Influence of Atmospheric Propagation on Performance of Laser Active Imaging System

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Abstract. Atmospheric propagation has serious influence on the performance of a good designed laser active imaging system. Atmospheric attenuation and turbulence are two main effects on laser atmospheric propagation. Imaging SNR (Signal-Noise-Ratio) and resolution are two key indexes to describe the performance of a laser active imaging system. Establishing the relation between system performance index and atmospheric propagation effect is significant. The paper analyzed the relation between imaging performance and atmospheric attenuation and turbulence through simulation. And also the experiments were done under different weather to validate the conclusion of simulation.

Key words: Laser active imaging system, Atmospheric propagation, Imaging performance

1. Introduction
Because of scattering and absorption of atmospheric aerosols and atmospheric elements, and also haze, fog, snow and rain, laser energy declines a lot through atmosphere. Atmospheric turbulence causes the laser beam deflection, jitter, intensity fluctuations (blinking) and other effects, so that laser beam quality gets worse¹. All this make the performance of laser active imaging system worse. Laser image can reflect how atmosphere propagation influenced. Studying the relation between image quality and atmosphere was important. In this paper, the relation between atmospheric visibility and turbulence and image quality was studied by simulation. Experiments were done under different weather to validate the conclusion of simulation.

2. Laser Atmospheric Propagation
2.1. Laser Atmospheric attenuation
Horizontal propagation atmospheric attenuation can be described by transmittance as follow:
\[
\tau(\lambda) = \exp\left[-\mu(\lambda) \cdot L\right]
\] (1)

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Here L is distance, \(\mu(\lambda)\) is attenuation coefficient, \(\mu(\lambda) = \alpha(\lambda) + \beta(\lambda)\), \(\alpha(\lambda)\) and \(\beta(\lambda)\) are absorption coefficient and scattering coefficient.
In application, atmospheric transmittance can be calculated through experiential formula which described by visibility. Visibility was defined as follows

\[ V_M = \frac{3.912}{\beta} \]  

(2)

\( \beta \) is total extinction coefficient in 0.55 \( \mu m \) wavelength. The relation between Attenuation coefficient and \( V_M \) is as follow:

\[ u = \frac{3.912}{V_M} \left[ \frac{0.55}{\lambda} \right]^b \]  

(3)

Here \( V_M \) is visibility, \( \lambda \) is wavelength, and

\[
\begin{array}{c|c}
V_M & b \\
\hline
\geq 50\text{km} & 1.6 \\
6\text{km} \leq V_M < 50\text{km} & 1.3 \\
1\text{km} \leq V_M < 6\text{km} & 0.16V_M + 0.34 \\
0.5\text{km} \leq V_M < 1\text{km} & V_M - 0.5 \\
V_M \leq 0.5\text{km} & 0 \\
\end{array}
\]  

(4)

We can use this formula when \( \lambda = 0.35 \sim 1.54\mu m \).

For computational purposes, we suppose target distance is 3km and 5km, the relation between transmittance and \( V_M \) is as follow:

![Figure-1: Transmittance as a function of \( V_M \) for 3km and 5km](image)

### 2.2. Atmospheric turbulence

Turbulence causes atmospheric refractive index stochastic changes. The value of change is \( 10^{-6} \), and turbulence has a big influence on laser far distance propagation. Turbulence can be described by Kolmogorov model as usual. In local even area, atmospheric refractive index structure function \( D_n(r) \) is as follow:

\[ D_n(r) = C_n^2 r^{2/3} \quad (l_0 << r << L_0) \]  

(5)

\( r \) is the distance of two statistical points, \( l_0 \) \( L_0 \) is inner scale and outer scale, \( C_n^2 \) is the refractive index structure parameter, which is essential parameter of atmospheric optics. It can show turbulence intensity. The value of \( C_n^2 \) is little, and turbulence intensity is weak. The value of \( C_n^2 \) is changing with place, altitude, weather and season, etc.
Laser propagation through turbulence atmosphere, the intensity, phase, propagation direction, etc, get random changes. Here simulated the laser fluctuation in different turbulence using phase screen\(^2\). The propagation distance is 10km.

3. Influence of laser atmospheric propagation on the performance of imaging

3.1. The decline of SNR

Imaging SNR is an important index to judge a system. SNR is defined as follow

\[
SNR = \frac{Q_{\text{target, pix}}}{Q_{\text{backgr, pix}} + Q_{\text{bsc, pix}} + Q_{\text{noise, pix}}}
\]

Here, \( Q_{\text{target, pix}} \), \( Q_{\text{backgr, pix}} \), \( Q_{\text{bsc, pix}} \) are signal energy, background radiation energy and backscattered energy of every pixel. \( Q_{\text{noise, pix}} \) is the equivalent noise energy of ICCD.

Based on the theory of laser active imaging, SNR can be further described as follow\(^3\)

\[
SNR = \frac{P_i\Delta \tau \cdot T_e \cdot T_r \cdot \rho \exp\left(-2\sigma_{\text{e}} R\right)}{L_e \Delta \lambda \int \frac{R^2}{\pi} \exp\left(-2\sigma_{\text{e}} R\right) dR + \frac{Q_{\text{noise, pix}} \times f^2 N_p^2}{G \cdot A_p}}
\]

Here \( P_i \) is laser emitting power, \( T_e \) , \( T_r \) are emitting and receiving optical system transmittance, \( \rho \) is target diffuse reflection coefficient, \( \sigma_{\text{e}}(R) \) is total attenuation coefficient, \( R \) is distance, \( L_e \) is
background spectrum radiation brightness, $\Delta \lambda$ is optical filter bandwidth, $\Omega_r$ receiving system solid angle, $\rho_b$ is background average reflection coefficient, $R_1$ and $R_2$ are gate range, $A_r$ is entrance pupil area, $f$ is focus, $N_p$ ICCD resolution, $G$ ICCD gain.

From (7), signal energy and backscattered energy lose because of attenuation. At night, $f=800\text{mm}$, $N_p=60\text{lp/mm}$, $Q_{\text{noise, pix}}=6 \times 10^{-20}\text{J/pix}$, $R=5\text{km}$, SNR is a function of $V_M$ in different laser emitting power, graph as follow

![Figure 4: Relation between SNR and $V_M$](image)

From the simulation, $V_M<5\text{km}$, imaging quality is bad, even imaging system cannot work. With visibility getting better, SNR is getting better. When $V_M>20\text{km}$, current of improving draws bit. Another, when laser power decuple, SNR improves about 10 dB.

3.2. Imaging resolution declines through turbulence

We use MTF to judge the resolution decline when studying laser active imaging system resolution. Without considering system itself, because the time of range-gated is short, imaging integral time is less than the time of atmospheric fluctuation when imaging in atmosphere. Intensity and phase are both important when Far-field propagation. Based on the studying of Fried, $\text{MTF}_{\text{tur}}$ of Image blur which caused by atmospheric turbulence in short exposure is described as follow:

$$\text{MTF}_{\text{tur}}(F) = \exp\left\{ -3.44\left(\frac{\lambda f}{r}\right)^{5/3} [1 - 0.5(\frac{\lambda f}{D})^{1/3}] \right\}$$

Here $F$ is space frequency ($\text{lp/mm}$), $\lambda$ is wavelength, $f$, $D$ are focus and diameter of receiving optical system, $r$ is atmospheric coherent length, described as follow

$$r = 2.1\rho_0 = 2.1(1.46k^2C_n^2R)^{3/5}$$

Where $k=2\pi/\lambda$, $R$ is distance.

The strength of turbulence was classified in the following way:

- Weak turbulence: $1.0 \times 10^{-15}(\text{m}^{-2/3})$,
- Medium turbulence: $1.0 \times 10^{-14}(\text{m}^{-2/3})$,
- Strong turbulence: $1.0 \times 10^{-13}(\text{m}^{-2/3})$.

We simulate the graph of $\text{MTF}_{\text{tur}}$ through three turbulence above. $\lambda=0.532\text{um}$, $f=800\text{mm}$, $D=200\text{mm}$, target distance $R=5\text{km}$.

![Figure 5: Influence on imaging resolution through three classes turbulence](image)

It is evident that influence of atmospheric turbulence on imaging resolution is strong. For high frequency target, it is difficult to distinguish details from laser imaging through medium and strong
turbulence. For low frequency target, Image resolution declines acutely. Imaging quality through medium turbulence is about 60% less than that weak turbulence. Imaging quality through strong turbulence is about 90% less than that weak turbulence.

4. Experiment and analysis

4.1. Calculation of image SNR

Based on the character of laser active imaging, we use local area standard deviation to calculate image SNR. For digital image, signal intensity and image gray are linear relation in ICCD response range, so we could use gray to replace intensity to calculate. The ratio of average gray value and local area standard deviation is image SNR, steps as follow:

1. Calculate the target signal area average gray value \( M \) of noise image;
2. Divide image according 4×4, calculate every standard deviation of 4×4 image \( \text{LSD} \);
3. Calculate average value of all standard deviation of 4×4 images \( \text{LSD}_m \);

\[
\text{SNR} = 20 \times \log_{10} \left( \frac{M}{\text{LSD}_m} \right)
\]

4.2. Imaging experiment

The imaging system is designed and carried out by ourselves. It contains detector, lasers, optical system and control unit. Type of detector is 1XC18/18WHS-G range-gated ICCD. The spectrum response range is 450nm~900nm. Its resolution is more than \( \geq 500 \text{TV-line} \). The least gate-time is 20ns. The laser we use to do far-distance imaging is Nd:YAG laser. Wavelength is 532nm and 1064nm. Single pulse energy is 80mJ. Pulse width is 10ns. The focus and diameter of receive optical system are 1800mm and 150mm.

Laser active imaging experiments were done at different time in different day. The target distance is about 4km. The values are in table 1. The data of visibility are from weather record web.

![Image of laser images](image-url)

Figure 6.- Laser images of 3.7km distance target.

Then, we calculate SNR of every image using the method in 3.1. The values are in table 1.

| Image | Time           | humidity | Visibility/km | SNR     |
|-------|----------------|----------|---------------|---------|
| a     | 21:00˜21:30,5th. Aug | 40%      | 30            | 17.1328 |
| b     | 20:30˜21:00,4th. Aug  | 80%      | 25            | 14.8788 |
| c     | 20:30˜21:00,21th. Jul | 70%      | 20            | 11.6972 |
| d     | 22:30˜23:00,21th. Jul | 78%      | 8             | 10.9255 |
From the calculation results, visibility is so small that the laser energy declines too much because of atmospheric attenuation. So we can’t see target through laser active imaging system. With visibility get far, we can see the target. And SNR of image get bigger. SNR of image in 30km visibility improves 36% more than in 8km. The result is close to the simulation result of 30%. Good visibility image has better details also. Because of different humidity and other reasons, experiment results have difference from theory results.

Then, we use blind deconvolution way\(^7\) to calculate atmospheric MTF. From the calculation result of image (a)(b)(c)(d), we could qualitative see that value of MTF is getting small with Visibility getting worse. The imaging resolution is getting worse.

5. Conclusion

The influence on imaging quality of atmospheric propagation is complex. This paper analyzed that how imaging SNR and resolution declines with visibility getting worse and turbulence getting strong by simulation way. And we did experiments to analyze the influence.

The performance of laser active imaging system in sunshine day \((V_M>20\text{km})\) can improve 20%-30% more than in light fog day \((V_M\text{ is about }10\text{km})\). If laser energy is not enough, the system can’t see far target in strong fog day \((V_M<5\text{km})\). And power of laser decuple, SNR improves about 10dB. Atmospheric turbulence has strong influence on imaging resolution. It can make target image detail blurred. Imaging quality through strong turbulence is about 90% less than that weak turbulence.

6. References

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