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Science and technology of atmospheric effects on optical engineering: Progress in 3rd quinquennium of 21st century

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Brief introduction with remarks is given for recent work in optical properties of turbulent and turbid atmospheres and their effects on optical engineering. Emphasis about turbulence investigation is paid on spatial structure characteristics of optical turbulence, turbulence profiling with lidar technology, and turbulence prediction based on mesoscale atmospheric model. Discussion of turbid atmosphere study is focused on light scattering by non-spherical aerosol particles, high resolution atmospheric transmittance from solar radiation measurement, total sky imaging with high spectral resolution, and the modulation transfer function of a turbid medium. Key points about light propagation through turbulence include non-Kolmogorov turbulence effects, probability distribution models of scintillation, and combined beam propagation. Atmospheric effects on quantum communication are discussed, and statistical characteristics of atmospheric effects on optical engineering are introduced.

optical engineering, atmospheric effect, light propagation, turbulence, aerosol particles

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1 Introduction

Optical engineering has found more and more applications in a variety of areas in scientific activity, military service, and everyday life. Any kind of optical engineering could not get rid of the effects of atmosphere if it was used in the terrestrial environment. Along with the progress of technologies related to optical engineering the performance of an optical system gradually tends to get the ideal expectations. For example, the resolution of a perfect imaging system is determined by the scale of the aperture. In this situation the practical performance of an optical engineering system is mainly or ultimately determined by the effects of atmosphere on the system.

Mechanisms of atmospheric effects on the optical engineering relate to the operation principle of the system. They could be classified into five categories.

The first one is attenuation of the operational radiation in opt-electrical systems such as a high energy laser weapon or a visual apparatus. This effect reduces the energy propagated to the target and decreases the visual range. The effect is mainly due to the absorption of atmospheric gases and scattering of aerosol particles. Common technical terms for the total effects are atmospheric transmittance, transmission, and attenuation.

The second one is degradation of the image quality in opt-electrical systems such as a imaging system or a remote sensing system. The effect worsens the resolution and the contrast of the target and background. The effect is mainly due to the scattering of aerosol scattering and turbulence effect.

The third one is the distortion of the spatial-temporal distribution of the radiation in laser engineering, optical communication systems and other systems. This effect could introduce

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error rate increasing, intensity fluctuation (scintillation), laser beam wander and spread. The effect is due to the atmospheric turbulence.

The fourth one is the introduction of the radiation background into nearly all kinds of optical engineering. The effect introduced unwanted noise to the optical system. The effects are mainly due to the multiple scattering of solar radiation by atmospheric molecules and aerosol particles, and also by atmospheric radiation.

In above four effects only the radiation is affected by the atmospheric medium, but the latter is independent of the former. In some kind of optical engineering the radiation is intense enough to heat the atmosphere and change its status, and to affect further the spatial-temporal distribution of the radiation field. The typical effect of this kind is the thermal blooming of high energy laser beam propagation. The effect is due to the absorption of the radiation by atmospheric molecules and particles. Even higher intensity could introduce other kinds of nonlinear effects.

The subject about the mechanism of atmospheric effects on optical engineering and the study of the optical properties of the turbid and turbulent atmosphere constitute the modern atmospheric optics [1]. Some classical works have been provided scientific foundation of atmospheric optics. Goody and Yung [2] provides fundamental physics about absorption by atmospheric gases. van de Hulst [3] and Bohern and Huffman [4] gave detailed treatment for the scattering by spherical particles. Theories for multiple scattering and atmospheric radiation are presented systematically in some books [5,6]. The propagation theory of light in turbulent atmosphere under weak fluctuation condition could be found in Tatarskii's classical book [7] and a collection of papers edited by Strohbehn [8]. Detailed formulae for various kinds of turbulent effect could be found in Sasiela's book [9]. Andrews and Phillips [10,11] give detailed discussion in their books about special case of laser beam propagation.

There are also some well applied softwares for evaluation of atmospheric effects on optical engineering. Algorithm for Mie theory is used to solve the problem of light scattering [12]. The famous MODTRAN software is widely used for atmospheric absorption and transmittance calculation with different spectral resolution [13], with aid of DISORT algorithm for radiative transfer the sky radiance could also be calculated with some required accuracy [14]. The calculation of transmittance corresponding to a vast number of absorption lines at a lot of temperature and pressure conditions is rather time-consuming. An algorithm based on fitting the line-by-line results of transmittance at different conditions is applied in a related software [15,16].

Qualitatively evaluation of atmospheric effects on optical engineering depends on the reliable knowledge about optical properties of atmospheric molecules, aerosols, and turbulence. These properties are characterized by some key parameters directly related to the micro-physical properties of atmosphere, and determined by the spatial-temporal distribution of atmospheric components and turbulence. In order to qualitatively evaluated the atmospheric effects of an optical engineering system we have to obtain the parameters *in situ* with enough high precision.

Statistical atmospheric models from long period measurement are essential for the design and performance prediction of the optical engineering. These models could be divided into three categories. The general atmospheric models give vertical distribution of temperature, pressure, and amount of main gases. The most widely used model is U.S. Standard Atmosphere 1976 [17]. This model along with other five models, i.e., Tropical, Mid-Altitude Summer, Mid-Altitude Winter, Sub-Arctic Summer, and Sub-Arctic Winter models are embedded into MODTRAN software. All these six models were built with consideration of only latitude difference. In China region and continental region all over the world the longitude difference and special geological region difference exist. Thus the standard models are not suitable for applications in many special regions. The second kind of models deals with some properties of aerosol particles which contain the refractive index, number density, and size distribution. One of such models is OPAC [18]. The third kind of models is for atmospheric turbulence, and they give information of turbulence strength, characteristic scales and their vertical distribution [19]. Efforts have been paid to build these three kinds of models in China typical regions [20].

2 Optical properties of atmospheric turbulence

2.1 Spatial structure characteristics of optical turbulence

In the theory of light propagation in turbulence the spatial spectrum of turbulence plays a central role in the formulae for evaluating all kinds of propagation effects. For local homogenous isotropic turbulence, i.e., the so called Kolmogorov turbulence, the 3D spatial spectrum has a $-11/3$ power-law behavior. The spectrum of so called non-Kolmogorov turbulence has a power other than $-11/3$. The 3D spatial spectrum is obtained usually by a transformation from the 1D temporal spectrum which is measured at a fixed position under Taylor's frozen turbulence hypothesis. A lot of measurements reveal that the spectral power of the actual turbulence has a probability distribution with a mean value being about $-11/3$ for 3D or $-5/3$ for 1D power spectrum, and Figure 1 shows an example [21]. One possible cause of the non-Kolmogorov atmospheric turbulence was proposed as the so-called coherent structure resulted from the action of self-organizing nonlinear process [22].

Atmospheric optical turbulence strength is usually characterized by the structure constant of refractive index C_n^2. In case of non-Kolmogorov turbulence the structure constant of refractive index C_n^2 is not suitable for indicating the strength of turbulence. The standard deviation of refractive index, the out scale and the power of the spectrum must be employed together to characterize the turbulence [23]. But for convenience in engineering application some methods were proposed to find a equivalent C_n^2 in general turbulence status [24].

With aid of recently-developed fiber sensors the spatial distribution of atmospheric turbulence could be measured simultaneously in any kind of configuration, such as in an equal logarithm spacing [25,26]. Thus the spatial characterizations of turbulence, such as the power spectrum and the spatial correlation scales could be obtained. From measurement results in Figure 2 it is found that the out scale has obviously a linear relationship with the turbulence strength. This finding is different from the long-believed knowledge that the out scale depends only on the altitude [27].

Usually the turbulence strength over land has a distinct diurnal behavior. The turbulence strength is high in the daytime around noon and presents two minimal values at sunrise and sunset times. Limited measurements carried out in the atmos-

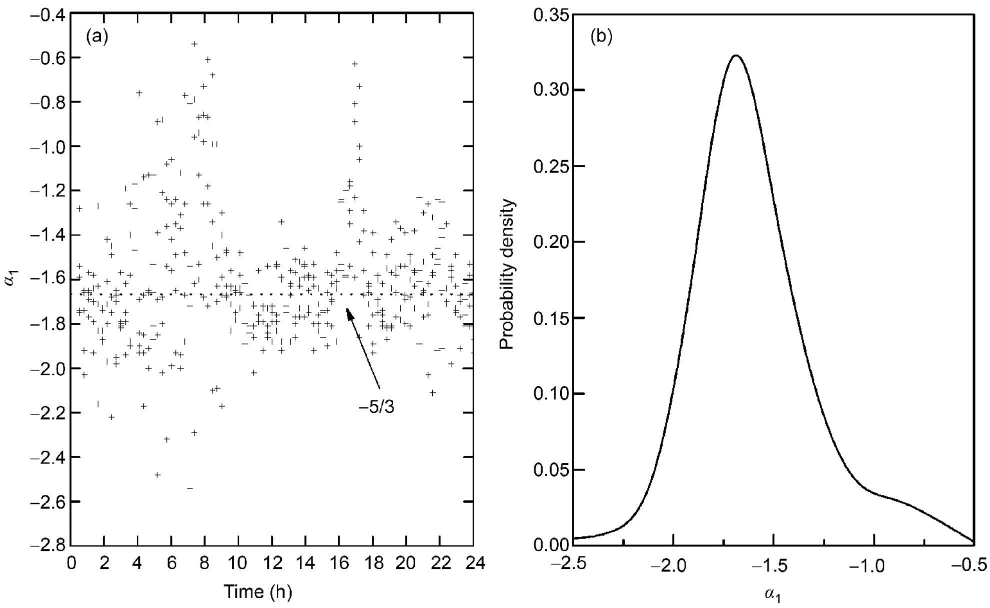

Figure 1 Diurnal behavior (a) and probability distribution (b) of the 1D spectral power of atmospheric turbulence.

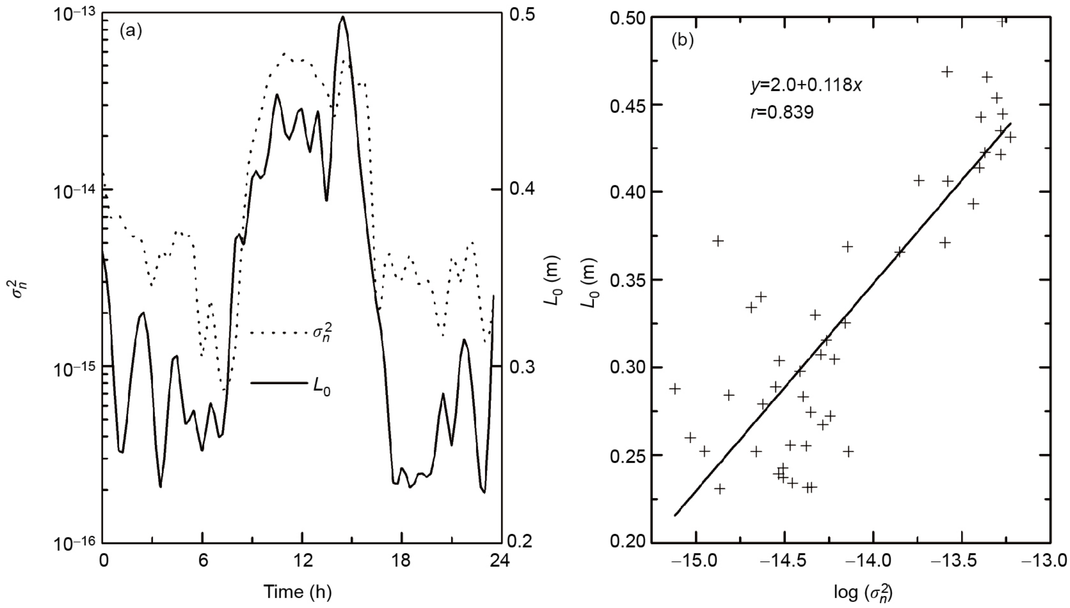

Figure 2 Diurnal behavior of the standard variance of refractive index (a) and the outer scale (b) of atmospheric turbulence near ground surface [27].

phere over deep sea surface indicate that the turbulence strength has a more smooth temporal variation behavior [28].

2.2 Local and profile detection technology of turbulence

Local turbulence strength is usually measured through fluctuations of air temperature with a platinum resistance thermometer or an ultrasonic anemometer. Average turbulence strength over a long path could be obtained by measuring some light propagation effects, such as scintillation, image motion. This kind of technique has also been applied to local turbulence measurement for indoor applications [29].

However, in many optical engineering applications range-resolved turbulence strength is required. A lot of approaches were proposed for this purpose. Mainly for the need of aeronautics safety application a kind of UV Rayleigh lidar was developed for remote clear air turbulence detection by measuring the density fluctuation through the backscattering by molecules [30]. This technique has been verified in both ground-based and airborne scenarios [31,32].

Turbulence profile cross the whole atmosphere is very important for astronomy observation, especially when the adaptive optics is applied to compensate turbulence induced imaging distortion. Scindar technique has been developed and practically used in some observatories [33,34]. Turbulence profiles obtained from both two-star and single-star Scindar have poor spatial resolution. These profiles may provide valuable reference for astronomic site selection, but they are not suitable for optical engineering applications. In order to get C_n^2 profiles with high spatial resolution two kinds of turbulence lidar were developed.

One approach is a hybrid of two techniques: The DIMM, in which light from a natural star is used to measure the integrated effect of atmospheric turbulence in terms of Fried parameter r_0, and a bi-static imaging lidar with a CCD camera as depicted in Figure 3 [35]. The lidar beam provides images with high spatial and temporal resolution at different altitudes, and conventional DIMM method can be used to calculate the turbulence strength parameter r_0 at corresponding altitude. The feasibility of this approach is verified theoretically and experimentally [35,36]. Since the direct output is r_0 at different distance the retrieval of C_n^2 profile is not straight forward, satisfactory scheme still remains investigation.

Another apparatus for turbulence profile detection is so called scintillation lidar. The principle of scintillation lidar is to deduce turbulence strength profile from the residual scintillation of the lidar returns [37–39]. Simulation and first experimental results gave verification of this approach. In conventional applications of lidar measurements the signals are averaged in some way and then to be used to deduce some information such as aerosol extinction coefficient. Actually lidar returns always fluctuate in the atmosphere and then lidar is more suitable for fluctuation than average measurements. But there are also strict requirements for a stable light source

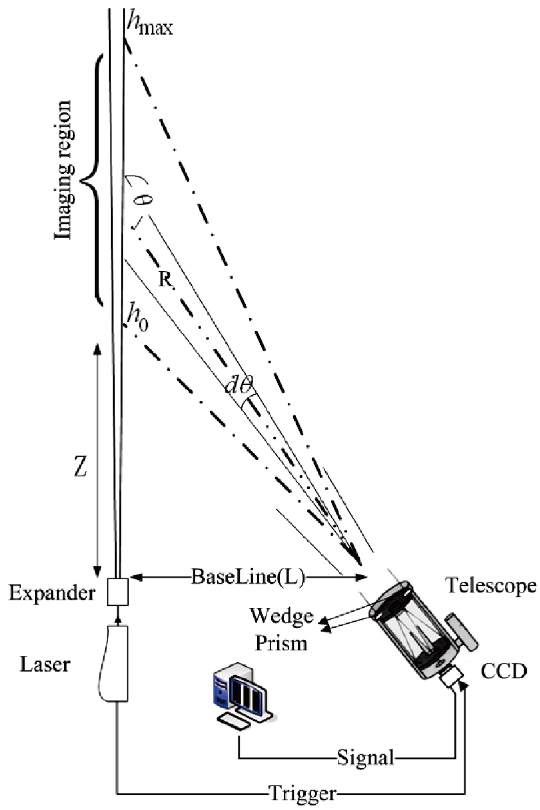

Figure 3 Schematics of a two-beam imaging turbulence profile lidar [35].

and a low-level-noise detector. Therefore, only the results with limited distance were obtained up to date [40].

2.3 Turbulence prediction based on mesoscale atmospheric model

General atmospheric model contains vertical distribution of main meteorological parameters. Vast amount of data over a long period have been collected benefitting from the most powerful meteorological observation stations all over the world. A general atmospheric model for any region could be developed by statistical analysis of these observation data. Data for visibility and optical thickness of the atmosphere which could be used to deduce some optical properties of aerosol particles are also in the library of meteorological observation. Moreover, direct observations about amount and compositions of atmospheric aerosol particles and their spatial-temporal distribution have been carried out at a lot of environmental monitoring stations. Similarly, the atmospheric aerosol model for a particular region could be developed by statistical analysis of these observation data.

Unfortunately, information about atmospheric turbulence is not concerned in both meteorological observation stations and environmental monitoring stations. Limited measurements over surface or even rare ones on floating platforms have been carried out only for scientific experiments or engineering applications. No enough data could be used for developing statistical turbulence model with high reliability. The practical way to get such model indirectly is building a relationship between turbulence strength and meteorological parameters and taking vantage of the meteorological data. Turbulence models built in such way have to be modified and improved through real measurements.

An optical turbulence algorithm was developed by making use of the information on turbulence kinetic energy provided by a planetary boundary layer scheme available in the fifth-generation Pennsylvania State University—NCAR Mesoscale Model (MM5), and it was validated by optical turbulence data collected on Mauna Kea [41]. Similarly, the mesoscale atmospheric model called Weather Research and Forecasting (WRF) model was also used for optical turbulence parameterization, the profile simulation results were compared with measurements at Gaomeigu observing station [42]. The WRF model coupled with Monin-Obukhov similarity theory can be used to estimate surface layer C_n^2. WRF is used to forecast the routine meteorological parameters, and C_n^2 is calculated with Bulk model based on the Monin-Obukhov similarity theory. Sea surface C_n^2 values obtained in such a way are verified by measurement with micro-thermometer on the ship [43]. This approach is also validated through 9-d measurements over snow and sea ice in the field campaign of the 30th Chinese National Antarctic Research Expedition [44]. Using WRF outputs and Tatarskii scheme for optical turbulence parameterization the vertical profiles of C_n^2 distribution could also be developed in similar way. Turbulence profile models in three typical regions were developed, and a typical profile is presented in Figure 4 [45].

Turbulence profiles predicted with atmospheric models could be verified with direct measurements by balloon-borne micro-thermal sensors. However, directly-obtained high-resolution turbulence profiles are usually fluctuated abruptly with height in a range of about 2 orders. Methods for averaging or smoothing of measurement data are requested for C_n^2 profile modeling. A CEEMD technique was proposed to represents a C_n^2 profile as a sum of some components [46].

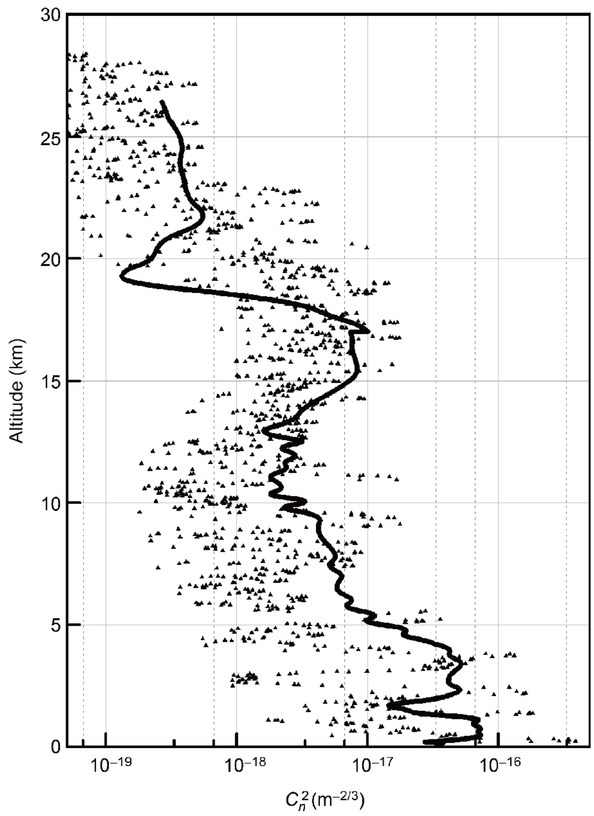

Figure 4 Atmospheric C_n^2 profile simulated and measured at Maoming.

3 Optical properties of turbid atmosphere

3.1 Light scattering characteristics of nonspherical aerosol particles

Light scattering by aerosol particles is a fundamental scientific problem and has been deeply involved in applications of optical engineering such as lidar technology. Almost all practical algorithms for engineering purpose are based on Mie scattering theory. As the actual aerosol particles have very complicated forms other than a sphere Mie theory, which is about light scattering by a perfect sphere, can only give results in a statistical manner with some degree of discrepancy.

Study on light scattering by irregular nonspherical particles has attracted many scientists including physicists, chemists, astronomers, biologists, and geophysicists. A series of books titled *Light Scattering Reviews* were published every two-year or one-year starting from 2006 [47]. The scattering properties of one kind of nonspherical particles, i.e., the rotational symmetrical ellipsoidal particles, could be investigated numerically with a T-matrix approach [48]. Light scattering by randomly oriented polydispersions of ellipsoidal particles were studied numerically with similar mathematical technique [49]. Scattering by arbitrarily irregular particles could be investigated by a Discrete-Dipole-Approximation (DDA) method [50].

Using DDA algorithm light scattering by some particles with special forms and components has been studied [51–55]. The particles were constructed from simple to complex both in form and internal structure in consideration of actual atmospheric aerosol particles. Scattering properties of these particles were compared with those of spherical particles and some equivalences were proposed in order that these results could be used in practical engineering applications.

3.2 High resolution atmospheric transmittance from solar radiation measurement

Total atmospheric transmittance measurements from solar radiation by sun photometer or aureole-meter have become a routine procedure for air quality monitoring and an approach for retrieving atmospheric aerosol properties. The transmittance thus measured usually has low spectral resolution at some discrete wavelengths, and thus limited applications. In recent years high spectral resolution solar spectrum measurements with laser heterodyne detection technology has been developed rapidly. Related measurements have been used to retrieve vertical distribution of atmospheric gases, such as CO_2, O_3, N_2O, CH_4, CCl_2F_2, H_2O [56–59]. This technology has also been used to evaluate total atmospheric transmittance in laser applications [60].

3.3 Total sky imaging with high spectral resolution

Total sky imager or whole sky camera is an automatic ground-based sky radiance observation instrument. The sky images are usually used for monitoring of cloud condition and other atmospheric sciences, and they could also be used for determination of sky background radiance which introduces noise into a lot of systems in optical engineering. Unfortunately this kind of instrument constructed with cameras provide three-color images with low spectral resolution. Thus such images are not suitable for qualitative study of atmospheric transfer problem and application in optical engineering.

A new kind of total sky imager is developed with a fiber optical spectrometer [61]. The instrument operates with both polar and azimuthally scanning at given spatial resolution. The spectral resolution is 0.5 nm, and more than 2000 images from 200 to 1100 nm spectral range could be constructed after one circle of scanning. These high-spectral-resolution images provide much more detailed information than conventional total sky imagers, and they could be taken as valuable datasets for atmospheric radiation research and application in optical engineering. If this instrument was put on a floating platform to measure sky radiances in all directions within both upward and downward hemispheres at any height then the radiative transfer solution could be verified at each atmospheric layer. The instrument will be a great facility in atmospheric radiation study since only ground-based and satellite-based instruments nowadays are employed to measure downward radiance emerging from bottom and upward radiance from top of the atmosphere. Figure 5 presents some samples of these high-spectral-resolution images.

3.4 MTF of a turbid medium

Both turbid and turbulent atmosphere degrade imaging quality and the degradation is usually quantitatively described by the modulation transfer function MTF, the module of the optical transfer function. Knowledge of the MTF of a turbid or turbulent media is then important for the design of an imaging optical system, imaging processing, and other related areas.

The theoretical solution of the short-term and long-term MTFs of a turbulent medium was obtained early in 1960’s [62], and they have been used widely. The currently used MTF expression for a turbid medium based on small-angle-approximation which is valid only for a relatively narrow frequency range [63,64]. The complete behavior of the MTF of the turbid medium was obtained recently through numerical simulation [65,66], but an convenient analytical expression of the MTF is not obtained.

The MTF of a turbid medium is equivalent to the transmitted radiance from the medium under isotropic diffuse illumination with unit intensity, i.e.,

$$\mathrm{MTF}(\Omega = \tan\theta) = J(\theta),$$

where Ω is the spatial frequency with unit of rad^{-1}, and θ is the inclination to the downward normal with unit of rad.

For visible imaging in the atmosphere the Rayleigh scattering is dominant. In this case the scattering is close to isotropic. An analytical two-stream-approximation solution of such a radiative transfer problem exists [6]. Thus, a formula of MTF for an isotropic scattering medium could be obtained as follows:

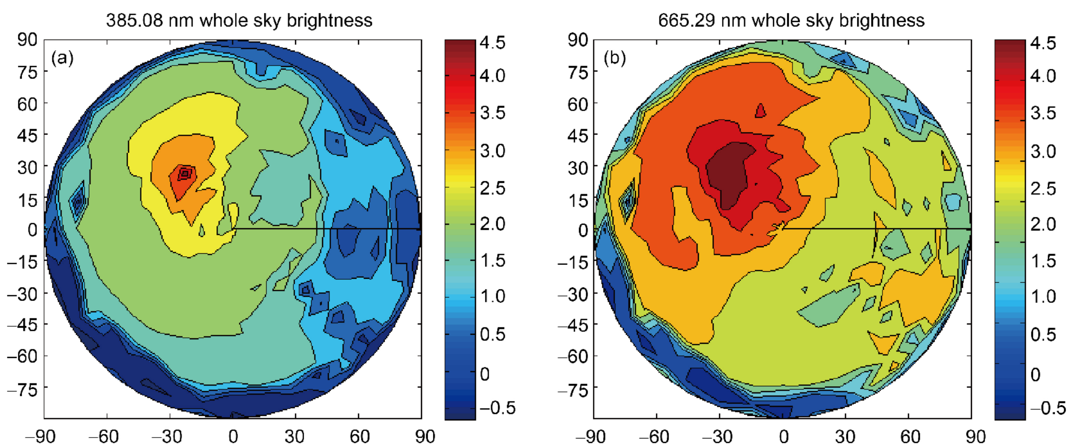

Figure 5 (Color online) High-spectral-resolution images of total sky background radiation. (a) 385.08 nm; (b) 665.29 nm [61].

$$\mathrm{MTF} = D^{-1}\Big[C^{-} - \rho^{2}C^{+} + (1 - C^{-})\mathrm{e}^{(\Gamma-\mu^{-1})\tau} - \rho^{2}(1 - C^{+})\mathrm{e}^{-(\Gamma+\mu^{-1})\tau}\Big],$$

where $\mu = \cos(\tan^{-1}\Omega)$, $\bar{\mu} = 1/\sqrt{3}$, $\Gamma = \sqrt{1-a}/\bar{\mu}$, $\rho = (1-\bar{\mu}\Gamma)/(1+\bar{\mu}\Gamma)$, $C^{\pm}(\mu) = (1\pm\bar{\mu}\Gamma)/(1\pm\mu\Gamma)$, $D = \mathrm{e}^{\Gamma\tau} - \rho^{2}\mathrm{e}^{-\Gamma\tau}$, τ is the optical thickness, and a is the single-scattering albedo. Though this is the most simple case the formula is complicated enough for applications.

The MTF of a homogenous turbid medium with Henyey-Greenstein phase function with different asymmetric factors and MTF for an isotropic scattering medium evaluated through above formula and its corresponding exact value obtained numerically are plotted in Figure 6. The analytical expression of MTF is very close to the accurate value in the low frequency range and is slight different at high frequency.

4 Light propagation through turbulence

4.1 Misconceptions of light propagation through turbulence

Theoretical frame of light propagation through turbulence was fundamentally built during 1960's to 1980's, and most applicable results were also obtained during that period. From then on related works have been mainly focused on the application of the theory and its results in various optical engineering. Misconceptions and uncorrected usages were frequently emerged.

For example, the strength of turbulence and the condition of light fluctuation have been frequently and confusedly used. The strength of turbulence depends only on turbulence itself, and the structure constant of refractive index C_n^2 is usually used for quantitative description. The condition of light fluctuation depends on turbulence, light wavelength, and propagation distance, and the Rytov index is used for quantitative description. A strong turbulence does not mean a strong fluctuation, and a weak turbulence plus a short wavelength or long distance could produce very strong fluctuation.

In the current century the term "deep turbulence" is used widespread in light propagation and related areas. This term may be defined by Tyler as an turbulence degraded propagation path for which the Rytov index being much greater than one [67]. So the usage of "deep turbulence" for description of strong fluctuation condition deeply intensifies above-mentioned confusion.

A dozen of such kind of mistakes and omissions were discussed by Charnotskii [68,69].

4.2 Numerical simulation and long-path experiments

In propagation study concerned for complicated light source, non-homogenous propagation path, and non-weak propagation condition numerical simulation has long been an efficient tool. The simulation uses a split-step solution for the paraxial propagation equation under the assumption that the propagated field is a Markov process along the propagation direction. The phase screen construction is the key step of the simulation. Traditional techniques include the widespread Fourier series based method and some others. Large number of screens (i.e. small increments) are needed for strong fluctuation condition, and long ribbons of screens also required for the time evolution study. Very closed screens could not guarantee the Markov assumption. This problem has been solved by non-Markov phase screens constructed with a sparse spectrum model [70–73]. Using the sparse spectrum

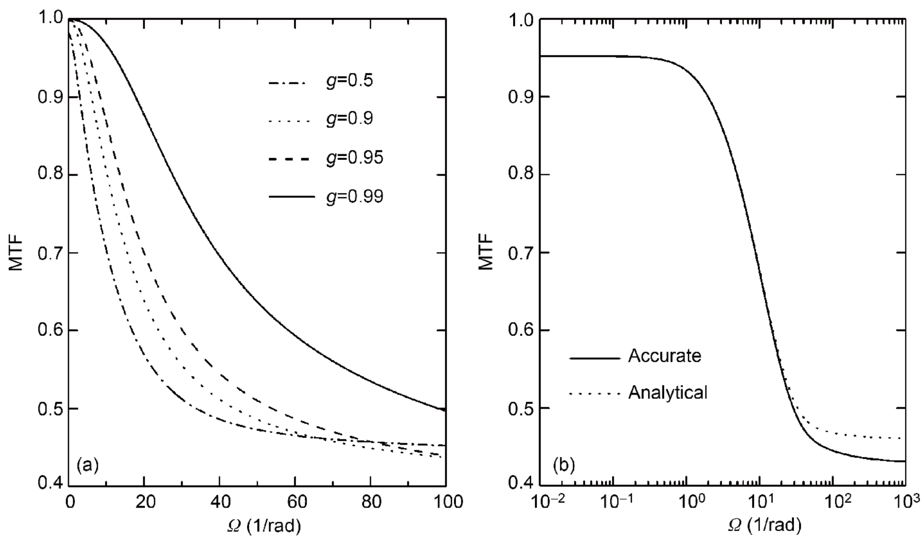

Figure 6 (a) MTF of a homogenous turbid medium with Henyey-Greenstein phase function with different asymmetric factors, the optical thickness τ=0.1 [65]; (b) MTF of an isotropic scattering media evaluated from analytical expression and accurate numerical algorithm, τ=0.1 and a=1.0

model it is possible to generate 3D samples of refractive-index fluctuations with prescribed spectral density at a very reasonable computational cost. With this kind of phase screens phase fluctuation under deep turbulence condition was investigated [74,75].

The numerical simulation motioned above refers to the whole path propagation simulation step by step. However, there is also another kind of simulation just for the distorted field after light propagation. Most of this kind of simulation has been limited to the distorted phase field and neglecting the amplitude fluctuation. As in many optical engineering both phase and amplitude fluctuations are concerned a method of random wave vectors was developed to simulate simultaneously these fluctuations [76]. This method was extended recently for simulation of atmospheric turbulence effects in optical systems with extended sources [77].

Most numerical simulation results were verified by field experiments except some for special propagation conditions such as very strong fluctuation due to practical difficulties. Profiting from the need of optical engineering such as free space optical communication long-path experiments were carried out. Although a 145 km distance propagation experiment along the eastern foothills of the Rocky Mountains was performed in early 1969 new experiments with 142, 144, and 149 km distance between Canary Islands and between Hawaii Islands were reported in recent years [78–81]. In these experiments the turbulence distribution along the path cannot be monitored and only the Fried parameter r_0 or a path-averaged C_n^2 was measured. Thus unfortunately no new physical insights were revealed by these experiments.

4.3 Effects of non-Kolmogorov spectrum turbulence on light propagation

Explosive theoretical research in recent years has been carried out about effects of non-Kolmogorov turbulence on light propagation and on optical engineering such as adaptive optics. For general light propagation problems traditional approach is applied, and results are obtained by insert the turbulence power index into corresponding formulae. The propagation effects are presented mainly as functions of the power index. There are also some works about light propagation through non-isotropic turbulence. Increasing works are reported on propagation through non-Kolmogrov turbulence of light from special sources, such as Bessel beam, Airy beam, and a lot of partially coherent light beams. These works lack experimental verification and seem to be ahead of time because there currently are no practical such kind of sources available in optical engineering.

These works are mainly based on the extended Huygens-Fresnel principle or the cross spectral density function, and mean values of propagation effects are evaluated and no fluctuation properties are presented. It is a complicated mathematical work to apply the method for Kolmogorov turbulence in the research of light propagation through non-Kolmogorov turbulence, and it does not provide new physical insight. In consideration of inhomogeneous turbulence along the propagation path numerical simulation instead of analytical method should be applied in the research work on light propagation through practical non-Kolmogorov turbulence. Knowledge about optical properties of practical atmospheric turbulence and validation of the theoretical results are the key research points of light propagation through non-Kolmogorov turbulence. Emphasis of the future research work should be put on measurement of the optical properties of practical atmospheric turbulence, simulation of light propagation using practical turbulence parameters, and validation of the simulation results with light propagation experiment in practical non-Kolmogorov turbulence [82,83].

4.4 Intensity probability distribution

Scintillation statistics has been the central problem of the theory of light propagation through atmospheric turbulence. Many models have been proposed for the probability distribution of the intensity. The log-normal model at weak fluctuation condition and other models with reasonable physical argument were verified experimentally. The probability expression for the moderate fluctuation condition was not solved both theoretically and experimentally, while complicated formations were used. New formulations are still to be proposed, and they have to be verified only through numerical simulation results. The skewness and kurtosis could be served as quantitative description of a practical distribution [84,85]. Recently the Gamma-Gamma model has been used rather widely in both theoretical propagation studies and applications. This model is based on the equivalent turbulence spectrum which couples both turbulence spectrum and light propagation parameters [11]. However, experimental results showed that the log-normal model is still a good approximation under strong fluctuations especially for photo counts occurrences [86]. In Capraro's paper [86], the diameter of the transmitter is 22 cm, but the diameter of the receiver is not given. Meanwhile, there was no information about the turbulence inner scale and the Fried parameter r_0. Considering the aperture averaging by both the transmitter and receiver apertures, the scintillation index is unbelievably high to 3.07 [87].

New models are still emerging for the general formulation of the fluctuation probability distribution under general fluctuation conditions, such as the so called M model [88]. Another model called Webull distribution based on numerical simulation results from some propagation conditions was recently proposed in consideration of mathematical convenience [89,90]. Though the model was questioned as no physical reasoning it was still used quickly in some analysis in optical engineering like optical communications [91,92]. As expected atmospheric effects evaluated with this model should be very close to those obtained with traditional models. No insights could be get but new mathematical formulae can be derived and papers be published.

4.5 Light propagation through oceanic turbulence

Because of the increasing applications of optical imaging, sensing, and communication in coastal and deep water scenarios light propagation in the ocean have been investigated in recent years. The most significant feather of the propagation is the very poor transmittance with a visual range of several tens meters, and thus a practical propagation distance is only about tens or hundreds meters. The oceanic turbulence depends both on temperature fluctuation and the salinity. Thus atmospheric turbulence spectrum is not suitable for oceanic turbulence.

Once a mathematical expression for the power spectrum of oceanic turbulence was proposed tremendous papers have been published for light propagation problems [93]. Approaches are exactly the same as those for light propagation in atmospheric turbulence and only similar expressions with different parameters are provided. In order to describe the strength of oceanic turbulence equivalent structure constant as atmospheric turbulence was introduced [94]. For several years little attention was given to real properties of the oceanic turbulence.

Fortunately, a direct measurement of the structure constant C_n^2 in the ocean was carried out recently [95]. It was found that in a depth of about 140 m, C_n^2 is in the range of 10^{-14}–10^{-10} $m^{-2/3}$ which is much large than that of atmospheric turbulence.

4.6 Light propagation of combined beams through atmospheric turbulence

Because of the fast progress of fiber laser technology and the limited power of a single fiber laser the combining of several fiber lasers has been considered as a major technical approach for high-power laser applications [96]. The coherent combining technique asks for much more severe constraints on the individual lasers than the incoherent combing technique and special technical difficulty exists for ideal combining. Without atmospheric effects the coherent combined beam could present advantage in far-field propagation properties.

One of the optical engineering with high power lasers is the directed-energy system. As a result of effects of atmospheric turbulence and thermal blooming, the intensity transmitted through a distance does not depend solely on the initial power and beam quality. If the coherent combining technique was used in the target-in-the-loop scenario with adaptive mitigation of turbulence the transmitted laser beam could be well focused [97–99]. Theoretical and experimental investigation reveals that without phase compensation there is little difference in the energy on target between coherently and incoherently combined laser beams for multi-km propagation ranges and moderate to high levels of turbulence [100–102]. This finding is important since that introduction of coherent combining technique to the high-power laser energy system may result in high complexity and cost.

5 Atmospheric effects on optical engineering

5.1 Atmospheric effects on quantum key distribution

One kind of optical engineering so-called quantum communication attracts government and public attention in an astonished manner because of its claiming of absolute security and soon-coming practicability. Related scientific terms may be misinterpreted to the public by the press or scientists. The true affair is the quantum key distribution (QKD) for cryptography. There are two kinds of schemes for QKD. One is the prepare-and-measure scheme, such as the Bennet-Brassard-1984 (BB84) protocol, and another is the entanglement-based scheme. When a communication channel is established in free space both schemes experience atmospheric effects. Some hundred-kilometer experiments in the free space near surface [103,104] and a few experimental and numerical simulation of earth-space communication reveal technical challenges for practical feasibility [105,106]. Nevertheless, a Chinese quantum satellite was launched in 2016.

Some works have been made about atmospheric effects on QKD, and most of them are about turbulence effects. However, just like general light propagation problems, atmospheric absorption and scattering are also important for QKD. 1) They decrease the received photon number quantitatively by atmospheric transmittance; 2) atmospheric scattering changes the polarization states; 3) in the forward and backward directions the polarization state of the scattered light keeps unchanged no matter what kinds of aerosol particles concerned [4].

Even though QKD deals with the photons traditional approaches for propagation of light as electromagnetic wave have been also used for analysis. It was said and could be comprehended from related papers that all results for light wave can be regarded as probability distribution of photons. Similar to works about classical light communication Shapiro paid attention to sift and error probabilities and investigated turbulence effects on QKD with BB84 protocol in both near-field and far-field scenarios [107–109]. In the near-field scenario atmospheric turbulence imposes at most a modest decrease in the sift probability and a modest increase in the conditional probability of error given that a sift event has occurred. In the far-field scenario, such as earth-space applications, scintillation has virtually no impact on the sift and error probabilities. The result contrasts rather sharply with laser communications over such paths, in which deep, long-lived scintillation fades present a major challenge to high-reliability operation.

The single photon source required for QKD is currently not practical and usually heavily-attenuated laser pulse has been used as an alternative. Some works were carried out on the counting distribution and fade probability for weak laser pulses [110]. In these the term "transmission" was misused to describe the normalized intensity after propagation through turbulence which fluctuates around unity. Normalized light intensity within a finite area could be larger than unity because of the focusing effect by turbulence, but for a quantum propagation the normalized received photon number should not be greater than unity. Thus, using the probability model such as log-normal model for the "transmission" is questionable. On the other hand, in the scenario of long distance free space communication the Rytov index is usually large enough that log-normal model is not suitable for the statistics [86].

A similar problem is the unnecessary emphasis of beam wandering effect of turbulence [110,111]. In above-mentioned scenario the beam wandering could not usually be observed since other turbulence effects make the beam pattern much spread and randomly distributed.

Finally atmospheric effects on the pure quantum properties of photons such as the violations of the Bell inequalities under strong turbulence are out of the understanding range for general optical scientists and engineers [112,113].

Investigations using both classical wave theory and quantum theory give a very interesting result that atmospheric turbulence may benefit QKD or entangle teleportation in free space. It was claimed that fluctuating loss channels may preserve entanglement properties better than standard loss channels if post-selected measurements are applied [114]. The argument is that for strong atmospheric turbulence the events with randomly occurring large values of the transmission coefficient will be dominant in the post-selected measurements. Thus a scintillation-based data grouping scheme was proposed as a tool for increasing secure key rates in the case of fluctuating loss, especially for long-range free-space QKD [86,115]. In this scheme the scintillation index is calculated from statistical parameters of another traditional propagation channel.

5.2 Probability of atmospheric effects

Due to the spatial and temporal random fluctuation of atmospheric status the atmospheric effects on optical engineering also have random behaviors. For any practical applications the effects must be described in a statistical manner. In Figure 7 the diurnal behaviors of the beam quality parameter for a laser beam propagating through 5 and 10 km in March and August are presented. Also presented is the occurring probability density of the parameter. It could be found that the probability presents rather complicated behavior which departs heavily from normal distribution. It is not easy to say simply the atmosphere is in good or bad condition because the atmospheric effects depend on the optical engineering operation principle, meteorological, aerosol and turbulence conditions together. Sometimes, atmospheric models built according to some special effects are thought as good, average, and poor. We must keep in mind that these "good" or "poor" models closely relate to the particular optical engineering and generally not suitable for other engineering applications. One "good" atmospheric model may results in poor effects for other optical engineering.

5.3 Illusions about atmospheric effects on optical engineering

Even though atmospheric effects on optical engineering attract increasing attentions of both the scientific team and clients but there are still some illusions prevailing in the related area. One of the most remarkable illusions is that a clear sunny weather is a good condition for optical engineering applications. Similarly a bad weather condition meaning

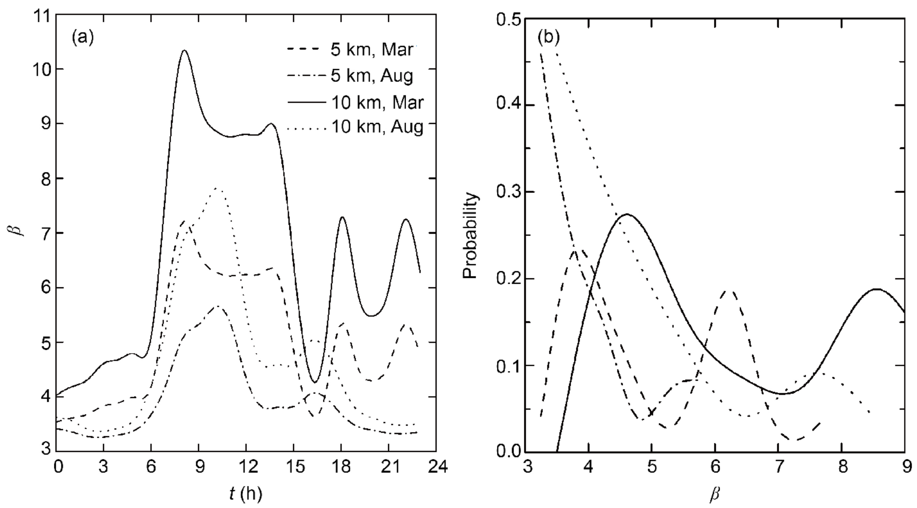

Figure 7 (a) Diurnal behaviors of the beam quality parameter for a laser beam propagating through 5 and 10 km in March and August [1]; (b) corresponding probability density of the beam quality parameter.

a bad optical atmosphere, and further a heavy negative effect on optical engineering. For example, a good transmittance along a path near surface in cloudy weather after rain is surprising for some people. Actually this phenomenon is easy to understand because there is no cloud along the path, the path could be very clean after rain, and the transmittance is independent of sunlight. Another example is that a laser beam presents a rather good behavior when propagating in haze for a certain distance. This phenomenon astonishes some people since they think the haze is a symbol of very bad weather and it should introduce a bad effect on laser beam. In fact, the haze may introduce a certain degree of attenuation of laser power, but atmospheric turbulence may be weak in this situation, and thus there is no obvious distortion of the spatial distribution of the beam. The total effect of both haze and weak turbulence may keep the laser beam having a remarkable focusing power.

Such kinds of illusions may bring very harmful consequence. Illusions like above mentioned two examples make some people believe that the atmosphere could not introduce much heavy negative effects on optical engineering. Quiet on the contrary atmospheric effects could not be neglected in most cases, and in some cases the effects may be very heavy and could make the optical engineering entirely losing function.

6 Summary

Progress in the first three five-years of the 21 century on the subject of science and technology of atmospheric effects on optical engineering is briefly introduced with some remarks. As many kinds of optical engineering have played more and more important roles in scientific research, defense, and everyday life, the atmospheric effects on optical engineering have also attract growing research interests. The theoretical foundation, the related analytical, simulation technical tools for light propagation through atmosphere and some main effects were already well known for general purpose. If the optical properties of atmosphere and the operation principle of an optical engineering were given the atmospheric effects could be well investigated. However, in recent years much theoretical research efforts have been paid to investigate effects of unrealistic atmospheric turbulence on unrealistic special optical beams. A vast number of papers have been published but rare results have been verified by experiments.

There are some kinds of work request scientist's attention. One of them is the quantitative probing and description of the optical properties of atmospheric turbulence and aerosol particles, including their composition, structure, spatial distribution and temporal variations. Another is the development of optical models of atmospheres in typical regions. The third is the development of some efficient tools for light propagation study, such as for atmospheric absorption with high spectral resolution, scattering by particles with arbitrary structure and compositions, and non-isotopic turbulence simulation. After all the real experimental verification of atmospheric effects on optical engineering is necessary for all kinds of investigations.

Good performance of an optical engineering depends not only on itself but also on atmospheric effects during its operation. In order to get better performance any serious optical engineering system must take into consideration of atmospheric effects in the design and operation. A qualified optical engineering system should contain a subsystem which detects key optical parameters of the atmosphere along light propagation path and evaluating atmospheric effects in real time. With aid of such a subsystem the decision of the system operation, correction or compensation of atmospheric effects could be performed.

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