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Araştırma Makalesi / Research Article

Effects of Atmospheric Attenuation on LIDAR Wavelength

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Abstract

In this paper, the effects of atmospheric attenuation parameters on the emission wavelength of LIDARs used in aviation and space studies have been investigated. In this context, simulations of attenuation factor (q), attenuation coefficient (β) and atmospheric attenuation (η_{atm}) changes have been performed for LIDAR wavelength variations in the range of 800 - 1600 nm, based on the LIDAR visibility standard used in atmospheric measurements and computations. In response to the change in wavelength between 800 nm and 1600 nm, the values of q, β, and η_{atm} have varied respectively in the ranges of 0.01874 - 0.13218 dB/km, 0.99278 - 0.86685 km^{-1}, and 0.05084 - 0.07425 dB. On the other hand, the change of the atmospheric attenuation with wavelength has been computed as 2.925 × 10^{-5} dB(nm^{-1}). Furthermore, equations giving the mathematical relationships between the attenuation factor, attenuation coefficient, and LIDAR wavelength for atmospheric attenuation have been derived using Beer-Lambert law. According to this information, it has been observed that as the wavelength increases, the attenuation factor and the atmospheric attenuation increase, while the attenuation coefficient decreases. In conclusion, this study emphasizes the critical importance of evaluating the effects of wavelength selection on atmospheric attenuation parameters in LIDARs and provides valuable information to the researchers in this field.

Keywords: LIDAR, Laser wavelength, Atmospheric attenuation, Beer-Lambert law, Attenuation factor.

Atmosferik Zayıflamanın LiDAR Dalgaboyu Üzerindeki Etkileri

Öz

Bu makalede, atmosferik zayıflama parametrelerinin, havacılık ve uzay çalışmalarında kullanılan LiDAR'ların ışıma dalgaboyu üzerindeki etkileri incelenmiştir. Bu kapsamda, atmosferik ölçüm ve hesaplamalarda kullanılan LiDAR görünürlük standardı esas alınarak, 800 – 1600 nm aralığındaki LiDAR dalgaboyu değişimleri için zayıflama faktörü (q), zayıflama katsayısı (β) ve atmosferik zayıflama (η_{atm}) değişimlerinin simülasyonları gerçekleştirilmiştir. Dalgaboyunun, 800 nm ile 1600 nm arasındaki değişimine karşılık, q, β, ve η_{atm} değerleri sırasıyla, 0.01874 – 0.13218 dB/km, 0.99278 – 0.86685 km^{-1} ve 0.05084 – 0.07425 dB aralığında değişmiştir. Diğer yandan, atmosferik zayıflamanın dalgaboyu ile değişimi, 2.925 × 10^{-5} dB.(nm^{-1}) olarak hesaplanmıştır. Ayrıca, Beer-Lambert yasasından yararlanılarak zayıflama faktörü, zayıflama katsayısı ve atmosferik zayıflama için LiDAR dalgaboyu arasındaki matematiksel ilişkileri veren denklemler türetilmiştir. Bu bilgilere göre, dalgaboyu arttıkça zayıflama faktörü ve atmosferik zayıflama artış gösterirken, zayıflama katsayısında azalma olduğu görülmüştür. Sonuç olarak, bu çalışma, hava LiDAR'larda dalga boyu seçiminin atmosferik zayıflama parametreleri üzerindeki etkilerinin değerlendirilmesinde kritik önemi vurgulamakta ve bu alandaki araştırmacılara değerli bilgiler sunmaktadır.

Anahtar Kelimeler: LiDAR, Lazer dalgaboyu, Atmosferik zayıflama, Beer-Lambert yasası, Zayıflama faktörü.

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1. Introduction

LIDAR (Light Detection and Ranging) sensors use electromagnetic (EM) waves in ultraviolet, optical, and infrared wavelengths especially to measure the distance and range of the objects. In other words, a LIDAR sensor is a device used to measure distances of the objects and timing the reflection of the light back to the receiver of the system (Blackburn, 2002; Reutebuch et al., 2005; Jelalian, 1992; Höfle, 2011; Goodman, 2013; Yan et al., 2015). As an active sensor, a LIDAR sensor emits an EM wave and receives the reflected signal. LIDAR technology is similar to microwave Radar but operates at much shorter wavelengths. This implies that it will achieve superior angular resolution compared to Radar but will be ineffective in penetrating fog or clouds (McManamon, 2019).

LIDAR sensors typically use visible, ultraviolet, or infrared laser beams to image objects in the environment. These sensors can target materials such as rocks, chemical compounds, non-metallic objects, aerosols, and clouds. Thus, they can be used for detecting these materials, measuring distances to objects, and determining the presence or absence of objects. To serve these purposes, the LIDAR wavelength can range from approximately 250 nm to 10 µm (Cracknell and Hayes, 2007). The light beam produced in the LIDAR system is usually backscattered by objects rather than pure reflection as seen in mirrors. There are different scattering mechanisms used in LIDAR applications. These scattering mechanisms are Mie scattering, Rayleigh scattering, Raman scattering and fluorescence (Dakin and Brown, 2017).

Figure 1 shows the basic layout of a LIDAR system (Weitkamp, 2006, Islam et al., 2022). As shown in Figure 1, a LIDAR system comprises three primary components: the laser source, the receiver, and the optical systems for aiming the LIDAR. A LIDAR sensor basically consists of transmitter and receiver units. The transmitter unit includes a laser light source, and the receiver unit consists of a photodetector where the laser light beam reflected from the object is detected and a data acquisition unit.

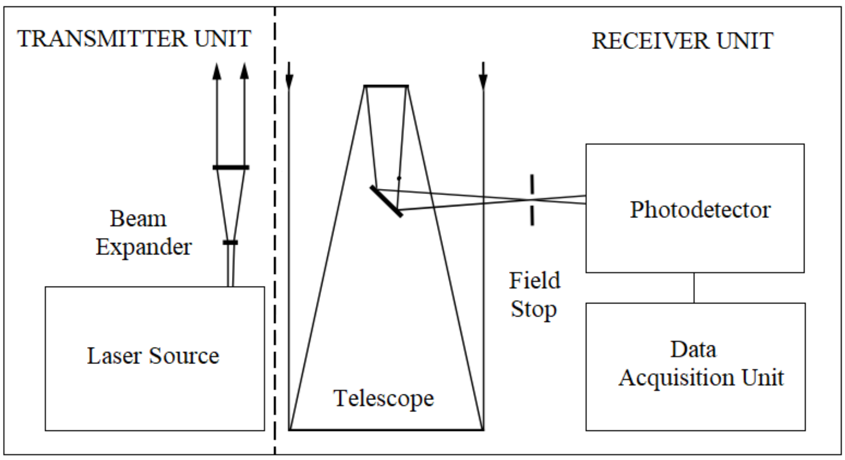

Figure 1. Basic layout of LIDAR

The beam expander employed in the transmitter unit is generally used to reduce the branching of the light beam before it is emitted into the atmosphere. In the configuration shown in Figure 1, the telescope at the receiver's end collects the photons backscattered by the atmosphere. Typically, this is succeeded by an optical analysis system that isolates specific wavelengths or polarization states from the collected light, based on the application. The chosen light wave is then directed to the photodetector in the receiver unit, where the optical signal received is transformed into an electrical signal (Weitkamp, 2006; Islam et al., 2022).

The fixed field stop used in the LIDAR configuration is located at the telescope focus. The field of view is determined by a field stop in the focal plane of the receiver optics. The field stop is used to block strong backscattering signals from the atmosphere to prevent overloading the photodetector (Weitkamp, 2006; Islam et al., 2022). As a result of processing the optical signal received from the photodetector in the data acquisition unit, the distance between the object and the LIDAR sensor is precisely measured.

Airborne LIDARs are widely used in mapping, autonomous air and ground vehicles, and geographic information systems (Collis, 1970; Anderson et al., 2005; Allahverdi et al., 2009; Yılmaz, 2016; Yakar et al., 2021). In these types of LIDARs, lasers that emit various wavelengths are preferred as light sources. In airborne LIDAR sensors, when the laser beam is directed toward the target area, it interacts with objects in the medium. In other words, when the laser beam encounters particles in the air, a variety of optical interactions take place. As a result of this interaction, the backscattered LIDAR wave is detected by the receiver of the detection system, i.e. the photodetector, and the optical signal is converted into an electrical signal. Hence, meaningful and usable information is obtained (Allahverdi et al., 2009).

The effectiveness and high accuracy of LIDAR systems depend on a good analysis of the parameters affecting the performance of these systems and a correct interpretation of atmospheric losses. The changes in atmospheric conditions may cause the LIDAR light to weaken, thus preventing the production of correct information from the optical signal directing to the sensor and being converted into an electrical signal. To put it differently, the beam produced by the laser light source, which is an important part of LIDAR systems, can significantly be influenced by atmospheric conditions such as fog, haze, rain, snow, and dense cloud and may weaken due to phenomena such as scattering and absorption while moving in these environments. As a result of this situation, the detection and measurement ability of LIDAR sensors may decrease (Wunderlich, 2003; Allahverdi et al., 2009).

Atmospheric phenomena such as rain, fog and clouds can each affect different wavelengths in various ways. This situation can affect the detection and measurement performances of LIDAR and Radar systems positively or negatively compared to each other. For example, the wavelength ranges of laser lights used in air LIDAR systems is smaller than that of radio waves used in Radar (Radio Detection and Ranging) systems. Therefore, while LIDAR wavelengths interact with fog particles, this is not the case for Radar systems. In other words, LIDAR sensors are subject to greater attenuation in foggy weather. This is also the case during active operations in dark environments. Thus, the selection of LIDAR wavelengths influences the absorption and scattering characteristics based on atmospheric conditions. For these reasons, the simulations and the mathematical analyses conducted in this area are crucial for assessing LIDAR performance. Additionally, the variation of LIDAR wavelength and the change of light power levels due to atmospheric attenuation and scattering mechanisms, determine the use of these sensors in aircraft, autonomous vehicles, mapping and land imaging applications (Wunderlich, 2003; Allahverdi et al., 2009).

Hence, the effects of parameters such as the attenuation factor (q), the attenuation coefficient (β), and atmospheric attenuation (η_{atm}) on the emission wavelengths of LIDAR have been investigated in this study. In this manner, Matlab simulations have been performed to analyze the relationship between these parameters and LIDAR emission wavelengths changing in the range of 800 – 1600 nm. Moreover, corresponding equations expressing the variation of the attenuation coefficient and η_{atm} with LIDAR wavelength have been derived using the simulations. Thus, numerical data regarding the variations of these parameters with wavelength have been obtained.

2. Materials and Methods

The effectiveness of LIDAR systems depends on how many particles and gases in the atmosphere scatter and absorb laser light. Atmospheric attenuation reduces light intensity as it causes scattering of the laser beam (Rayleigh and Mie scattering) and absorption by water vapor, CO_2 and O_3 (ozone) present in the atmosphere. Put another way, due to atmospheric attenuation, the intensity of the electromagnetic wave produced by the LIDAR decreases as it passes through the atmosphere. This can negatively affect measurement accuracy and lead to measurement errors (McManamon, 2019).

The atmospheric attenuation depending on the laser radiant intensities (I_0 and I_R) is expressed as

$$I_R = \frac{I_0}{R^2} e^{-\beta R} \tag{1}$$

where I_0 and I_R denote the emitted and transmitted laser radiant intensity, respectively, R and β denote the range from the laser scanner, and the attenuation coefficient, respectively (Ratcliffe, 2005; Rueger, 1990; Reshetyuk, 2006; Weichel, 1990).

The attenuation coefficient can be written by

$$\beta = \alpha_m + B_a + \alpha_a + B_m \tag{2}$$

where α and B are the absorption and scattering coefficients, respectively, and m and a stand for molecular and aerosol, respectively (Weichel, 1990).

The degree of attenuation depends on the LIDAR wavelength, distance to the target, temperature, pressure, gas composition of the atmosphere, weather conditions, and the presence of microscopic particles of various sizes in the air (Rueger, 1990).

The atmospheric attenuation directly or indirectly affects the strength of the detected signals and thus the measurement accuracy. The Beer-Lambert law used for computing the atmospheric attenuation states that light is absorbed while passing through a medium and that this absorption depends on the properties of the medium. To rephrase, this law shows that the degree of light is directly proportional to the path length traveled by the light and the concentration of absorbing entities in the material (Heath, 1993).

The absorption parameter of the light is stated as

$$A = \varepsilon \,.\, c \,.\, l \tag{3}$$

where A refers to the absorption parameter, ε is the specific absorption coefficient for the material, c is the concentration change, and l is the length of the material through which the light passes (Heath, 1993).

In Eq. (3), the absorption parameter (A) is expressed in uncertain units. The units of ε are given as L/(mol·cm) or L/(g·cm), and the units of parameters c and l are given as mol/L or g/L and cm, respectively.

The attenuation factor is a parameter used to determine how much LIDAR light is attenuated in the atmosphere. Therefore, the attenuation factor which affects the LIDAR wavelength, provides a parameterization to determine the atmospheric attenuation coefficient depending on the LIDAR wavelength (McManamon, 2019).

The attenuation factor (q) is expressed as a function of the wavelength as

$$q(\lambda) = 1.428 \times 10^5 . \lambda - 0.0947 \tag{4}$$

where λ is the LIDAR wavelength and its unit is nm. Hereby, the attenuation factor is dB/km.

The atmospheric attenuation coefficient (β) is written as

$$\beta \approx \left(\frac{\lambda_0}{\lambda}\right)^q \tag{5}$$

where λ_0 is the LIDAR wavelength defined in the LIDAR visibility standard (U.S. standard) used in atmospheric measurements and computations and its value is 0.55 µm (McManamon, 2019).

The atmospheric attenuation (η_{atm}) is a measure of how much light passes through the atmosphere, essentially indicating how much the atmosphere diminishes the laser light (McManamon, 2019).

The atmospheric attenuation is expressed with

$$\eta_{atm} = e^{-\beta R} \tag{6}$$

where R is the distance traveled by the LIDAR light or the distance of the LIDAR system from the object. The units of β and η_{atm} given in Eq. (6) are km^{-1} and dB, respectively.

In Eq. (6), R is taken as 3 km. In addition, for the change of LIDAR wavelength in the range of 800 – 1600 nm, the visibility and contrast parameter values are taken as 7 km and 2 %, respectively (McManamon, 2019).

LIDARs are directly affected by scattering and absorption caused by gases and particles in the atmosphere. For this reason, considering the effects of atmospheric conditions on the LIDAR wavelength are important to optimize system performance. Put another way, the atmospheric attenuation (η_{atm}) and other parameters are too important in LIDAR design and performance analysis in terms of explaining the behavior of light in the atmospheric environment. The Beer-Lambert law is highly beneficial for accurately analyzing these effects, thus enhancing the precision of LIDAR systems employed in practical applications.

3. Findings and Discussion

In this paper, simulations regarding the attenuation factor, attenuation coefficient, and atmospheric attenuation changes for the wavelength variations in the range of 800 – 1600 nm have been carried out. In obtaining simulations representing the relationships between these parameters, the LIDAR visibility standard used in atmospheric measurements and computations have been taken as basis.

Figure 2 shows the change in the attenuation factor depending on the variation of the LIDAR wavelength in the range of 800 – 1600 nm. As seen in Figure 2, as the laser emission wavelength increases, the attenuation factor increases linearly. In this wavelength range, the attenuation factor varies between 0.01874 dB/km and 0.13218 dB/km.

Attenuation factor values for different LIDAR wavelengths are given in Table 1. The attenuation coefficient is obtained as 0.05618 dB/km at 1064 nm, which is the emission wavelength of Nd: YAG (Neodymium-doped Yttrium Aluminum Garnet, Nd: $Y_3Al_5O_{12}$) lasers widely used in airborne LIDARs.

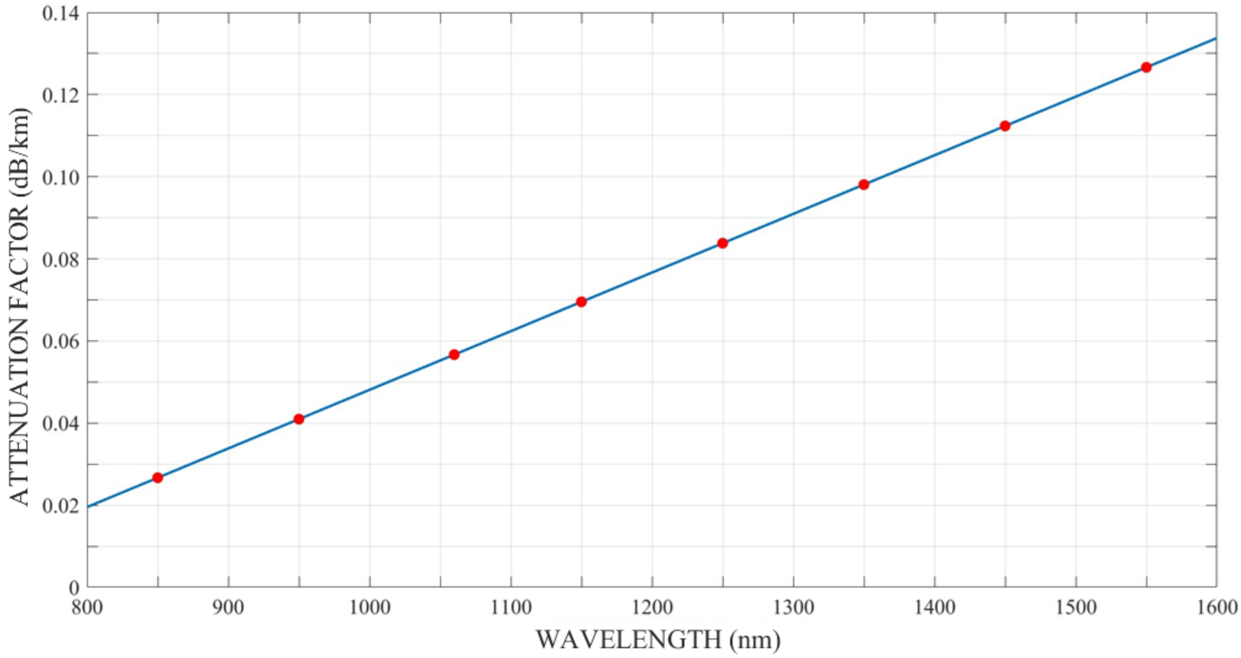

Figure 2. Variation of the attenuation factor with LIDAR wavelength

Table 1. Attenuation factor values for some LIDAR wavelengths

LIDAR Wavelength (λ) (nm)	Attenuation Factor (q) (dB/km)
850	0.02583
950	0.04001
1064	0.05618
1150	0.06897
1250	0.08255
1350	0.09673
1450	0.11091
1550	0.12509

The simulation related to the wavelength dependence of attenuation coefficient for wavelength variation between 800 nm and 1600 nm is shown in Figure 3. As is seen from the figure, the plot representing the change between wavelength and attenuation coefficient is not linear but exponential form. As a result of the analyses carried out in the Matlab R2023a environment, it has been observed that the change between both parameters is in the form of a third-order equation.

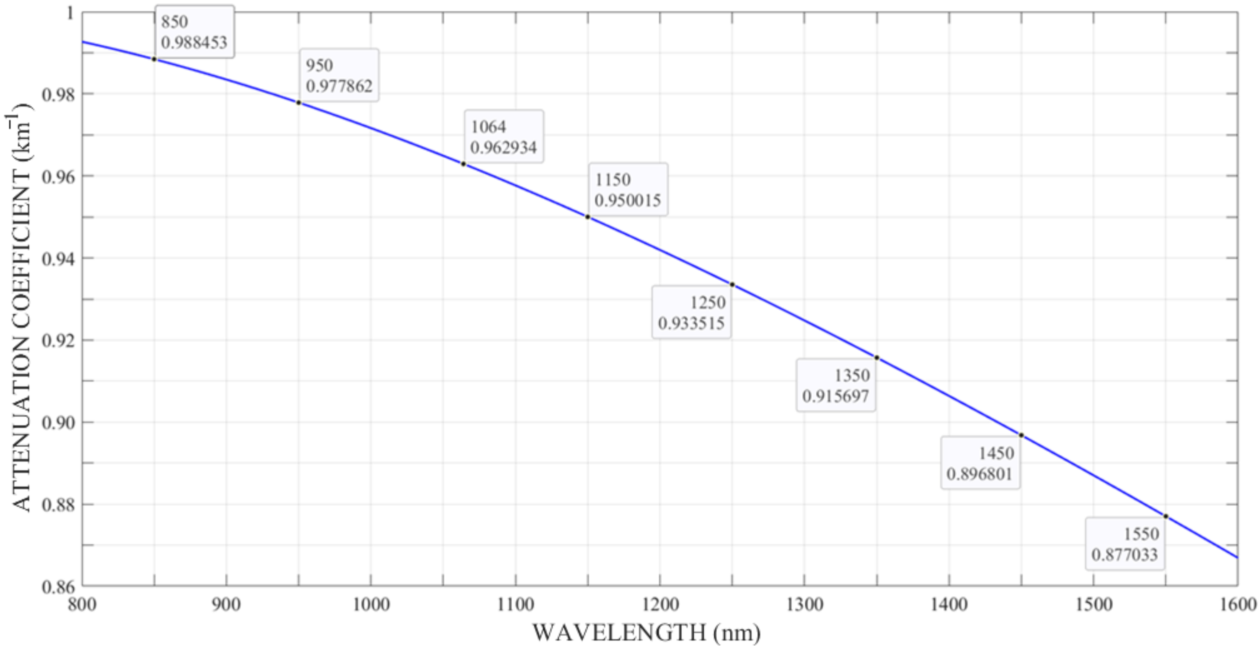

Figure 3. Variation of attenuation coefficient versus LIDAR wavelength

Using curve fitting method, the relationship between attenuation coefficient (β) and LIDAR wavelength (λ) is obtained as in Eq. (7). The equation that best gives the relationship between these parameters is the third-degree equation. In Eq. (7), the correlation coefficient converges to 1.

$$\beta(\lambda) = 4.914\ x\ 10^{16}.\lambda^3 - 2.524\ x\ 10^{11}.\lambda^2 + 2.282\ x\ 10^5.\lambda + 0.9466 \quad (7)$$

As the LIDAR wavelength varies between 800 – 1600 nm, the attenuation coefficient β takes values varying between 0.99278 – 0.86685 km^{-1}. Therefore, as λ increases, β tends to decrease exponentially. Thus, knowing the variation of the attenuation coefficient (β) with wavelength is a crucial data source for selecting the laser emission wavelength in LIDAR designs and analyzing the system performance. Put it differently, accurately estimating or having knowledge of the amount of atmospheric attenuation that occurs depending on the wavelength in the frequency spectrum provides important information in designs.

Figure 4 shows the simulation of the relationship between atmospheric attenuation and wavelength variations in the range of 800 – 1600 nm. As shown clearly in Figure 4, there is an exponential increase in atmospheric attenuation with the rise in wavelength. This plot shows that as the wavelength increases, the light's attenuation by the atmosphere also increases. From the simulation, it is seen that the atmospheric attenuation (η_{atm}) varies between 0.05084 dB and 0.07425 dB for the change of LIDAR wavelength between 800 nm and 1600 nm.

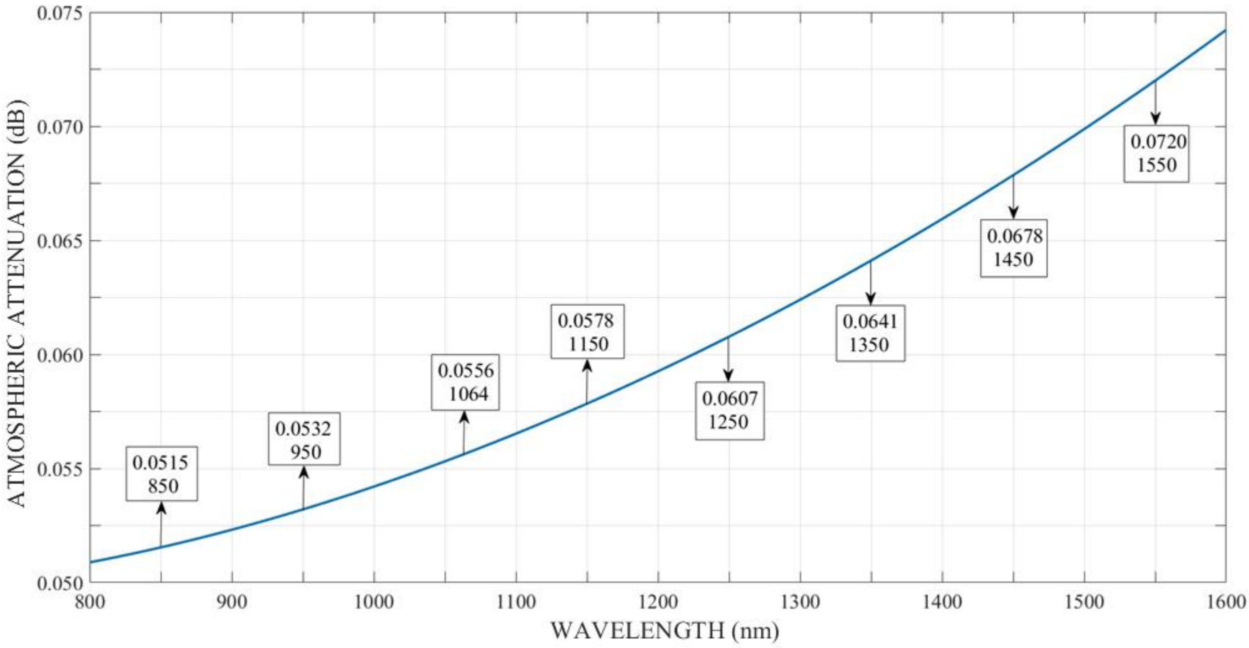

Figure 4. Variation of atmospheric attenuation with LIDAR wavelength

The atmospheric components such as water vapor, CO_2, and O_3 have higher absorption and scattering abilities at longer wavelengths. As seen from the simulation in Figure 4, atmospheric attenuation is more effective at longer wavelengths. This shows the fact that atmospheric components are important factors in evaluating LIDAR performance.

Applying the curve fitting method to the data in Figure 4, the equations representing the relationship between wavelength and atmospheric attenuation are obtained in quadratic and cubic forms. These equations are given as in (8.a) and (8.b), respectively.

$$\eta_{atm}(\lambda) = 2.055\ x\ 10^{10}.\lambda^2 - 2.006\ x\ 10^4.\lambda + 0.05374 \quad (8.a)$$

$$\eta_{atm}(\lambda) = -1.17\ x\ 10^{15}.\lambda^3 + 2.476\ x\ 10^{10}.\lambda^2 - 2.50\ x\ 10^4.\lambda + 0.05562 \quad (8.b)$$

Using the regression analysis, the correlation coefficients, i.e. R^2 values, for equations (8.a) and (8.b) are found to be 0.99 and 1, respectively. As can be understood from the correlation coefficients, the relationship between atmospheric attenuation and LIDAR wavelength is explained best compatible with the equation in cubic form. Additionally, the metric values of MSE (mean square error) and RMSE (root mean square error) for Eq. (8.b) have been computed as approximately 0.47×10^{-6} and 6.85×10^{-4} dB, respectively. Therefore, considering the MSE and RMSE metrics, it is evident that the values are almost close to zero. This means that the obtained η_{atm} curve can be explained in a manner more consistent with equation (8.b).

4. Conclusion

In this paper, the simulations have been performed to analyze the relationships between the wavelengths used in LIDAR systems and the attenuation factor, attenuation coefficient and atmospheric attenuation parameters. The data obtained from the simulations and analyses have shown that atmospheric attenuation increases linearly with increasing wavelength. For the change in LIDAR wavelength between 800 – 1600 nm, which is the basis of the study, the attenuation factor (q) and atmospheric attenuation (β) values have increased, while the attenuation coefficient (η_{atm}) has taken decreasing values. Alternatively, within the given wavelength range, q, β, and η_{atm} have taken values ranging from 0.01874 to 0.13218 dB/km, 0.99278 to 0.86685 km^{-1}, and 0.05084 to 0.07425 dB, respectively.

As seen in this study, high-frequency waves attenuate faster in the atmosphere, by the attenuation coefficient (β) definition. However, low-frequency waves are slower attenuated in the atmosphere. In other words, the amount of attenuation of low-frequency LIDAR waves in the atmosphere is less than that of high-frequency waves. This is because at low frequencies, the energy of the light photons produced by the laser is higher. Because, according to the photoelectric law, as the frequency of light waves decreases, the photon energy increases.

The relationship between LIDAR wavelength and atmospheric attenuation also applies to microwaves, radio waves, ultraviolet rays, and X-rays. Academic studies and practical application data in literature support this phenomenon. When LIDAR is evaluated in terms of wavelength, since wavelength and frequency change inversely proportional, atmospheric attenuation decreases as the LIDAR wavelength decreases. Therefore, lasers that emit high frequency radiation should be preferred in LIDARs. This matter is crucial and should be considered in practical applications involving LIDAR, communication, and remote sensing systems. In conclusion, when designing LIDAR systems, the selection of wavelength, transmission distance, and atmospheric attenuation should be considered. This can enhance the accuracy and reliability of LIDARs.

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Authors' Contributions

The contribution role of A. Günday includes conceptualization, data curation, checking simulations and academic review of the paper, methodology, project administration, supervision, visualization, scholarly writing, review & editing. The contribution role of T. Sipahi includes project administration, supervision processes, review & editing and the contribution roles of A. Balabey, C. Utar, M. Demir, M.M. Yılmaz include Matlab simulations, data curation, methodology, theoretical analysis, investigation, and draft writing of the article, accordingly.

Statement of Conflicts of Interest

There is no conflict of interest between the authors.

Statement of Research and Publication Ethics

The authors declare that this study complies with Research and Publication Ethics.

References

Allahverdi, K., Baykara, T., Hüseyinoğlu, F., and Seçgin, A. (2009). LIDAR. *Türkiye Bilim ve Teknik Dergisi*, 42(636), 72 – 75.

Anderson, E. S., Thompson, J. A., and Austin, R. E. (2005). LIDAR density and linear interpolator effects on elevation estimates. *International Journal of Remote Sensing*, 26(18), 3889 – 3900. https://doi.org/10.1080/01431160500181671

Blackburn, G.A. (2002). Remote sensing of forest pigments using airborne imaging spectrometer and LIDAR imagery. *Remote Sensing of Environment*, 82(2–3), 311–321. https://doi.org/10.1016/S0034-4257(02)00049-4

Collis, R. T. H. (1970). LIDAR. *Applied Optics*, 9(8), 1782 – 1788. https://doi.org/10.1364/AO.9.001782

Cracknell, Arthur P., Hayes, Ladson (2007). *Introduction to Remote Sensing* (2nd ed.). London: Taylor and Francis. ISBN 978-0-8493-9255-9. OCLC 70765252.

Dakin, P. J., Brown, R. (2017). *Handbook of Optoelectronics: Concepts, Devices, and Techniques (Volume One)*. CRC Press. p. 678. ISBN 978-1-4822-4179-2.

Goodman, J.A., Purkis, S.J., Phinn, S.R. (Eds.). (2013). *Coral Reef Remote Sensing – A Guide for Mapping, Monitoring and Management.* pp. 115 – 143, Springer, Netherlands.

Heath, D.R. (1993). *Telecommunications Engineer's Reference Book*. Ch. 7, Optics and vision, p. 1 – 13. Butterworth-Heinemann, Elseiver, Oxford.

Höfle, B., and Rutzinger, M. (2011). Topographic airborne LiDAR in geomorphology: A technological perspective. *Zeitschrift für Geomorphologie*, Vol. 55, Suppl. 2, 1 – 29.

Islam, S. et al. (2022). *Autonomous Driving Vehicle System Using LiDAR Sensor*. In: Hemanth, D.J., Pelusi, D., Vuppalapati, C. (eds) Intelligent Data Communication Technologies and Internet of Things. Lecture Notes on Data Engineering and Communications Technologies, vol 101. Springer, Singapore. https://doi.org/10.1007/978-981-16-7610-9_25.

Jelalian, R. (1992). *Laser Radar Systems*. – Artech House, Boston, London, pp. 292.

McManamon, P. (2019). *LIDAR Technology and Systems*. SPIE Press, Bellingham, Washington. http://spie.org.

Ratcliffe, S., 2005. *A digital signal processing technique for time-off-light laser rangefinding.* In Optical 3D Measurement Techniques VII, A. Grün / H. Kahmen (Eds.). Vol. 2, pp. 359 – 364.

Reshetyuk, Y. (2006). Calibration of terrestrial laser scanners for the purposes of geodetic engineering. *3rd IAG Symposium of Geodesy for Geotechnical and Structural Engineering and 12th FIG Symposium on Deformation Measurements* (s. 1 – 10). Baden, Austria.

Reutebuch, S. E., Andersen, H. E., & McGaughey, R. J. (2005). Light detection and ranging (LIDAR): an emerging tool for multiple resource inventory. *Journal of forestry*, 103(6), 286 – 292.

Rueger, J.M. (1990). *Electronic distance measurement, An Introduction.* 3rd totally revised edition. Springer. p. 266.

Weichel, H. (1990). *Laser beam propagation in the atmosphere*. (Vol. 3). SPIE press.

Weitkamp, C (ed). (2006). *LiDAR: Range-resolved optical remote sensing of the atmosphere*. 102, Springer Science & Business. Springer series in optical sciences, ISSN 0342-4111; 102, ISBN 0-387-40075-3.

Wunderlich, T.A. (2003). Terrestrial Laser Scanners - an Important Step towards Construction Information. *FIG Working Week*. 13 – 17 April, Paris, France.

Yakar, İ., Çelik, M.Ö., Hamal, S.N.G., and Bilgi, S. (2021). Kültürel Mirasın Dokümantasyonu Çalışmalarında Farklı Yazılımların Karşılaştırılması: Dikilitaş (Theodosius Obeliski) Örneği. *Geomatik*, 6(3), p. 217-226. https://doi.org/10.29128/geomatik.761475.

Yan, W.Y., Shaker, A., El-Ashmawy, N. (2015). Urban land cover classification using airborne LiDAR data: A review. *Remote Sensing of Environment*, Vol. 158, 295 – 310, ISSN 0034-4257. https://doi.org/10.1016/j.rse.2014.11.001.

Yılmaz, H., and Yakar, M. (2016). LIDAR (Light Detection and Ranging) Tarama Sistemi. *Yapı Teknolojileri Elektronik Dergisi*, 2(2), 23 – 33.