Remote Sensing for Nd:YAG Laser Harmonics Propagation in Polluted Atmosphere

Senior Researcher Dr. Husham Abdul Malek[1], Dr. Talib Zeedan Taban[2]
[1] *Nuclear Researches & Application Directorate,*
hishamabid62@gmail.com
[2] *Collegeof Science,University of Al-Mustansiriya*
talibmosowi@ymail.com

Abstract

The study is done by applying a mathematical model for laser propagation through atmosphere. The study shows how much the laser light is affected by released gaseous pollutants from industrial plants to the atmosphere. Laser scattering and absorption coefficients for released gases give indication of detecting and determining concentration of atmospheric pollutants for certain height in atmosphere.

Nd:YAG laser and its harmonics are applied for analyzing nature of ingredients of atmosphere. The mathematical model is tested for adding 10% Nitrogen dioxide gas to the standard atmospheric ingredients for 500 m height. A database is set for standard atmospheric ingredients and also for probable pollutants according to particles size, dust, and aerosols which its radiI range (1 – 10 µm). Beside the effect of applied laser wavelength in determining optical elements specification for receiving unit for remote sensing technique, detecting values of extinction coefficient for different gases give a measure of how much the atmospheric transmittance is affected , hence intensity of received laser which determines the geometrical specifications of receiving unit.

التحسس النائي لانتشار توافقيات ليزر النميديوم ياك خلال الجوالملوث

الباحث العلمي الاقدم د . هشام عبد الملك[1] و د . طالب زيدان تعبان[2]
مديرية البحوث و التطبيقات النووية / وزارة العلوم والتكنولوجيا [1]، كلية العلوم / الجامعة المستنصرية / وزارة
التعليم العالي والبحث العلمي [2]

الخلاصة

اجريت الدراسة على عمل نموذج رياضي لسلوك شعاع الليزر خلال انتشاره في الجو.بينت الدراسة مدى تأثر شعاع الليزر بالملوثات الغازية المطلقة الى الجو من المنشأت الصناعية و التي تشمل الاكاسيد النتروجينية و الكبريتة و الكاربونية علاوة على بعض الغازات الخاملة و العضوية التي لايمكن السيطرة عليها اثناء طرحها الى الجو.على ضوء تفاعل شعاع الليزر مع الملوثات الجوية تم كشف و قياس تراكيز هذه الملوثات الغازية على ارتفاعات معينة من الغلاف الجوي , حيث تم حساب معاملي الاستطارة و الامتصاص لشعاع الليزر خلال انتشاره في الجو. تم اعتماد ظروف الجو القياسي من تغير في درجة الحرارة و الضغط و الكثافة

مع الارتفاع كأساس لمقارنة معامل التوهين الجوي لشعاع الليزر قبل و بعد انبعاث الملوثات الغازية الى الجو. ان معرفة قيم معامل التوهين امكن من حساب معامل الانكسار الجوي تم استخدام ليزر النميديوم ياك و توافقياته الاخرى في تحليل طبيعة مكونات الغلاف الجوي, حيث تم اختيار النموذج الرياضي بأضافة غاز ثاني اوكسيد النتروجين بنسبة 10 % الى مكونات الجو القياسية و على ارتفاع 500 متر. تم اعداد قاعدة بيانات لمكونات الغلاف الجوي القياسي و كذلك الملوثات المحتملة من حيث حجم الدقائق و نوعيتها و طرق تفاعلها كبخار الماء و الغبار و الايروزولات التي تتراوح انصاف اقطارها (1 – 10) مايكرون. علاوة على ان الاطوال الموجية لليزر المستخدم تحدد المواصفات البصرية لوحدة الاستلام الليزرية المتعلقة بتقنية التحسس النائي فأن تحديد معاملات التوهين للغازات الجوية المختلفة تعطي مؤشرا على نفاذية الجو و بالتالي مدى تأثر شدة شعاع الليزرالمستلم الذي بدوره يحدد المواصفات الهندسية لوحدة الاستلام الليزرية.

1- INTRODUCTION

One of major problems associated with measurement of optical radiation at long-range distances is the attenuation of light by the atmosphere. An inherent uncertainty is created when atmospheric attenuation is ignored. This problem is typically found in lidar applications for remote sensing. Propagation of electromagnetic radiation at ultraviolet, optical and infrared frequencies through the atmosphere is affected by absorption and scattering by air molecules and by particulate matter (haze. dust, fog, and cloud droplets) suspended in the air. Scattering and absorption by haze particles or aerosols becomes the dominant factor in the boundary layer near the earth's surface, especially under low visibility conditions. Atmospheric aerosol particles in the atmosphere vary greatly in their concentration, size, and composition, and consequently in their effects on optical and IR radiation. There are many scientific and technical reasons why it is necessary to develop models for atmospheric aerosols. They are needed to make estimates of the transmittance, of light scattering distribution, or other atmospheric optical properties or effects. Atmospheric aerosol particles in the atmosphere vary greatly in their concentration, size, and composition, and consequently in their effects on optical and IR radiation [1].

2- ATMOSPHERIC ATTEUNTION OF LASER POWER

The attenuation of laser power through the atmosphere is described by the exponential Beers-Lambert Law [2]:

$$\tau(R) = \text{Power}(Z) / \text{Power}(0) = \text{EXP}(-\alpha_g Z) \ldots\ldots\ldots\ldots\ldots\ldots\ldots.. (1)$$

Where $\tau(R)$ = transmittance at range Z,

Power (Z) = laser power at Z,

Power (0) = laser power at the source, and

α_g = attenuation or total extinction coefficient (per unit length),

Z = atmospheric range.

The attenuation coefficient has contributions from the absorption and scattering of laser photons by different aerosols and gaseous molecule in the atmosphere. Since laser wavelengths of Nd:YAG harmonics are chosen to fall inside transmission windows within the atmospheric absorption spectra, the contributions of absorption to the total attenuation coefficient are vary among these wavelengths [3]. The effects of scattering, therefore, dominate the total attenuation coefficient. The type of scattering is determined by the size of the particular atmospheric particle with respect to the transmission laser wavelength. This is described by a dimensionless number called the size parameter α.

$$\alpha = 2\,\pi\, r / \lambda \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ (2)$$

Where r = radius of the scattering particle, and
λ = laser wavelength.

Rayleigh scattering occurs when the atmospheric particles are much smaller than the wavelength. For the laser wavelengths of interest, Nd:YAG and its harmonics, Rayleigh scattering occurs primarily off of the gaseous molecules in the atmosphere [4]. The radiation from Rayleigh scattering is equally divided between forward and back scattering. The attenuation coefficient varies as λ^{-4}. Since blue light is scattering much more than red light, Rayleigh scattering is responsible for the blueness of the sky[5]. Another consequence of Rayleigh scattering varying as λ^{-4} is that for the laser wavelengths of interest, the effect of Rayleigh scattering on the total attenuation coefficient is very small. As the particle size approaches the laser wavelength, the scattering of radiation off the larger particles becomes more dominant in the forward direction as opposed to the backward direction. This type of scattering, where the size parameter varies between 0.1 and 50, is called Mie scattering. The laser wavelengths are Mie scattered by haze and smaller fog particles. For Mie scattering, the exponent in the power law dependence on wavelength for the attenuation coefficient varies from 1.6 to 0.17. The third generalized scattering regime occurs when the atmospheric particles are much larger than the laser wavelength. For size parameters greater than 50, the scattering is called geometric or non-selective scattering. The scattering particles are large enough that the angular distribution of scattered radiation can be described by geometric optics. Rain drops, snow, hail, cloud droplets, and heavy fogs will geometrically scatter laser light. The scattering is called non-selective because there is no dependence of the attenuation coefficient on laser wavelength, i.e. the power law wavelength exponent is zero [6]. The question of this paper addresses whether the amount of atmospheric scattering critical for telecom-type short laser links is wavelength dependent (Mie scattering), or wavelength independent (geometrical or non-selective scattering). This is an important factor when it comes to the wavelength selection for free-space laser systems.

3- MODELING OF ATMOSPHERIC CONSTETITEUNTS EFFECT ON Nd:YAG LASER HARMONICS

Atmospheric constituents play a very important role in the Earth’s climate system [7] and its study must be approached from different points of view. Atmospheric constituents have appreciable influence on Earth’s radiation budget, air quality, visibility, human health, clouds, precipitation and chemical processes in the troposphere and stratosphere [8]. Therefore, investigation on the atmospheric particles is needed.

The atmosphere is formed by gases and particles in suspension. Two basic types of gases can be distinguished depending on whether their concentration is permanent or variable. Permanent gases includes Nitrogen (N_2), Oxygen (O_2), Argon (Ar) and the like, see table (1). They represent the 99.03 % of total volume and have constant volumetric proportions even though air density dwindles with height. The variable gases , which basically encompass Ozone (O_3) , Water vapor (H_2O), Carbon dioxide (CO_2), Carbon monoxide (CO), Nitric acid, (HNO_3), Ammonium (NH_3), Hydrogen sulphide (H_2S), Sulphid dioxide (SO_2), Nitrogen dioxide (NO_2) and Nitrogen oxide (NO). Atmospheric dimensions and concentrations are given in table (2) [9].

Table (1) shows permanent concentration gases.

Gas	Symbol	Volume %	ppm
Nitrogen	N_2	78.084	780840
Oxygen	O_2	20.946	30946
Argon	Ar	0.934	9340
Neon	Ne	18.18 E-04	18.18
Helium	He	5.24 E-04	5.24
Methane	CH_4	1.6 E-04	1.6
Krypton	Kr	1.14 E-04	1.14
Hydrogen	H_2	0.5 E-4	0.5
Nitrogen oxide	N_2O	0.5 E-04	0.5
Xenon	Xe	0.087 E-04	0.087

Table (2) shows radii and concentrations for some atmospheric particles.

Particle Type	Radius (µm)	Concentration (Cm^{-3})
Air molecules	10^{-4}	10^{19}
Aerosols	10^{-2} - 1	10 - 10^{3}
Clouds	1 - 10	300
Fog droplet	1 - 20	100
Water droplet	10^{2} - 10^{4}	10^{-2}

In ***standard atmospheric model*** [10] up to 100 Km, where most important atmospheric parameters are taken into account for only permanent concentration gases.

Within the troposphere, the following approximation is assumed for the ***temperature*** under stable conditions:

$$T(Z) = T_o + a Z \qquad \ldots\ldots (3)$$

Where a = temperature gradient (- 6.5 Kelvin / Km).
T_o = initial temperature.

Approximation model for ***Pressure*** is given as:

$$P(Z) = P_o [T(Z) / T_o]^{5.256} = P_o [1 - 6.5 Z / T_o]^{5.256} \qquad \ldots\ldots (4)$$

The following expression is for ***atmospheric refractive index***, n:

$$n = 1 + [237.2 + (526\, \nu_1^2 / (\nu_1^2 - \nu^2) + (11.69\, \nu_2^2 / (\nu_2^2 - \nu^2)] (P / T)\, 10^{-6} \;\ldots.\; (5)$$

where: ν = wavenumber (Cm^{-1}) , which is given as $2\pi / \lambda$
$\nu1 = 114.000\ Cm^{-1}$
$\nu2 = 63.\ 400\ Cm^{-1}$
P = atmospheric pressure [KPa] (1 atm = 1.013 E+5 Pa; 1 mb = 100 Pa)
T = temperature (K)

This useful relation merges temperature and pressure effects into a single expression. If Eq. (3) and (4) are substituted into Eq. (5) it yields:

$$n = 1 + [237.2 + (526\, \nu_1^2 / (\nu_1^2 - \nu^2) + (11.69\, \nu_2^2 / (\nu_2^2 - \nu^2)] (P_o / T_o^{5.256}) (T_o - 6.5\, Z)^{4.256}\, 10^{-6} \;\ldots\ldots\; (6)$$

Rayleigh scattering takes place whenever the particle radius is much lower than the wavelength, otherwise Mie's scattering must be considered.

Rayleigh total absorption cross section **σ_R (λ)** over $\Omega = 4\pi$ is given as:

$$\sigma_R (\lambda) = (8\pi / 3) [\pi^2 (n^2 - 1)^2 / (N^2 \lambda^4)] [(6 + 3 P_n) / (6 - 7 P_n)] \;\ldots\ldots(7)$$

where N is number density of the scatterers, number of moles, which is given as:

$$N = n_{gas} N_{av} \;\ldots\ldots\; (8)$$

Where n_{gas} is molar concentration of specific gas per cubic meter, and given as:

$$n_{gas} = \text{Gas percentage} \,.\, P / R.\, T \;\ldots\ldots\; (9)$$

Where R is molar constant (0.0825 atm.l / mol.K = 8.314 J/ mol.K)
N_{av} is Avogadros constant (6.023 E+23 molecule / mol)

The ***backscatter coefficient*****, β_g,** represents the scattering cross section per unit volume and solid angle unit at the observation angle $\theta = \pi$, can be expressed mathematically as:

$$\beta_g = N\, \sigma (\lambda, \theta = \pi) \approx [\pi^2 (n^2 - 1)^2 / (N^2 \lambda^4)] [(6 + 3 P_n) / (6 - 7 P_n)] \;..\; (10)$$

Blending of both **absorption & scattering** effects yields the **extinction coefficient**, **α_g.**

$$\alpha_g = N\, \sigma (\lambda) = \sigma_R (\lambda) + \beta_g (\lambda, \theta = \pi) \;\ldots\ldots(11)$$

There, an empirical relation was derived that again took into account wavelength, pressure and temperature variables.

$\alpha_g = 2.9154\ 10^{-4}\ (1 + 6.6\ 10\text{-}3\ \lambda^2\ )^2\ \lambda^4\ P\ /\ T$ …………………..………(12)

4- METHODOLOGY

This work is based on a multi-wavelength lidar operated. This paper is based on a Nd:YAG laser that emits simultaneously at 1064, 532 , 355 and 266 nm. The radiation is transmitted into the atmosphere and, after interactions with the atmospheric components (molecules and aerosols); the backscattered radiation data are collected and analyzed to infer atmospheric properties. Choosing the appropriate laser wavelength which be used in lidar with lest attenuation is the goal of paper.

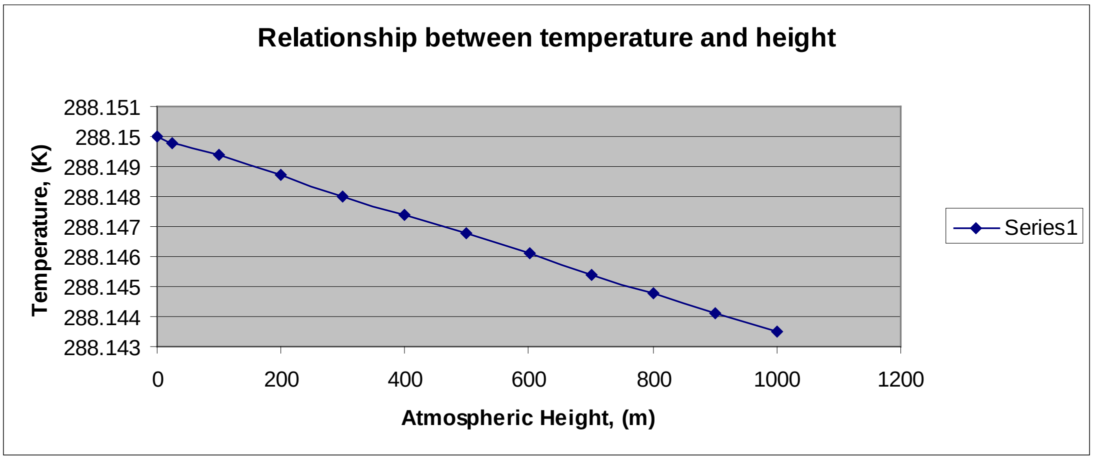
5- RESULTS

First, let us calculate the temperature decrease as a function increasing height, see table (1).

Table (1) shows temperature decrease with increasing height.

Height, (m)	**Temperature, (Kelvin)**
1	288.15
1000	288.1435

Table (1) is plotted as graph (1).



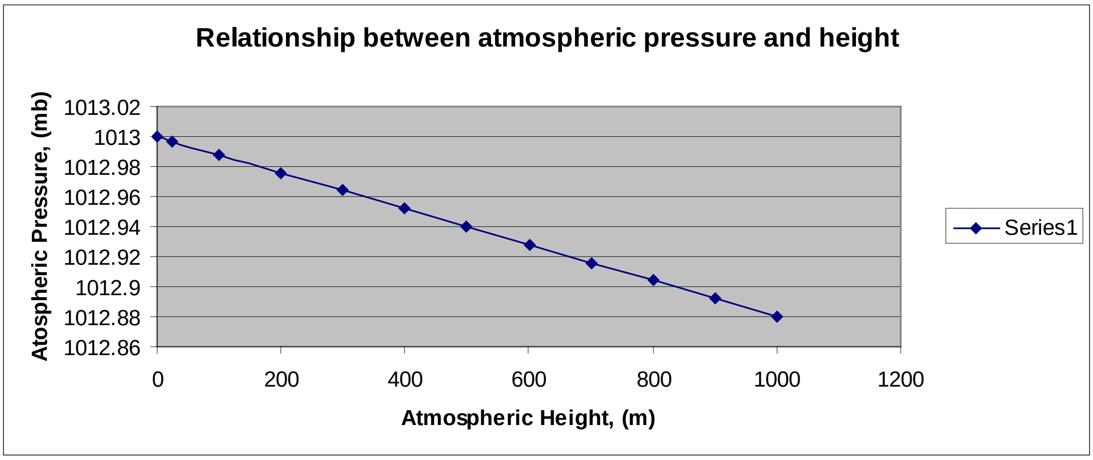
Graph (1) shows temperature versus height.

Second, let us calculate atmospheric pressure decrease as a function of increasing height, see table (2).

Table (2) shows pressure decrease with increasing height.

Height, (m)	**Pressure, (mb)**
1	1013
1000	1012.188

Table (2) is plotted as graph (2).



Graph (2) shows pressure versus height.

Third, let us calculate size parameter of the following atmospheric constituents for wavelengths of Nd:YAG harmonics in table (3).

Table (3) shows size parameter of some atmospheric constituents for laser wavelengths of Nd:YAG and its harmonics.

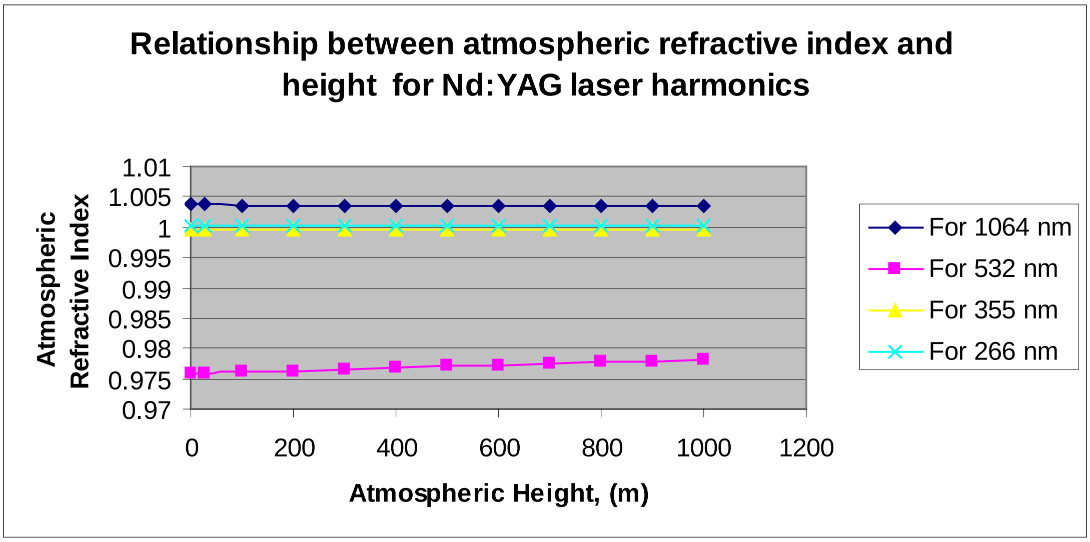
Type	**Radius (µm)**	**Size Parameter, α**			
		1064 nm	**532 nm**	**355 nm**	**266 nm**
Air Molecules	10^{-4}	5.907 E-4	1.181 E-3	1.770 E-3	2.363 E-3
Aerosols	10^{-2} - 1	5.9 E-2 5.9	0.118 11.81	0.177 – 17.7	0.236 23.63
Clouds	1 - 10	5.9 59.07	11.81 118.15	17.7 177.06	23.63 236.3
Fog droplet	1 - 20	5.9 118.15	11.81 236.3	17.177 354	23.63 472.6
Water droplet	10^{2} - 10^{4}	1181 59076	2363 118152	3541 177062	4726 236305

Fourth, let us calculate atmospheric refractive index for atmospheric height ranges (1 - 1000) meter in table (4).

Table (4) shows atmospheric refractive index at ground and 1 Km height for laser wavelengths of Nd:YAG harmonics.

Wavelength, (nm)	**Atmospheric Refractive Index, n**	
	n @ 1 m height	**n @ 1000 m height**
1064	1.003675	1.003335
532	0.9758766	0.9781069
355	0.9995179	0.9995624
266	1.000269	1.000244

Table (4) is plotted as graph (3).



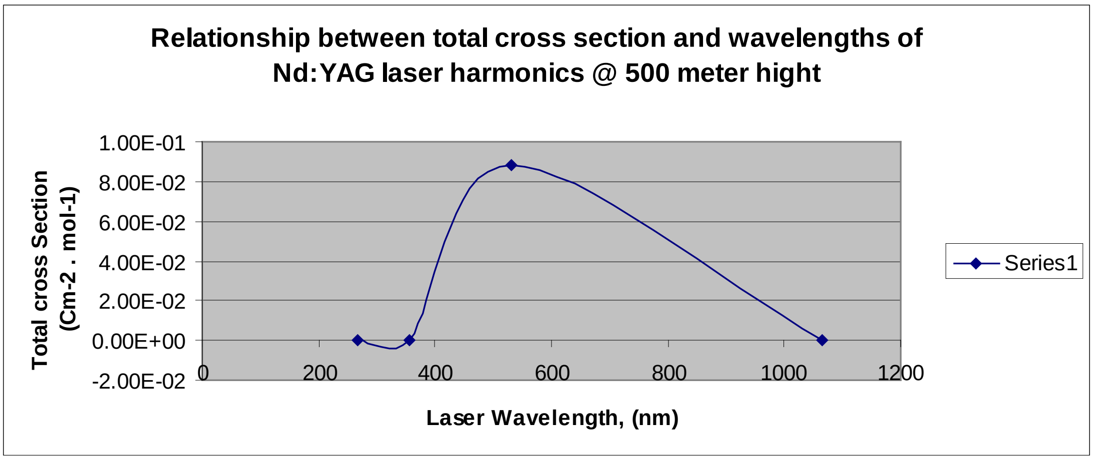
Graph (3) shows atmospheric refractive index versus height for laser wavelengths of Nd:YAG harmonics.

Fifth, let us calculate atmospheric total cross section coefficient for height ranges (1 - 1000) meter and for laser wavelengths of Nd:YAG harmonics for standard atmosphere in table (5).

Table (5) shows atmospheric total cross section at ground and 1 Km height for laser wavelengths of Nd:YAG harmonics for standard atmosphere.

Wavelength, (nm)	**Atmospheric Total Cross Section, (Cm^{-2}. mol^{-1})**	
	σ_R (λ) @ 1 m height	**σ_R (λ) @ 1000 m height**
1064	1.447545 E-04	1.191981 E-04
532	9.704752 E-02	8.012059 E-02
355	2.002259 E-04	1.649309 E-04
266	1.984818 E-04	1.634805 E-04

Table (5) is plotted as graph (4).



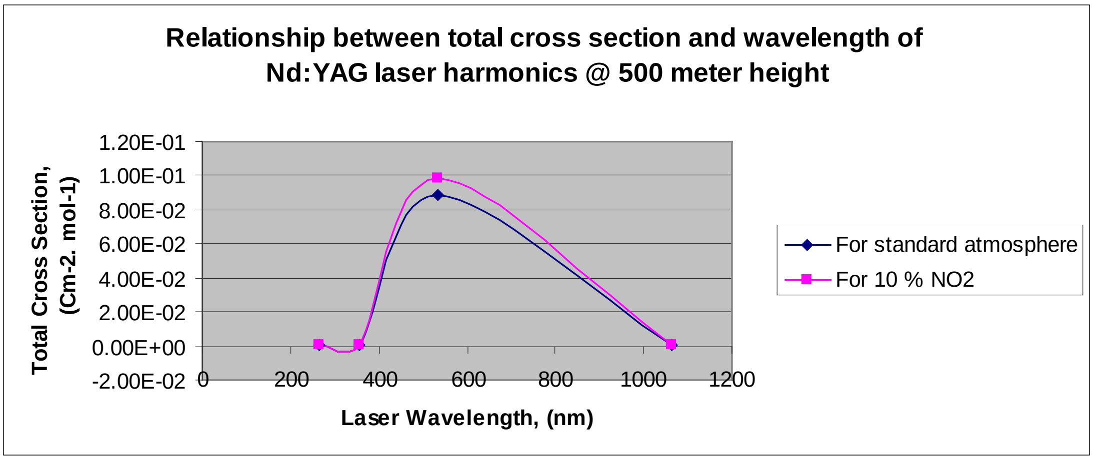
Graph (4) shows atmospheric total cross section versus height for laser wavelengths of Nd:YAG harmonics for standard atmosphere.

Now, total cross section is calculated for 10 % NO_2 increase as pollutant released from a plant, see table (6).

Table (6) atmospheric backscatter coefficient at ground and 1 Km height for laser wavelengths of Nd:YAG harmonics for standard atmosphere.

Wavelength, (nm)	**Atmospheric Total Cross Section, (Cm^{-2}. mol^{-1})**	
	σ_R (λ) @ 1 m height	**σ_R (λ) @ 1000 m height**
1064	1.608384 E-04	1.324423 E-04
532	10.78306 E-02	8.902288 E-02
355	2.224732 E-04	1.832566 E-04
266	2.205354 E-04	1.816451 E-04

Table (6) is plotted again @ 500 meter height with 10 % NO2, see graph (5).



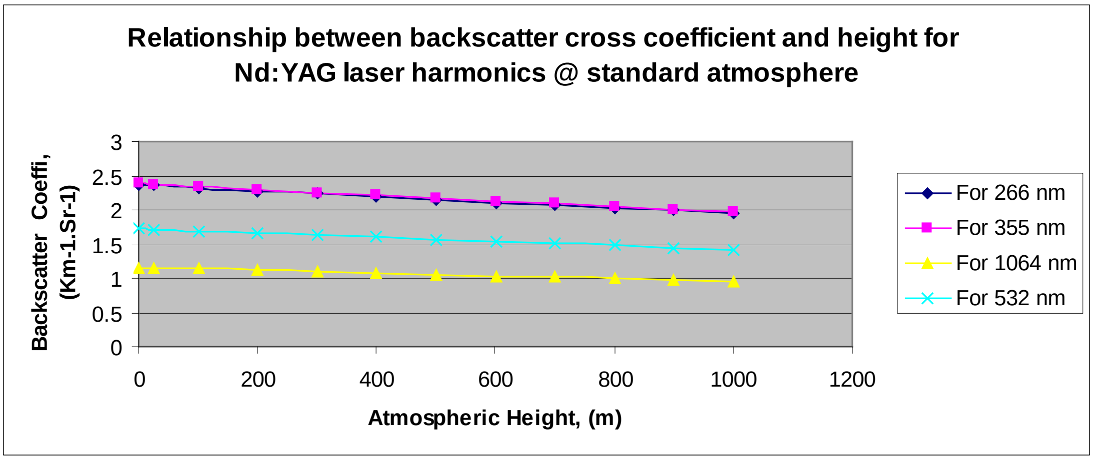
Graph (5) shows atmospheric total cross section versus wavelength of Nd:YAG laser harmonics for standard atmosphere compared with polluted atmosphere.

Sixth, let us calculate atmospheric total backscatter coefficient for height ranges (1 - 1000) meter and for laser wavelengths of Nd:YAG harmonics for standard atmosphere in table (7).

Table (7) shows atmospheric backscatter coefficient at ground and 1 Km height for laser wavelengths of Nd:YAG harmonics for standard atmosphere.

Wavelength, (nm)	**Atmospheric Backscatter coefficient, (K^{-1}. Sr^{-1})**	
	β_g (λ) @ 1 m height	**β_g (λ) @ 1000 m height**
1064	1.727185 E-05	1.42225 E-05
532	1.157953 E-02	9.559843 E-03
355	2.368249 E-05	1.95062 E-05
266	2.38905 E-05	1.967926 E-05

Table (7) is plotted as graph (6).



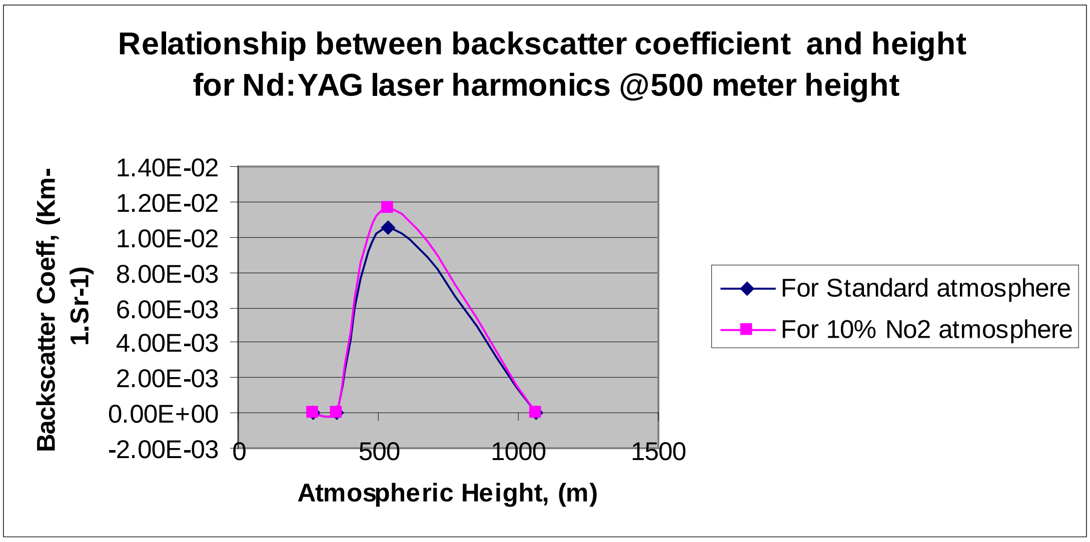
Graph (6) shows atmospheric backscatter cofficient versus height for laser wavelengths of Nd:YAG harmonics.

Now, backscatter cross section is calculated for 10 % NO_2 increase as pollutant released from a plant, see table (8)

Table (8)

Wavelength, (nm)	**Atmospheric Backscatter coefficient, (K^{-1}. Sr^{-1})**	
	β_g (λ) @ 1 m height	**β_g (λ) @ 1000 m height**
1064	1.919094 E-05	1.580278 E-05
532	1.286615 E-02	1.062205 E-02
355	2.65451 E-05	2.18658 E-05
266	2.631388 E-05	2.167356 E-05

See graph (7)



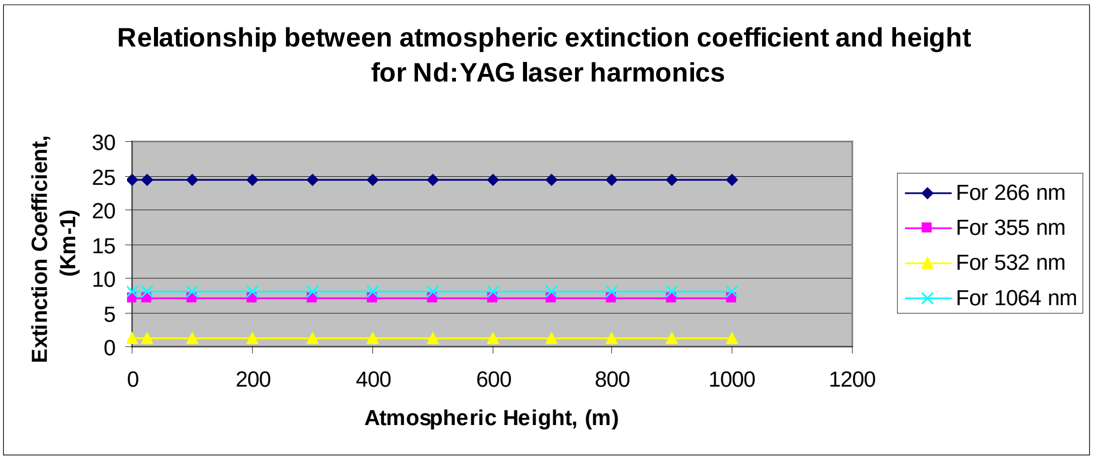
Graph (7) shows backscatter coefficient versus wavelengths @ 500 m.

Seventh, let us calculate atmospheric extinction coefficient for height ranges (1 - 1000) meter and for laser wavelengths of Nd:YAG harmonics for standard atmosphere in table (9).

Table (9)

Wavelength, (nm)	**Atmospheric extinction coefficient, (Km^{-1})**	
	α_g (λ) @ 1 m height	**(α_g λ) @ 1000 m height**
1064	1.620264 E-04	1.334205 E-04
532	10.86271 E-02	8.968043 E-02
355	2.241165 E-04	1.846102 E-04
266	2.221643 E-04	1.829867 E-04

See graph (8).



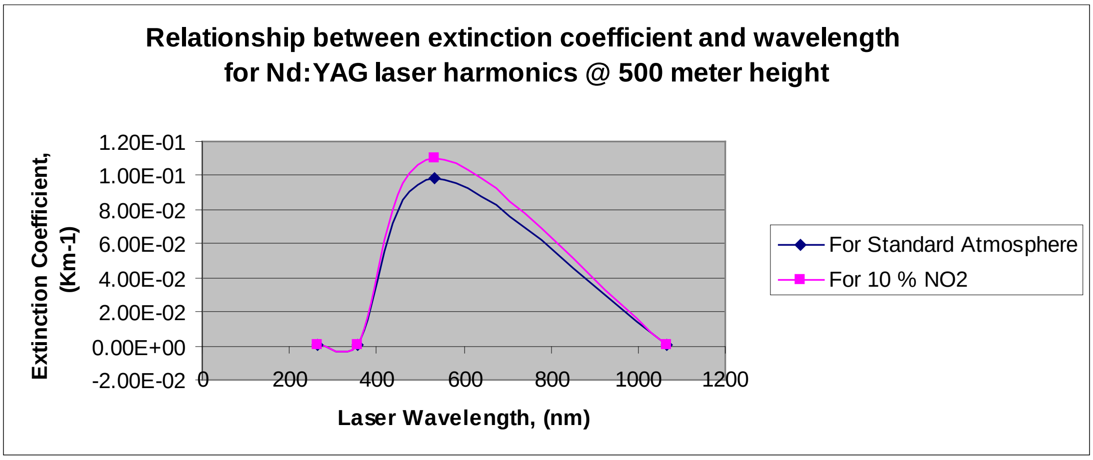
Graph (8)

Now, backscatter cross section is calculated for 10 % NO_2 increase as pollutant released from a plant, see table (10).

Table (10)

Wavelength, (nm)	**Atmospheric extinction coefficient, (K^{-1})**	
	α_g (λ) @ 1 m height	**(α_g λ) @ 1000 m height**
1064	1.8200293 E-04	1.482451 E-04
532	12.06967 E-02	9.96443 E-02
355	2.490183 E-04	2.051225 E-04
266	2.468493 E-04	2.033186 E-04

Table (10) is plotted as graph (9).



Graph (9)

Eighth, let us calculate atmospheric transmittance coefficient as a result of atmospheric effect on specific wavelength for height ranges (1 - 1000) meter and for laser wavelengths of Nd:YAG harmonics for standard atmosphere in table (11).

Table (11)

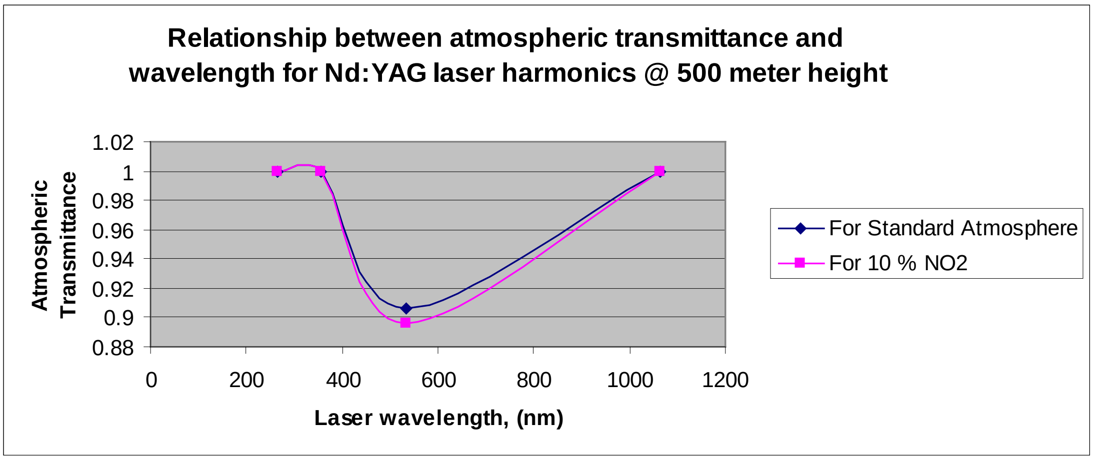
Wavelength, (nm)	**Atmospheric transmittance coefficient**	
	$\tau(\lambda)$ @ 1 m height	**$\tau(\lambda)$ @ 1000 m height**
1064	0.9999997	0.9997332
532	0.9997827	0.8358042
355	0.9999995	0.9996309
266	0.9999996	0.9996341

Now, atmospheric transmittance is calculated for 10 % NO_2 increase as pollutant released from a plant, see table (12).

Table (12)

Wavelength, (nm)	**Atmospheric transmittance coefficient**	
	$\tau(\lambda)$ @ 1 m height	**$\tau(\lambda)$ @ 1000 m height**
1064	0.9999996	0.9997035
532	0.9997587	0.8193124
355	0.9999995	0.9995899
266	0.9999995	0.9995934

Table (11) & (12) are plotted as graph (10)



Graph (10) shows atmospheric transmittance for standard & 10 % NO_2 pollutant as a function of Nd:YAG harmonics laser wavelength s @ 500 meter height.

6- CONCLUSION

Knowing precise parameters related to atmospheric transmittance is the key of designing an optical system for atmospheric far field applications such as lidar.

Extinction coefficient, the main controller of atmospheric transmittance, is strongly affected by laser wavelength.

Nd:YAG laser harmonics are widely applied in lidar system. It is found the following:

- 1064 nm wavelength is the convenient wavelength for remote sensing because it is minimally affected by the atmosphere; beside its generation in laser system does not need a nonlinear crystal.
- 532 nm wavelength is strongly affected by atmosphere, so it is recommended to avoid it for far field applications. It is recommended for short marine applications.
- 355 nm and 266 m are recommended as an alternative for 1064 nm but these wavelengths need a nonlinear crystal to be generated.

REFERENCES

1- W. K. Pratt, ***Laser Communication Systems***, J. Wiley & Sons, New York, 1969.
2- H. Weichel, ***Laser Beam Propagation in the Atmosphere***, SPIE, Bellingham WA, 1990.
3- E. P. Shettle, "**Models of aerosols, clouds, and precipitation for atmospheric propagation studies,**" *Atmospheric Propagation in the UV, Visible, IR, and MM-Wave region and Related Systems Aspects AGARD Conf. Proc.*, **454**, pp. 15-1 to 15-13, 1989.
4- E. J. McCartney, ***Optics of the Atmosphere***, J. Wiley & Sons, New York, 1976.
5- W. E. K. Middleton, ***Vision through the Atmosphere***, U. of Toronto Press, Toronto, 1952.
6- J. M. Wallace and P. V. Hobbs, ***Atmospheric Science: An Introductory Survey***, Academic Press, Orlando, 1977.

7- M. Pahlow, D. Müller, M. Tesche, H. Eichler, G. Feingold, W. L. Eberhard, and Y. Cheng, ***Retrieval of aerosol properties from combined multiwavelength lidar and sunphotometer measurements***, Appl. Opt., 45, 7429–7442 (2006).
8- C. Weitkamp, ***Lidar: Range-resolved Optical remote sensing of the Atmosphere,*** **Springer series in optical sciences**, New York, USA (2005).
9- M. E. Thomas, and D. D. Duncan**, "Atmospheric transmission, in *Atmospheric Propagation of Radiation*"**, SPIE Press, Bellingham, 1993.
10- G. Nykolak, P. F. Szajowski, A. Cashion, H. M. Presby, G. E. Tourgee, J. J. Auborn, "**A 40 Gb/s DWDM free space optical transmission link over 4.4 km**," *Free-Space Laser Communication Technologies XII*, Proc. SPIE, **3932**, pp. 16-20, 2000.