

Investigation of intensity laser effects on environment

Abstract

In this paper different types of weather conditions which effect laser beam quality are being study. Atmospheric conditions such as rain, snow, fog and dust are discussed. Atmospheric turbulence effect on size and intensity of laser beam is described and background optical power relations and received power by receiver are presented. Ground target reflection coefficient and related charts are presented.

Keywords: laser, atmosphere, scattering, turbulence

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Introduction

In research, especially in the military field, extensive studies have been conducted on guided laser equipment. Use of laser-guided equipment began in America Air Force during the Vietnam War since the 1970s. The first advantage of this type of weapons was confirmed in this war proved in precision destroying targets with relatively small dimensions but with high importance. Today, laser weapons are used much wider for operations against enemy targets armor and protection. The biggest advantage of this type of weaponry is their high precision that can destroy the precise goals with the least amount of ammunition. Another advantage of using these weapons is the possibility of targeting a point precisely for consecutive times that is very efficient to eliminate armor targets. In recent years, military studies and the correct choice of materials for the manufacture of tracker systems pay special attention to laser detectors. Before transmitting a laser beam inside the environment, it is important to identify the effects of the environment on the beam. Molecules and particles such as dust, fog, smoke, steam, and aerosols, have significant effects on the dispersion, reflection and absorption of laser beams, which themselves contribute to the degradation, deviation, and reduction of laser beam coherence. In this paper, the effects of the environment on the laser beam and the ways to reduce these effects are examined.

Discussion

Atmospheric obscurants reduce the performance of sensors by reducing the signal radiation reaching the sensor because of reduced atmosphere transmittance in the sensor wave length response region, increasing noise at the sensor due to scattering of atmospherically radiation or system illuminator energy into the sensor and reducing the signal – to – noise ratio through turbulence induced wave – front degradation. The three curves indicate a tropical atmosphere with high water vapor content, a subarctic atmosphere, which has a low water vapor content, and a typical us or midlatitude atmosphere, which has a moderate content. These curves illustrate the effect of water vapor content on thermal transmittance. Extinction is defined as the reduction, or attenuation of radiation passing through atmosphere.

Extinction comprises two process: absorption of energy and scattering of energy. In absorption, a photon of radiation is absorbed by an atmosphere molecular or an aerosol particle. In scattering, the direction of the incident radiation is changed by collisions with atmospheric molecular or aerosol particle. Absorption usually dominates scattering at IR and mmw wave length. Scattering is the major factor in visible extinction but may also be important at IR wave length.

Scattering effectiveness is given by the scattering efficiency $Q(n, r)$ which is ratio of the effective scattering cross of a particle of radius r to its geometric cross section as:^{1,2}

$$Q(\lambda, r) = \frac{\delta_s}{\pi r^2} = \frac{2}{r^2} \int_0^{\delta} \sigma_s(\theta) \sin \theta d\theta \quad (1)$$

Where

r = particle radius, m

σ = angular scattering cross section, m/sr

θ = scattering angle, rad

If the particle size is much smaller than the radiation wave length, Rayleigh scattering results, and scattering efficiency simplifies to the expression:¹

$$Q(\lambda, r) = \frac{8}{3} (2\pi)^4 \frac{r^4 \left[n(\lambda)^2 - 1 \right]^2}{\lambda^4 \left[n(\lambda)^2 + 2 \right]^2} \quad (2)$$

Where

$n(\lambda)$ = real part of index of refraction, r = particle radius, m.

Particle size for several common obscurants are given in tables 1 and 2. If the particle size is much larger than the radiation wave length, scattering efficiency calculated by geometrical scattering. According to the table 2, types of atmospheric particles (steam, aerosols, rain, snow, ...) have different scattering relations.

Steam

The following equation shows the atmosphere transmittance coefficient for steam and molecular particles.¹

$$T_m(\bar{e}) = e^{-\tilde{O}_m(\bar{e})R} \quad (3)$$

Where

T_m =atmosphere transmittance coefficient for steam and molecular
 \tilde{O}_m =steam and molecular attenuation coefficient.

R =Path length

The average value of \bar{e} for low humidity (lower water vapor than 3.5 g /m³) in visible spectrum is between 0.4 and 0.7 and for high humidity (water vapor more than 14 g /m³) is about 0.02. In the near – infrared range (between 0.7 and 1.1) for low humidity the average value of \bar{e} is about 0.02 and for high humidity is about 0.03. The water vapor atmosphere transmittance coefficient within 3 to 5 μm is specified in table 3 and within 8 to 12 μm in Table 4. Also according to Table 5, the attenuation coefficient for 10.591 wave length and mmw in different humidities

Aerosol (fog, cloud, dust)

The equation below shows the atmosphere transmittance coefficient for aerosols:¹

$$T_a(\bar{e}) = e^{-\tilde{O}_a(\bar{e})R}$$

where T_a atmosphere transmittance coefficient

\tilde{O}_a reduce coefficient of aerosols and R= path length. The average of \bar{Y}_a in visible spectrum (between 0.4 to 0.7) is:

$$\tilde{O}_a(0.4 - 0.7 \text{ m}) = 3.912/V \quad (5)$$

Where V is visible distance in km

Visible distance is defined as the distance which you can diagnose an object properly by the contrast of 1 against background by the contrast of 0.02.¹ In Table 6 visibility is provided for different regions. In IR area for the yag laser: two values will be obtained for aerosols attenuation coefficient one for visible distance more than 0.6 km which is equal to:¹

$$\tilde{O}_{al}(1.06i \text{ m}) = 10^{-0.136 + 1.16 \log(3.912/V)} \quad (6)$$

And for a visible distance less than 0.6 km and equal to 0.6 km:¹

$$\tilde{O}_{a2}(1.06i \text{ m}) = 3.912/V \quad (7)$$

In near-IR range (between 0.7 to 1.1) the average value of \bar{Y}_a is equal to:¹

$$\tilde{O}_a(0.7 - 1.1 \text{ m}) = 0.6(3.912/V) \quad (8)$$

Table7 shows the attenuation coefficient for other wavelength (Table 7).

Radiation fog forms when the weather cools down until the dew point and advection fog forms when vertical air mixture with different temperatures manufactures until the dew point. In these two types the size of fog particle are different.

Rain:

The following equation defines the atmosphere transmittance coefficient for the precipitation in the air.¹

$$T_p(\bar{e}) = e^{-\tilde{O}_p(\bar{e})R} \quad (9)$$

Where

. T_p = the atmosphere transmittance coefficient for the precipitation in the air

. \tilde{O}_p = the precipitation attenuation coefficient

R=path length

The average value of \tilde{O}_p (in visible spectrum range to thermal wavelength) determines based on the amount of rainfall for three different types of rainfall.

For the drizzle we have:¹

$$\tilde{O}_{prd}(\text{Visible} - \text{Thermal}) = 0.51r^{0.63} \quad (10)$$

For the widespread we have:

$$\tilde{O}_{prw}(\text{Visible} - \text{Thermal}) = 0.36r^{0.63} \quad (11)$$

And for the thunderstorm we have:

$$\tilde{O}_{prt}(\text{Visible} - \text{Thermal}) = 0.16r^{0.63} \quad (12)$$

Where r=amount of rainfall (mm per hour (mmph))

Snowfall:

The atmosphere transmittance coefficient equation for both rainfall and snowfall are the same. The only difference is the attenuation coefficient. The snowfall attenuation coefficient depends on visible distance and equals to:¹

$$\tilde{O}_{ps}(\text{Visible} - \text{Thermal}) = 3.912/V \quad (13)$$

Dust:

The following equation defines the atmosphere transmittance coefficient for dust in the air.¹

$$T_d(\bar{e}) = e^{-\tilde{a}_d(\bar{e})Cl} \quad (14)$$

Where

. T_d =Atmosphere transmittance coefficient for dust in the air

. \tilde{a}_d =Attenuation coefficient of dust in the air

And cl=Path length density by g/m²

Cl achieves from multiplication of upload mass by path length R generally for the a we could write.¹

$$\tilde{a}_d(\bar{e}) = \ll \frac{Q\sigma}{M} \gg \quad (15)$$

Where:

σ =Cross-sectional area of particle

Q=The dispersion coefficient

M=Mass of the particle

The internal bracket is identifier of solid angle average and the external bracket is the identifier of mass distribution average of the particle. For the cl we have:

$$Cl = \int_{r_1}^{r_2} C(r) dl \quad (16)$$

Where

$C(r)$ = density at r

dl = longitudinal element of the doped area

$r_2 - r_1$ = length of the doped area

The Table 9 shows the dust attenuation coefficient for different wavelength

Smoke:

The following equation defines the atmosphere transmittance coefficient for smoke in the air:¹

$$T_s(\bar{e}) = e^{-\alpha_s(\bar{e}) Cl} \quad (16)$$

Where

T_s = atmosphere transmittance coefficient for smoke in the air

α_s = attenuation coefficient of smoke in the air, g/m²

And cl = path length of density, g/m²

Cl also defines according to the equation (17)

According to the equation 17 we could calculate the amount of cl so that 1 is the length of infected area .then due to the equation 16 we could calculate the atmosphere transmittance coefficient for smoke for the all of atmosphere transmittance coefficient in the absence of precipitation we have:

$$T(\bar{e}) = T_m(\bar{e}) T_a(\bar{e}) T_s(\bar{e}) T_d(\bar{e}) \quad (17)$$

And in presence of snowfall or rainfall we have:

$$T(\bar{e}) = T_m(\bar{e}) T_p(\bar{e}) T_s(\bar{e}) T_d(\bar{e}) \quad (18)$$

Light turbulence

The atmospheric turbulence reduces by wavelength enhancement. Atmospheric turbulence causes beam extension beam divagation flashing and fluctuation in the brightness of the beam.⁴ These effect will be describe by radius of beam displacement of the center of beam compatibility or confliction of radiation of the beam. The scintillation effect causes the reduction of pendulous power average at the receiver aperture. Movement of picture or the blur of the caused turbulence describe by optic function (coherence length) and also wave front tilt. The atmospheric turbulence could be considered as a compound of cell with different size and refractive index. These cells move within the beam and cause the effect which is explained at the above. Assuming still and freezed atmosphere the speed and direction of this uniform movement determines by the wind average speed. Based on the size of dominant cell and beam diameter the turbulence cells cause the beam scattering in different direction. When size of the cell is smaller than the beam diameter refraction and diffraction happens. The beam radiation figure turns into a small ray and the dark area results of

interference of wave front refraction and diffraction (flicker). Based on the turbulence power ratio each one of the two cases of the above may be observed singly or together. Strehl is the ratio of the average of radiation on the axis with turbulence to the average of radiation on the axis without turbulence .so that the ratio of the beam diameter with turbulence to the beam without turbulence is equal to:

For the long term turbulence cases we have:¹

$$S_l = \left[1 + \left(\frac{D}{r_0} \right)^2 \right]^{-1} \quad (19)$$

And for the short term turbulence if $\left(\frac{D}{r_0} \right) \leq 3$:

$$S_{s1} = \left[1 + 0.182 \left(\frac{D}{r_0} \right)^2 \right]^{-1} \quad (20)$$

And if $\left(\frac{D}{r_0} \right) > 3$:

$$S_{s2} = \left[1 + \left(\frac{D}{r_0} \right)^2 - 1.18 \left(\frac{D}{r_0} \right)^{5/3} \right]^{-1} \quad (21)$$

Where

D= effective diameter of the laser aperture

S_l = ratio of the long term strehl

S_s = ratio of the short term strehl

And r_0 = coherence length

If the turbulence is uniform we have:

$$r_0 = 0.3325 \left(10^{-6} \lambda \right)^{5/6} \left(10^3 C_n^2 R \right)^{-3/5} \quad (22)$$

Where C_n^2 = constant of the refraction index by $m^{-2/3}$

The amount of C_n^2 changes between 10^{-14} for the weak turbulence $6*10^{-14}$ for the medium turbulence and $6*10^{-13}$ for hard turbulence

For the non-uniform turbulence this effect is strong the flicker effect due to atmosphere is estimated by the following equation

$$\delta_I^2 = 1.24 C_n^2 \left(2\pi/\lambda \right)^{5/6} \left(10^3 R \right)^{11/6} \quad (23)$$

In the spread range or hard turbulence the amount of δ_I^2 wont be more than 0.5 sigma is by w for the consubstantial turbulence the amount of δ_x^2 variance of the movement of the center of the picture is equal to:

$$\delta_x^2 = 1.093 C_n^2 F^2 D^{-1/3} 10^3 R \quad (24)$$

Where f= focal length of the receiver

The reflection coefficient of ground targets

At first reflection coefficient is reviewed for very important ground targets. Generally natural targets are divided to 5 total categories which three categories of water cloud and snow due to close nature are mentioned in one.^{5,6}

- i. Agricultural land trees bushes and meadows
- ii. Ground
- iii. Rocks
- iv. Water cloud and snow

v. Metals

Received power

To determination of the most range of object location and tracing the lightened object by the laser pulse first of all it's necessary to find the light level in optical receiver sensitive position. It's specified as well that the angle measurement error is highly dependent to noise signal ratio in output receiver ring. In more analysis according to Table (1-7) geometric characteristic of the laser, the lightened object and the optical receiver are in use to specify the optical power level at the optical receiver input (Table 1).⁷

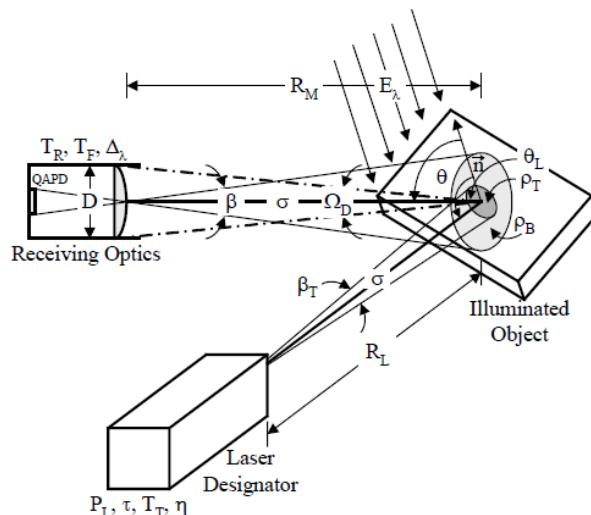


Table 1 The effect of the particles on the order dispersion wave length¹

Effect	Distribution type	Radius of particle
Symmetric distribution	Rayleigh scattering	less than $\lambda/10$
Most distribution	Mie scattering	more than $\lambda/10$
Most scattering forward	Mie scattering	about $\lambda/4$
All scattering forward	Mie scattering	more than λ
Refraction , reflection , diffraction	Light scattering geometry	more than 10λ

Table 2 Particle size distribution and the effect of atmospheric turbulence¹

mm waves	Ir waves	vision waves	Diameter of particle (μm)	Particle size
Rayleigh scattering	Rayleigh scattering	Rayleigh scattering	10^{-4}	Atmosphere Molecule
Rayleigh scattering	Rayleigh scattering	Rayleigh and Mie scattering	10^{-2} to 10^{-1}	Haze
Rayleigh scattering	Mie scattering	Mie and geometric scattering	0.5 to 100	Fog
Rayleigh scattering	Mie scattering	Mie and geometric scattering	2 to 200	Cloud
Mie scattering	Geometric scattering	Geometric scattering	10^2 to 10^4	Rain
Mie and geometric scattering	Geometric scattering	Geometric scattering	5×10^3 to 5×10^5	Show
Rayleigh scattering	Mie scattering	Mie and geometric scattering	1	Smoke
Rayleigh scattering	Mie scattering	Mie and geometric scattering	1 to 100	Dust

Table 3 Transmission coefficient for water vapor in the atmosphere of moisture and different distances ranging from 3-5 μm^{-1}

Transmission coefficient for water vapor in the atmosphere of moisture $T_m(\lambda)$							
Along the way in terms km						Temperature	The moisture content
15	10	7	5	3	1	($^{\circ}\text{C}$)	
0.47	0.53	0.58	0.62	0.68	0.77	0	
0.42	0.48	0.53	0.58	0.61	0.74	10	10
0.38	0.44	0.49	0.53	0.6	0.71	20	
0.33	0.39	0.44	0.48	0.55	0.67	30	
0.35	0.41	0.47	0.51	0.58	0.7	0	
0.3	0.36	0.41	0.46	0.53	0.66	10	40
0.24	0.3	0.35	0.4	0.47	0.61	20	
0.19	0.25	0.3	0.35	0.42	0.56	30	
0.3	0.36	0.41	0.46	0.53	0.66	0	
0.24	0.3	0.35	0.4	0.47	0.61	10	70
0.18	0.24	0.29	0.34	0.41	0.56	20	
0.13	0.18	0.23	0.28	0.36	0.5	30	
0.27	0.33	0.39	0.44	0.51	0.64	0	
0.21	0.27	0.33	0.37	0.45	0.59	10	
0.15	0.21	0.26	0.31	0.39	0.53	20	90
0.1	0.15	0.2	0.25	0.33	0.48	30	

Table 4 Transmission coefficient for water vapor in the atmosphere of moisture and different distances ranging from 8-12 μm^{-1}

Transmission coefficient for water vapor in the atmosphere of moisture $T_m(\lambda)$							
Along the way in terms km						Temperature	The moisture content
15	10	7	5	3	1	($^{\circ}\text{C}$)	
0.86	0.89	0.91	0.93	0.95	0.97	0	
0.82	0.86	0.89	0.91	0.93	0.97	10	10
0.76	0.81	0.85	0.87	0.91	0.95	20	
0.65	0.72	0.78	0.82	0.87	0.94	30	
0.72	0.78	0.82	0.86	0.89	0.95	0	
0.55	0.65	0.72	0.77	0.84	0.92	10	40
0.31	0.43	0.54	0.62	0.73	0.87	20	
0.09	0.18	0.28	0.39	0.54	0.78	30	
0.56	0.66	0.73	0.78	0.84	0.93	0	
0.3	0.42	0.53	0.62	0.73	0.87	10	70
0.07	0.15	0.26	0.36	0.52	0.77	20	
0	0.02	0.05	0.11	0.25	0.59	30	
0.46	0.57	0.66	0.72	0.8	0.91	0	
0.18	0.3	0.41	0.51	0.64	0.83	10	
0.02	0.06	0.13	0.023	0.39	0.69	20	90
0	0	0.01	0.04	0.12	0.46	30	

Table 5 Molecules attenuation coefficient for wavelength $10.591 \mu\text{m}$ and millimeter waves at different Humidities¹

	Absolute humidity in terms of g/m^3	Attenuation coefficient Υ_m In terms of $K_m -'$		
		$10.591 \mu\text{m}$	35 GHz	94 GHz
1		0.083	0.018	0.025
3		0.091	0.021	0.043
5		0.109	0.024	0.067
10		0.185	0.032	0.108
15		0.311	0.041	0.154
20		0.383	0.049	0.201

Aerosol (fog, cloud, dust)

Table 6 Visible distances for different regions³

0 to 50 meter	Dense dust
50 to 200 meter	Thick dust
200 to 500 meter	The average dust
500 to 1000 meter	Dust weak
1000 to 2000 meter	Low dust
2000 to 4000 meter	Fog
4000 to 10000 meter	May the poor
10000 to 20000 meter	clean Air
20000 to 50000 meter	Very clean air
more than 50000 meter	Ultra-clean air

Table 7 Attenuation coefficient of suspended particles in the air for wavelength $10.591 \mu\text{m}$, $8-12 \mu\text{m}$, $3-5 \mu\text{m}$ ¹

Particle size	Attenuation coefficient Υ_a in terms of $K_m -'$		
	$10.591 \mu\text{m}$	$8-12 \mu\text{m}$	$3-5 \mu\text{m}$
May city			
Visibility to 2 km	0.16	0.18	0.29
Visibility to 5 km	0.06	0.07	0.11
Visibility to 10 km	0.03	0.04	0.6
Visibility to 15 km	0.02	0.02	0.04
May incident			
Visibility to 0.5 km	1.7	2.4	10.1
Visibility to 1 km	0.9	1.2	5.1
May rose			
Visibility to 0.5 km	8.9	9	8.4
Visibility to 1 km	4.5	4.5	4.2

Table 8 Precipitation

Rainfall intensity	Annual rate
Heavy	More than 7.7 mm/h
Average	2.5 to 7.7 mm/h
Light	Less than 2.5 mm/h

Table 9 Dust in the air attenuation coefficient for different wavelengths¹

Rainfall intensity	Annual rate
Heavy	More than 7.7 mm/h
Average	2.5 to 7.7 mm/h
Light	Less than 2.5 mm/h

Table 11 Smoke attenuation coefficient obtained from a variety of sources, to different wavelengths¹¹

Smoke sources	Attenuation coefficient smoke						
	wavelength in terms of micrometer						
	0.4 – 0.7	0.7 – 1.2	1.06	3-5	8-12	10.6	35.94 GHz
Fuel evaporates into mechanical							
	6.58	4.59	3.48	0.25	0.02	0.02	0.001
Spray fuel into diesel engines	5.65	4.08	3.25	0.25	0.03	0.03	0.001
Burning phosphorus							
	4.05	1.77	1.37	0.29	0.83	0.38	0.001
Burning zinc compounds							
	3.66	2.67	2.28	0.19	0.04	0.03	0.001
Coal	6	3.5	2	0.23	0.05	0.06	0.001

In analysis, in order to generalize, it's assumed that laser and optical receiver are placed in different places.

Analysis of the power level of the background and reflected optical signal of laser behaves according to the main known equation which is radioscopy. For the background and object it's assumed that scattered reflections are reflected of the Lamberty surfaces. Also it's assumed that all of the laser beam is on the object which is lightened by laser.

Background power

Background optical power which receives from a optical receiver sensitive to location at entrance is equal to:⁷

$$P_B = L_\lambda G T_R T_F T_{at} \quad (25)$$

Where

. L_λ =son radiance spectrum

G= geometric factor

. T_R =transference coefficient of optical receiver

. T_F =transference coefficient of optical filter

Table 10 Mass loading of dust visible for different distances¹

Visible distance, Km	Mass loading, g/m ³
0.2	1.1×10^{-1}
0.47	6.9×10^{-2}
1	2.1×10^{-2}
3.2	5.2×10^{-3}
8	2×10^{-3}

And T_{at} =atmosphere transference coefficient

G the geometric factor is obtained from two small area radiative exchange factor and equals to:

$$A_D \text{COS}\theta \cdot A_R \text{COS}\theta_{po} \quad (26)$$

Where

. A_D = Quad detector footprint area in background

. $A_R \text{COS}\theta_{po}$ = The effective area of the photoreceptor

. θ = The angle between the vector perpendicular to the surface of the object and filed lines between the object and the receiver

. θ_{po} = The angle between the vector perpendicular to the surface receptor filed with the line between the object and the receiver

. R_M = The distance between the object and the photoreceptor

In cases where tracking and positioning is good, The photoreceptor is always face to the object so $\theta_{po} = 0$

For the whole radiance of the sun L_λ which caused by a diffuse reflector we have:

$$T_{at} = e^{-YR_M} \quad (27)$$

Where

E_λ = the whole of the sun .

And. ρ_B = background reflect

The amount of E_λ per wavelength can be obtained from standard charts

T_{at} atmospheric transfer coefficient is obtained from the following relationship comes to

$$T_{at} = e^{-YR_M} \quad (28)$$

Where

. Y =Atmospheric extinction coefficient.

The back ground power that obtained from equation(25),when combined with equations (26) and (27) has to be obtained as follows.

Where

Δ_λ = The whole bandwidth Optical Filter

. β = photoreceptor visibility range

D_{po} = Diameter optical receiver

Signal power

P_S the optical signal received by the laser radiation reflected from the object is lightened with a laser when the laser beam cross-sectional area of the object is smaller than, equals to:

$$P_S = L_T A_T \Omega_D T_R T_F e^{-YR_M} \cos\theta \quad (29)$$

Where

. L_T =Spectrum reflected from the object

. A_T =The area of the laser spot on the object

And Ω_D in accordance with Figure 3-7 angle created by the opening of an optical receiver

. L_T spectrum is⁷⁻⁹

$$L_T = \frac{4P_L T_T \eta \rho_T e^{-YR_L} \cos\theta_L}{\pi^2 \beta_T^2 R_L^2} \quad (30)$$

Where

. P_L = peak power laser

. T_T =transmission coefficient of light

η =efficiency of collection optical transmission

. ρ_T =target reflection coefficient

. θ_T =angle between the vector perpendicular to the surface with a laser beam

. β_T =divergence angle of the laser beam

and R_L =distance between the laser and the object

. A_T area of the laser spot on the object of value follow below

$$A_T = \frac{\pi R_L^2 \beta_T^2}{4 \cos\theta_L} \quad (31)$$

And for Ω_D angle we have:

$$\Omega_D \approx \frac{\pi D_{po}^2}{4 R_M^2} \quad (32)$$

By combining equations (31) to (33) with equation (30), we finally have for the P_S

$$P_S = \frac{D_{po}^2}{4 R_M^2} P_L \rho_T T_T \eta T_R T_F e^{-Y(R_L + R_M)} \cos\theta \quad (33)$$

Conclusion

According to the formula of laser attenuation by atmospheric conditions such as temperature, humidity, dust, rain, snow polished and smoke and ... which are dependent to the laser wavelength and the distance and the light intensity in order to minimize the laser must:

1. Reduse the target distance
2. Increase the incident laser beam intensity
3. Increase the Selective laser wavelength because the more higher frequency, the more attenuation efficiency and Conversely is the same situation
4. The purpose of reflecting surface so that the reflection coefficient is higher, For example, hitting a building is better that the laser to hit on smooth surfaces such as metallic windows.

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Conflicts of interest

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