# Transfocation Technique to Overcome Atmospheric Scintillation Effect on a Laser Detection and Tracking System (LDTS)

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**Abstract**

Atmospheric transmission is disturbed by scintillation, where scintillation caused more beam divergence. In this work target image spot radius was calculated in presence of atmospheric scintillation. The calculation depend on few relevant equation based on atmospheric parameter (for Middle East), tracking range, expansion ratio of applied beam expander's, receiving unit lens F-number, and the laser wavelength besides photodetector parameter.

At maximum target range $R_{max}$ =20 km, target image radius is at its maximum $R_s$=0.4 mm. As the range decreases spot radius decreases too, until the range reaches limit (4 km) at which target image spot radius at its minimum value (0.22 mm). Then as the range decreases, spot radius increases due to geometric optical law. So tracking is possible only in the range from 3 to 11 km, depending on tracking criteria. Target image size minimized to required ratio by using transfocation technique to overcome tracking filler, this technique uses zoom lens.

We find that atmospheric scintillation is affective parameter which reduced the maximum tracking range, and to avoid tracking failure at minimum and maximum range, the transfocation technique is suitable.

**Keywords**
*Laser application*
*Atmospheric scintillation*
*Laser tracking*

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## استعمال تقنية البؤرة المتغيرة للتغلب على تأثير التلألؤ الجوي على منظومة كشف وتتبع ليزرية

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**الخلاصة**

يؤثر التلألؤ الجوي على نفوذية الجو حيث يعمل على زيادة انفراجية الحزمة. في هذا البحث تم حساب نصف قطر صورة هدف جوي حيث أخذ تأثير التلألؤ الجوي بنظر الاعتبار. وأن عملية الحساب اعتمدت على عدد من العلاقات الرياضية التي تستند على معلمات الجو حيث اعتمدت معلمات جو الشرق الأوسط، علماً أن الحسابات تتطلب معرفة مدى التتبع ونسبة التوسيع لموسع الحزمة و F-number لعدسة المستقبلة والطول الموجي لليزر المستعمل بالإضافة إلى معلمات الكاشف الضوئي. ولقد وجد عند اقصى مدى 20km اكبر نصف قطر للصورة هو 0.4mm. وقطر الصورة يتناقص مع نقصان المدى إلى أن تصبح قيمته 0.22mm عند المدى 4km وهو اصغر نصف قطر للصورة. وعندما يتناقص المدى إلى أقل من ذلك فأن نصف قطر الصورة يبدأ بالازدياد طبقا لقوانين البصريات الهندسية. لذلك فأن التتبع للهدف ممكن فقط عند المدى من 3-11km اعتمادا على معايير التتبع.

ولغرض المحافظة على نصف قطر ثابت لصورة الهدف عند المديات القريبة والبعيدة لتجنب الفشل الذي قد يحدث لعملية التعقب بفعل خروج نصف قطر صورة الهدف عن الحد المطلوب تم استعمال تقنية البؤرة المتغيرة. ومن

خلال الحسابات وجد أن التلألؤ الجوي ذو تأثير كبير على التتبع ويعمل على تقليل المدى الأعظم. وأن تقنية البؤرة المتغيرة مناسبة لذلك.

## Introduction

Tracking process began since the birth of life when human being was going for hunting. At that time the tracking system was in a simplest form where the eye played the role of tracking system. The tracking system became more complicated with the development of science. Tracking system has received considerable attention in recent years and several designs of such systems are given in the literature. Cook [1] and M. Staron [2] in 1972 made an automatic laser tracking and ranging system. Thomas in 1975 [3] applied linear quadratic optical estimation and control to design process controller.

Yang Xuanhai in 1986 [4], presented a relationship between target image spot size and tracking sensitivity to solve the technical problems in auto tracking technology. Hisham, Abdul Mulik in 2005 [5] conduct analytical study for simulating laser detection and tracking system. Chang Lee in 2009 developed a laser tracking system for a robotic tower crane [6]. Also in 2009 Shenzhen study a laser tracking system for laser atmospheric communication [7].

The aim of present work is to deducing target spot size formed by laser detection and tracking system (LDTS) (which is the receiving unit for this system consist from receiving lens to collect the target radiation and quadric photodetector (QPD) to detect the target radiation) in presence of atmospheric scintillation effect, where in case of target image spot size larger than quadrant photodetectors' active area, a tracking failure may take place. In this work we suggest a transfocation technique to solve this problem.

## Theory

Atmospheric transmission is disturbed by refraction and scintillation. Atmospheric turbulence causes fluctuate in the intensity of laser beam propagation the atmosphere [8]. The turbulence consists of fluctuations in the refractive index of air which is caused by temperature fluctuations and gradients. Since variation of atmospheric temperature along the transmission path gives rise to refraction of the beam, so continual changes in this refraction give rise to scintillation, an effect commonly seen as the twinkling of stars. Scintillation caused more beam divergence [9].

### A) Target image spot size and scintillation effect:

Tracking process is affected by some factors like LDTS field of view, minimum tracking range (R) and tracking criteria which can be divided into two parts [10]:

i) Target image spot radius should be smaller than quadrant photodetectors' (QPD) radius ($R_d$).
ii) Target image spot radius ($R_s$) should be larger than metallurgical separation between two segments of (QPD).

Minimizing field of view (FOV) imply by minimizing background noise, securing detecting and tracking target. Minimizing quadrant photodetectors' area, hence its diameter this will lead to enlarged receiving lens diameter [11], hence long focal length for given F-number
(F-Number = F/D), where D receiving lens diameter and F lens focal length [12].

Target image spot size is the core of tracking criteria. Combining a few relevant equations biased on atmospheric parameters (tracking range, expansion ratio of applied beam expander, receiving unit dimensions, and laser wavelength) and photodetectors' response time which are constitute a solid base for deducing target image spot size in presence of atmospheric scintillation.

The minimum angular size of the target $\gamma_{min}$ at maximum range $R_{max}$ is given as:

$$\gamma_{min} = L\theta / R_{max} \qquad \text{--------------(1)}$$

where L = Targets' length

θ = Aspect angle.

So, target image spot size $S_A$ on photodetectors' plane is:

$$S_A = \gamma_{min}(\text{rad}) \times \text{Focal length for receiving unit} \text{-- (2)}$$

When there is no scintillation effect.

Radius of target image spot $S_A/2$ on the photodetectors' plane could deduced as follow [13].

$R_s$ =2F/ k $\sqrt{\eta(1+\beta)}$ ----------- (3)

where F = The focal length of the receiving lens.

k= Wave number which is given as $2\pi/\lambda$

λ = Laser wavelength.

β is given as:

$$\beta = \frac{2\xi\gamma^2 k^2}{\eta(16\xi + k^2\gamma^2)} - - - - - - (4)$$

where η is given as

$$\eta = \frac{k^2 r_n^2}{4R^2} + \frac{1}{r_n^2} + 0.1(k^2 C_n^2 R)^{\frac{6}{5}} - -(5)$$

where $r_n$ = Radius of receiving lens

$C_n^2$ = Scintillation index, which is a measure of variance of refractive index,

$C_n$ = $1.8\times10^{-6}$ $m^{-1/3}$ for strong turbulence in Middle East.

ξ is given as

$$\xi = \frac{1}{r_u^2} + \frac{1}{\rho_1^2} + \frac{k^2 r_u^2}{4R^2} +$$

$$0.1(k^2 C_n^2 R)^{\frac{6}{5}} - - - - - - - - (6)$$

where $r_u$ is beam radius on the output lens of the transmitting unit.

$\rho_1$ is primary radius of coherent laser beam after passing the beam expander, which is given as:

$\rho_1=2\chi/\theta_i k$ ---------------------- (7)

where $\theta_i$: initial laser beam divergence.

χ: beam expansion ratio.

**B) Transfocation technique:**

This technique uses zoom lens to minimize target image size to a required ratio. Zoom lenses that give the same target image spot size (unity design) consist of three lenses $L_1$, $L_2$ and $L_3$ besides the receiving objective lens L. Two of them are positive ($L_1$ and $L_3$) and one is negative, $L_2$. Lens $L_1$ and $L_2$ are separated by a distance $d_1$. Focal length of $L_1$, $L_2$ and $L_3$ are given as $F_1$, $F_2$ and $F_3$ respectively, as shown in Fig. (1).

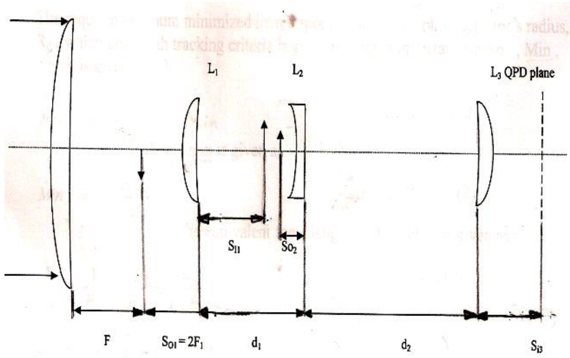


*Fig. (1): Transfocation technique zoom lens.*
*Lens $L_1$ can form an image the same as the object (the image formed by receiving objective lens L, can be considered as an object for $L_1$) provided that the distance between the image formed by L and $L_1$ is $2F_1$ and lies to the left of $L_1$.*

$$\frac{1}{F_1} = \frac{1}{S_{o1}} + \frac{1}{S_{i1}} - - - - - - (8)$$

where $S_{o1}$: Object distance from L1.

$S_{i1}$: Target image distance.

For $S_{i1} = 2F_1$ $- - - - - - -(9)$

Substituting Eq.(8) into Eq. (9) and solving it for $S_{i1}$ , yield

$$S_{i1} = S_{o1} - - - - - - - - - (10)$$

Magnification of $L_1$ is:

$$M_1 = -\frac{S_{i1}}{S_{o1}} - - - - - - (11)$$

$$M_1 = -1$$

Target's image spot radius formed by L1 is:

$$R_{s1} = R_s \times M_1 - - - (12)$$

The image spot formed by $L_1$ is real, lies on the right of $L_1$, inverted and has the same size of object size. The image spot of lens $L_1$can are considered as an object for $L_2$, so the distance between image formed by lens$L_1$ and lens $L_2$ is $S_{o2}$ which can calculate as:

$$S_{o2} = d_1 - S_{i1} - - - -(13)$$

Also

$$\frac{1}{F_2} = \frac{1}{S_{o2}} + \frac{1}{S_{i2}} - - - -(14)$$

Substituting Eq.(13) into Eq.(14) and solving it for $S_{i2}$, yield:

$$S_{i2} = \frac{F_2(d_1 - S_{i1})}{d_1 - S_{i1} - F_2} - - - (15)$$

Magnification of $L_2$ is:

$$M_2 = -\frac{S_{i2}}{S_{o2}} - - - - - - - - (16)$$

Substituting Eq.(15) into Eq.(16), yield:

$$M_2 = -\frac{F_2(d_1 - S_{i1})}{S_{o2}(d_1 - S_{i1} - F_2)} - -(17)$$

So image spot radius formed by $L_2$ is:

$$R_{s2} = R_{s1} \times M_2 - - - -(18)$$

This image is virtual, lies on the left of $L_2$, minimized and erect.

Since we want to get a target image spot size as same as that formed by $L_1$, magnification of $L_3$ should be the reciprocal of that of $L_2$, namely:

$$M_3 = -\frac{1}{M_2} - - - - - (19)$$

Also

$$M_3 = -\frac{S_{i3}}{S_{o3}} - - - - - -(20)$$

where $S_{o3}$ is the distance of the image formed by lens $L_2$ from lens $L_3$, and this distance considered object to $L_3$. Solving Eq.(20) for $S_{i3}$ yields:

$$S_{i3} = M_3\, S_{o1} - - - -(21)$$

$$\frac{1}{F_3} = \frac{1}{S_{o3}} + \frac{1}{S_{i3}} - - - (22)$$

Substituting Eq.(21) into Eq.(22), and solving it for $S_{i3}$, yield:

$$S_{i3} = F_3\,(M_3 + 1) - - - (23)$$

Since

$$S_{o3} = S_{i2} + d_2 - - - (24)$$

So,

$$d_2 = S_{o3} - S_{i2} - -(25)$$

where $d_2$ is separation between $L_2$ and $L_3$.

Image spot radius formed by $L_3$ is:

$$R_{s3} = R_{s2} \times M_3 - - - (26)$$

## Design, calculations and results

### 1- Given data

The basic requirements for proposed LDTS designs are based on the following given data:

A) Target parameters

- The maximum range to the target 20 km.
- Target length 7 m.
- Target linear speed 0.9 M (M = target velocity / sound velocity).

B) Laser emitter parameters:

- Laser type Nd-YAG.
- Laser wavelength 1.06 μm.
- Impulse energy 0.2 J.
- Impulse duration 8 ns.
- Radiation beam divergence 10mrad.
- Output beam diameter from active crystal 6 mm.
- Impulse repetitive frequency 20 Hz.
- Beam expander expansion ratio 13.

C) Receiving unit

- Focal length of receiving lens 330 mm.
- Lens F- number 1.2.
- Photodetector type (PIN –quadrant photodetector).
- Photodetector diameter 0.5 mm (A = 0.2 $mm^2$).

D) Scintillation index $C_n$ =1.8 × $10^{-6}$ $m^{-3}$.

E) Aspect angle ± 20°.

### 2- Target image spot radius $R_s$ verse target range R calculations and discussions.

From Eqs.(3-7) and given data target image spot radius calculated in presence of atmospheric scintillation. Fig.(2) it is shown the dependence of target image radius $R_s$ on the range to target R. From Fig.(2) it follows that at decreasing of range to target its size at the beginning becomes to decrease due to decreasing of atmosphere turbulence influence and reach its minimum value 0.22 mm (Rs = 0.22 mm) at the range about 4 km. At further decreasing of range to target the image size becomes to increase quickly in compliance geometric optics laws. So tracking is possible only in the target range from 3 km to 11 km depending on tracking criteria, where the target image spot size in the plane of (QPD) is small than the photodetector areas, all values lower than one, for Rs/Rd, see Fig. (3).

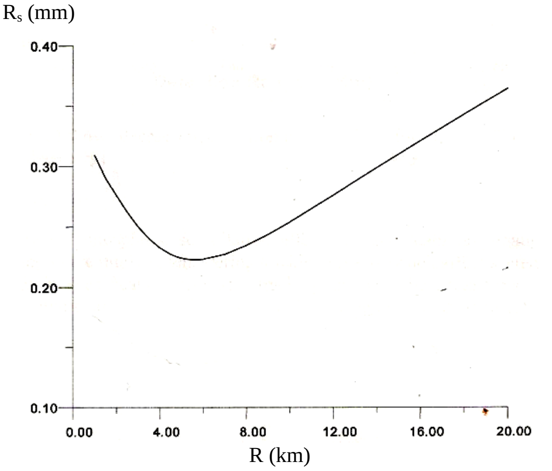


*Fig. (2): Target image spot radius Rs (mm) function to target detection range R (km) with atmospheric scintillation effect.*

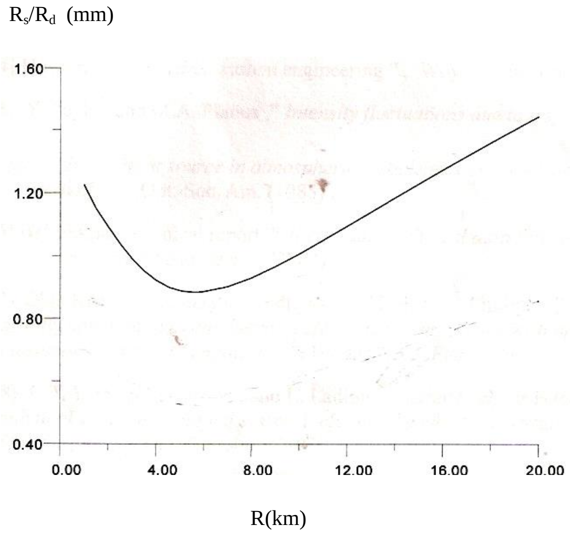


*Fig. (3): Target image spot radius and (QPD) radius ratio ($R_s/R_d$) function to target detection range R (km) with atmospheric scintillation effect.*

## 3- Transfocation technique calculation for meeting tracking criteria.

At maximum target range Rmax target image spot is at its maximum size on photodetectors' plane due to atmospheric scintillation. As the range decreases, spot size decreases too, until the range reaches limit at which spot size is at its minimum value because the atmospheric scintillation is at its minimum value too. Then as the range decreases, spot size increases due to geometrical optical law.

Zoom lens which gives unity size should be adjusted to the required minimization ratio, Min, to meet tracking criteria at maximum and minimum range Min is given as [13]

$$M_{in} = \frac{R_s''}{R_s}$$

where $R_s''$ : Required spot radius at curve bottom with zoom lens.

$R_s$ : Actual spot size at curve bottom without zoom lens.

Also

$$M_{in} = \frac{r_{opt}}{R_d}$$

where $r_{opt}$: The optimum radius of the target image in the plane of (QPD).

$R_d$: The radius of the active area of the (QPD) [4].

$$r_{opt} = \frac{R_d}{2\sqrt{2}}$$

$$M_{in} = \frac{R_d/2\sqrt{2}}{R_d}$$

$$M_{in} = \frac{1}{2\sqrt{2}} = 0.35$$

Also

$$M_{in} = -\frac{S_{i3}}{S_{o3}}$$

Where $S_{i3}$ : Image distance from $L_3$. $S_{o3}$ : Object distance from $L_3$.The calculated zoom lens parameters which are meet tracking criteria shown in Table (1).

*Table (1): Zoom lens parameters value to meet tracking criteria, at long and short range.*

| $F_1$ mm | $F_2$ mm | $F_3$ mm | $d_1$ mm | $d_2$ mm | $S_{o1}$ mm | $S_{i3}$ mm | $M_{in}$ |
|---|---|---|---|---|---|---|---|
| +50 | -50 | +50 | 124.22 | 80.7 | $2F_1$ | 36.2 | 0.35 |

## Conclusions

From our result we conclude the following:

1- Atmospheric scintillation is affective parameter in laser tracking system.

2- Scintillation index $C_u$ in medal east has large value, so that limits the maximum tracking range in (LDTS) to about 11 km.

3- The receiving optical system of (LDTS) should have unit for changing target image size in the admissible range to avoid tracking failure in minimum range and maximum range.

## References


[1] Cook, C. R. "Automatic Laser Tracking System", Sylvania Ins.: Applied Optics, 11 (2), (1972), 60.

[2] Staron, M.., "Control Optimization of a Laser Automatic Tracking System Influence of the Space-Time Returns of the Echoes": Applied Optics, 11 (2), (1972),95.

[3] Thomas, Y.A., "Linear Quadratic Optical Estimation Control with and Recording Horizon": Electronics Letter, 11 (1) (1975).

[4] Yang, M. "The Design of Echo and Optical Focusing in Automatic Laser Tracking": Opt. L. Tech., 18 (2), April (1986).

[5] Hisham, A. M.: "An Analytical Study on a Laser Detection and Tracking System" Ph.D. Thesis submitted to the Al-Rasheed College of Engineering and Science, University of Technology (2005).

[6] Ghang L. , Hong-Hyun K., Chi-Joo L., Sung-Il H., Seok-Heon Y., Hunhee C., Bong Keun K., Gu Taek K., Kyunghwan K.," A laser-technology-based lifting-path tracking system for a robotic tower crane": Automation in Construction, 18(2009) 865-874.

[7] Li Da S., Naichang X., Huazhen, "Study of APT system for laser atmosphere communication" APCIP, vol. 2 (2009) 517-520. Asia Pacific Conference on Information Processing 2009.

[8] Druse, P. W. "Elements of Infrared Technology: Generation, Transmission and Detection", John Wiley and Sons, Inc., New York (1962).

[9] Gowar, J. “Optical Communication System Prentice", Hall International Series in Optoelectronics, Second Edition (1993).

[10] Olg, K., Lary, C. A., and Roland, L. Ph., "Model for Partially Coherent Gaussian Beam in Atmospheric Turbulence with Application in Laser" Com. Optical Engineering, 43(2), Feb.(2004).

[11] Christian, G. B., "Laser Radar SystemTechniques" Massachuestts, Willington (1978).

[12] Hudson, Jr., "Infrared System Engineering", John Wiley and Sons, Inc., New York (1968).

[13] [13]Belorussian Technical Report, "Tactics and Technical data for Calculation of Laser Tracking System", (2002).