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Reflection & refraction
- Snell's laws
- Fresnel coefficients
- Geometric optics

Surface scattering
- Rayleigh criterion

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- Knife-edge
- Fresnel zones
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# Elementary propagation mechanisms

Electromagnetics
and
Remote Sensing Lab
(ERSLab)

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# Introduction



The major propagation mechanisms that provide a theoretical framework to understand the performance of a wireless communication system are briefly reviewed.

## Propagation mechanisms

1. Reflection.
2. Refraction or transmission.
3. Scattering.
4. Diffraction.

# Introduction


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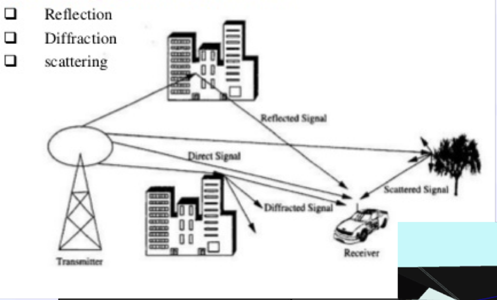


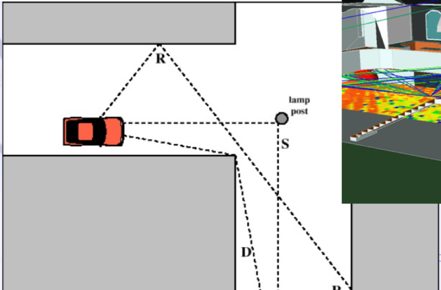


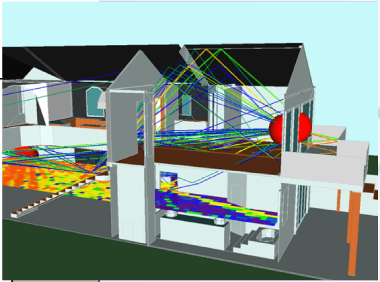

# Reflection

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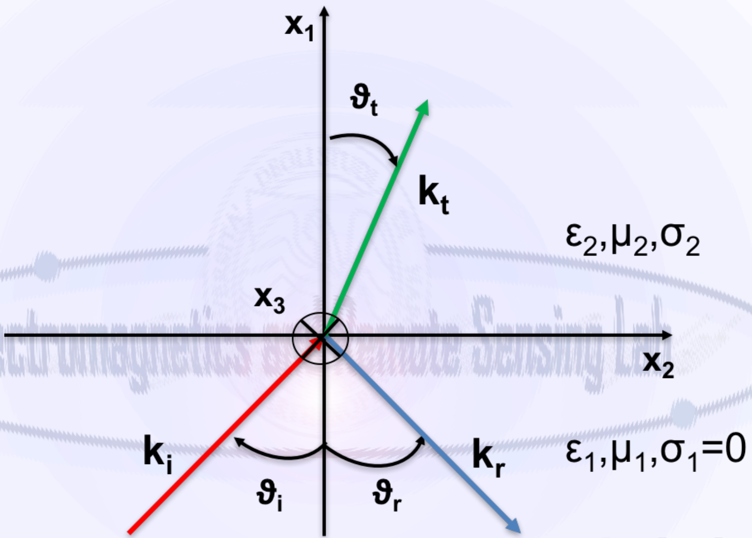
# The scenario





# The scenario

- The scenario consists of two homogeneous media characterized by different electrical parameters.
- When dealing with homogeneous media, one can describe uniform plane waves in terms of rays. The latter are always parallel to the Poynting vector and perpendicular to the wavefronts.
- Let an incident plane wave $\mathbf{E}_i$ hits the plane interface between the two media with and angle $\theta_i$ w.r.t. the surface normal.

# The scenario

Solving Maxwell's equations for this scenario one can easily show that - in genaral - two waves are generated which:

- share the same frequency of the incident wave;
- have their Poynting vectors lying in the scattering plane, i.e.; the plane that contains both the incidence direction and the normal to the plane interface.

Reflected wave ($\mathbf{E}_r$)

- It results from the mechanism of reflection.
- It propagates in medium 1.
- It forms and angle $\theta_r$ with the normal.

Transmitted wave ($\mathbf{E}_t$)

- It results from the mechanism of refraction.
- It propagates in medium 2.
- It forms and angle $\theta_t$ with the normal.

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# Snell's laws - loss-less case

They relate the angles $\theta_r$ and $\theta_t$ to $\theta_i$ accounting for the characteristics of the media and the em waves.

## Loss-less case

Unless explicitly stated, loss-less media are assumed, i.e.:

- $\sigma_1 = \sigma_2 = 0$
  - $k = \beta = \omega\sqrt{\epsilon\mu} \in \mathbb{R}$.
  - $Z = \sqrt{\frac{\mu}{\epsilon}} \in \mathbb{R}$.

Snell's laws derive from the Fermat's principle that states that every ray path represents an extremum (usually the maximum) of the total electrical length *kd* of the ray.

# Snell's laws - loss-less case

- Snell's law of reflection:

$$k_1 \sin\theta_i = k_1 \sin\theta_r \quad \rightarrow \quad \theta_i = \theta_r. \tag{1}$$

- Snell's law of refraction:

$$k_1 \sin\theta_i = k_2 \sin\theta_t. \tag{2}$$

Introducing the refraction index:

$$n = \frac{c}{v} = \frac{ck}{\omega} \tag{3}$$

Snell's law of refraction can be rewritten in a completely equivalent way:

$$n_1 \sin\theta_i = n_2 \sin\theta_t. \tag{4}$$

# Snell's laws - loss-less case



- Since eq.(4) can be rewritten as follows:

$$\sin\theta_t = \frac{n_1}{n_2}\sin\theta_i.$$

One can note that:

- When $n_2 > n_1$: $\mathbf{E}_t$ tends to ben to the surface normal and $v$ in the medium 2 reduces. This implies that, since both $\mathbf{E}_i$ and $\mathbf{E}_t$ have the same frequency, the wavelenght in the medium 2 is longer.
- When $n_2 < n_1$: $\theta_t$ is not always defined and there exists a critical angle $\theta_c = \arcsin(\frac{n_2}{n_1})$ such that $\theta_t = \pi/2$. Hence, when $\theta_i > \theta_c$ there is no transmitted wave (total reflection).

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# Fresnel reflection and transmission coefficients



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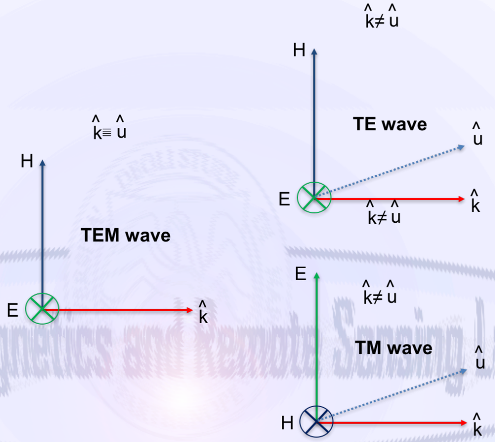
Once the geometry of the reflection problem has been characterized, the reflected and transmitted waves must be expressed as function of the incident wave.

- The simplest approach consists of expanding the incident wave into two linearly-polarized (i.e. both **E** and **H** are real vectors) independent polarizations.
- Reflection and refraction are studied separately for those two waves and then results are superimposed.
- TE wave refers to a unit vector $\hat{u}$ lying in the plane defined by **H** and **k**.
- TM wave refers to a unit vector $\hat{u}$ lying in the plane defined by **E** and **k**.

# TE and TM waves




Note that “TE” and “TM” polarizations are aka “horizontal” and “vertical” polarizations or “perpendicular” and “parallel” polarizations.

# Fresnel reflection and transmission coefficients

- The incident, reflected and transmitted waves can be expressed in terms of their component parallel ($\|$) and perpendicular ($\perp$) to the scattering plane:

$$\begin{aligned} \mathbf{E}_i &= E_{i\|}\mathbf{d}_{\|} + E_{i\perp}\mathbf{d}_{\perp} \\ \mathbf{E}_r &= E_{r\|}\mathbf{d}_{\|} + E_{r\perp}\mathbf{d}_{\perp} \\ \mathbf{E}_t &= E_{t\|}\mathbf{d}_{\|} + E_{t\perp}\mathbf{d}_{\perp} \end{aligned} \quad (5)$$

where $\mathbf{d}_{\|}$ and $\mathbf{d}_{\perp}$ are two unit vectors parallel and orthogonal to the scattering plane, respectively.

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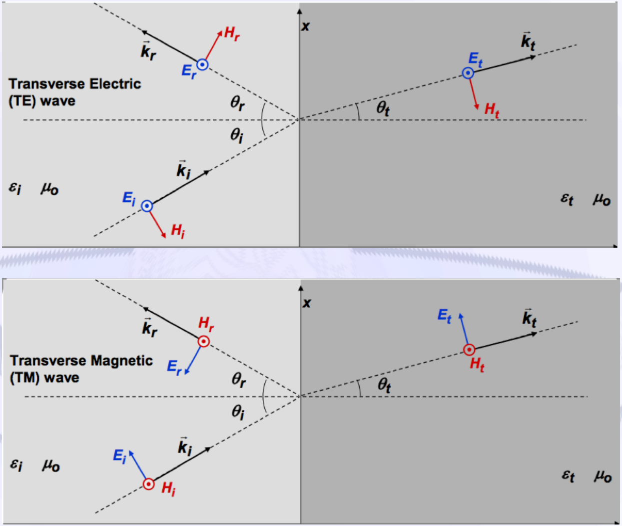
# Fresnel reflection and transmission coefficients



# Fresnel reflection and transmission coefficients

- The reflected and transmitted waves are given by:

$$\begin{aligned} \mathbf{E}_r &= \mathbf{R}\mathbf{E}_i \\ \mathbf{E}_t &= \mathbf{T}\mathbf{E}_i \end{aligned} \quad (6)$$

where **R** and **T** are the reflection and transmission matrices, respectively.

$$\mathbf{R} = \begin{pmatrix} R_{\parallel} & 0 \\ 0 & R_{\perp} \end{pmatrix} \qquad \mathbf{T} = \begin{pmatrix} T_{\parallel} & 0 \\ 0 & T_{\perp} \end{pmatrix} \quad (7)$$

# Fresnel reflection and transmission coefficients



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- Reflection coefficients:

$$R_{\parallel} = \frac{E_{r\parallel}}{E_{i\parallel}} = \frac{Z_1 \cos\theta_i - Z_2 \cos\theta_t}{Z_1 \cos\theta_i + Z_2 \cos\theta_t} \tag{8}$$

$$R_{\perp} = \frac{E_{r\perp}}{E_{i\perp}} = \frac{Z_2 \cos\theta_i - Z_1 \cos\theta_t}{Z_1 \cos\theta_t + Z_2 \cos\theta_i} \tag{9}$$

- Transmission coefficients:

$$T_{\parallel} = \frac{E_{t\parallel}}{E_{i\parallel}} = \frac{2Z_2 \cos\theta_i}{Z_1 \cos\theta_i + Z_2 \cos\theta_t} \tag{10}$$

$$T_{\perp} = \frac{E_{t\perp}}{E_{i\perp}} = \frac{2Z_2 \cos\theta_i}{Z_1 \cos\theta_t + Z_2 \cos\theta_i} \tag{11}$$

# Fresnel reflection and transmission coefficients



- It can be noted that:

$$\|T_{\parallel}\|^2 = 1 - \|R_{\parallel}\|^2 \tag{12}$$

$$\|T_{\perp}\|^2 = 1 - \|R_{\perp}\|^2 \tag{13}$$

- It can be proven that $R_{\perp} \neq 0 \quad \forall\theta_i$; while there is an incident angle $\theta_B$ such that $R_{\parallel} = 0$:

$$\theta_B = \tan^{-1}\frac{n_2}{n_1} \tag{14}$$

This angle is termed as Brewster angle. Note that an unpolarized wave incident at this angle will be reflected to have a purely horizontal component!

# Lossy media

## Snell's law and Fresnel coefficients

- Snell's law of refraction no longer applies in the form given by eq.(4).
- Snell's law of reflection still applies in the form given by eq.(1).
- Fresnel coefficients are still given by the previous equations but a complex impedance must be used: $Z = \sqrt{\frac{j\omega\mu}{\sigma + j\omega\mu}}$.

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# Geometric optics



It is a method to describe the propagation of electromagnetic waves in inhomogeneous media. Note that the media must be slowly varying.

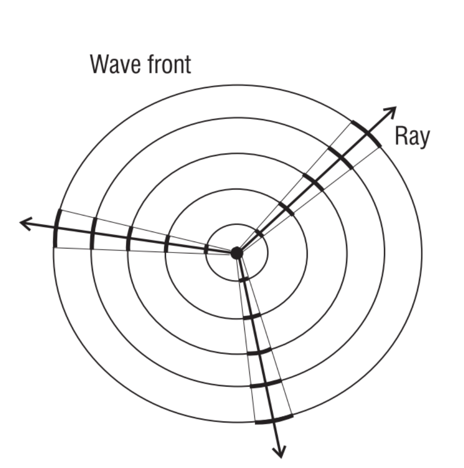
## Geometric optics (GO)

GO is a high frequency method that allows accountig for interaction with em waves and:

- Surfaces of finite extent.
- Boundaries among media characterized by different electrical parameters.
- Ground curvature.

# From wavefronts to rays

A ray is a line perpendicular to a series of successive wave fronts specifying the direction of energy flow in the wave.



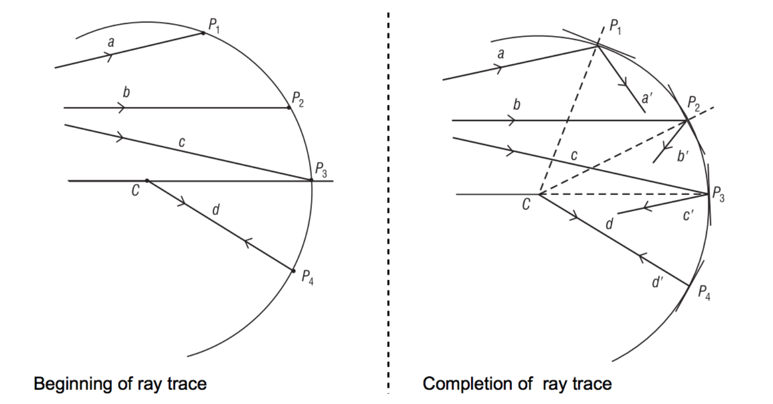
# Geometric Optics



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

- Wavefronts are locally plane and waves are TEM.
- The wave direction is specified by the normal to the equiphase planes ("rays").
- Rays travel in straight lines in a homogeneous medium.
- Polarization is constant along a ray in an isotropic medium.
- Power in a flux tube ("bundle of rays") is conserved.
- Reflection and refraction obey Snell's law.
- The reflected field is linearly related to the incident field at the reflection point by a reflection coefficient.

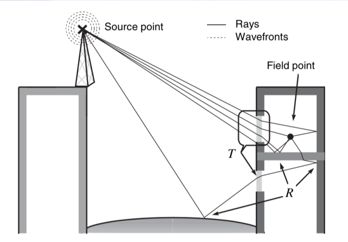
## Example of ray tracing



# The scenario



A realistic propagation scenario where one is interested in evaluating the em wave transmitted by a TX antenna located on the roof of a building ("source point") and received at a "field point" by a RX antenna located within a different building.

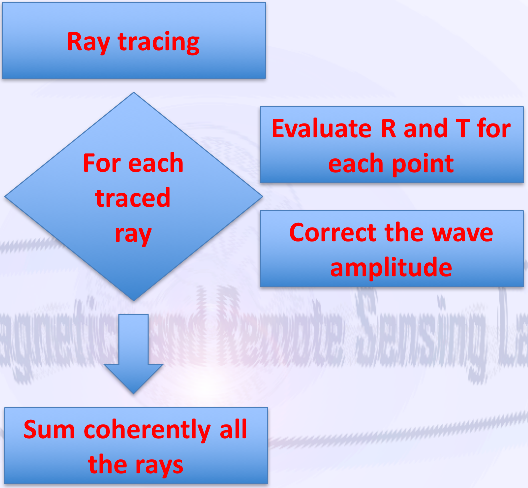



Hence, in this realistic case:

- TX antenna radiates spherical waves;
- The interacting surfaces are finite in extent.
- Boundaries among media calling for different electrical parameters are involved.

# Ray tracing




Ray tracing
For each traced ray
Evaluate R and T for each point
Correct the wave amplitude
Sum coherently all the rays

# GO method

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- The total GO predicted wave is given by:

$$\mathbf{E} = \mathbf{E}_0 A_0 e^{-jk_0 r_0} + \sum_{l=1}^{Nr} \mathbf{R}\mathbf{E}_l A_l e^{-jk_l r_l} + \sum_{m=1}^{Nt} \mathbf{T}\mathbf{E}_m A_m e^{-jk_m r_m} \quad (15)$$

where:

- $Nr$ and $Nt$ are the total number of reflected and transmitted rays traced from TX to RX;
- $r$ and $A$ stand for the distance and the spreading factor associated to a given ray, respectively;
- $\mathbf{E}$ is the em wave immeditely adjacent to the reflection/transmission point.

Note that the subscript 0 stands for the direct path (if any) between TX and RX.

# GO method



## Ray tracing

- It consists of invoking Snell's laws to identify all the possible ray paths between TX and RX.
- It is a simple but time consuming procedure; hence, tipically, only rays experiencing few interactions are actually traced.

# GO method

## Evaluation of Fresnel reflection/transmission coefficients

- The key assumption is that the em wave is considered locally plane at the points of interaction.
- This assumption is reasonable when the em wavelength is much smaller than:
  - the distance bewteen TX and the first interaction point for each ray;
  - the distance between interactions;
  - the size of involved surfaces.

GO is a high-frequency method

# Surface scattering



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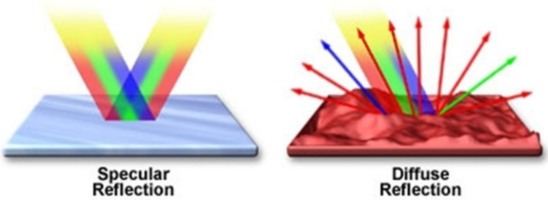
It applies when the interacting surface is no longer smooth.


The reflected wave is scattered by a large number of scattering points on the surface broadening the scattered energy.

# Surface scattering



## TWO KIND OF REFLECTIONS




The reflection of light can be roughly categorized into two types of reflection: **specular reflection** is defined as light reflected from a smooth surface at a definite angle, and **diffuse reflection**, which is produced by rough surfaces that tend to reflect light in all directions

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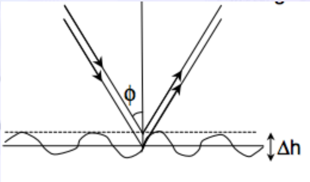
# Rayleigh criterion: Is the surface smooth ?

## Apparent roughness

The apparent roughness of the surface reduces:

- for incidence close to grazing angle ($\theta_i \approx \frac{\pi}{2}$);
- for longer em wavelength.




A surface that results in reflected waves whose phase shifts (with respect to each other):

$$\Delta\phi = \frac{4\pi \Delta h \cos\theta_i}{\lambda} \tag{16}$$

are very small can be considered smooth.

# Rayleigh criterion

- If the maximum admitted phase shift is $\Delta\phi = \frac{\pi}{8}$, one obtains that:

$$\sigma_s = \Delta h < \frac{\lambda}{32 \cos \theta_i} \tag{17}$$

## Rayleigh criterion

Rayleigh criterion is important since it shows that the apparent roughness depends on both em wavelength and incidence angle. However, it does not include any information on the correlation length of the surface.

$\sigma_s$ is also termed as Rayleigh parameter

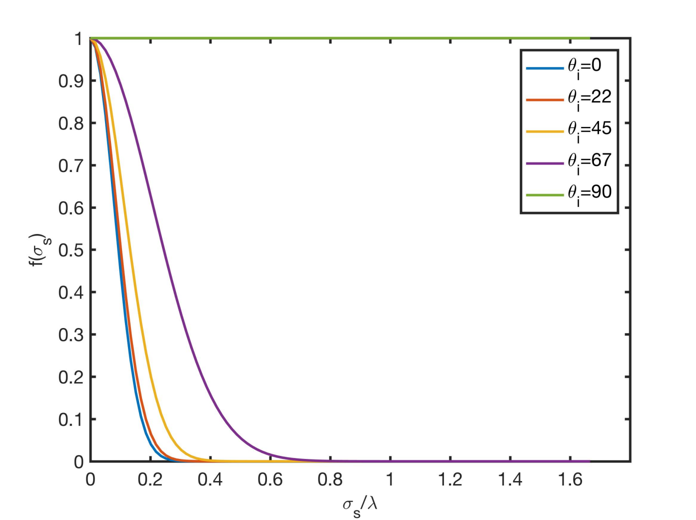
# Surface scattering

- When the surface is considered rough, the amplitude of the specular component is reduced.
- This reduction is modeled by a roughness factor:

$$f(\sigma_s) = exp\left[-\frac{1}{2}\left(\frac{4\pi\sigma_s\cos\theta_i}{\lambda}\right)^2\right] \quad (18)$$

- Hence, an effective reflection coefficient can be used to account for surface roughness: $R_{eff} = Rf(\sigma_s)$.

# Surface scattering




f=1GHz; $\sigma_S$=linspace(0,0.5,100)/lambda

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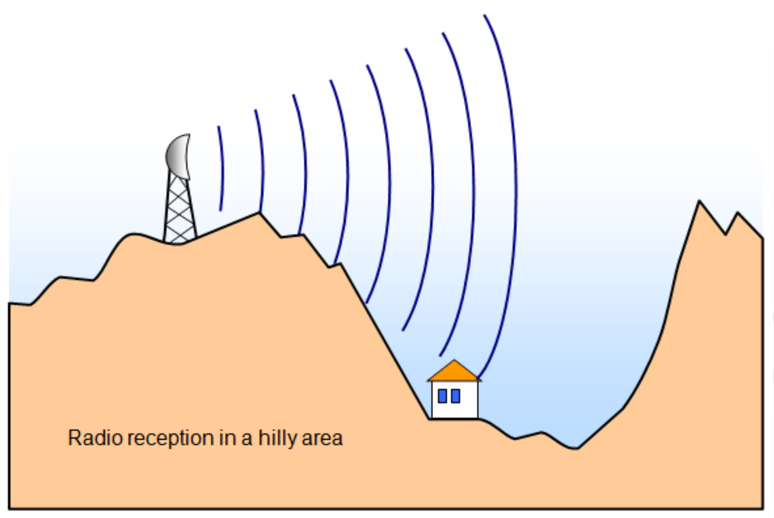
# Diffraction



# Huygens

## CHRISTIAAN HUYGENS

Huygens is a Dutch physicist, mathematician, and an astronomer. He is renowned for his arguments that light was in the form of waves.

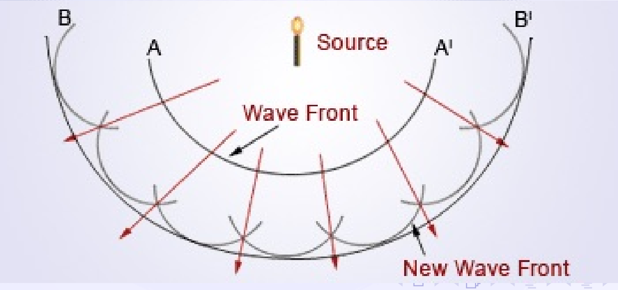
Huygens contributed in the field of astronomy by discovering Saturn's largest moon Titan in 1655. He also provided detailed studies about Saturn's rings and discovered that its rings are made up of rocks.

*Mons Huygens and the Huygens probe (part of the Cassini-Huygens Saturn satellite) were named after Christiaan Huygens.*

# Huygen's principle

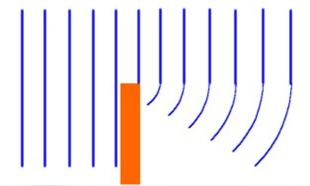
## Huygens' principle

Each element of a given wavefront can be considered as a source of a secondary disturbance that produces spherical wavelets. The envelope of all such wavelets gives rise to the next wavefront.



# Diffraction

Huygen's principle provides the physical framework to understand diffraction phenomena, i.e.; the behavior of em waves at the edge of absorbing materials.



Even if a region is shadowed by an obstruction, diffraction around the object's edges produces waves that propagate into the shadowed region.

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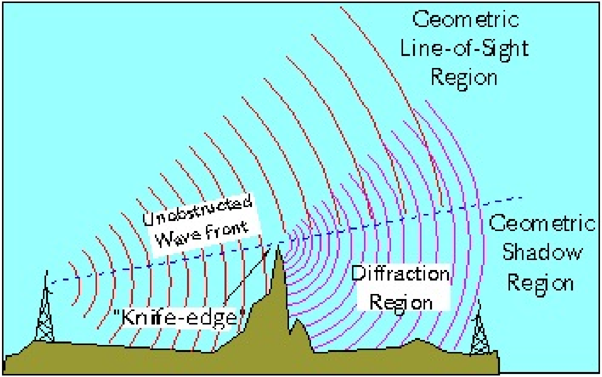
# Knife-edge



A simplified model is assumed, termed as knife-edge diffraction, which consists of approximating the obstruction as a knife edge. This model can be used to conservatively estimate more realistic diffraction effects.




knife-edge effect

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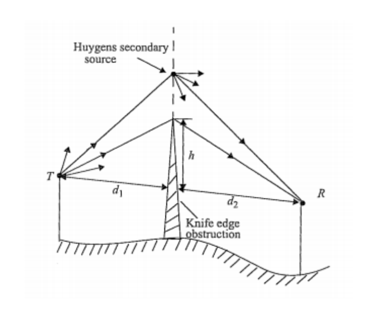
# Single knife-edge diffraction

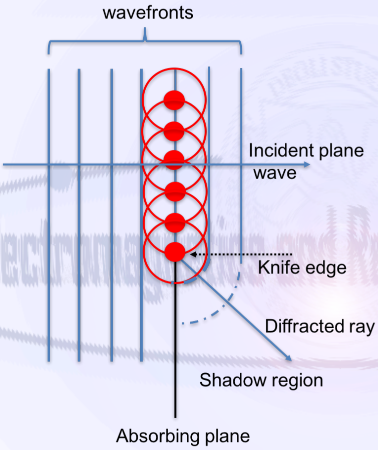
The single knife-edge diffraction model assumes that:




- A knife-like obstruction protrudes into the LOS path.
- The obstacle is assumed to have infinite extent.
- No signal can penetrate the obstruction, therefore, some of the rays emanating from the transmitter will not reach the receiver.

# Single knife-edge diffraction

According to Huygen's principle:




- In an imaginary plane located in line with the obstruction, points above the obstruction can be considered secondary sources of wavelets, which combine to form waves propagating toward the receiver to the right of the screen.

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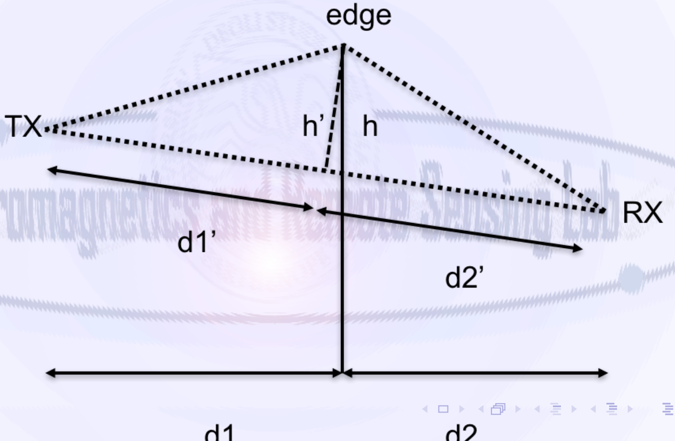
# Single knife-edge diffracted waves

To predict the diffracted waves, we start with the analysis of a single wave; then the superposition principle is invoked to deal with all the diffracted contributions.

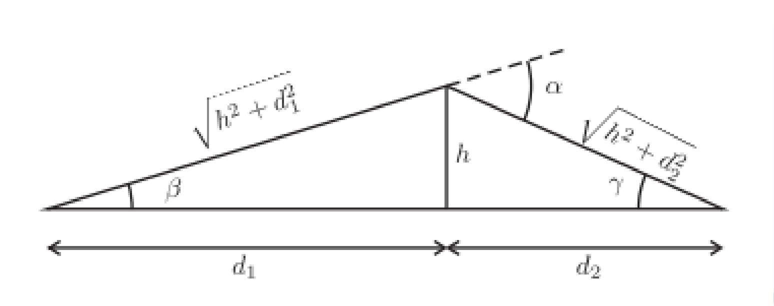


# Single knife-edge diffracted waves



- $h_{obs}$,$h_t$ and $h_r$ stand for the heights of the obstacle, TX and RX, respectively.
- The distance TX/obstacle ($d_1$) and RX/obstacle ($d_2$) are considered wrt the LOS path.
- The diffracted ray makes an angle $\beta$ and $\gamma$ with respect to LOS path on the transmitter and receiver sides, respectively.
- Although in the picture $h_t = h_r$, this is not a limiting assumption provided that the separation distance between TX and RX is large compared to their heights.

# Diffracted wave




## Diffracted wave

We are interested in finding the wave received from the diffracted path with respect to the LOS path.

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# Diffracted wave

- The path difference between the LOS and diffracted paths is given by:

$$
\begin{aligned}
\Delta &= \sqrt{d_1^2 + h^2} + \sqrt{d_2^2 + h^2} - (d_1 + d_2) \qquad (19)\\
&= d_1\sqrt{1 + \frac{h^2}{d_1^2}} + d_2\sqrt{1 + \frac{h^2}{d_2^2}} - d_1 - d_2\\
&\approx d_1\left(1 + \frac{h^2}{2d_1^2}\right) + d_2\left(1 + \frac{h^2}{2d_2^2}\right) - d_1 - d_2\\
&= \frac{h^2}{2}\left(\frac{1}{d_1} + \frac{1}{d_2}\right)\\
&= \frac{h^2}{2}\frac{d_1 + d_2}{d_1 d_2}
\end{aligned}
$$

the approximation holds since $(1 + x)^n \approx (1 + nx)$.

# Diffracted wave

- Since the distances $d_1, d_2$ are much larger than $h$:

$$\beta = \tan^{-1}\frac{h}{d_1} \approx \frac{h}{d_1} \tag{20}$$

$$\gamma = \tan^{-1}\frac{h}{d_2} \approx \frac{h}{d_2} \tag{21}$$

$$\alpha = \beta + \gamma \approx \frac{h(d_1+d_2)}{d_1 d_2} \tag{22}$$

- The electrical length of the path difference $\Delta$ is given by:

$$\phi = k\Delta = \frac{2\pi}{\lambda}\frac{h^2}{2}\frac{d_1+d_2}{d_1 d_2} = \frac{\pi}{2}\nu^2 \tag{23}$$

$$\nu = h\sqrt{\frac{2(d_1+d_2)}{\lambda d_1 d_2}} = \alpha\sqrt{\frac{2d_1 d_2}{\lambda(d_1+d_2)}} \tag{24}$$

- where $\nu$, which is termed as Fresnel-Kirchhoff parameter, is related to the height of the obstacle.

# Single knife-edge diffraction



- The diffracted wave that reaches RX, normalized wrt the LOS wave, is given by (assuming the same magnitude for both the waves):

$$\frac{E_d}{E_{LOS}} = e^{-j\beta\Delta} = e^{-j\frac{\pi}{2}\nu^2} \tag{25}$$

- This is the effect of a single diffracted wave.

## Fresnel integral

To include the effect of all the other rays produced by the Huygen's sources above the obstacle, we need to integrate from $\nu$ to $\infty$:

$$\frac{E_d}{E_{LOS}} = F(\nu) = \frac{1+j}{2} \int_{\nu}^{\infty} e^{-\frac{j\pi t^2}{2}} dt \tag{26}$$

$F(\nu)$ is termed as Fresnel integral

# Do it yourself - Fresnel Integral



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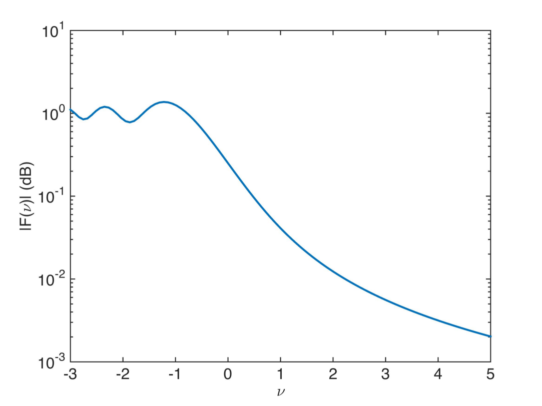


$$F(\nu) = \frac{1+j}{2}\left\{\left(\frac{1}{2} - C(\nu)\right) - j\left(\frac{1}{2} - S(\nu)\right)\right\} \qquad (27)$$

A step drop is observed starting from $\nu = -1$.

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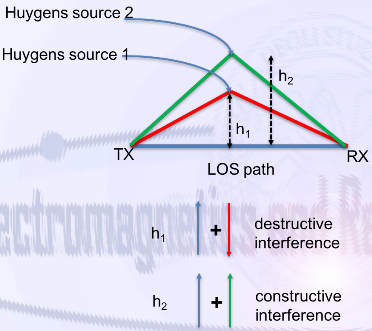
# Fresnel zones

Let $h$ be the height of the Huygen's source in the diffraction problem wrt the LOS path.




- If $h$ is such that $\Delta = \frac{\lambda}{2}$, the phase shift $\phi$ between LOS and diffracted wave is $\pi$. A destructive interference occurs (see $h_1$).
- If $h$ is such that $\Delta = \lambda$, $\phi$ is $2\pi$. A constructive interference occurs (see $h_2$).

This is true over a locus of points forming a ring in the plane of the screen that is termed as Fresnel zone.

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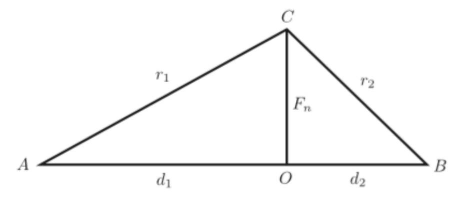
# Fresnel zones

- This process repeats when increasing $h$, i.e.; Fresnel zones that provide constructive and destructive interference to the total received signal alternate every $\frac{\lambda}{2}$ increase of $h$.

## *n*th Fresnel zone

The loci of points at which propagation produces an excess path length $\Delta$ equal to $n\frac{\lambda}{2}$ is termed as *n*th Fresnel zone.



# Radius of the Fresnel zones

- To evaluate the radius of the *n*th Fresnel zone we consider the triangle ABC; where AB stands for the LOS path and ACB stands for the diffracted path.
- The point C is in the *n*th Fresnel zone when the following equation is satisfied:

$$r_1 + r_2 = d_1 + d_2 + n\frac{\lambda}{2}. \qquad (28)$$

- This equation can be rewritten as:

$$\sqrt{d_1^2 + F_n^2} + \sqrt{d_2^2 + F_n^2} = d_1 + d_2 + n\frac{\lambda}{2}. \qquad (29)$$

- Since $F_n$ is much smaller than $d_1, d_2$, eq.(29) can be approximated as follows:

$$d_1 + \frac{F_n^2}{2d_1} + d_2 + \frac{F_n^2}{2d_2} = d_1 + d_2 + n\frac{\lambda}{2}. \qquad (30)$$

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# Radius of the Fresnel zones

- Hence, one obtains:

$$\frac{F_n^2}{2}\left(\frac{1}{d_1}+\frac{1}{d_2}\right)=n\frac{\lambda}{2} \tag{31}$$

## Radius of the $n$th Fresnel zone

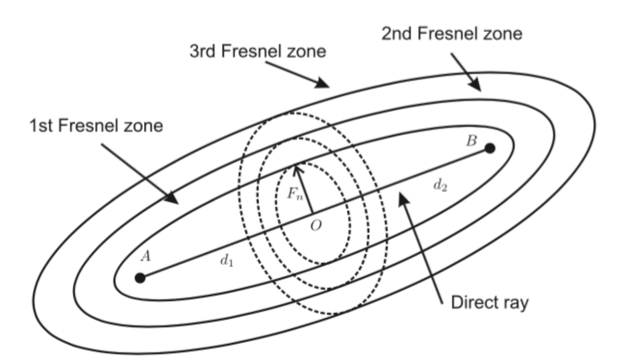
The radius $F_n$ is given by:

$$F_n=\sqrt{\frac{n\lambda d_1 d_2}{d_1+d_2}} \tag{32}$$

- Each circle of radius $F$ results in a $\Delta$ equal to $\lambda/2$, $\lambda$, $3\lambda/2$,etc.
- $F_n$ is maximum when $d_1 = d_2$.

# Fresnel zones

Fresnel zones are the geometric loci (ellipsoids) characterized by all the points resulting in $\Delta$ equal to an integer multiple of $\frac{\lambda}{2}$.



# Total phase shift

When a signal is reflected two things happen:

1. The phase of the signal reverses and the signal changes in phase by 180°.
2. Since the signal is being reflected and not going in a direct line, it travels slightly further to the refection point and then on to the receiver. Therefore, the signal is shifted further in phase, by the difference in path length $\phi = k\Delta$.
3. This implies that the received signal results from the coherent combination of the LOS signal and the reflected one that will exhibit a phase shift equal to $\pi + \phi$.

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# Fresnel zones

## 1st Fresnel zone

Most of the energy associated with the em wave lies in the 1st Fresnel zone.
In fact, the reflected signal is shifted by 180° of path distance plus $\phi = k\frac{\lambda}{2} = \pi$ from the actual reflection point totals 360° of phase shift. Hence, the LOS and reflected signals add togheter and they do not affect receiver performance.

- An absorbing obstacle that enters this zone will significantly affect the received power.

# Fresnel zones



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## 1st Fresnel zone

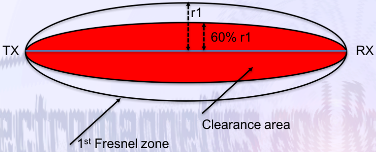
Most of the energy associated with the em wave lies in the 1st Fresnel zone. This is due to the fact that contributions within the first zone are all in phase.

- An absorbing obstacle that enters this zone will significantly affect the received power.
- The diffraction parameter can be expressed in terms of a Fresnel zone clearance:

$$\nu \approx \frac{h}{r_n}\sqrt{2n} \tag{33}$$

# Fresnel zones

- According to eq.(26), when $\nu = -0.8$, $L_{ke} = 0$dB.
- This $\nu$ value, according to eq.(33) , corresponds to an obstacle that enters into the 1st Fresnel zone.
- The 60% of the 1st Fresnel zone is still clear.




- This clearance (60% of the 1st Fresnel zone free of abstacles) is often assumed as a criterion to decide the importance of an obstacle.

When the red area is free of obstacles the obstruction loss is 0 dB. hence, the attenuation path is not increased by the obstacle.

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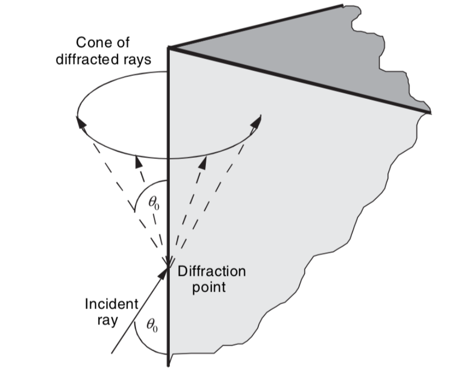
# Geometric theory of diffraction

It extends Fermat's principle to predict diffracted rays that can be treated in a fashion similar to GO.

- It allows analyzing situations where knife-edge approximation does not apply.



# Geometric theory of diffraction

- The wave diffracted at the diffraction point is given by:

$$\mathbf{E}_d = \mathbf{D}\mathbf{E}_i A_d \tag{34}$$

where the diffraction matrix:

$$\begin{pmatrix} D_{\parallel} & 0 \\ 0 & D_{\perp} \end{pmatrix} \tag{35}$$

consists of two polarization-dependent diffraction coefficients.

- $\mathbf{E}_i$ and $\mathbf{E}_d$ are the incident and diffracted fields whose parallel and perpendicular components are defined with respect to the plane containing the incidence direction and the diffraction point, the diffraction point and the diffraction direction, respectively.

# Geometric theory of diffraction

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- GTD diffraction coefficients are derived starting from canonical diffraction problems making asimptotic assumptions. Hence, even GTD is a high-frequency approximation method.
- GTD allows explaining fluctuations that appears at negavite $\nu$ values.
- They result from the coherent composition of the direct and diffracted rays.

It fails in predicting the field behavior close to the shadow boundary.

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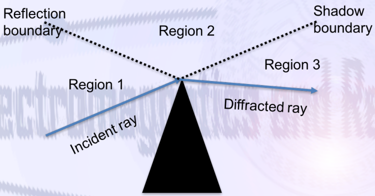
# Uniform theory of diffraction

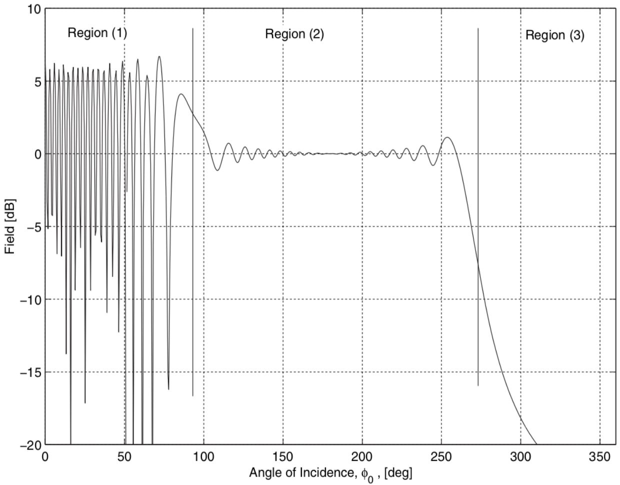
It allows prediction the total wave as the composition of the direct, reflected and refracted rays.




- Region 1 (visible region): the total wave consists of the direct, the reflected and the diffracted rays.
- Region 2: the total wave consists of the direct and the diffracted wave.
- Region 3 (shadow region): the only wave is the diffracted one.

# Uniform theory of diffraction





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# Uniform theory of diffraction

In the visible region, the field is the sum of the direct ray and the diffracted ray, plus a ray reflected from the surface. Since the wedge is perfectly conducting, the reflected wave has the same amplitude as the incident ray and complete cancellation of the two fields occurs at intervals, since the diffracted ray has negligibly small amplitude by comparison. In region 2, there is no reflection point on the wedge which can obey Snell's law, so no reflection exists, and the diffraction is still very small, so the field is nearly at its free space value. In region 3, the shadow region, only the diffracted ray is present, and it diminishes in amplitude in a similar way to the simple knife-edge approximation