Analysis and Study of the Effect of Atmospheric Turbulence on Laser weapon in Iraq

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Abstract:
One of the most important challenges facing the development of laser weapons is represented by the attenuation of the laser beam as it passed through the layers of atmosphere.

This paper presents a theoretical study to simulate the effect of turbulence attenuation and calculates the decrease of laser power in Iraq. The refractive index structure $C_n^2$ is very important parameter to measure the strength of the atmospheric turbulence, which is affected by microclimate conditions, propagation path, season and time in the day.

The results of measurements and predictions are based on the Kolmogorov turbulence theory. It was demonstrated by simulations that the laser weapons in Iraq were severely affected due to the large change in temperatures, the limited effective range of laser weapon to a few kilometers as a result of high attenuation and the middle of stratosphere considered as a homogeneous and a suitable area for the work of laser weapons, so be a favorite area of fighter aircraft.

Key words: turbulence attenuation, Laser Weapon, refractive index structure $C_n^2$, Fried parameter $r_0$, Beam divergence.

Introduction:
The atmosphere around the globe is composed of a diverse mass of which gravitate toward the earth's surface by gravity. The importance of the atmosphere is as follows [1,2]:
- It protects life on Earth by UV absorption
- Surface warming through the greenhouse effect
- To attenuate the power of sunlight falling on the earth's surface and reduce the temperature.
The International Standard Atmosphere (ISA) and properties of it at mean sea level (MSL) is shown in Table 1[2].
Table (1): Properties of atmosphere

| Composition      | Layers            | Temperature $T_0$ | Pressure $P_0$ | Density $\rho_0$ | Mass $M_0$   |
|------------------|-------------------|-------------------|---------------|-----------------|--------------|
| Nitrogen 78.09%  | Troposphere       | 288.15 K          | 101325 N/m^2  | 1.225 Kg/M^3    | 5.15×10^{18} Kg |
| Oxygen 20.95%    | Stratosphere      |                   |               |                 |              |
| Argon 0.93%      | Mesosphere        |                   |               |                 |              |
| Carbon Dioxide 0.039% | Thermosphere      |                   |               |                 |              |
| Water Vapor 0.4 - 1 % | Exosphere         |                   |               |                 |              |

The beam of laser weapons can be affected by the atmosphere layers when it propagates through it. The attenuation due to absorption, scattering, thermal blooming and turbulence, changing the power of the beam as well as beam wander and beam breakup [3].

The quality of the laser beam is determined by interactions with the atmospheric species and aerosol particles. The value of beam power at the target is a measure of this quality [4].

The turbulence of laser beam arises as a result of the heterogeneity of atmosphere layers, causing temporal and spatial fluctuations of direction propagation, spot dancing, beam spread and scintillations.

This work is limited to the study and analysis the effect of turbulence attenuation on the beam of laser weapon.

**Theory of Atmospheric turbulence**

The gradient in temperature (positive or negative) between the surface of the earth and the atmosphere leads to the generation of so-called air turbulence. Since the Earth’s surface during the daytime will be at higher temperature than the air above, a negative gradient will causes a difference in refractive index values, beam direction (according to the Snell’s Law) refraction upward with angle depends on strong gradient. At nighttime, the gradients are positive which causes the beam direction refraction downward. [2]

To calculate temperature ($T$), pressure ($P$) and density ($\rho$) as a function of the altitude in meter, the Standard model of Atmosphere was used to calculate the temperature ($T$), pressure ($P$) and density ($\rho$) within the troposphere layer. Temperature decreases with altitude at a constant rate of -6.5 K/km up to the troops (Border line between the troposphere and the stratosphere). The standard tropopause altitude is 11 km. The (ISA) temperature model within the troposphere is: [2, 4]

$$ T = T_0 - 0.0065 \times h \quad \ldots (1) $$

From 11 to 20 km, the change of temperature is 0 K/km, but from 20 to 32 km the change is 1 K/km. The ISA pressure model within the troposphere is [4]:

$$ P = P_0 \left(1 - 0.0065 \times \frac{h}{T_0} \right)^{5.2561} \quad \ldots (2) $$

$$ \frac{P}{P_0} = \left( \frac{T}{T_0} \right)^{5.256} \quad \ldots (3) $$

$$ \frac{\rho}{\rho_0} = \left( \frac{T}{T_0} \right)^{4.256} \quad \ldots (4) $$

The temperature is constant at altitudes above the tropopause, the ISA pressure model become:

$$ P = P_{11} \quad e^{-\frac{\rho}{R_{11}} (h-h_{11})} \quad \ldots (5) $$

Where the parameters with subscript “11” correspond to the values at the tropopause ($P_{11} = 226.32 \text{ N/m}^2, \quad T_{11} = 216.65 \text{ K}, \quad h_{11} = 11 \text{ km}$) and R universal gas constant 8.31447 1/(mol•K). (Earth-surface gravitational acceleration 9.80665 m/s^2). In the
for the propagation of laser beam in the atmosphere, the variances in refractive index \( d \) to the variations in temperature and wind velocity create unstable air mass called turbulent eddies. Eddies can occur in the whole path propagation of the laser beam as different scale sizes from a micro scale to a macro scale. That’s mean, variance in the refraction index depends on the local temperature, atmospheric pressure or particle density [5,6].

The refractive index \( n \) is a function of temperature \( T \) (in Kelvin), pressure \( P \) (in mbar) and wavelength of laser weapon (in this work \( \lambda = 1.075 \mu m \)). The index of refraction, neglecting water vapor pressure, is given by: [6]

\[
n = 1 + \frac{77.6 P}{T} \times 10^{-6} \left[ 1 + \frac{0.00753}{\lambda^2} \right] \quad (8)
\]

For laser weapons systems, the coherence of the laser beam is very important for the propagation of laser energy through the atmosphere layers, so that they constructively interfere to form a high irradiance spot size on target. In addition, the constructive interference will disrupt as a result of the variations in refractive index due to turbulence [6,7].

The index-of-refraction structure parameter \( C_n^2 \) (in units of m\(^{-1/3}\)) is used to measure the strength of the turbulence. Andrey Kolmogorov was the first theoretically parameterized. Kolmogorov’s theory utilizes a statistical approach in describing the flow of kinetic energy from large-scale eddies (about 10’s of meters to 1cm in size). Eddy is defined as relatively homogeneous and isotropic within smaller regions of space, This assumption is allowed for Kolmogorov to utilize \( C_n^2 \) to measure the strength of the turbulence. The related structure function exhibits asymptotic behavior [5,6]

\[
\frac{P}{P_{20}} = \left( \frac{T}{T_{20}} \right)^{-34.1632} \quad \ldots (6)
\]

\[
\frac{P}{P_{20}} = \left( \frac{T}{T_{20}} \right)^{-35.1632} \quad \ldots (7)
\]

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\[
D_n(R) = \left\{ \begin{array}{ll}
C_n^2 R^{2/3} & , \quad l_0 \ll R \ll L_0 \\
C_n^2 l_0^{-4/3} R^2 & , \quad R \ll l_0 
\end{array} \right. \quad (9)
\]

Where \( R \) is scalar distance, \( L_0 \) is the outer scale of turbulence and \( l_0 \) is the inner scale of turbulence. \( C_n^2 \) is a defined as the mean-square difference in the refractive index at two locations divided by the distance \( r \) raised to the 2/3 power, i.e., [5,6]

\[
C_n^2 = \frac{(n_2-n_1)^2}{R^{2/3}} \quad \ldots (10)
\]

The other important quantity used to describe turbulence of the propagating laser beam is Fried parameter \( r_0 \) in (m), which represents an atmospheric coherence diameter. The \( r_0 \) parameter is a circular diameter over the laser beam which maintains coherence in the propagation distance. A lower \( r_0 \) value implies stronger turbulence. If the \( r_0 \) value is significantly smaller than the laser beam director size, the laser beam will break up into many smaller, incoherently radiating beam. The relation between \( r_0 \), \( C_n^2 \), \( \lambda \), and the distance to target \( d \) can be given by [8,9,10]:

\[
r_0 = 0.33 \frac{\lambda^{6/5}}{(\rho \delta c_0)^{3/5}} \quad \ldots (11)
\]

The power of laser weapon \( P \) on target through the earth’s atmosphere which can be calculated by [9,11]:

\[
P = \frac{AP_t}{a^2 R_t^2} e^{-\varepsilon d} \quad \ldots (12)
\]

Where \( P_t \) represents the total output power from the laser weapon (100 kw), \( R_t \) area of spot size at target A is area of spot size at weapon, \( \varepsilon \) is the total extinction coefficient due to atmospheric, absorption and scattering (in m\(^{-1}\)) and \( d \) represents the distance to target [12,13].

\[
\varepsilon = \frac{3.912}{d} \left( \frac{r_0}{\lambda} \right)^q \quad \ldots (13)
\]
The value of \( q \) depends on the range of laser weapon, when \( d \leq 6 \text{ km} \) \( q \) is given by 0.585 \((d)^{1.13}\) and when \( 6 \text{ km} < d < 50 \text{ km} \) \( q \) is equal to 1.3.

The effect of turbulence on the laser spot size \( R_s \) On target can be estimated by [9,14,15]:

\[
R_s \approx \frac{\lambda d}{\pi r_0} \quad \ldots \ldots (14)
\]

Where \( d \) represents the distance to target and the Fried parameter \( r_0 \)

**Results and Discussion:**

In this paper, the results were obtained by simulation using Matlab software. The effectiveness of laser weapons can be greatly affected by the layers of atmosphere. Table 1 shows the properties of atmosphere and international Standard Atmosphere ISA assumes the mean sea level MSL condition.

Table 2 clearly shows the atmospheric turbulence, generated by a temperature differential between the Earth’s surface and the atmosphere. Fig (1) shows that the temperature \( T \) (K) decreases with altitude \( h \) (km) at a constant rate of -6.5 K/Km (Eq.1) in the troposphere layer, then \( T \) remains at a constant value of 216.65 K from Stratosphere layer up to 20 km. Then, the temperature increases at a rate of one degree up to 32 km (middle of the stratosphere).

The pressure \( P\) (mbar) and density \( \rho \) \((\text{kg/m}^3)\) Varies with altitude \( h \) (km) depending on Eqs.3, 4,5,6,7 as shown in Figs. 2,3. It can be shown the \( P \) and \( \rho \) drops exponentially with

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| Table (2): Shows the data of various parameters, generated by a temperature differential between the Earth’s surface and the atmosphere |
|---|
| h(km) | T(k) | P(mbar) | \( \rho \left( \text{kg/m}^3 \right) \) | N | \( C_r^2 \) \((\text{m}^{-2})\) | \( r_0 \)(m) |
|---|---|---|---|---|---|---|
| 0 msl | 288.15 | 1013.25 | 1.225 | 1.0002749 | 6.48 \times 10^{-12} | 0.00975 |
| 1 | 281.65 | 989.74 | 1.111 | 1.0002495 | 5.59 \times 10^{-12} | 0.01065 |
| 2 | 275.15 | 974.94 | 1.006 | 1.0002259 | 4.81 \times 10^{-12} | 0.01166 |
| 3 | 268.65 | 970.08 | 0.909 | 1.0002040 | 4.09 \times 10^{-12} | 0.01287 |
| 4 | 262.15 | 616.39 | 0.819 | 1.0001838 | 3.47 \times 10^{-12} | 0.01419 |
| 5 | 255.65 | 540.19 | 0.736 | 1.0001652 | 2.97 \times 10^{-12} | 0.01557 |
| 6 | 249.15 | 471.8 | 0.659 | 1.0001480 | 2.47 \times 10^{-12} | 0.01740 |
| 7 | 242.65 | 410.6 | 0.589 | 1.0001323 | 2.11 \times 10^{-12} | 0.01912 |
| 8 | 236.15 | 355.99 | 0.525 | 1.0001178 | 1.75 \times 10^{-12} | 0.02139 |
| 9 | 229.65 | 307.41 | 0.466 | 1.0001046 | 1.44 \times 10^{-12} | 0.02405 |
| 10 | 223.15 | 264.35 | 0.412 | 1.0000926 | 1.21 \times 10^{-12} | 0.02670 |
| 11 | 216.65 | 226.31 | 0.363 | 1.0000816 | 1.42210^{-12} | 0.02942 |
| 12 | 216.65 | 193.3 | 0.310 | 1.0000697 | 1.040 \times 10^{-13} | 0.03292 |
| 13 | 216.65 | 165.1 | 0.265 | 1.0000595 | 7.60 \times 10^{-13} | 0.03529 |
| 14 | 216.65 | 141.01 | 0.226 | 1.0000508 | 5.50 \times 10^{-13} | 0.03825 |
| 15 | 216.65 | 120.44 | 0.193 | 1.0000434 | 3.98 \times 10^{-13} | 0.05203 |
| 16 | 216.65 | 102.87 | 0.165 | 1.0000371 | 2.92 \times 10^{-13} | 0.06267 |
| 17 | 216.65 | 87.86 | 0.141 | 1.0000317 | 2.21 \times 10^{-13} | 0.07405 |
| 18 | 216.65 | 75.04 | 0.120 | 1.0000270 | 1.50 \times 10^{-13} | 0.09344 |
| 19 | 216.65 | 64.1 | 0.103 | 1.0000231 | 1.16 \times 10^{-13} | 0.10896 |
| 20 | 216.65 | 54.74 | 0.088 | 1.0000197 | 8.74 \times 10^{-14} | 0.12921 |
| 21 | 216.65 | 46.77 | 0.074 | 1.0000168 | 6.79 \times 10^{-14} | 0.15034 |
| 22 | 216.65 | 39.93 | 0.061 | 1.0000142 | 4.43 \times 10^{-14} | 0.19425 |
| 23 | 216.65 | 34.22 | 0.054 | 1.0000121 | 3.25 \times 10^{-14} | 0.23392 |
| 24 | 220.65 | 29.3 | 0.046 | 1.0000103 | 2.26 \times 10^{-14} | 0.29089 |
| 25 | 221.65 | 25.49 | 0.039 | 1.0000088 | 1.69 \times 10^{-14} | 0.34631 |
| 26 | 222.65 | 21.53 | 0.033 | 1.0000075 | 1.21 \times 10^{-14} | 0.42318 |
| 27 | 223.65 | 18.47 | 0.028 | 1.0000064 | 8.31 \times 10^{-15} | 0.53020 |
| 28 | 224.65 | 15.86 | 0.024 | 1.0000055 | 6.42 \times 10^{-15} | 0.61898 |
| 29 | 225.65 | 13.62 | 0.021 | 1.0000047 | 4.92 \times 10^{-15} | 0.72614 |
| 30 | 226.65 | 11.71 | 0.018 | 1.0000040 | 3.61 \times 10^{-15} | 0.84735 |
| 31 | 227.65 | 10.08 | 0.015 | 1.0000034 | 2.51 \times 10^{-15} | 1.08742 |
| 32 | 228.65 | 8.67 | 0.013 | 1.0000029 | 1.39 \times 10^{-15} | 1.23565 |
increasing altitude above mean sea level MSL; this is because most of the atmospheric mass is concentrated in a troposphere layer (It contains approximately 75% of the atmosphere's mass and 99% of its water vapor and aerosols).

Fig (1) shows the temperature differential between the Earth’s surface and the atmosphere layers.

Fig (2) shows the pressure P(mbar) varies with altitude h (km)

Fig (3) shows the density ρ (kg/m³) varies with altitude h (km)

Fig (4) shows the refractive index decreases in exponential function with increasing altitude.

The negative gradient in values T and ρ causes variation in the refraction index n (Eqs. 7,8). Fig.4 shows the refractive index decreases in exponential function with increasing altitude. In troposphere layer, the laser beam of weapon is affected by attenuation due to variation of n. In high altitudes the refractive index n approaching to 1 in order to decrease the density and changing the slight temperature (as shown in Figs 5,6), which leads to consider the middle of stratosphere, homogeneous and suitable for the work of laser weapons.

Based on the above, the refractive index structure constant $C_n^2$ is inversely proportional with altitude as shown in Fig.7, $C_n^2$ is a tool to measure the strength of atmospheric turbulence and an increase in $C_n^2$ value yields an increase in atmospheric turbulence, at MSL the $C_n^2 \approx 10^{-12} \text{ m}^{-2/3}$ (during day and strong turbulence conditions).

The Fried parameter $r_0$ parameter defines a circular diameter over which the laser beam maintains coherence. Fig.8 shows the relation between $r_0$ and $C_n^2$, a lower $r_0$ value implies stronger turbulence. For wavelength ($\lambda = 1.075 \mu\text{m}$) and target ranges for laser weapons, $r_0$ can range from strong turbulence 0.975 cm (at MSL) to weak turbulence 1.23565 cm at 32 km (middle of stratosphere) (as shown in Fig.9)
Fig (5) shows the refractive index decreases with increasing temperature.

Fig (6) shows the refractive index increases with increasing density.

Fig (7) shows the refractive index structure constant $C_n^2$ is inversely proportional with altitude.

Fig (8) shows the relation between $r_0$ and $C_n^2$.

Fig (9) shows the relation between $r_0$ and altitude.

Fig (10) shows the curve of $T$ for every month in year 2015.
In Baghdad – Iraq, the change of temperature varies from season to season and also differs in one day. Table (3) shows the rate of change in refractive index as a result of the temperature difference at sea level. Fig.10 shows the variation in temperature minimum and maximum recorded in Baghdad on different months of the year (2015). It is clear that the July record the highest average temperature, as well as there is a variation in temperature in one day. This variation in temperature will lead to a variation in the P, n and $C_n^2$ as shown in Figs. 11, 12, 13 respectively. It is noted, the greatest variation in the $C_n^2$ recorded in the October as a result of the transition from summer to winter. Thus, the laser beam will be affected negatively as a result of rising temperatures rates in Iraq and the consequent increase in Atmospheric turbulence.

**Table (3): shows the rate of change in refractive index as a result of the temperature difference at sea level In Baghdad – Iraq (2015).** [16]

| month     | T(k) | P(mbar) | Wind (m/s) | n     | $C_n^2$ ($m^{-2}$) |
|-----------|------|---------|------------|-------|--------------------|
| January   | Min: 277.15 | 825.78  | 2.6        | 1.0002495 | 11.34 x 10^{-12} |
|           | Max: 290.15 | 1050.76 | 2.6        | 1.0002831 | 21.72 x 10^{-12} |
| February  | Min: 278.15 | 841.57  | 2.9        | 1.0002366 | 35.21 x 10^{-12} |
|           | Max: 293.15 | 1109.14 | 2.9        | 1.0002958 | 23.33 x 10^{-12} |
| March     | Min: 281.15 | 890.38  | 3.2        | 1.0002476 | 56.35 x 10^{-12} |
|           | Max: 299.15 | 1233.77 | 3.2        | 1.0003225 | 35.56 x 10^{-12} |
| April     | Min: 285.15 | 959.01  | 3.2        | 1.0002630 | 86.70 x 10^{-12} |
|           | Max: 306.15 | 1393.62 | 3.2        | 1.0003559 | 37.13 x 10^{-12} |
| May       | Min: 292.15 | 1089.39 | 3.3        | 1.0002951 | 83.92 x 10^{-12} |
|           | Max: 312.15 | 1542.90 | 3.3        | 1.0003865 | 67.55 x 10^{-12} |
| June      | Min: 295.15 | 1149.49 | 3.9        | 1.0003045 | 96.48 x 10^{-12} |
|           | Max: 315.15 | 1622.45 | 3.9        | 1.0004025 | 71.90 x 10^{-12} |
| July      | Min: 298.15 | 1212.24 | 4          | 1.0003179 | 146.84 x 10^{-12} |
|           | Max: 321.15 | 1802.10 | 4          | 1.0004388 | 146.11 x 10^{-12} |
| August    | Min: 299.15 | 1217.63 | 3.4        | 1.0003182 | 91.24 x 10^{-12} |
|           | Max: 317.15 | 1677.3  | 3.4        | 1.0004135 | 139.17 x 10^{-12} |
| September | Min: 293.15 | 1109.14 | 3          | 1.0002958 | 126.46 x 10^{-12} |
|           | Max: 316.15 | 1649.69 | 3          | 1.0004080 | 156.72 x 10^{-12} |
| October   | Min: 290.15 | 1050.76 | 2.6        | 1.0002831 | 107.40 x 10^{-12} |
|           | Max: 312.15 | 1542.90 | 2.6        | 1.0003865 | 215.02 x 10^{-12} |
| November  | Min: 279.15 | 857.59  | 2.5        | 1.0002402 | 68.04 x 10^{-12} |
|           | Max: 299.15 | 1233.77 | 2.5        | 1.0003225 | 107.61 x 10^{-12} |
| December  | Min: 273.15 | 765.03  | 2.5        | 1.0002190 | 73.43 x 10^{-12} |
|           | Max: 295.15 | 1149.49 | 2.5        | 1.0003045 | 30.38 x 10^{-12} |

Fig (11) shows the curve of pressure for every month in year 2015

Fig (12) shows the curve of n for every month in year 2015
It is clear, that the effective range of laser weapon in Iraq does not exceed a few kilometers as a result of higher attenuation that occurs to the laser beam due to high temperatures as shown in Fig.15.

It is clear, that the effective range of laser weapon in Iraq does not exceed a few kilometers as a result of higher attenuation that occurs to the laser beam due to high temperatures as shown in Fig.15.

**Conclusions:**

1. The middle of stratosphere considered as a homogeneous and a suitable area for the work of laser weapons, so is a favorite area of fighter aircraft.
The effectiveness of laser weapons in Iraq severely affected due to large change in temperatures.

The effective range of laser weapon in Iraq does not exceed a few kilometers as a result of higher attenuation.

The greatest variation in the $C_n^2$ recorded in the October as a result of the transition from summer to winter.

The refractive index structure $C_n^2$ is affected by microclimate conditions, propagation path, season and time of day.

The value of $C_n^2$ in Iraq, grades ranging from strong $6.48 \times 10^{-12}$ $m^{-2/3}$ at sea level to the weak $2.51 \times 10^{-15}$ $m^{-2/3}$ at 31 km.

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تحليل ودراسة تأثير الاضطرابات الجوية على سلاح الليزر في العراق

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الخلاصة:

واحدة من أهم التحديات التي تواجه تطوير أسلحة الليزر تتمثل بالتوهين الحاصل لحزمة الليزر أثناء مرورها خلال طبقات الغلاف الجوي.

هذا البحث قدم دراسة نظرية لمحاكاة تأثير توهين الاضطرابات واحتساب انخفاض قوة الليزر في العراق. ان معامل الانكسار الهيكلي $C_n^2$ مهم جدا لقياس قوة من الاضطراب في الغلاف الجوي، والذي يتأثر بتغير الظروف المناخية ومسار الانتشار والموسم والتوقيت في اليوم الواحد.

نتائج القياسات والتنبؤات مبنية على نظرية الاضطراب كولوموجروف. وقد بين من خلال المحاكاة، ان فعالية سلاح الليزر في العراق تتأثر كثيرا بسبب التغير الكبير في درجات الحرارة، وأن المدى الفعال لسلاح الليزر لا يتجاوز بضعة كيلومترات نتيجة للتوهين العالي، وأن انتقال منطقة منجاسة لعمل سلاح الليزر هي منتصف طبقة الستراتوسفير، لذلك تمثل منطقة مفضلة للطائرة المقاتلة.

الكلمات المفتاحية: توهين الاضطراب، سلاح الليزر، معامل الانكسار الهيكلي $C_n^2$، معامل فريد $r_0$، انفراج الحزمة.