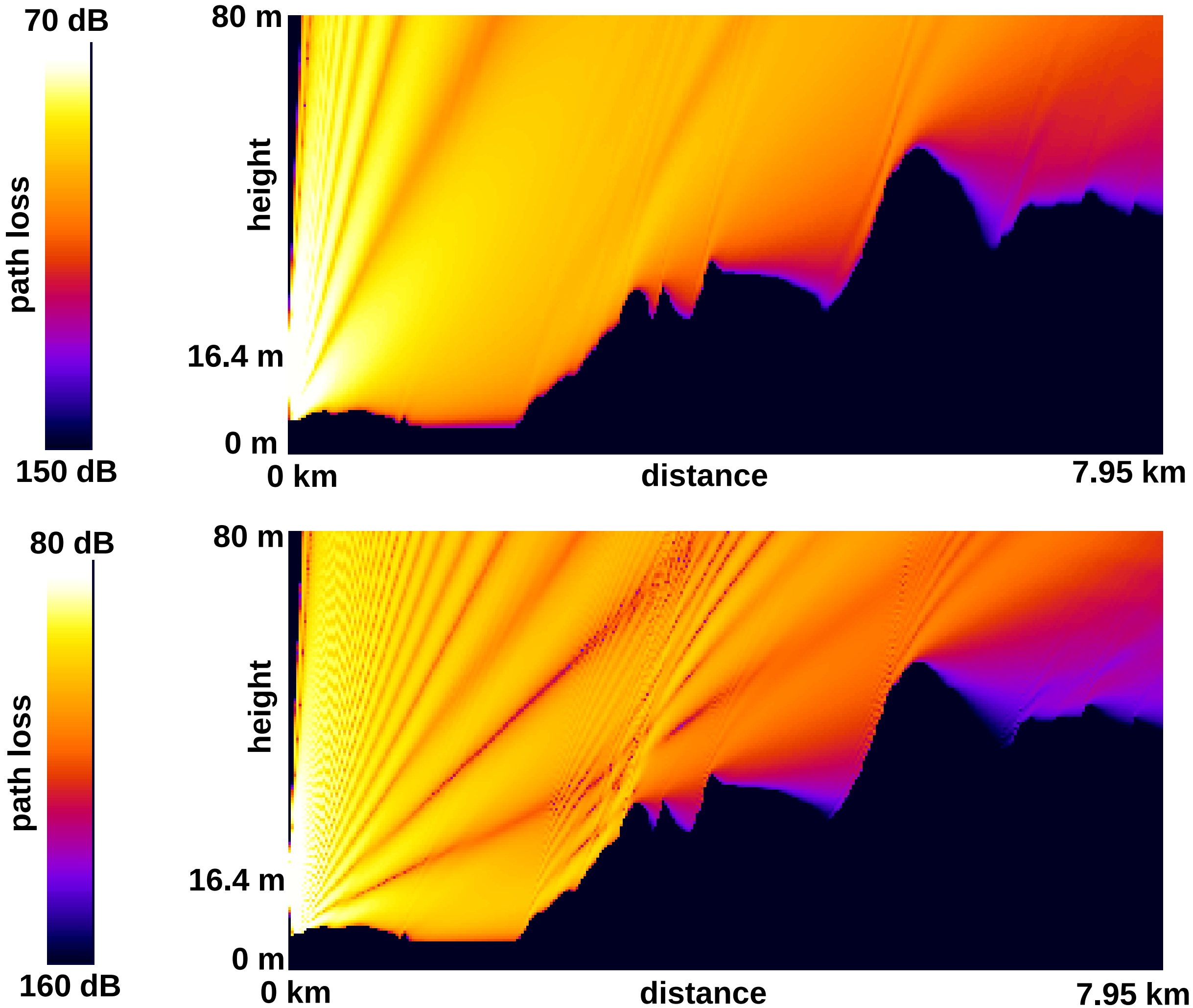
scattering:
- rough surface scattering
- volume scattering

diffraction:
- knife edge diffraction

refraction in the troposphere:
- not considered

In general multipath propagation leads to fading at the receiver site

Path Loss Prediction over Natural Terrain



- ***f*** **= 435 MHz**

- **Tx height = 16.4 m**
- **vertical polarization**

- ***f*** **= 1900 MHz**