Daily Variation Analysis of Atmospheric Turbulence from Inland to Open Sea

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Abstract. Random fluctuation of turbulence brings random fluctuation of refractive index, which makes atmosphere become a random fluctuation medium and destroys the coherence of light wave especially laser transferring in it. Exploration of atmospheric turbulence is essentially investigation of atmospheric refractive index. The atmospheric structure constant of refractive index is a basic parameter of expressing atmospheric turbulence, and was measured using HTP-2 micro-thermal meter at different areas from inland to open sea. It is analysed that the relation of atmospheric structure constant of refractive index with corresponding temperature and wind speed. The conclusion of turbulence and main influencing factors is to deepen the research in atmospheric optical transmission, and to provide data support for the siting of ship board photoelectric systems.

1. Introduction

With the rapid development of modern advanced photoelectric technology, the capability of their various components, which restricts the overall performance of photoelectric system, has been close to the ideal limit level. The overall performance of different photoelectric systems worked in atmospheric environment lies on atmospheric medium to a considerable degree, and atmospheric turbulence is one of the important factors.

Atmosphere is always in turbulence motion, the reason is that wind shear caused by gas flow drag due to earth surface, heating difference at different areas irradiated by sun, or heat convection induced by radiation from earth surface. Turbulence structure and corresponding physical parameters random change at various spatial-temporal dimensions. Energy, momentum and materials in atmosphere are transported by turbulence, whose transmission speed is several orders than molecular thermal motion. The transform of optical wave in atmosphere is seriously affected by turbulence[1,2]. The understanding of turbulence developing law and its main influencing factors is to deepen the research of atmospheric optical transmission.

2. Measuring principle and technique

Small size turbulence motion is emphases while its effect is assessed for transform of light wave
and electromagnetic wave in atmosphere. Kolmogorov introduced structure function to explore statistic structure of turbulence which accorded with local uniform and isotropy assumption[3-5]. Due to dimensional analysis, turbulence spectra in the inerial subrange conforms to ”2/3” power law[6,7]. Fluctuation of atmospheric temperature and refractive index can be expressed as

\[ D_n(r) = \left[ \frac{n(r_1 + r) - n(r_1)}{r} \right]^2 = C_n^2 r^{2/3} \]  

(1)

\[ D_T(r) = \left[ \frac{T(r_1 + r) - T(r_1)}{r} \right]^2 = C_T^2 r^{2/3} \]  

(2)

\( D_n(r) \) and \( D_T(r) \) are respectively structure function of refractive index and temperature. \( C_n^2 \) and \( C_T^2 \) are structure constant of refractive index and temperature. To local uniform and isotropy turbulence, structure constant can be indicated intensity of turbulence, which usually be represented by atmospheric structure constant of refractive index \( C_n^2 \).

To light wave and electromagnetic wave, refractive index \( n \) can be written as function of atmospheric pressure \( P \) and temperature \( T \).

\[ n - 1 = 79 \frac{P}{T} \times 10^{-6} \]  

(3)

refractive index \( n \), atmospheric pressure \( P \) and temperature \( T \) can be decomposed average term and fluctuation term, respectively written as \( n = \bar{n} + n', T = \bar{T} + T', P = \bar{P} + P' \), so the fluctuation term of refractive index is[8].

\[ n' = 79 \left( \frac{P}{P} - \frac{T'}{T} \right) \times 10^{-6} \]  

(4)

\[ \frac{P'}{P} \ll \frac{T'}{T} \] in true atmosphere, that is to say, the fluctuation term of refractive index is main affected by temperature without considering the fluctuation of pressure etc under general circumstance[9].

\[ n' = -79 \frac{P}{T} T' \times 10^{-6} \]  

(5)

\[ C_n^2 = \left( 79 \frac{P}{T} \right)^2 \times 10^{-12} \]  

(6)

Formula (6) reveals the method measuring atmospheric structure constant of refractive index \( C_n^2 \).

It is realized that the measurement of atmospheric structure constant of temperature \( C_T^2 \) using HTP-2 micro-thermal meter, whose detector consists of two spacing 1m platinum wires, each platinum
wire 10 \( \mu m \) diameter and 2.4 \( cm \) length. The temperature difference \( T_1 - T_2 \) of above mentioned two platinum wires is measured under frequency 0.05~30 \( Hz \) and system noise 0.002 \( K \) [10,11].

\[
C_n^2 = \frac{(T_1 - T_2)^2}{r^{3/2}}
\]  

(7)

Over the past ten years, many times field experiments, pointed at the atmospheric structure constant of refractive index \( C_n^2 \), have been implementing at multiple locations from inland to open sea. A part of measured results in 2013 and 2014 are selected for analysis on characteristics and influencing factors. The evolution of \( C_n^2 \) with atmosphere temperature and wind speed will be discussed below.

3. Results and discussion

Firstly, experiment data of four inland fields at sunny day are displayed, and the relation among \( C_n^2 \), temperature fluctuation and wind speed shear is explored here. The measurement equipments are all fixed at top of a pole from the ground 4 to 6 meters high.

\[
\begin{align*}
&\text{Mianyang} & \text{2013.05.12} & \text{(31.5N,104.7E)} \\
&\text{Mulanhu} & \text{2014.10.22} & \text{(35.5N,114.2E)} \\
&\text{Daocheng} & \text{2014.04.13} & \text{(29.1N,100.1E)} \\
&\text{Lijiang} & \text{2014.03.13} & \text{(26.9N,100.3E)}
\end{align*}
\]

\[\text{Figure 1. The relation of atmospheric structure constant of refractive index with corresponding temperature and wind speed in inland sites}
\]

Figure 1 Shows the daily variation of atmospheric structure constant of refractive index, local temperature and wind speed, which includes four inland measurement sites, respectively Mianyang
and Daocheng in Sichuan province, Mulanhu in Hubei province, and Lijiang in Yunnan province. Temperature fluctuation value of inland areas is mainly caused by sun irradiation, which is regular according to sun movement. Usually, it is weak that the temperature fluctuation at morning, dusk and night in a day, beyond question, the most intense time interval appear at front and back of midday. On the basis of formula (6), the change of daily variation of atmospheric structure constant of refractive index is also like this. In other words, daily variation of atmospheric structure constant of refractive index $C_n^2$ directly relates to temperature fluctuation from sun irradiation. It also can be seen from Figure 1 that wind speed is impacted by temperature fluctuation, since its maximal and most dramatic change time interval often overlap with corresponding temperature fluctuation. Certainly, the degree of consistency of both is also affected by the underlying surface. The analysis shows that cement and soil underlying surfaces are more susceptible to atmospheric temperature fluctuations, such as Mianyang and Daocheng, and grass or grass around the cement ground underlying surfaces are not easy related to temperature fluctuations, for example Mulanhu and Lijiang. The reason is that the thermal capacity of cement or soil floor is relatively small, air above them easy to form convection current by temperature fluctuation. Comparatively, the thermal capacity of grass floor is so huge like a energy absorption black body that the corresponding affection can be ignored.

The other feature of above inland sites $C_n^2$ is distinct conversion time, which represents the weakest moment of turbulence in a day. Conversion time appears at twilight time when the heat from sun irradiation and earth surface heat radiation is in equilibrium. In the premise of latitude and longitude of corresponding experiment site, sunrise time and sunset time can be calculated.

| Geographic Information, sunrise/sunset time calculation and Conversion Time of Turbulence to Different Experiment Sites |
|--------------------------------------------------|
| **Site**                      | **Latitude and longitude** | **Altitude (m)** | **Calculation** | **Measurement** | **Time Difference (min)** |
| Mulanhu                       | 30.5N                      | 114.2E          | 07:05/17:41    | 07:15/17:07    | 10/34                     |
| Mianyang                      | 31.5N                      | 104.7E          | 06:11/19:43    | 06:46/19:17    | 35/26                     |
| Lijiang                       | 26.9N                      | 100.3E          | 07:34/19:23    | 08:15/19:06    | 41/17                     |
| Daocheng                      | 29.1N                      | 100.1E          | 07:00/19:41    | 07:57/19:28    | 57/13                     |

By literature, the conversion time usually appears at the time interval after sunrise and before sunset for about an hour. This is clearly too vague concept of time to scientific research. Using astronomy Julian angel, sunrise time and sunset time are precise calculated in the case of latitude and longitude. From Table 1, the time interval between conversion time and sunrise/sunset time is influenced by local altitude. It is gradually extended that the time interval between conversion time and sunrise time with altitude elevation, and vice versa to the time interval between conversion time and sunrise time with altitude elevation. Such as Mulanhu and Daocheng, altitude respectively 55m and 4692m, the intervals of conversion time and sunrise are 10 minutes and 57 minutes, lengthening with altitude rising, but corresponding intervals between conversion time and sunset are 34 minutes and 13 minutes, shortening with altitude rising. In a word, it is obvious that the precision of time interval between conversion time
and sunrise/sunset time can be improved to minutes.

Secondly, measurement data of four offshore experimental sites at sunny day is picked out for analysis. The Qingdao site is port, whose underlying surface is sea water. The distance of Maoming, Zhanjiang and Sanya sites to corresponding seacoast respectively is 6 nautical miles, 15 nautical miles and 20 nautical miles. The measurement equipments at Qingdao were fixed at the top of a pole from the ground 4m meters high. The same equipments at Maoming were fixed on a place 14m high at an iron tower which lied in sea water. The ones at Zhanjiang and Sanya were fixed on each 4m high pole which seated ship deck.

![Figure 2](image)

Figure 2. The relation of atmospheric structure constant of refractive index with corresponding temperature and wind speed in offshore areas

Figure 2 displays the development trend of offshore $C_n^2$, atmospheric temperature and wind speed with time. In general, the value range of $C_n^2$ in offshore areas is general smaller than in inland. It is obvious that the daily variation characteristics of $C_n^2$ still retains in Qingdao and Maoming, at the same time, $C_n^2$ is also mainly affected by temperature fluctuation although the impact of wind speed shear has begun to show, but the relation is weak between temperature and wind speed owing to underlying surface and surrounding environment. In comparison, the daily variation characteristics of
$C_n^2$ in Zhanjiang and Sanya are fuzzy without distinct conversion time. The $C_n^2$ of Zhanjiang and Sayan is gradually affected by both temperature fluctuation and wind speed fluctuation, in addition, the influence degree of wind speed fluctuation is seemingly to increase as the offshore distance more and more far.

Finally, it is selected that four sets experiment data of open sea sites in Pacific Ocean and Indian Ocean. In period of experiment, the HTP-2 micro-thermal meter was fixed 2m away on starboard side of the cockpit, where about 20m height above sea water.

![Figure 3. The relation of atmospheric structure constant of refractive index with corresponding temperature and wind speed in open sea](image)

The wind speed used in above chart is absolute wind speed after ship speed subtracted, and the time also Beijing time during the whole period of experiment. The ship routes contained in upper left corner and lower right corner in Figure 3 are all straight line navigation between two sites, which represented by longitude and latitude. There is no way to forecast the weather in open sea, so the sudden change of temperature mostly originates in sudden rain, sudden thick cloud cover or sudden sun irradiation.

What need to be explained is the steady decline of temperature after 10:00 in 7 Jan 2015 attributes the ship towards the Chinese East Coast where in cold winter. As Figure 3 shows, whether Pacific Ocean or Indian Ocean, the change of $C_n^2$ without any regular pattern at all, totally different to inland. The fluctuation of $C_n^2$ is mainly affected by wind speed fluctuation by each other compared. That is, the
temperature fluctuation act on turbulence in open sea maybe caused by wind speed shear not by change of temperature itself. The value of $C_n^2$ is likely proportional to wind speed shear, in other words, the temperature fluctuation act on turbulence is greater when the wind speed is higher. Figure 3 also reveals that, in open sea, the correlation between $C_n^2$ and wind speed shear has nothing to do with the ship motion or not. The ship in 7 Jan 2015 is actually in the East China Sea, China’s inland sea. The conclusion of offshore sea $C_n^2$ is also applicative here as mentioned above, that is, the value range of $C_n^2$ is small.

4. Summary

By comparison of $C_n^2$, temperature and wind speed at different experiment sites from inland to open sea, the conclusion can be brought out here on the daily variation.

1) The turbulence of inland sites have obvious daily variation characteristic, and conversion time clear. The sunrise time and sunset time can be calculated according to corresponding longitude and latitude. The time interval between conversion time and sunrise/sunset time is effected by local altitude. The time interval between conversion time and sunrise time is gradually extended with elevation, and the time interval between conversion time and sunset time is vice versa. With the distance to the land increase, the conversion time of turbulence of offshore sites is more and more indistinct and finally disappear. In open sea, there is no any regular pattern for turbulence;

2) The turbulence structure of inland is mainly affected by temperature fluctuation, and the wind speed fluctuation tends to agree with temperature fluctuation for small thermal capacity underlying surface, such as soil and cement floor. The consistence declines to high thermal capacity underlying surface, for example grass. The turbulence structure of open sea is mainly decided by wind speed fluctuation, and the turbulence value is like to proportional to wind speed shear. The turbulence structure of offshore areas is influenced by both temperature and wind speed fluctuation, and the influence degree of wind speed shear is more and more high with the distance to the land increase;

3) The numerical range of turbulence first decreases and then increases from inland to open sea, and the weakest turbulence fluctuation appears in inland seas where tens of nautical miles. That is, in the process from land to ocean, there may be a sea area where the effect of wind speed and temperature fluctuation on the turbulence formation is cancel out each other, in other words, small thermal capacity land and large thermal capacity sea water on the atmosphere are equilibrium and atmosphere is the most quiet. This maybe provide data support for the siting of ship board photoelectric systems.

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