11 Channel modelling and simulation

In this section, we try to simulate photon movement in underwater environment. Photon movement can be studied in both analytical method which consist of radiative transfer theory(RTE) or using numerical method. However we prefer to focus on numerical simulations based on monte carlo simulation. In Monte carlo simulation method, we simulate trajectory of photon in water environment from transmitter position to receiver position. During photon travel, it encounters two interaction - absorption and scattering. Absorption causes photon energy to reduce while scattering makes photon deflect from it's current path. Such large number of photons are generated at transmitter and their trajectories are recorded. Based on their trajectories and receiver characteristics, we check for successful reception of photon. Such large number of photons are simulated to average out the results. Hence this is statistical method. The accuracy depends on number of photon trajectories simulated. In our simulations we generate 10^6 photons.

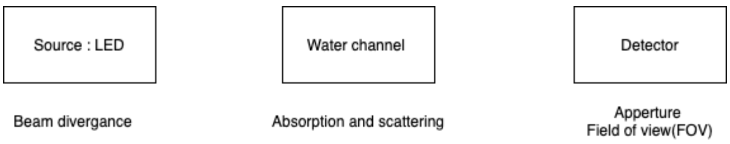

Fig. 11.1. Simulation setup

Fig 11.1 shows abstract setup of simulation and various system parameters.

- **Source divergence :** We consider LED as our light source(As used in experiments). Divergence is parameter we consider with LED. Photons are emitted from center of source having initial scattering angle related to divergence of source.

- **Channel absorption and scattering :** Water channel is characterised by absorption and scattering coefficient. Absorption coefficient (a(λ)) causes energy of photon to reduce while scattering coefficient(b(λ)) is associated with dispersive nature of channel. Channel extinction coefficient is calculated as sum of these two. $c(\lambda) = a(\lambda) + b(\lambda)$. These values are function of wavelength and are measured by Haltrin[15]. Based on these measurements we characterise water channel in four different categories- Pure sea, clear ocean, Costal water and Harbor water. Their channel coefficient are as given in table below(for $\lambda = 450nm$). These values are based on model given haltrin[15].

Water type	a(m^-1)	b(m^-1)	c(m^-1)
Pure sea	0.053	0.003	0.056
Clear ocean	0.069	0.08	0.15
Costal water	0.088	0.216	0.305
Harbor water	0.295	1.875	2.17

These channel parameters are wavelength dependent. Harltrin[15] modeled variation of these coefficients based on single parameter - chlorophyll concentration as given. Based on this model variation of absorption coefficient and scattering coefficient are shown in Fig 11.2, 11.3, 11.4 for various chlorophyll concentration.

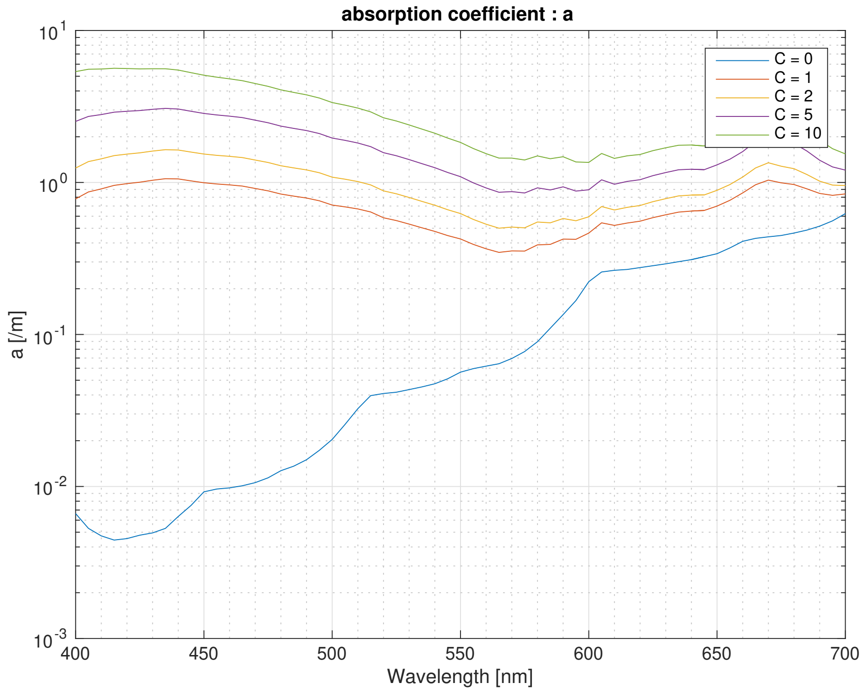

Fig. 11.2. Variation of absorption coefficient

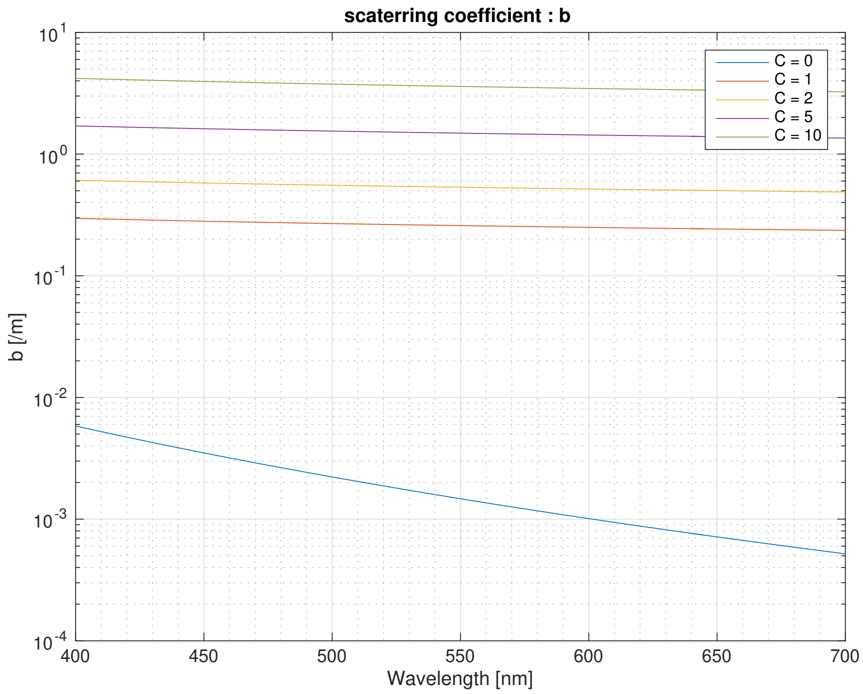

Fig. 11.3. Variation of scattering coefficient

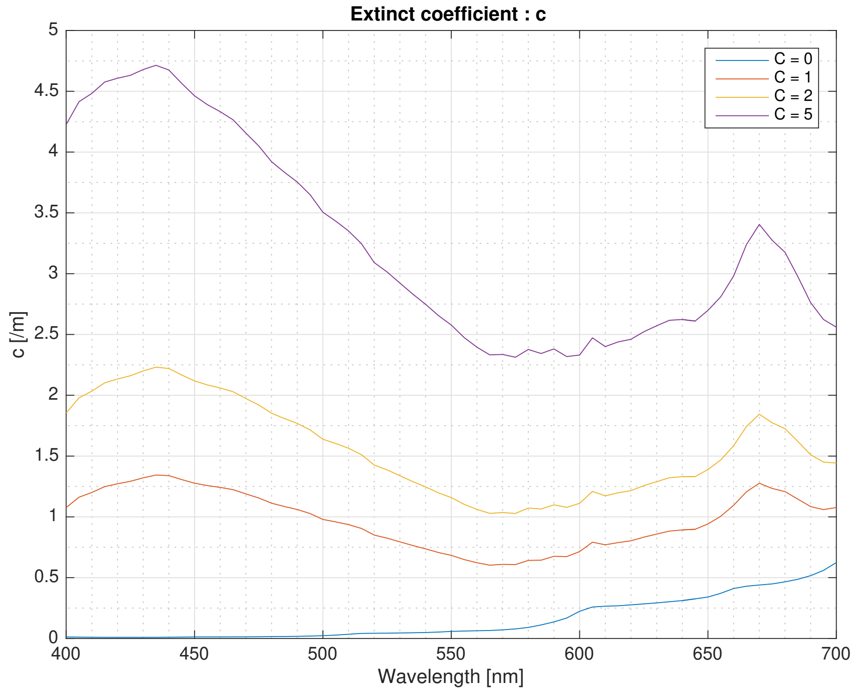

Fig. 11.4. Variation of extinction coefficient

- **Detector aperture and FOV :** These are receiver parameters we consider for simulation. Detector is Si PIN photodiode. Those photons are considered to be received which fall within receiver Field Of View(FOV) and are within receiver aperture diameter. Simulations were performed for different FOV and aperture values in order to understand the effect of them on channel performance.

11.1 Simulation method

Fig 11 shows the flow chart of simulation in MATLAB. This method is based on simulations performed by Cox[17]. We use cartesian coordinate system to simulate photon trajectories. Various steps in simulation are described as follows.

- **Initialization :**
Considering cartesian coordinate system, transmitter is placed at coordinates(0,0,0) pointing in positive z direction. Direction of propagation is along z direction. Receiver is placed at distance 'z' from transmitter on z axis perfectly in LOS configuration. Photon is given weight of 1 (unity), this is nothing but normalized power given to photon for simulation purpose. Photon is assigned with initial scattering angle and azimuth angle based on divergence of source. As we define scattering events based on scattering angle and azimuth angle, which are based on spherical coordinate system, and relative to current direction of propagation of photon, we have to convert this relative quantities into absolute or global cartesian coordinates. Hence we use direction cosines for this purpose. Initial values of direction cosines are taken as follows. Where μ_x, μ_y and μ_z are direction cosines along X, Y and Z

axis respectively.

$$\begin{aligned} \mu_x &= 0 \\ \mu_y &= 0 \\ \mu_z &= 1 \end{aligned} \tag{8}$$

Fig 11.5 shows the direction cosines. Vector AB is sample step size of photon.

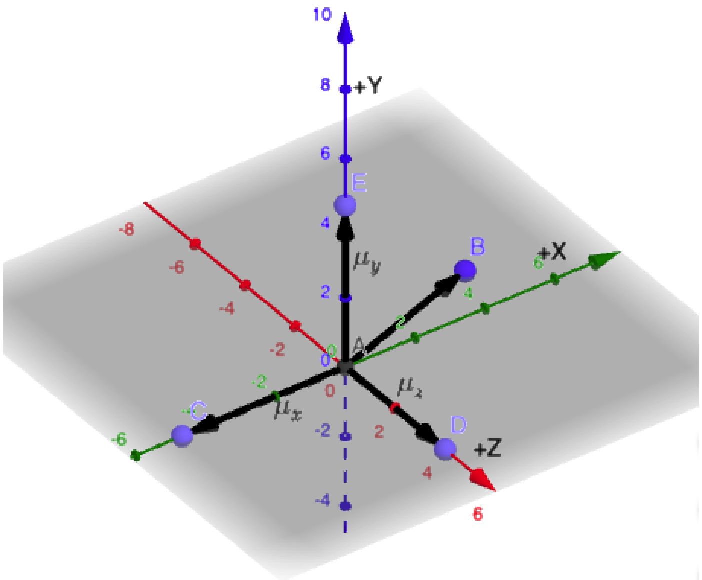

Fig. 11.5. Illustration of direction cosines[drawn using math10.com]

μ_x, μ_y and μ_z are it's projection on X,Y and Z axis respectively, represented by direction cosines. Direction of propagation of photon is along +Z axis as shown in Fig 11.5.

- **Step size generation:**
  Photon is moved by the random distance defined by step size(δ). Step size is generated as follows:

$$\begin{aligned} \delta &= \frac{-log(\chi_d)}{c} \\ \chi_d &\sim u[0, 1] \end{aligned} \tag{9}$$

  Where c is extinction coefficient and χ_d is uniform random variable in 0 to 1.

- **Scattering and azimuthal angle generation**
  Now, to model dispersive nature of water channel, we scatter photon based on scattering angle and azimuthal angle defined by following equations. These equations are based on scattering phase function defined as HG functions in [ref].

$$\begin{aligned} cos(\theta) &= \left(\frac{1}{2g}\right)\left[1 + g^2 - \left(\frac{1 - g^2}{1 - g + 2g\xi}\right)^2\right] \\ \xi &\sim uniform[0, 2\pi] \\ \phi &\sim uniform[0, 2\pi] \end{aligned} \tag{10}$$

  where θ is scattering angle and ϕ is azimuthal angle.

- **Move photon**
  Once we get scattering angle and azimuthal angle, we move photon in that perticular direction by distance of δ or step size. New cartesian coordinates of photons are calculated as follows:

$$\begin{aligned} x &= x + \mu_x\delta \\ y &= y + \mu_y\delta \\ z &= z + \mu_z\delta \end{aligned} \tag{11}$$

  where $\mu_x\mu_y$ and μ_z are direction cosines for current position along x, y and z direction respectively. Hence position of photon is updated as given in above equations. Once we update positions, we calculate direction cosines corresponding to new position of photon, which will be used to move photon next time. New direction cosines are calculated as follows:

$$\begin{aligned} \mu_x &= \frac{sin(\theta)(\mu_x\mu_z cos(\phi) - \mu_y sin(\phi))}{\sqrt{1-\mu^2}} + \mu_x cos(\theta) \\ \mu_y &= \frac{sin(\theta)(\mu_y\mu_z cos(\phi) + \mu_x sin(\phi))}{\sqrt{1-\mu^2}} + \mu_y cos(\theta) \\ \mu_z &= -\sqrt{1-\mu_z^2} sin(\theta)cos(\phi) + \mu_z cos(\theta) \end{aligned} \tag{12}$$

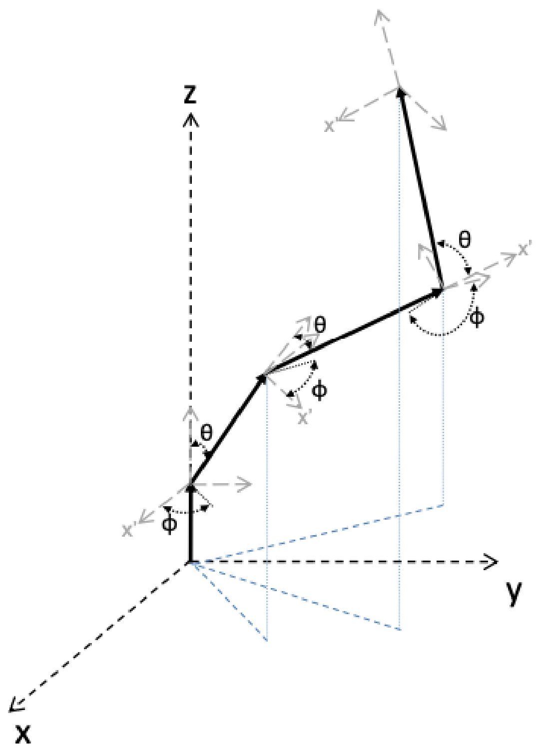

Fig. 11.6. Propagation of photon

Fig 11.6 shows sample photon propagation along Z direction. Note that scattering angle θ and azimuth angle ϕ are with respect to current direction of propagation of photon as shown in this figure.
When $\mu_z = 1$

$$\begin{aligned} \mu_x &= sin(\theta)cos(\phi) \\ \mu_y &= sin(\theta)sin(\phi) \\ \mu_z &= cos(\theta) \end{aligned} \tag{13}$$

when $\mu_z = -1$

$$\begin{aligned} \mu_x &= sin(\theta)cos(\phi) \\ \mu_y &= -sin(\theta)sin(\phi) \\ \mu_z &= -cos(\theta) \end{aligned} \tag{14}$$

- **Update weight of photon**
  Once photon is moved from one position to another. It's direction cosines are updates. Now due to it's interaction with water particles, some of it's fraction gets absorbed. This is modelled by reduction in weight of photon. Consider W_{pre} is previous weight of photon before interaction and W_{post} is weight of photon after absorption. Then these two are related as given in below equation.

$$W_{post} = W_{pre}(1 - \frac{a}{c}) \tag{15}$$

where, a is absoption coefficient and c is extinction coefficient. Fig 11.7 shows random trajectory of sample photon inside water channel. Where w_i is weight of i^{it} photon and δ_i is distance travelled by it before next interaction.

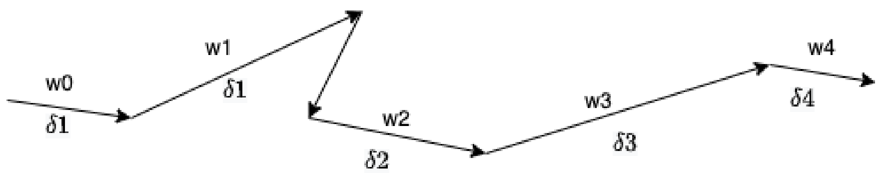

Fig. 11.7. Movement of photon in water

- **Photon termination**
  This process of generation of photon and moving in trajectory defined by above model continues till one of the following event occurs.
  - When photon weight is less than 10^{-4}, photon is no longer considered as contributing to power at receiver. Hence such photon is considered as a candidate for termination.
  - When photon reached receiver plane. At such position we consider photon has reached the receiver and consider for termination.

- **Photon collection**
  Once photon is considered for termination. We apply some checks on it. Here we consider receiver characteristics - FOV(Field of view) and aperture. Throughout the simulation we keep saving the cartesian coordinates and direction cosines of each photons. We use this information to check weather photon considered for termination is within the receiver FOV and aperture or not. If photon is within receiver FOV and aperture, we mark that particular photon as successfully received photon, else we simply terminate that photon and continue generating new photons. We assume aperture of receiver to be circular. So while checking for aperture we define equation of circle centered on z axis having diameter equivalent to aperture of receiver. Now we find point of intersection of photon trajectory with XY plane. If this point of intersection lies within this circle, aperture test is passed. While checking for FOV. We find angle of incidence of photon on receiver aperture. This angle of incidence is calculated as $acos(\mu_z)$. If this quantity is less than FOV/2 , then FOV test is passed. To mark photon as successfully received, we need to make sure both of these tests pass.

- **Routleting photon**
  In out simulation, at each scattering even, photon losses it's weight. When photon's weight is below some threshold(here 10^{-4}), we drop that photon. But simply dropping that low weight photon violets law of conservation of energy. Hence to satisfy this law, low weight photon should be given fair chance to survive. This is governed by the equation given below.

  $$w' = \begin{cases} 0 & if X > \frac{1}{\alpha} \\ \alpha w & if X < \frac{1}{\alpha} \end{cases}$$

  Once photon's weight falls below threshold. We generate uniform random number X between 0 to 1. Now we define routlet threshold α. If X is greater then inverse of α then photon is terminated, else photon's weight is multiplied by factor α and photon is given a chance to survive. w' is new weight of photon while w is weight of photon before routletting. α is taken as 10 in our simulation.

- **Flow chart and simulation summery**
  The flow chart summarised in Fig 11 summarises the simulation. We first initialize the photon at location (0,0,0) with unity weight(power) and initial scattering angle determined by divergence of source. Then random step size is generated followed by generation of scattering angle and azimuthal angle. Then photon is moved as per the governing equations discussed before by distance δ and it's weight is modified. Now we check for weight of photon. If is is less than 10^{-4}, then we go for routlet method, else we check if photon has reached receiver plane. If it has not reached receiver plane, we repeat the movement of photon again. Else if it has reached receiver plane, we check weather photon is within the receiver FOV and aperture. If it satisfies these checks then photon is marked as successfully collected. If either of these two tests fails, photon is marked as rejected. Trajectory and weight of each successfully received photon is saved for future use. Now we generate 10^6 number of photons, and apply same algorithm on them and save the data corresponding to each photon. Using this data we calculate total power received and impulse response of water channel.

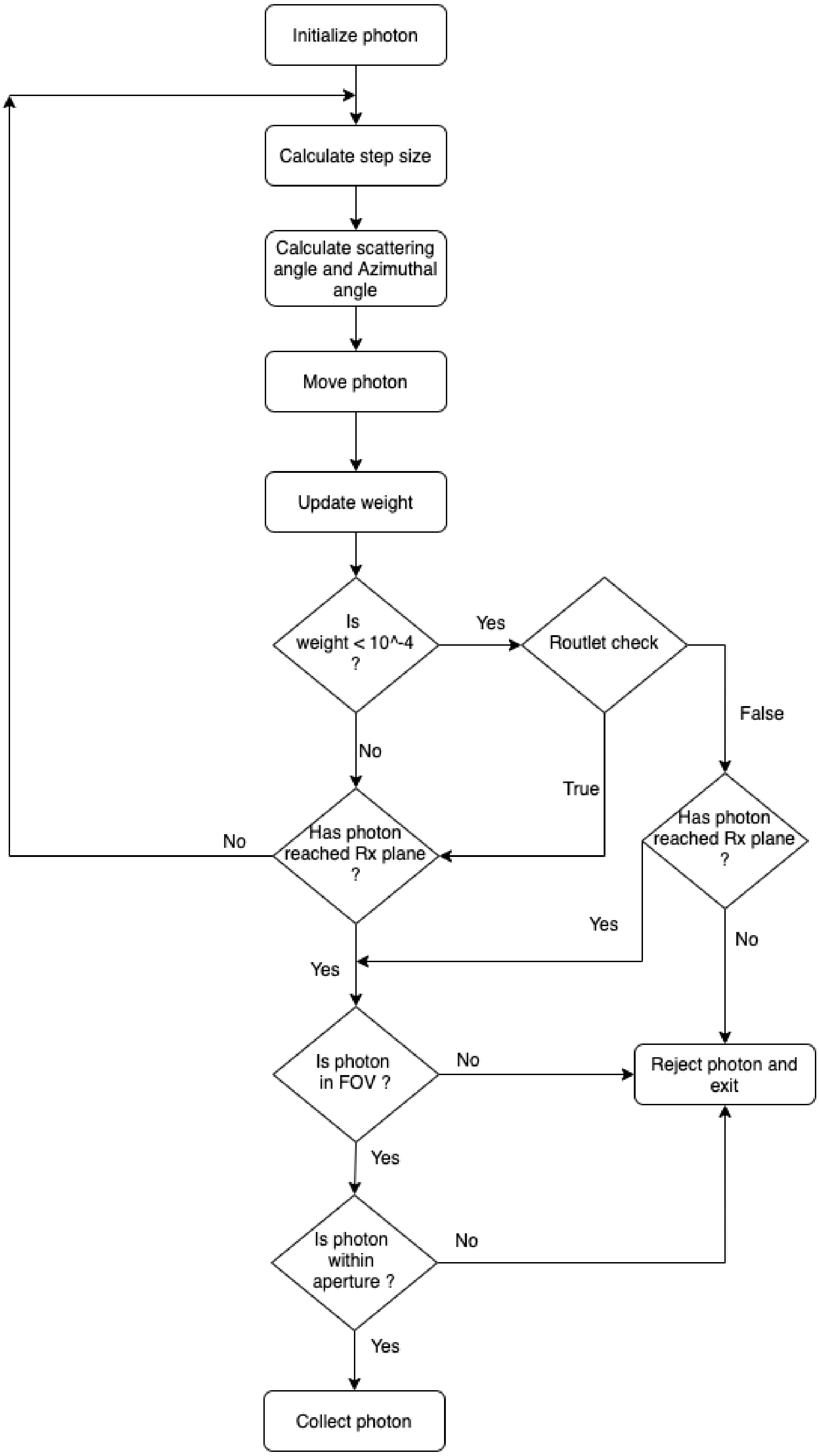

Fig. 11.8. Flow chart of simulation

11.2 Path loss/power attenuation results

Wavelength	450nm
Number of photons	10^6
aperture	20cm
FOV	150°
Number of positions	20

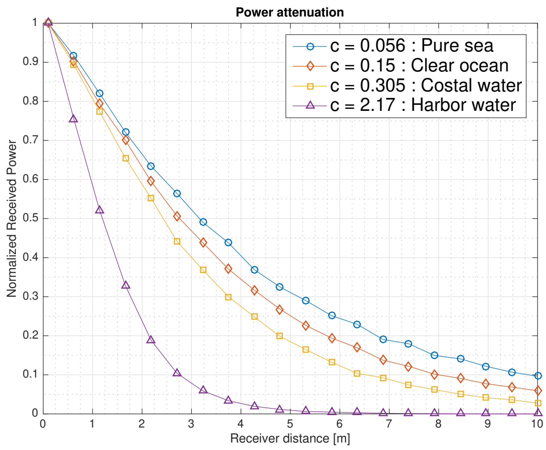

Fig. 11.9. Path loss/power attenuation

Wavelength	450nm
Number of photons	10^6
aperture	20cm
FOV	150°
Number of positions	20

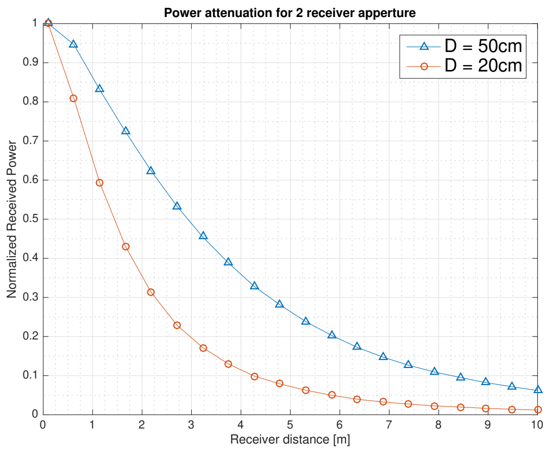

Fig. 11.10. Path loss/power attenuation for different aperture

Fig 11.9 shows the variation of normalized power over distance for different water types. It can be observed that power attenuation is more severe for turbid water type as compared to others, as it was expected.

To calculate power, we generate 10^6 number of photons and simulate their trajectories. Power received is sum of weight of all successfully received photons. Then we normalize this power with total transmitted photons. Results resembles trend of beer lambert's law which was simplest channel model we discussed before.

11.3 Impulse response

- **Impulse response at different distances**

Wavelength	450nm
Number of photons simulated	10^6
aperture	0.8cm
FOV	150°
Water type	Harbor($c = 2.17cm^{-1}$)

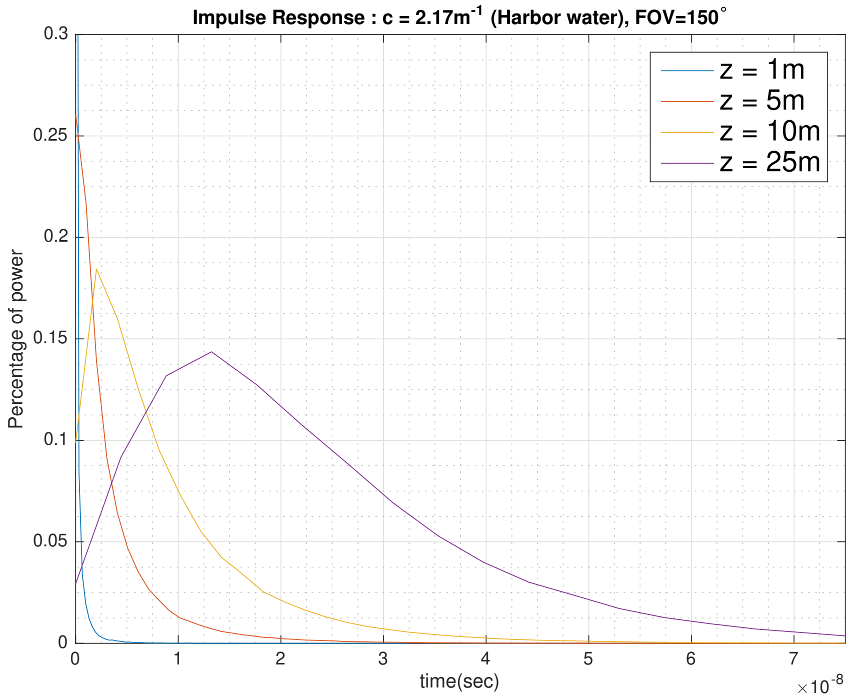

Fig. 11.11. Impulse response at different distances

- **Impulse response at different field of view(FOV)**

Wavelength	450nm
Number of photons simulated	10^6
aperture	0.8cm
Water type	Harbor(c = $2.17cm^{-1}$)
Receiver distance(z)	10m

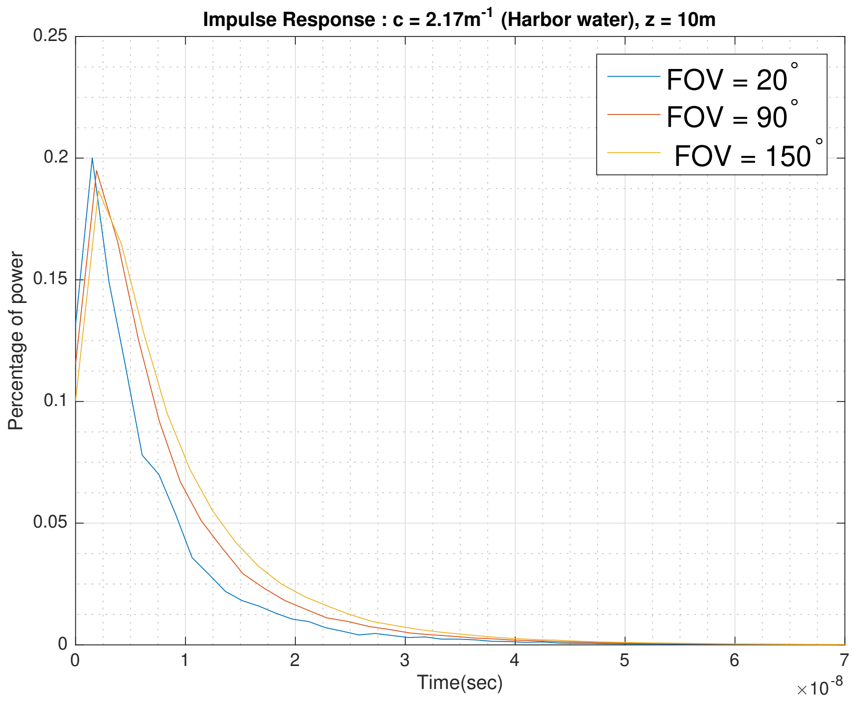

Fig. 11.12. Impulse response for different FOV

- **Impulse response in different water types**

Wavelength	450nm
Number of photons simulated	10^6
aperture	0.8cm
FOV	150°
Receiver distance(z)	10m

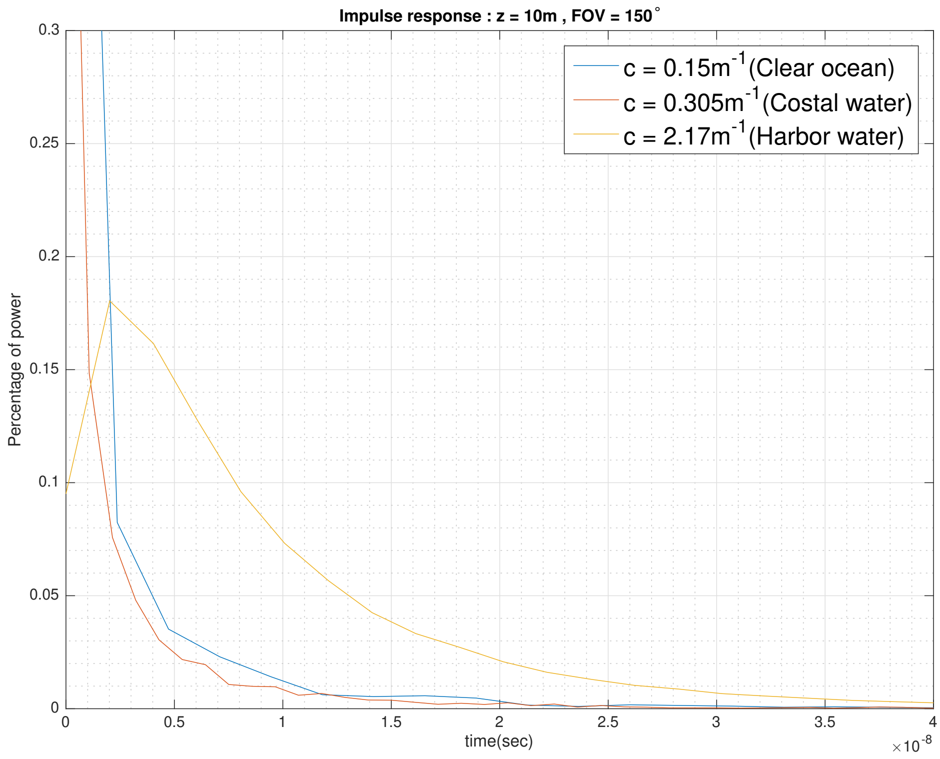

Fig. 11.13. Impulse response for different water types

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