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Calculating the Microstructure of Atmospheric Optical Turbulence

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Abstract

Turbulent fluctuations in air density can cause significant distortions of an electromagnetic signal or image. Density fluctuations can be described in terms of air temperature, air pressure, water vapor, and CO_2 content. We can calculate the refractive index structure constant, C_n^2, with the fine-scale dynamics of heat, moisture, and momentum diffusion. This helps us to quantify the intensity of turbulence-induced refraction. A better understanding of turbulence-induced refraction can provide a means of evaluating sensors under various atmospheric conditions or be used in the development of turbulence-compensation adaptive optic systems. This report annotates one set of equations for the refractive index structure constant, C_n^2, taken from the literature.

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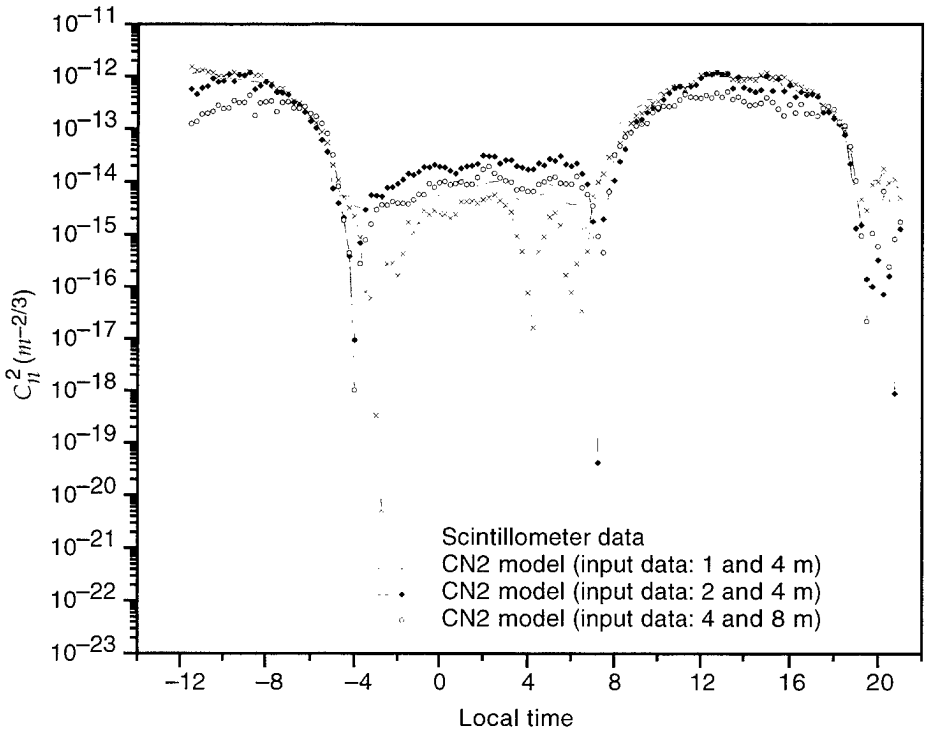
1. Introduction

Atmospheric optical turbulence can modify the refractive index in air in a way that can significantly alter the transmission and propagation of an electromagnetic image or signal [1]. Even through weak turbulence, a laser beam can become highly scintillated and exhibit strong intensity fluctuations if propagated over a long distance [2]. Also, optical turbulence can reduce the efficiency of laser systems propagated from the ground to an object in space [3]. In this regard, Walters [4] presented the results of an investigation to develop a data-reduction algorithm for sequences of balloon-borne data aimed at providing vertical profiles of the refractive index structure constant. Walters asserts that knowledge of both turbulence and wind speed profiles could be helpful for the development of turbulence-compensation adaptive optic systems.

Andreas [5] defines the problem of estimating the refractive index structure constant from meteorological point measurements and raises the question of whether or not point measurements can be used to predict a path-averaged assessment of turbulence-induced refraction. He cites Davidson et al [6] for an example of a bulk-layer method applied to estimating overwater optical turbulence. Also, Tunick et al [7] reported on an experiment wherein radiation and energy budget-derived turbulence data are compared to scintillometer-retrieved data taken over a bare soil path of 450 m. The semi-empirical models presented in Rachele and Tunick [8] and Tunick [9] have also made estimates of the refractive index structure constant for comparison to observed turbulence (scintillometer) data. However, these types of first-order difference routines can result in significant and sometimes extreme errors when point data in space and time are used to represent area or path averages (see fig. 1), particularly throughout periods before or after sunrise and sunset.

However, with increasing interest in high-performance computing, modeling the intensity turbulence-induced refraction is being re-investigated through the use of large eddy simulations [10,11]. The refractive index structure constant is recast as a variable that can be determined locally, given values for the heat and momentum flux and gradients of pressure, temperature, wind speed, and specific humidity. As a means of illustrating a calculation of atmospheric optical turbulence of this type, an algorithm could be derived from equations collated from different articles in the open literature and tested using field experiment data. In this report, the algorithm MAOT (Microstructure of Atmospheric Optical Turbulence), derived from equations collated from different articles in the open literature, is presented and the calculation is tested using data generated from observations [12,7].

Figure 1. CN2 model output compared to scintillometer data taken at 2 m over a horizontal path of 450 m.



Source: A. Tunick, *The Refractive Index Structure Parameter/Atmospheric Optical Turbulence Model: CN2*, U.S. Army Research Laboratory, ARL-TR-1615 (1998).

2. Model Equations

2.1 Refractive Index Structure Constant

Hill [13] gives an expression for the refractive index structure constant as

$$C_n^2 = \frac{\langle [n(x) - n(x+r)]^2 \rangle}{r^{2/3}} = \frac{D_n(r)}{r^{2/3}} \ , \tag{1}$$

where n is the refractive index in air, (x) and $(x + r)$ denote position in space, and the ensemble mean variance $\langle [n(x) - n(x+r)]^2 \rangle$ is the scalar structure function. Batchelor [14] gives a connection between the function, $D_n(r)$, in r space, and the spectrum for the scalar, $\Gamma_n(k)$, in k space as

$$D_n(r) = 2 \int_0^\infty \left[1 - \frac{\sin(rk)}{rk} \right] \Gamma_n(k) \ dk \ , \tag{2}$$

where k is the wave number. Through dimensional analysis, the scalar structure function and the scalar spectrum can be expressed in terms of the dissipation rate of turbulent kinetic energy, ε, and the diffusive dissipation rate of the scalar variance, χ_n. Hill [13] gives χ_n as

$$\chi_n = 2\, d_n \langle |\nabla n|^2 \rangle \ , \tag{3}$$

where, $d_n \approx d_h$, assuming that the diffusion coefficients for the scalars refractive index and potential temperature are effectively the same [15]. Then

$$d_n = d_h = \langle w' \theta' \rangle / (\partial \theta / \partial z) \ . \tag{4}$$

The variable ε can be expressed as

$$\varepsilon = (g/\theta) \langle w' \theta' \rangle - \langle u' w' \rangle (\partial U / \partial z) \ , \tag{5}$$

where g is the acceleration due to gravity, $\langle u' w' \rangle$ is the ensemble mean eddy transport of horizontal momentum, $\langle w' \theta' \rangle$ is the ensemble mean kinetic heat flux, $\partial \theta / \partial z$ is the vertical gradient of potential temperature, and $\partial U / \partial z$ is the vertical gradient of the total horizontal wind [16].

The resulting expressions for the scalar structure function and the scalar spectrum are

$$D_n(r) = b_n \chi_n \varepsilon^{-1/3} r^{2/3} \ , \tag{6}$$

and

$$\Gamma_n(k) = \beta_n \chi_n \varepsilon^{-1/3} k^{-5/3} \ , \tag{7}$$

given the Kolmogorov 2/3- and –5/3-dependencies for r and k, respectively, where b_n and β_n are constants (Hill [17,18] gives $\beta_n = 0.72$). When equations (6) and (7) are substituted into equation (2), b_n is given as

$$b_n = -\frac{6}{5}\beta_n \int \left[\frac{\cos(x)}{(x)^{5/3}}\right] dx = \frac{9}{10}\Gamma(1/3)\,\beta_n \ . \tag{8}$$

Relationships among the gamma functions, $\Gamma(p)$, for $0 < p < 1$ are given by Weast et al [19]. Finally, the expression for the structure constant in equation (1) can be rewritten as

$$C_n^2 = 2\, b_n\, d_h\, \varepsilon^{-1/3}(\partial n/\partial z)^2 \ , \tag{9}$$

where $b_n = 1.736$.

2.2 Refractive Index of Air and Its Partial Derivatives

The refractive index of air for the visible and near-infrared (3650 to 6328 Å) region of the electromagnetic spectrum is expressed [20,21] in terms of wavelength (in micrometers), barometric pressure (P, in millibars), temperature (T, in degrees Kelvin), and vapor pressure (e, the partial pressure of the atmosphere due to water vapor content, also in millibars) in the form presented by Andreas [5]:

$$n_{vi} = 1.0 + \left[m_1 \frac{P}{T} + (m_1 + m_2)\frac{e}{T}\right] \times 10^{-6} \ , \tag{10}$$

where temperature, T, is defined as $T = \theta\,(P/P_s)^{(2/7)}$; P_s is normally defined as sea level barometric pressure,

$$m_1 = 23.7134 + \frac{6839.397}{130.0 - \sigma^2} + \frac{45.473}{38.9 - \sigma^2} \ , \tag{11}$$

and

$$m_2 = 64.8731 + 0.58058\,\sigma^2 - 0.007115\,\sigma^4 + 0.0008851\,\sigma^6 \ , \tag{12}$$

where $\sigma = 1.0/\lambda$ (μm^{-1}).

In the infrared region of the electomagnetic spectrum from 78,000 to 190,000 Å [20,22], the refractive index is expressed in the form

$$n_{ir} = 1.0 + \left[m_1 \frac{(P - e)}{T} + n_{irw}\right] \times 10^{-6} \ , \tag{13}$$

where the refractive index of water vapor is given as

$$n_{irw} = Q\left[\frac{957.0 - 928.0\,(T/T_o)^{0.4}\,(X - 1.0)}{1.03(T/T_o)^{0.17} - 19.8X^2 + 8.2X^4 - 1.7X^8} + \frac{3.747 \times 10^6}{12{,}449.0 - X^2}\right] \ , \tag{14}$$

where $Q = 0.2166847\ {}^{e}/_{T}$, absolute humidity is in kg/m^3, and

$$X = \frac{10.0\ (\mu m)}{\lambda\ (\mu m)}\ . \tag{15}$$

In equations (10) and (13), vapor pressure, e, in millibars, can be expressed [23] in terms of specific humidity, q, in units of grams of water vapor content per kilogram of moist air (dry air and water vapor combined) in the following form:

$$e = \frac{P\ q}{m_w/m_a + (1 - m_w/m_a)\ q}\ , \tag{16}$$

where specific humidity is defined [24] as

$$q = \frac{e_s\, m_w/m_a}{P}\ \frac{RH}{100.0}\ \exp\left(\frac{m_w L_v}{R^*}\left(\frac{1.0}{T_o} - \frac{1.0}{T}\right)\right)\ , \tag{17}$$

where $e_s = 6.1078$ mbar is the saturation vapor pressure at 0.0 °C; m_w and m_a are the molecular weights of water vapor and of dry air, respectively; $L_v = 2.5008 \times 10^6 + 2.3 \times 10^3\, T$ (T in degrees Celsius) is the latent heat of vaporization; $R^* = 8314.32$ J °K^{-1}kmol^{-1} is the universal gas constant; and RH is relative humidity in percent.

The derivatives of the refractive index given by equations (10) and (13) take the form

$$\frac{\partial n}{\partial z} = \frac{\partial n}{\partial T}\frac{\partial T}{\partial z} + \frac{\partial n}{\partial e}\frac{\partial e}{\partial z}\ , \tag{18}$$

so that

$$\frac{\partial n_{vi}}{\partial T} = \left(-\, m_1 \frac{P}{T^2} - (m_2 - m_1)\frac{e}{T^2}\frac{\partial e}{\partial T}\right) \times 10^{-6}\ , \tag{19}$$

where

$$\frac{\partial e}{\partial T} = -\frac{1.0}{T^2}\frac{L_v}{R^*/m_w}\exp\left(\frac{L_v}{R^*/m_w}\left(\frac{1.0}{T_o} - \frac{1.0}{T}\right)\right) \times \left(\frac{(e^2 - e)}{P\ q}\right)\ . \tag{20}$$

The partial derivative of n with respect to vapor pressure takes the form

$$\frac{\partial n_{vi}}{\partial e} = \frac{(m_2 - m_1)}{T} \times 10^{-6}\ . \tag{21}$$

The partial derivative of vapor pressure takes the form

$$\frac{\partial e}{\partial z} = \frac{\partial e}{\partial q}\frac{\partial q}{\partial z}\ , \tag{22}$$

where

$$\frac{\partial e}{\partial q} = \frac{m_w/m_a \; P}{(m_w/m_a + (1.0 - m_w/m_a)q)^2} \; . \tag{23}$$

The partial derivative of T in terms of the scalar potential temperature takes the form

$$\frac{\partial T}{\partial z} = \frac{\frac{\partial \theta}{\partial z} + \frac{2.0}{7.0} T \frac{P_s}{P^2} \left(\frac{P_s}{P}\right)^{-5/7} \frac{\partial P}{\partial z}}{\left(\frac{P_s}{P}\right)^{2/7}} \; . \tag{24}$$

Equations (13) and (14) can be rewritten as

$$n_{ir} = 1 + \left[m_1 \frac{P}{T} + (0.21668 f(T,X) - m_1) \frac{e}{T} \right] \times 10^{-6} \; , \tag{25}$$

where

$$[A] = \left[\frac{957.0 - 928.0\,(T/T_o)^{0.4}\,(X - 1.0)}{1.03\,(T/T_o)^{0.17} - 19.8X^2 + 8.2X^4 - 1.7X^8} + \frac{3.747 \times 10^6}{12449.0 - X^2} \right] \; . \tag{26}$$

The partial derivative of n_{ir} with respect to temperature can now take the form

$$\frac{\partial n_{ir}}{\partial T} = \left[- m_1 \frac{P}{T^2} - \frac{e}{T^2} (0.21668[A] - m_1) \frac{\partial [A]}{\partial T} \right] \times 10^{-6} \; , \tag{27}$$

where

$$\frac{\partial [A]}{\partial T} = - \frac{\frac{0.1751}{T_o} \left(\frac{T}{T_o}\right)^{-0.83} \left(957.0 - 928.0 \left(\frac{T}{T_o}\right)^{0.4} (X - 1.0)\right)}{\left(1.03 \left(\frac{T}{T_o}\right)^{0.17} - 19.8X^2 + 8.2X^4 - 1.7X^8\right)^2} - \frac{\frac{371.2}{273.15} \left(\frac{T}{T_o}\right)^{0.6}}{\left(1.03 \left(\frac{T}{T_o}\right)^{0.17} - 19.8X^2 + 8.2X^4 - 1.7X^8\right)} \; . \tag{28}$$

Lastly, the partial derivative of n_{ir} with respect to vapor pressure takes the form

$$\frac{\partial n_{ir}}{\partial e} = \left[\frac{(0.21668[A] - m_1)}{T} \right] \times 10^{-6} \; . \tag{29}$$

3. A Model of the Microstructure of Atmospheric Optical Turbulence

The equations presented in sections 2.1 and 2.2 were programmed in FORTRAN to produce a computer model called MAOT. The MAOT model computes the refractive index structure constant, given values for the heat and momentum flux and gradients of pressure, temperature, wind speed, and specific humidity as input. Table 1 gives values for the model's physical constants. Table 2 gives the results of testing the MAOT calculation for different conditions of atmospheric stability. The model input is generated from observed surface layer data that were reported by Tunick et al [7] except for the last column, which was derived from the micrometeorological data reported by Stenmark and Drury [12].

Values of C_n^2 have been generally observed to range from about 10^{-12} to 10^{-16} $m^{-2/3}$. The values of C_n^2 for the column labeled *Unstable* (approximately 10^{-12} $m^{-2/3}$) imply that the turbulence is intense, and considerable image blurring or signal distortion could occur (similar to that seen when one looks over an open field or a paved lot on a hot day). In contrast, the values of C_n^2 for the column labeled *Weakly stable* (approximately 10^{-16} $m^{-2/3}$) imply that the intensity of the optical turbulence might be considered negligible, except for where a light beam is transmitted over a long distance. Higher values of C_n^2 given in table 1 correlate with higher (absolute) values of kinematic heat flux and potential temperature gradient. The lower values of C_n^2 given in table 1 correlate with higher values of momentum flux and wind speed gradient. This observation makes the point that surface layer stability and turbulence are generally lessened by the effects of wind shear and surface stress.

Table 1. Microstructure of atmospheric optical turbulence model physical constants.

Parameter	Symbol	Unit	Amount
Kolmogorov or Corrsin constant	b_n	—	1.736
Acceleration due to gravity	g	m/s^2	9.8
Temperature scaling	T_o	$°K$	273.15
Molecular weight of water vapor	m_w	g/mol	18.016
Molecular weight of dry air	m_a	g/mol	28.966
Universal gas constant	R^*	$J\ °K^{-1}\ kmol^{-1}$	8314.32
Saturation vapor pressure at 0.0 °C	e_s	mbar	6.1078
Reference level pressure	P_s	mbar	1013.25

Table 2. Microstructure of atmospheric optical turbulence model input and output.*

Parameter	Unit	Condition of atmospheric stability			
		Unstable	Weakly unstable	Weakly stable	Stable
Kinematic heat flux	$°K\ m/s$	–0.470	–0.055	0.014	0.073
Momentum flux	m^2/s^2	–0.164	–0.217	–0.042	–0.191
Potential temperature gradient	$°K/m$	–0.670	–0.124	0.010	0.310
Wind speed gradient	$\frac{m}{s}/m$	0.330	0.510	0.303	0.812
Specific humidity gradient	$\frac{g}{g}/m$	-1.133×10^{-4}	-6.667×10^{-6}	1.000×10^{-4}	-2.500×10^{-4}
Pressure gradient	$mbar/m$	–0.10	–0.10	–0.10	–0.10
		Model output			
C_n^2 visible	$m^{-2/3}$	1.633×10^{-12}	3.382×10^{-14}	8.590×10^{-16}	1.176×10^{-13}
C_n^2 IR	$m^{-2/3}$	1.763×10^{-12}	3.479×10^{-14}	5.283×10^{-15}	1.154×10^{-13}

**Electromagnetic wavelength—visible 0.94 μm*
Electromagnetic wavelength—IR 10.6 μm

4. Summary

The propagation of a light beam through the atmosphere is affected by random fluctuations in the refractive index of air [24] and it is these fluctuations or discontinuities that cause optical turbulence. The refractive index structure parameter is the quantitative measure for such turbulence. In this report, I have presented the algorithm MAOT, derived from equations collated from different articles in the open literature. The MAOT calculation was tested using kinematic heat flux and momentum flux data generated from observations. MAOT was regarded as a step taken toward enhancing calculations of refractivity in the surface layer through the diurnal cycle.

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Turbulent fluctuations in air density can cause significant distortions of an electromagnetic signal or image. Density fluctuations can be described in terms of air temperature, air pressure, water vapor, and CO_2 content. We can calculate the refractive index structure constant, C_n^2, with the fine-scale dynamics of heat, moisture, and momentum diffusion. This helps us to quantify the intensity of turbulence-induced refraction. A better understanding of turbulence-induced refraction can provide a means of evaluating sensors under various atmospheric conditions or be used in the development of turbulence-compensation adaptive optic systems. This paper annotates one set of equations for the refractive index structure constant, C_n^2, taken from the literature.

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