Optical Design of Laser Zoom Beam Expander at near & far Ranges for Tracked Atmospheric Target

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Abstract

In this research, beam expander, BEX, is explained and designed for illuminating the remote flying target. The BEX is optically designed to be suited for Nd:YAG laser of given specifications. The BEX is modified to be zoom one to meet the conditions of preventing the receiving unit; i.e the photodetector, from getting saturated at near and far laser tracking. Decollimation could be achieved by automatic motor, which controls zoom lens of the BEX according to the required expansion ratio of beam expander.

Key Words: Optical design, Nd:YAG Laser, Beam Expander, Tracking, Zoom Lens.

التصميم البصري لموسع الحزمة الليزري المتغيرلتتبع هدف جوي عند المدى البعيد والقريب

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خلاصة

في هذا البحث , تم شرح و تصميم موسع الحزمة الليزري لانارة هدف جوي بعيد. تم تصميم موسع الحزمة بصريا ليتوافق مع ليزر النيميديوم ياك. تم تحوير موسع الحزمة ليتوافق مع حالة منع كاشف وحدة الاستلام الليزرية من بلوغ حالة التشبع عند التتبع البعيد و القريب للهدف الجوي. امكن تحقيق تغيير تجميع الاشعة الليزرية من خلال استخدام محرك ذاتي الحركة يسيطر على حركة عدسة تغيير البؤرة لموسع الحزمة وفقا لنسبة التوسيع المطلوبة لموسع الحزمة.

1. Introduction

Some applications require a laser beam with low divergence angle. To reduce divergence angle we must expand the waist of the beam. This could be achieved by expanding a laser beam with a beam expander which consists of two lenses. First, the beam is diverged with a short focal length lens and then the diverging beam is re-collimated with a large beam waist and smaller divergence. The lenses are positioned like in an inverted telescope. The light centers in the eyepiece lens and emerges from the objective lens [1], as in figure (1).

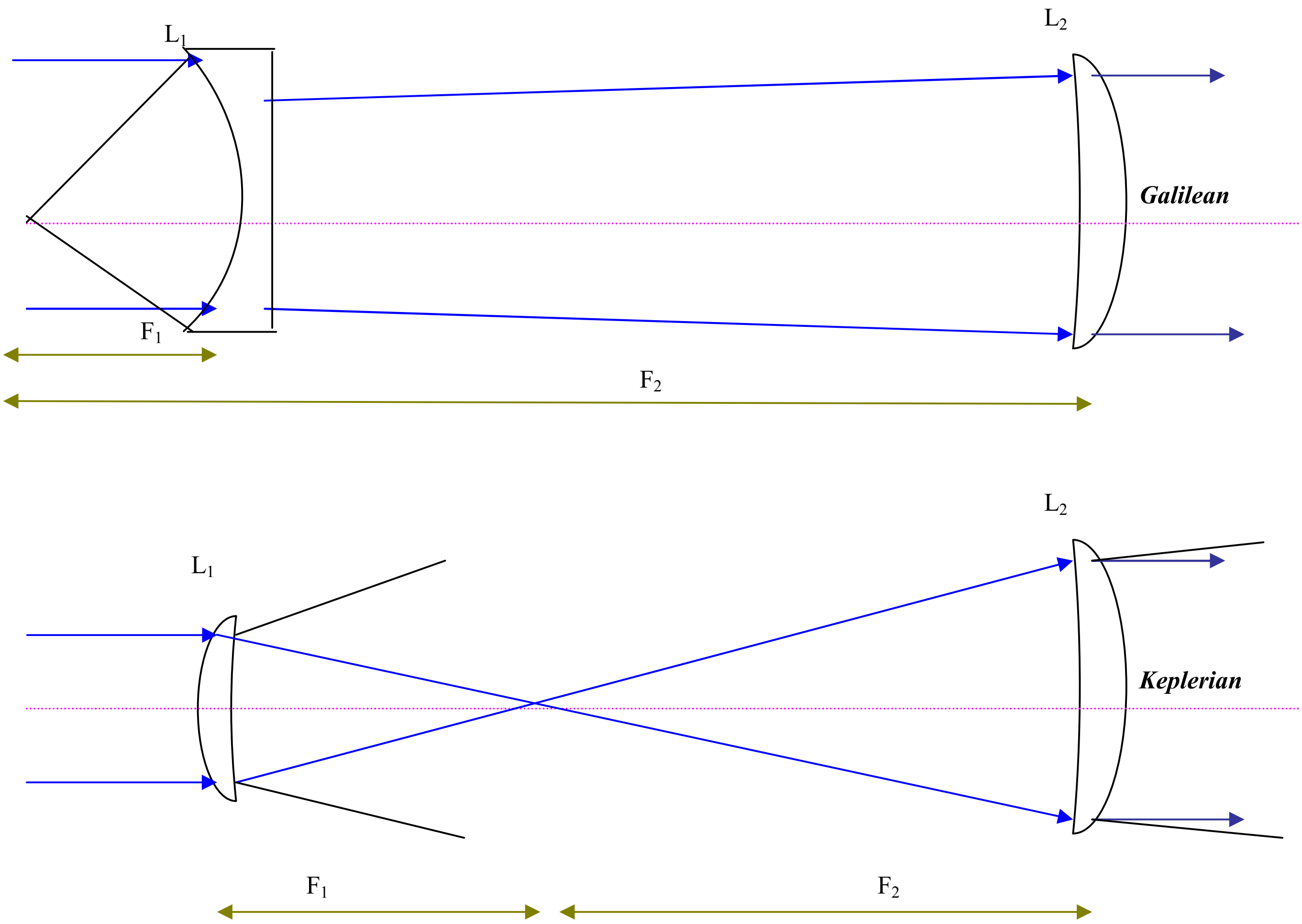

Figure (1) illustrates kinds of fixed beam expander.

After pas
divergence divided by the expansion ratio, ℵ, of the beam expander F_2 / F_1.

2. Fixed Beam Expander Design

Fixed beam expander is composed of i.e. two positive lenses or one positive and the other is negative, at least with different focal lengths and diameters. The first lens is denoted by L_1, and its diameter is D_1. D_1 should meet the condition:

$$D_1 \geq 2 W_o \qquad \ldots\ldots \ldots (1)$$

where W_o is the diameter of laser spot at the beam waist.
and its focal length is F. Generally, F– number of the lens, F#, is given as [2]:

$$F\# = F / D \qquad \ldots\ldots\ldots\ldots\ldots (2)$$

where F, D are focal length and diameter of the lens, respectively.
Combining Eqs. (1), (2) to be solved for F_1, yields:

$$F_1 \geq 2 W_o F\# \qquad \ldots\ldots (3)$$

The second lens is denoted by L_2, and the lens diameter is D_2, and its focal length is F_2 .Expansion ratio or magnification factor, ℵ ,of beam expander is given by [3]:

$$\aleph = \frac{F_2}{F_1} = \frac{D_2}{D_1} = \frac{\theta_i}{\theta_f} \qquad \ldots\ldots (4)$$

Where θ_i, θ_f are laser beam divergence of fist and second lenses, respectively, Solving Eq. (4) for F_2, yields:

$F_2 \geq ℵ F_1$ ……… (5)

Solving Eq. (4) for D_2 yields:

$D_2 \geq ℵ LD_1$ ………. (6)

So, beam expander length, BEL, is given as:

$BEL \geq F_1 + F_2$ ……….. (7)

Or

$BEL \geq 2 W_o F\# (1 + ℵ)$ …….(8)

3. Applying beam expander to LDTS

Applying beam expander to transmitting unit of **L**aser **D**etection and **T**racking **S**ystem, LDTS, which uses quadrant photodetector (QPD), is useful in decreasing system dimensions and meeting tracking criteria [4] which are:

(a) Target image spot radius, r_s, should be smaller than quadrant photodetectors radius, r_d.

(b) Target image spot radius, should be larger than quadrant photodetectors metallurgical separation between each two segments.

Two different lasers for comparison are applied, Nd: YAG and HF see figure (2). For laser of interest, namely Nd: YAG, whose its specifications are given in appendix A, it is clear that at ℵ =13, laser spot diameter on target surface, W(R), reaches its minimum limit, and any increase in ℵ doesn't corresponding any remarkable decrease in spot radius on target surface, but there is increase in objective lens of beam expander.

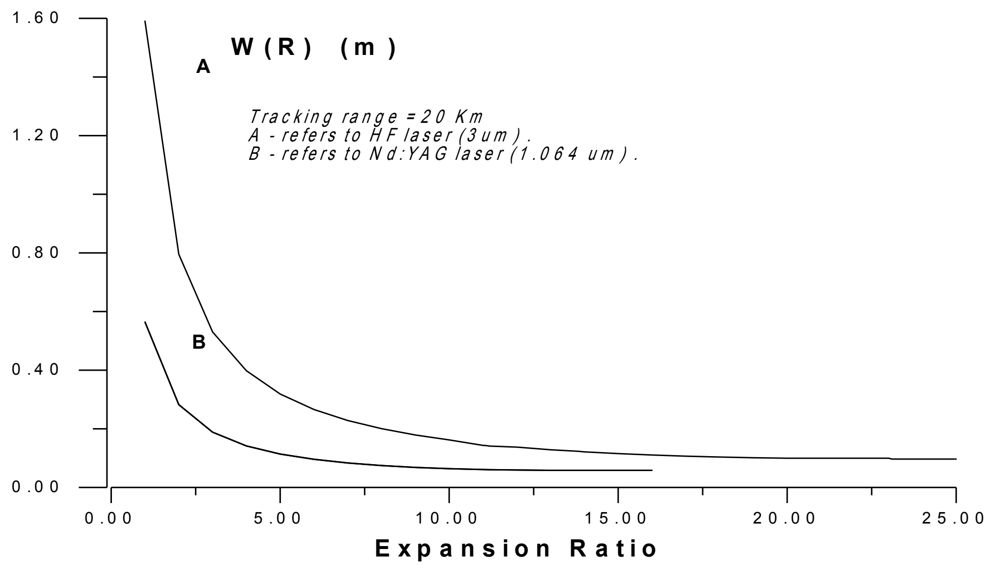

Figure (2) shows decreasing laser beam diameter at the target, W(R), at R_{max} for different wavelengths verses increased ℵ.

Table (1) shows the effect of applying beam expander on transceiver parameters for the following data: R_L = 1 KΩ, F# = 1.2, R_{max} = 20 Km, Pb = 1 μW, T = 300°K, L=7m, $C_n = 1.8 \times 10^{-6}\ m^{-1/3}$

As laser beam expander expansion ration, ℵ, increases:

- Objective lens of beam expander diameter increases.
- Laser beam divergence decreases, so that the spot diameter at the target will be decreased according to the following equation:

$$W(R) = w_o ℵ \sqrt{1 + \left(\frac{\lambda R}{\pi \left(\frac{w_o}{2} ℵ \right)^2} \right)^2} \quad \text{……. (9)}$$

- Laser spot irradiance on target surface at R_{max} increases, so P(r) will be greater according to the following equation:

$$P(r)=\frac{4E_{laser}\sigma_t A_c \tau_a^2 \tau_{to}\tau_{ro}\aleph}{\pi^2\theta_f^2\tau_{laset}R^4} \quad \text{... …….. (10)}$$

Hence receiving lens diameter, D_c, decreases; so that the area of receiving lens, A_c, will be decreased according to the following equation:

$$A_c \geq \frac{\pi^2(S/N)NEP\,\theta_f^2\tau_{laser}R^4}{4E_{laser}\sigma_t\tau_a^2\tau_{to}\tau_{ro}\aleph} \quad \text{…….. (11)}$$

4. Protecting Receiving Unit at Short Ranges

One can modify fixed beam expander design by adding a third lens , see Figure (3) , which will be negative , denoted by Fz and motorized to give expansion ratio , ℵ=13 ,
Motorized beam expander calculations are given as follows [5]:

$$\aleph=\frac{F2}{F_{eq}} \quad \text{……………………………… (12)}$$

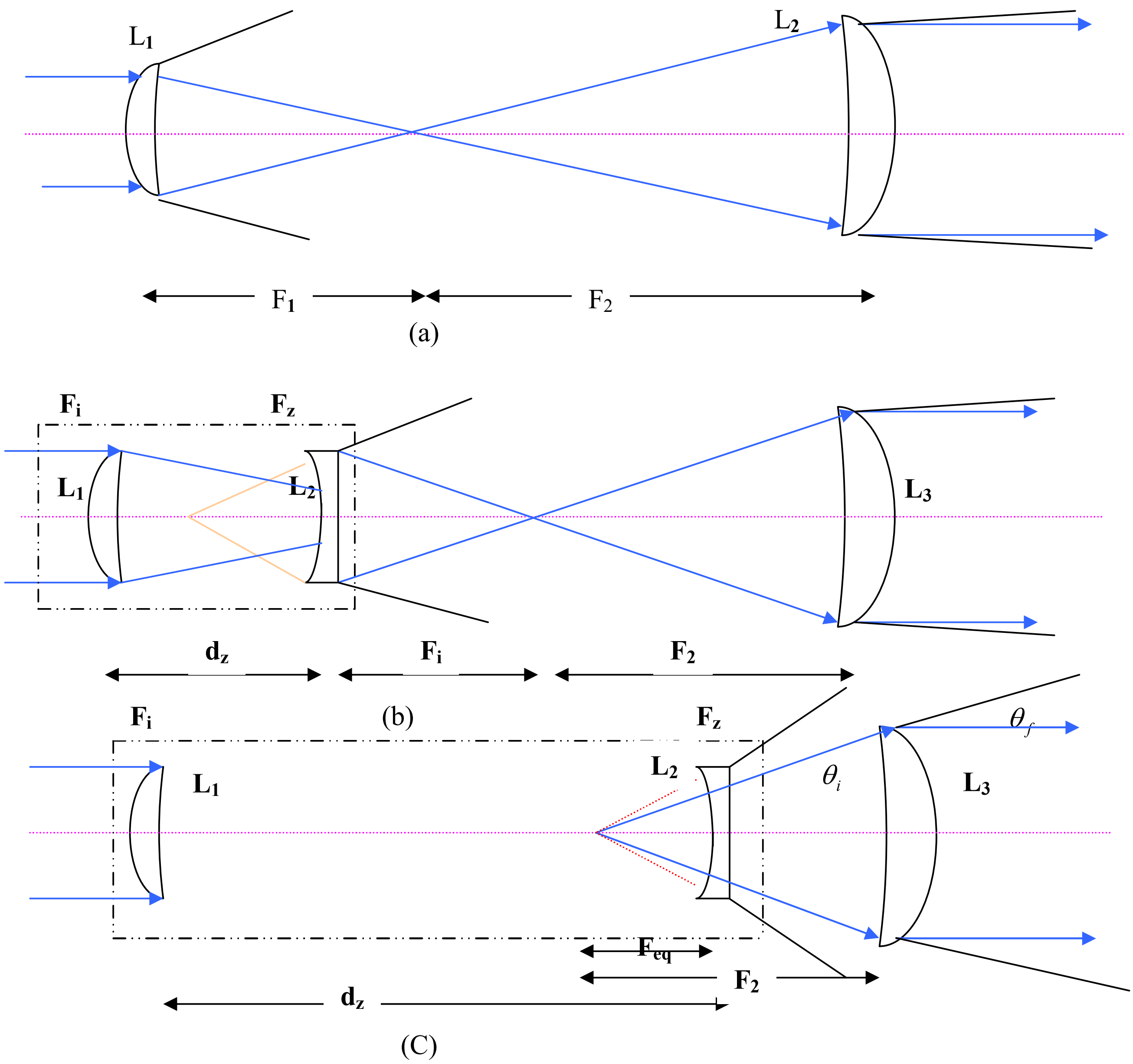

Figure (3) illustrates beam expander. (a) Fixed one with ℵ =13. (b) Zoom one with ℵ = 13. (C) Zoom one with ℵ = 1.

Where F_{eq}: Equivalent focal length of the ocular, F_1, and F_z focal lengths which is given as:

$$\frac{1}{F_{eq}} = \frac{1}{F_1} + \frac{1}{F_Z} - \frac{d_Z}{F_1 F_2} \qquad (13)$$

For given separation, d_Z, between ocular lens L_1 and L_2, one can solve Eq. (12):

$$F_z = \frac{F_{eq}(F_1 - d_z)}{(F_1 - F_{eq})} \qquad (14)$$

Since expansion ratio is given as:

$$\aleph = \frac{F_2}{F_{eq}} = \frac{\theta_i}{\theta_f} \qquad (15)$$

So, moving L_2 to the right towards L_3 will change F_{eq} due to change d_z, hence ℵ will get lower.

Solving Eq. (4) for θ_f yields:

$$\theta_f = \frac{F_{eq}}{F_2}\theta_i \qquad (16)$$

The equation above shows that laser beam divergence will be greater as L_2 moves towards L_3. This technique will saturate at short ranges.

At short ranges, required expansion ratio approaches $\aleph = 1$, in this case L_2 will move a distance, x, to the right towards L_3.

Figure (4) shows required distance, x, that L_2 should move as range decreases.

Knowing saturation intensity of PIN QPD leads to specify the range at which zooms beam expander should be operated for zooming. If we suppose that saturation intensity for a given area of PIN QPD is ($5\mu J/cm^2$), so LDTS should command zoom beam expander to be operated before the photodetector gets saturated, namely at R = 3.1 Km, intensity is ($4.828\mu J/cm^2$), see figure (5).

At R=3.1 Km, S/N=16681 for $\aleph = 13$, but for $\aleph = 1$, S/N =7.59 at which intensity is ($2.204286\ nJ/cm^2$), see figure (6).

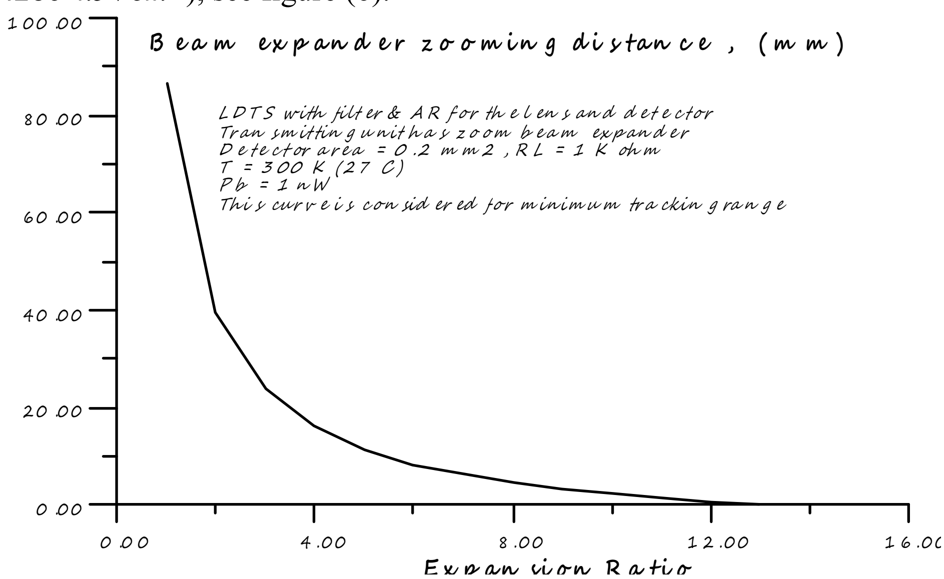

Figure (4) Shows decreasing ℵ of zoom beam expander versus the distance that zoom lens should be moved to maintain ℵ = 1.

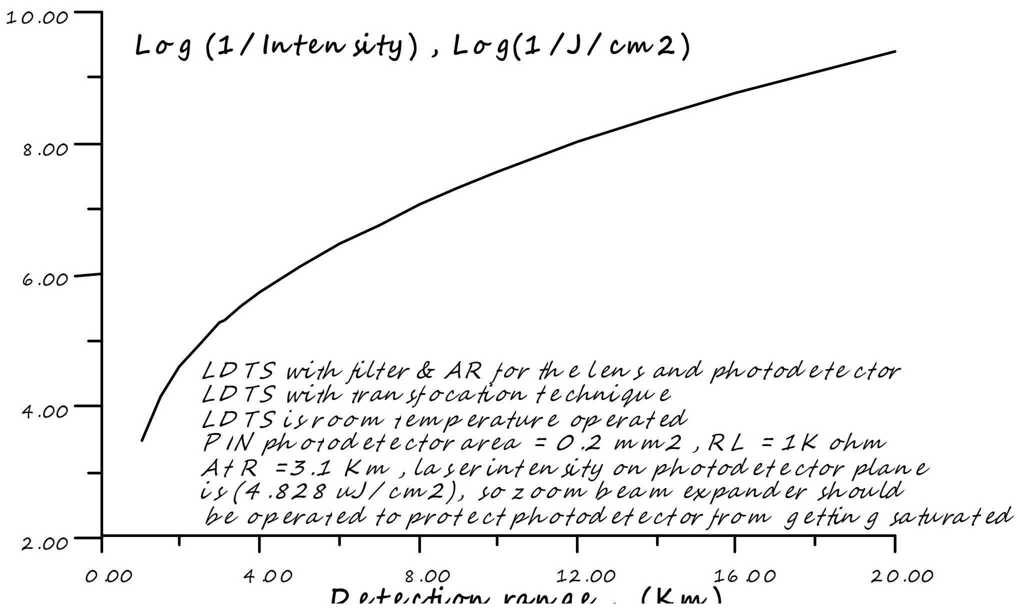

Figure (5) Shows decreasing detection range versus the received signal intensity.

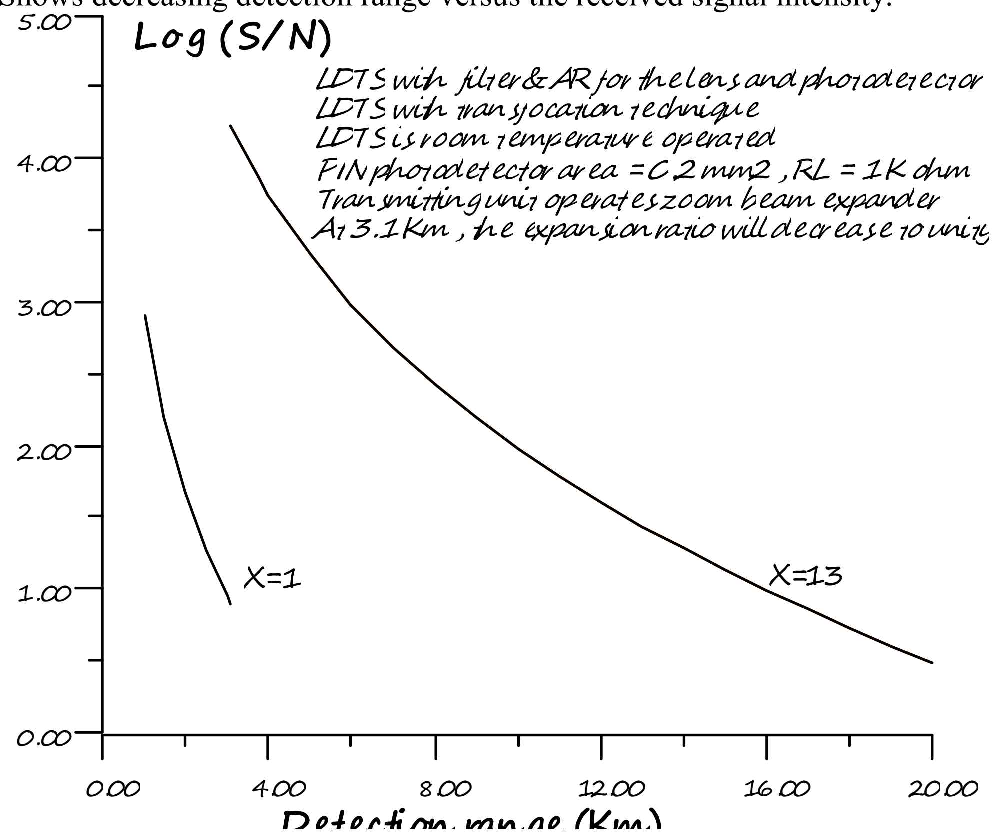

Figure (6) Shows decreasing $\aleph$ detection range versus S/N for $\aleph = 13$ and $\aleph = 1$.

Table (1) shows the effect of applying beam expander on transceiver parameters.

Parameter	Photodetector's area			
	0.2 mm^2		2.0 mm^2	
	ℵ =1	ℵ =13	ℵ =1	ℵ =13
D_C (m)	27.66	590.26	15.427	15.42
r_S(mm)	32.6854	0.49631	14.671	14.80524
r_S / r_d	129.569	1.967419	18.555	18.555
$D_{Surveillance}$	0.3039 m	14.24 m	1.272 m	1.72 m
Tracking Case	Failure	Failure	Failure	Success

4.Conclusion

It's found that $\aleph = 13$ is the limit at which of expansion ratio of beam expander approaches its minimum value for Nd: YAG laser limit of expansion ratio of beam expander for Nd: YAG laser wavelength, $\lambda = 1.06\ \mu m$ at which laser beam diameter at the remote target is at its minimum value. Using motorized or zoom beam expander with $\aleph = 13$, at R_{max} and $\aleph = 1$ at R_{min} for achieving tracking mode for flying remote target heading to LDTS , namely for near and far tracking system.

Decollimation could be achieved by automatic motor, controls zoom lens of beam expander by software receives its commanding signal from a range finder, attached to LDTS, supplies range data at which the received power flux approaches the limit which causes photodetector saturation.

Appendix A

Laser transmitting unit, has the following data:

a. Crystal is Nd: YAG.
b. Wavelength is $\lambda = 1.06\ \mu m$.
c. Pulse energy is E_{laser}= 0.2 J.
d. Pulse duration is $\tau_{laser} = 8\ n\sec$.
e. Pulse repetition rate is 20 Hz.
f. Beam diameter w_o =6 mm.

4. Nomenclature

QPD Quadrant photodetector.
L_l Load resistance attached to QPD.
P_b Background Noise Power.
T QPD's operating temperature.
L Target's length.
C_n^2 Atmospheric scintillation index.
σ Target's scattering cross-section.
τ_a Atmospheric transmittance.
τ_{to} Transmittance of transmitting unit.
τ_{ro} Transmittance of receiving unit.
NEP Noise Equivalent Power.
S/N Signal to Noise ratio.
X Beam Expander Zooming distance.

7. References

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