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LWKD and Sound Propagation in the Surface Boundary Layer

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Abstract

The objective of this report is to demonstrate how DRDC Valcartier's surface boundary layer model LWKD may be used to predict the vertical profile for the index of refraction or the refractivity, and the refractivity structure parameter for the propagation of sound waves through the air and over relatively flat land, ice or water.

DRDC Valcartier's LWKD model was originally developed to produce vertical profiles of air temperature, relative humidity, atmospheric pressure, and wind speed over water using Monin-Obukhov similarity theory. From the fundamental parameters obtained from its solution of the Monin-Obukhov similarity equations, the model determines structure parameters for temperature and humidity. From these parameters, it can also predict vertical profiles for the refractivity and the refractivity structure parameter, two of the most important parameters required to predict the propagation of electromagnetic radiation through the atmosphere. In its current version, it produces these values for optical, near infrared, mid-infrared and far-infrared wavelengths, and radio frequencies, but not for acoustical wavelengths.

The report gives a brief introduction of LWKD with particular attention to details of importance to acoustic propagation in the atmosphere, discusses the speed of sound in moist air, the determination of the vertical refractivity profile for sound, and the determination of the refractivity structure parameter for sound. It discusses how to use the most recent version of LWKD (Ver. 8.10) to obtain the required vertical profiles to determine the refractivity and the refractivity structure parameter, and how this version could be modified to produce these parameters by the addition of a new acoustic mode. Finally, it discusses the work that will remain to validate the acoustic mode using past and future experimental results.

Résumé

L'objectif de ce rapport est de montrer comment le modèle de couche atmosphérique de RDDC Valcartier LWKD peut être utilisé pour prédire le profil vertical de l'indice de réfraction ou de réfractivité, et le paramètre de structure de réfractivité pour la propagation des ondes acoustiques à travers l'atmosphère et au-dessus d'un terrain plat, de glace ou de l'eau.

Le modèle LWKD de RDDC Valcartier a été développé à l'originale pour produire les profils verticaux de température de l'air, de l'humidité, de la pression atmosphérique, et de la vitesse de vent au-dessus de l'eau en utilisant la théorie de similarité de Monin-Obukhov. Employant les paramètres fondamentaux obtenus de sa solution des équations de similarité de Monin-Obukhov, il détermine les paramètres de structure pour la température et l'humidité. À partir de ces paramètres, il est aussi capable de prédire les profils verticaux pour la réfractivité et la structure du paramètre de réfractivité, deux des plus importants paramètres requis pour prédire la propagation de la radiation électromagnétique à travers l'atmosphère. Dans sa version courante, il produit ces paramètres pour les longueurs d'ondes optiques, de proche infrarouge, de l'infrarouge moyen et de l'infrarouge lointain, et des fréquences radio, mais pas pour les ondes acoustiques.

Ce rapport donne une brève introduction du LWKD et accorde une attention particulière aux détails importants pour la propagation acoustique dans l'atmosphère, la vitesse du son dans l'air humide, la détermination de son profil vertical de réfractivité, et la détermination de son profil vertical de paramètre du structure de réfractivité. Il discute de la façon d'employer la plus récente version du LWKD (Ver. 8.10) pour obtenir les profils verticaux requis pour déterminer la réfractivité et le paramètre de structure de réfractivité, et comment cette version pourrait être changée afin qu'il produise ces paramètres avec l'addition d'un mode acoustique. Finalement, on discute du travail qui reste pour le mode acoustique avec des données expérimentales passées et futures.

Executive summary

LWKD and Sound Propagation in the Surface Boundary Layer

J. Luc Forand; DRDC Valcartier TR 2008-037; Defence R&D Canada – Valcartier.

Introduction: The use of sensors other than radar systems as a complement to better detect, recognize, classify and identify targets is becoming increasingly important in a world where asymmetric threats are increasingly becoming the principal risk to all armed forces. Consequently, there is an increasing interest in the simultaneous use of acoustic, visible, infrared, and radar sensors. However, the combined performance of such a suite of sensors is not easy to quantify, but is necessary, if an optimal choice of sensors is to be selected for a particular task. The first step in this process is to determine the performance of each sensor under its expected range of operating conditions.

Significance: To determine the performance of a sensor within the surface boundary layer, say the first 50 m above the surface, it is necessary to understand how the various types of waves propagate through the atmosphere. This requires a model characterization of the atmosphere between the sensor and possible targets; in particular, the refractivity and refractivity structure parameter at all points along the propagation path, for each type of wave. In recent years, mathematical models of the surface boundary layer model have improved greatly and have proven to be very reliable in predicting the propagation of optical, infrared and radar waves through the atmosphere. DRDC Valcartier's surface boundary layer model, LWKD, which has been developed and tested over the last 20 years, is capable of determining all required parameters using Monin-Obukhov similarity theory and measurements of the air temperature, relative humidity, atmospheric pressure and wind speed over ice, land or sea. However, while it was never developed to handle acoustic radiation, it is just as able in this domain as in the electromagnetic domain. In addition, compared to the current method of determining the vertical profile of the speed of sound, this proposed method is covert, as no acoustic or other radiative sources are required.

Future plans: This report shows how this new capability could be developed using outputs provided by the current version of LWKD, or by making certain modifications to the computer program so that it produces all required parameters for the prediction of the propagation of sound in the atmosphere.

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LWKD and Sound Propagation in the Surface Boundary Layer

J.Luc Forand; DRDC Valcartier TR 2008-037; R & D pour la défense Canada – Valcartier.

Introduction ou contexte: L'usage de capteurs divers pour complémenter des systèmes radar pour mieux détecter, reconnaître, classifier et identifier des cibles augmenter en importance dans un monde où les dangers asymétriques deviennent de plus en plus le risque principal pour toutes les forces armées. Par conséquent, il y a un intérêt grandissant d'employer simultanément des capteurs acoustiques, visibles, infrarouges, et radars. Néanmoins, la performance totale d'une telle suite de capteurs n'est pas facile à quantifier, mais c'est nécessaire si un choix optimal de capteurs peut être choisi pour une tâche particulière.

Importance: Pour déterminer la performance d'un capteur dans la couche atmosphérique de surface, disons les 50 premiers mètres au-dessus de la surface, il est nécessaire de bien comprendre comment tous les types d'ondes se propagent à travers l'atmosphère. Ceci requiert un modèle pour bien caractériser l'atmosphère entre le capteur et la cible possible; en particulier sa réfractivité et son paramètre du structure de réfractivité sur tous la longueur des sentiers, pour chaque sorte d'onde. Au cours des dernières années, les modèles mathématiques pour la couche atmosphérique de surface se sont beaucoup améliorés et nous avons montré qu'ils sont bien fiables pour prédire la propagation des ondes optiques, infrarouges et radars à travers l'atmosphère. Le modèle de couche de surface atmosphérique LWKD de RDDC Valcartier, qui a été développé et testé durant les 20 dernières années, est capable de déterminer tous les paramètres requis en employant la théorie de similarité de Monin-Obukhov, et les mesures discrètes de la température de l'air, l'humidité relative, la pression atmosphérique et la vitesse de vent au-dessus de la glace, de la terre ou de la mer. Mais, même s'il n'a jamais été développé pour la radiation acoustique, il est autant capable dans ce domaine que dans le domaine électromagnétique. En plus, comparé à la méthode traditionnelle pour la détermination du profil vertical de la vitesse du son, la méthode proposée est clandestine, parce qu'aucune source acoustique ou radiative n'est requise.

Perspectives: Ce rapport montre comment cette nouvelle capacité pourrait être développée en employant les sorties déjà produites par LWKD, ou en faisant certaines modifications à son programme pour qu'il fournisse directement tous les paramètres requis pour prédire la propagation du son dans l'atmosphère.

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Acknowledgements

I would like to thank Jacques Bédard oft DRDC Valcartier for providing the impetus for this work on developing the use of LWKD for acoustic propagation over water and land.

1 Introduction

At DRDC Valcartier we have been developing the surface boundary layer (SBL) model LWKD for almost 20 years. The Luc, Walmsley, KEL, DREV model (Ref. 1,2,3) was originally developed to produce vertical atmospheric profiles of the refractivity, the air temperature, the refractivity structure parameter, and other profiles given a specific set of meteorological parameters for the marine boundary layer (MBL). However, it has recently been adapted for the land boundary layer such that it is now a general SBL model.

The atmospheric profiles produced by LWKD can then be used by other programs to predict the optical, infrared or radio-frequency characteristics of the surface boundary layer. For example, refractivity profiles produced by LWKD were used within the SISWS (Shipboard Integration of Sensors and Weapons Systems) technical demonstration program to predict the performance of both infrared (IR) and radio-frequency (RF) sensors (Ref. 4).

Recently, DRDC Valcartier's in-air acoustic team expressed an interest in using its vertical profile outputs of temperature, humidity and wind speed to either provide information to predict the vertical profile of the index of refraction for acoustic waves or to include it as one of LWKD's outputs. In addition to the index of refraction, LWKD can also be used to determine the vertical profile of the index of refraction structure parameter (or speed of sound), such that they can both be used by acoustic propagation models to predict mean and turbulent sound levels.

Currently, in the acoustic community, the vertical profile of the speed of sound in air is given by either a linear (Eq. 1a) or logarithmic function (Eq. 1b) of height (Ref. 6,7):

$$c_a(z) = c_0 + g_0 z\,, \qquad (1a)$$

$$c_a(z) = c_0 + g_1 \ln(1 + z / z_0)\,, \qquad (1b)$$

where c_0 is the reference speed of sound, g_0 and g_1 are the speed of sound refraction parameters, and z_0 is the roughness height. For g_0 or g_1 positive the atmosphere is such that sound energy is refracted downwards, and if they are negative, sound energy is refracted upwards. To determine the parameters in Equation 1, the user has to determine the speed of sound at either two (linear case) or three (logarithmic case) heights. This is normally done by installing three radiating acoustic sources at various heights that are not very covert. This report proposes an alternative method that uses covert simple meteorological measurements and the LWKD model to obtain the required parameters and more.

Chapter two of this report presents the fundamental equations for the speed of sound in moist air, Chapter 3 the index of refraction and refractivity for sound, and Chapter 4 the refractivity structure parameter. Chapter five discusses how to use the most recent version of LWKD (Ver. 8.10) to obtain the required vertical profiles to determine the refractivity and the refractivity structure parameter, Chapter 6 discusses how LWKD could be modified to produce these parameters itself by the addition of an acoustic mode, and the document ends with a conclusion.

This work was carried out at DRDC Valcartier between November 2007 and February 2008 under Thrust 1A.

2 The Speed of Sound in Moist Air

In the following discussion about the speed of sound in air, all physical constants were obtained from the 60th Edition of the Handbook of Chemistry and Physics (Ref. 8) and are reproduced in the List of Symbols. The basic equations are taken from an article by Dennis A. Bohn (Ref. 5). It should be noted that, to avoid possible confusion with previous LWKD publications (Ref. 3), the previously used nomenclature is followed as much as possible.

Accordingly, the speed of sound in dry air, c_d, with no wind, is given by

$$c_d(T) = \sqrt{\gamma RT / M_a} = \alpha_d T^{1/2} = 20.05 T^{1/2} \tag{2}$$

where

$$\alpha_d = \sqrt{\gamma R / M_a} = 20.05 \,, \tag{3}$$

T is the air temperature in Kelvin, R (J/mol/K) is the universal gas constant, M_a (g/mol) is the molecular mass of dry air at STP (standard temperature and pressure), and γ (=7/5) is the ratio of the specific heat at constant pressure to that at constant volume. When water vapour is added to the air, we now have moist air, and the speed of sound for moist air, c_m, is given by:

$$c_m = \sqrt{\gamma_m RT / M_m} = \sqrt{\gamma RT_s / M_a} \,, \tag{4}$$

where T_s is the sonic temperature given by

$$T_s = (\gamma_m / \gamma)(M_a / M_m)T \,, \tag{5}$$

M_m is the molecular mass of moist air given by:

$$M_m = (1-r)M_a + rM_w = M_a[1 + r(M_w - M_a)/M_a] = M_a[1-(1-\mu)r] \,, \tag{6}$$

M_w is the molecular mass of water vapour, and

$$\mu = M_w / M_a \tag{7}$$

is the molecular mass ratio. The specific heat ratio for moist air, γ_m, is given by:

$$\gamma_m = (7+r)/(5+r) = \gamma(1 + r/7)/(1 + r/5) \,, \tag{8}$$

the vapour fraction, r, is given by:

$$r = \frac{P_w}{P} = \frac{H_r P_w^s(T)}{100P} = \frac{q/\mu}{1+(1-\mu)q/\mu} \approx q/\mu \,, \tag{9}$$

P_w is the water vapour pressure, P is the atmospheric pressure, H_r is the relative humidity, P_w^s is the saturated vapour pressure, and q is the specific humidity. The water vapour fraction can often be approximated by q/μ as the atmosphere's specific humidity is normally less than 0.01.

Combining Equations 6 and 8 into Equation 5 gives

$$T_s = \frac{[1 + r/7]}{[1 + r/5][1-(1-\mu)r]} T \tag{10}$$

for the sonic temperature. As the water vapour fraction is normally quite small, less than 0.05, Equation 10 can be approximated as

$$\begin{aligned} T_s &\simeq [1 + r/7][1 - r/5][1 + (1-\mu)r]T \\ &\approx [1 + (33/35 - \mu)r]T = (1 + \alpha_r r)T \end{aligned} \tag{11}$$

where only the first order in r has been kept, and

$$\alpha_r = 33/35 - \mu = 0.321 . \tag{12}$$

Substituting Equation 11 into Equation 2, finally gives

$$c_m(T,r) = \sqrt{\gamma R(1+\alpha_r r)T / M_a} = c_d(T)(1+\alpha_r r)^{1/2} \tag{13}$$

or

$$c_m(T,q) = c_d(T)(1+\alpha_q q)^{1/2} \tag{14}$$

where

$$\alpha_q = (33/35 - \mu)/\mu = 0.517 . \tag{15}$$

Note that α_r and α_q are two constant parameters associated with the water vapour fraction in Eq. 13 and specific humidity in Eq. 14 and are used such that the equations have similar forms.

Equation 14 can be expressed linearly in terms of q and T by assuming that q is small, and that the variation of T about some average temperature T_1 is also small. Then

$$c_m(T,q) = c_d(T_1)(1+t/T_1)^{1/2}(1+\alpha_q q)^{1/2} \tag{16}$$

where

$$T = T_1 + t = T_1(1+t/T_1) , \tag{17}$$

such that upon expansion

$$\begin{aligned} c_m(T_1;t,q) &= c_d(T_1)(1+t/2T_1)(1+\alpha_q q/2) \\ &= c_d(T_1)(1+t/2T_1+\alpha_q q/2+\alpha_q qt/4T_1). \end{aligned} \tag{18}$$

This expression is of particular importance for determining the index of refraction structure parameter. It should also be noted that if T_1 is chosen to be 273.15 K (0^{o}C), then t is the temperature in degrees Celsius.

Finally, the speed of sound in air, c_a, also depends on the wind direction along its direction of propagation, such that

$$c_a = c_m + u_s \tag{19}$$

where u_s is the wind speed along the direction of propagation such that the speed of sound increases if the wind blows in the same direction as the sound propagates, and decreases if the wind blows in the opposite direction of the sound propagation.

3 Acoustic Refractivity

Another way to express the speed of sound waves within inhomogeneous mediums is in terms of the index of refraction or the refractivity. For the purpose of this work, the index of refraction in air, n, at some height z above the surface is defined as the ratio of the speed of sound determined for dry air at the measured air temperature, T_1, obtained at the height, z_1 above the surface, to the speed of sound in air at the height z above the ground. This gives

$$\frac{1}{n(z)} = \frac{c_a(z)}{c_d(T_1)} = \frac{c_m(z)+u_s(z)}{c_d(T_1)} = \frac{c_m(z)}{c_d(T_1)} + \frac{u_s(z)}{c_d(T_1)}, \qquad (20)$$

where $c_m(z)$ is the vertical profile of the speed of sound in air, and $u_s(z)$ is the vertical profile of the wind speed along the direction of propagation in the moist atmosphere. Using Equation 14, Equation 20 can be restated as

$$1/n(z) = [1+t/T_1]^{1/2}[1+\alpha_q q(z)]^{1/2} + \frac{u_s(z)}{c_d(T_1)}, \qquad (21)$$

and further simplified using Equations 18 to

$$1/n(z) = 1 + t(z)/2T_1 + \alpha_q q(z)/2 + \alpha_q q(z)t(z)/4T_1 + \frac{u_s(z)}{c_d(T_1)}. \qquad (22)$$

To get an idea as to the importance of each term, consider the following typical conditions. Assume that P is about 1000 hPa, T_1 is 273 K (c_d = 330 m/s), and that P_w varies on the order of 1 hPa (i.e. q varies by about 0.001), t varies on the order of 1^oC, and u_s varies on the order of 1 m/s, then each term in equation 15 has the following relative importance:

$$1/n = 1 + \frac{0.2}{100} + \frac{0.03}{100} + \frac{5x10^{-5}}{100} + \frac{0.3}{100}. \qquad (23)$$

As can be seen, changes in air temperature and wind speed are the dominant effects and are similar in importance. The presence of water vapour has about 1/100 of the effect, and the combination term $1/10^4$ of the effect. Ignoring this term, we now have the following equation for the index of refraction, the refractivity (Z), or the modified refractivity (M):

$$1/n(z) = 1 + \frac{t(z)}{2T_1} + \frac{\alpha_q q(z)}{2} + \frac{u_s(z)}{c_d(T_1)} = 1 + n_0(t,q) + n_1(u_s) \qquad (24a)$$

$$Z(z) = [n(z)-1]x10^6 \qquad (24b)$$

$$M(z) = Z(z) + 0.157z \qquad (24c)$$

where

$$n_o(t,q) = \frac{t(z)}{2T_1} + \frac{\alpha_q q(z)}{2} = n_t t(z) + n_q q(z), \qquad (25a)$$

$$n_1(u_s) = \frac{u_s(z,\delta)}{c_d(T_1)} = \frac{u(z)\cos\delta}{c_d(T_1)} = n_u u(z), \qquad (25b)$$

$$u_s(z,\delta) = u(z)\cos\delta\,, \tag{26}$$

where u(z) is the wind speed, δ is the angle between the wind speed and the direction of propagation, and

$$n_t = \frac{1}{2T_1}; \quad n_q = \frac{\alpha_q}{2}; \quad n_u = \frac{\cos\delta}{c_d(T_1)}\,. \tag{27}$$

Thus, we have the result that increasing air temperature increases the speed of sound, increasing specific humidity (more moisture) increases the speed of sound, and increasing wind speed in the direction of propagation increases the speed of sound. This agrees with what is expected from Eq. 3, where the speed of sound increases with temperature and increases with decreasing air mass.

4 Acoustic Structure Parameters

The refractive index structure parameter, C_n^2, the refractivity index structure parameter, C_Z^2, and other structure parameters are also important parameters that determine the effects of atmospheric turbulence on the propagation of sound. As shown in Ref. 3, the refractive index structure parameter at an elevation, z, is given by

$$\begin{aligned} C_n^2(z) &= h^{-2/3} < [n(z) - n(z+h)]^2 >_{avg} \\ &= 1x10^{12} h^{-2/3} < [Z(z) - Z(z+h)]^2 >_{avg} = 1x10^{12} C_Z^2(z) \end{aligned} \tag{28}$$

where h is some incremental height, Z is the refractivity, C_Z^2 is the refractivity structure parameter, and where only their height dependence is explicitly shown. Using Eq. 25, the refractivity structure parameter can be expressed as

$$\begin{aligned} h^{2/3} C_n^2(z) = h^{2/3} n^4(z) C_{1/n}^2(z) &= n^4(z) < [n_0(z) - n_0(z+h) + n_1(z) - n_1(z+h)]^2 >_{avg} \\ &= h^{2/3}[C_{n_0}^2(z) + C_{n_1}^2(z) + 2C_{n_0 n_1}(z)] \end{aligned} \tag{29}$$

such that

$$C_n^2(z) = C_{n_0}^2(z) + C_{n_1}^2(z) + 2C_{n_0 n_1}(z) \tag{30}$$

where

$$h^{2/3} C_{n_0}^2(z) = n^4(z) < [n_0(z) - n_0(z+h)]^2 >_{avg} \quad . \tag{31a}$$

$$h^{2/3} C_{n_1}^2(z) = n^4(z) < [n_1(z) - n_1(z+h)]^2 >_{avg} \quad . \tag{31b}$$

$$h^{2/3} C_{n_0 n_1}(z) = n^4(z) < [n_0(z) - n_0(z+h)][n_1(z) - n_1(z+h)] >_{avg} \quad . \tag{31c}$$

The three structure parameters given in Equation 31, shall henceforth be named the Zeroth Index of Refraction (ZIR) structure parameter, the First Index of Refraction (FIR) structure parameter, and the Zeroth-First Index of Refraction (ZFIR) structure parameter, respectively.

Applying Equation 25 to Equation 31a gives the following result for the ZIR structure parameter:

$$C_{n_o}^2(z,t,q) = n^4(z)[n_t{}^2 C_t^2(z,t) + n_q{}^2 C_q^2(z,q) + 2n_t n_q C_{tq}(z,t,q)] . \tag{32}$$

All three terms can be given by LWKD, which would provide the desired turbulence structure parameter if no wind was present. The three structure parameters in Equation 32 are the Temperature structure parameter, the Specific Humidity structure parameter, and the Temperature-Specific Humidity structure parameter.

If a wind is present, then it is also necessary to consider the FIR structure parameter. Applying Equation 25 to Equation 31b gives the following result for the FIR structure parameter

$$C_{n_1}^2(z,s) = n^4(z) n_u^2 C_u^2(z) , \tag{33}$$

whose term, the Wind Speed structure parameter, is not currently provided by LWKD. Whether or not it could be provided by LWKD is discussed later in the document.

Finally, again using Equation 25 and Equation 31c, the ZFIR term can be expressed as

$$C_{n_0 n_1}(z,t,q,u) = n^4(z)[n_t n_u C_{tu}(z,t,u) + n_q n_u C_{qu}(z,q,u)]\,, \tag{34}$$

whose terms are also not provided by LWKD. Again, whether or not they could be will be discussed later in the document. The two structure parameters in Equation 34 are the Temperature-Wind structure parameter and the Specific Humidity-Wind structure parameter.

5 Current LWKD Capabilities

While Version 8.10 and earlier versions of the LWKD program are not able to produce the vertical profile of either the index of refraction (refractivity or modified refractivity) or the index of refraction (or refractivity) structure parameter for acoustic wavelengths, it is able to produce all the vertical profiles required to determine these parameters.

Its TDPXXX file contains the air temperature measured at height z_1, and vertical profiles of air temperature, relative humidity, atmospheric pressure, and wind speed (s) from which the temperature difference ($t=T-T_1$), and specific humidity (q) vertical profiles can be determined. The vertical profile of the wind speed along the direction of propagation, u, cannot be determined as its angle relevant to the wind direction, θ, is not provided. Thus, only the vertical profiles for n_0 and $n_1/\cos\theta$ can be determined.

Its CN2_XXX file and COND_XXX files can be used to determine many of the structure parameter vertical profiles. The CN2_XXX file contains the vertical profile for the temperature structure parameter, the specific humidity structure parameter, and the temperature-humidity structure parameter (Ref. 3). To determine the vertical profiles for the other structure parameters, the user can make use of the friction velocity, u_*, and the specific humidity scaling parameter, q_* or virtual potential temperature scaling parameter, θ_{v*}, contained in the COND_XXX file and the following relationships (Ref. 3):

$$C_u^2(z) = (u_* / q_*)^2 C_q^2(z) = (u_* / \theta_{v*})^2 C_{\theta_{v*}}^2(z) \tag{35a}$$

$$C_{qu}(z) = (u_* / q_*) C_q^2(z) = (u_* / \theta_{v*}) C_{\theta_{v*}q}(z) \tag{35b}$$

$$C_{\theta_{v*}u}(z) = (u_* / q_*) C_{\theta_{v*}q}(z) = (u_* / \theta_{v*}) C_{\theta_{v*}}^2(z) \tag{35c}$$

and

$$C_{tu}(z) = \frac{[P(z)/P_{ref}]^{(\gamma-1)/\gamma}}{[1+(1-\mu)q(z)/\mu]} C_{\theta_{v*}u}(z), \tag{36}$$

where P_{ref} is a reference pressure normally taken to be 1000 hPa. It is preferable to use the specific humidity scaling parameter terms rather than the temperature scaling parameter terms as it is often better behaved in that it rarely goes through zero. However, if this occurs, then the virtual potential temperature scaling parameter terms should be used.

6 Possible Future LWKD Capabilities

Even though the LWKD program has not been created to perform calculations of refractivity and the refractivity structure parameter for acoustics, versions after 8.10 can be modified to perform many of the required calculations with a minimum of effort and the introduction of an acoustic mode.

The introduction of an acoustic mode to LWKD to supplement the current optical, infrared and radio frequency modes would require a number of changes to both its batch and interactive modes of operation.

6.1 Batch Mode

For the batch mode or the batch process available through the interactive mode, no changes need to be made to the METDATA input file; although, its ability to handle an acoustic mode could be added. As for the output files, as the CONDXXX and TDPXXX files can remain exactly as they are, no changes to the parts of the code that produce these files are required. However, as the MP_H_XXX and CN2_XXX files depend on the index of refraction, the parts of the code that calculate the index of refraction, the index of refraction structure parameter, and other associated parameters need to be modified so as to handle the addition of an acoustic mode.

In particular, the code must be changed so that the file MP_H_XXX contains the term of the modified refractivity that corresponds to the n_0 and n_1 terms of Equation 24. The n_0 term and its gradients are easy to include as they only depend on the temperature and humidity profiles. The n_1 term is more difficult since it depends on the angle between the direction of propagation and the wind, something which is not known a priori. One solution, and probably the simplest, would be to assume that the angle is zero degrees (cos 0 = 1), and to allow the user to obtain this term and its gradients for any angle, δ, by multiplying the terms by cos δ. The file will also require a calculation of the characteristic height or duct height for which it would probably be best to calculate it for three cases, δ = 0, 90 and 180 degrees.

Similarly, the code must be changed so that the file CN2_XXX contains the refractivity structure parameter and some of its component terms. The terms should include those defined by Equations 30, 32, 33 and 34 and perhaps some of the terms contained within Equations 32, 33 and 34. Most of these terms are already determined by LWKD; however, calculations for all the wind speed terms would need to be added to the code. These terms would be calculated using the same functions currently used by LWKD (Ref. 3), that is by

$$C_u^2(z) = u_*^2 z^{-2/3} f(z/L) \ , \tag{37a}$$

$$C_{qu}(z) = u_* q_* z^{-2/3} f(z/L) \, , \tag{37b}$$

$$C_{\theta_v u}(z) = r_{\theta_v u} u_* \theta_{v*} z^{-2/3} f(z/L) \, , \tag{37c}$$

where $r_{\theta vu}$ is the virtual potential temperature-wind speed correlation coefficient, P_{ref} the reference (normally 1000 hPa), and *f* the structure parameter function. It should be noted that we assume that the same structure parameter functions are appropriate for all the structure parameters. It now remains to determine the correlation coefficient $r_{\theta vu}$. This is accomplished using the same approach as that given in Ref. 3 for the correlation coefficient $r_{\theta vq}$. The result is

$$r_{\theta_v u} = \frac{C_{\theta_v u}}{\sqrt{C_{\theta_v}^2 C_u^2}}, \tag{39}$$

where the correlation coefficient can be either positive or negative depending upon whether the atmosphere is unstable or stable, respectively. For this work, it will be assumed to behave in the same manner as the coefficient $r_{\theta vq}$ and to have an absolute value of 0.8. Finally, the flexibility that LWKD currently has in determining the refractivity structure parameter would be kept by including the scaling parameter E_z, and the refractivity ratio A_z into Equation 30 as follows:

$$C_n^2(z) = E_z\,[C_{n_0}^2(z) + A_z^2 C_{n_1}^2(z) + 2A_z C_{n_0 n_1}(z)]. \tag{40}$$

These proposed changes to the LWKD code should be such that our LWKD would have the same functionality in the acoustic mode as it currently does for the IR and RF modes.

6.2 Interactive Mode

For the interactive mode the code must also be changed so as to be able to produce the various outputs for the new acoustic mode. These outputs include the LWKD binary file, which also must be correctly read as an input file, the various refractivity files, the various structure parameter files, and profile parameter files.

7 Conclusions

This report has developed all the relevant equations required to determine the refractivity and its structure parameter, and other parameters required by an acoustic propagation program that determines the propagation of acoustic radiation through the atmosphere. It has also shown how to use parameters that are currently produced by DRDC Valcartier's surface layer model, LWKD, to obtain the required parameters, and how LWKD could be modified, by the addition of an acoustic mode, to produce them directly.

The next steps will be to use the present outputs from LWKD in acoustic propagation algorithms and to compare their results to previous experimental results and to acoustic propagation predictions that use techniques different from LWKD. For example, the speed of sound profiles provided by LWKD should be compared to the logarithmic representations currently used by the acoustic community. At the same time, the modifications discussed in Chapter 6 can be introduced into LWKD such that the intermediate steps presently required to determine the refractivity and its structure parameter can be directly provided to the acoustic propagation models.

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List of symbols

The following table provides a list of most symbols used in this document and, if applicable, their units and default values.

Quantity	Symbol	Value	Units
Speed of sound in air	c_a		m/s
Reference speed of sound	c_0		m/s
Speed of sound refractivity parameter	g_0		s^{-1}
Speed of sound refractivity parameter	g_1		m/s
Wind speed roughness length	z_0		m
Speed of sound in dry air	c_d		m/s
Air temperature	T		K
Universal gas constant	R	8.31451	J/mol/K
Molecular mass of dry air	M_a	28.966	g/mol
Ratio of heat capacities for dry air	γ	1.40	
Dry-air temperature parameter	α_d	20.05	$m/s/K^{1/2}$
Speed of sound in moist air	c_m		m/s
Molecular mass of moist air	M_m		g/mol
Ratio of heat capacities for moist air	γ_m		
Sonic temperature	T_s		K
Molecular mass of water	M_w	18.000	g/mol
Water vapour fraction	r		
Ratio of mol. Masses of water and dry air (= M_w/M_a)	μ	0.6214	
Water vapour pressure	P_w		hPa
Total atmospheric pressure	P		hPa

Saturated water vapour pressure over water	P_w^s		hPa
Relative humidity	H_r		%
Specific humidity	q		g/g
Water vapour fraction parameter	α_r	0.3215	
Specific humidity parameter	α_q	0.5173	
Air temperature at height z_1	T_1		K
Air temperature	t		K
Speed of sound in air	c_a		m/s
Wind speed along the direction of propagation	u_s		m/s
Index of refractivity	n		
Height above surface (land or water)	z		m
First measurement height	z_1		m
Refractivity	Z		
Modified refractivity	M		
Zeroth index of refraction term	n_0		
First Index of refraction term	n_1		
Temperature index parameter	n_t	$1/(2T_1)$	1/K
Specific humidity index parameter	n_q	$\alpha_q/2$	
Wind index parameter	n_u	$1/c_d(T_1)$	s/m
Wind speed	u		m/s
Angle between wind direction and sound propagation direction	δ		degrees
Incremental height	h		m
Refractive index structure parameter	C_n^2		$m^{-2/3}$

Refractivity structure parameter	C_Z^2		$m^{-2/3}$
Zeroth index of refraction structure parameter	$C_{n_0}^2$		$m^{-2/3}$
First index of refraction structure parameter	$C_{n_1}^2$		$m^{-2/3}$
Zeroth-First index of refraction structure parameter	$C_{n_0 n_1}$		$m^{-2/3}$
Wind speed structure parameter	C_u^2		$m^{4/3}/s^2$
Specific humidity structure parameter	C_q^2		$m^{-2/3}$
Virtual potential temperature structure parameter	$C_{\theta v}^2$		K^2-$m^{-2/3}$
Wind speed scaling constant	u_*		m/s
Specific humidity scaling constant	q_*		g/g
Virtual potential temperature scaling constant	θ_v^*		K
Specific humidity-wind speed structure parameter	C_{qu}		$m^{1/3}$
Virt. pot. temp.-specific humidity structure parameter	$C_{q\theta v}$		K-$m^{-2/3}$
Virt. potential temp.-wind speed structure parameter	$C_{u\theta v}$		K-$m^{1/3}$
Temperature-wind speed structure parameter	C_{tu}		K-$m^{1/3}$
Reference pressure	P_{ref}	1000	hPa
Monin-Obukhov length	L		m
Structure parameter function	f		
Virt. pot. temp.-wind speed correlation coefficient	$r_{\theta vu}$	±0.8	
Virt. pot. temp.-specific hum. correlation coefficient	$r_{\theta vq}$	±0.8	
Refractivity structure parameter scaling parameter	E_z	1	
Refractivity ratio parameter	A_z	1	

List of abbreviations

LWKD	Luc, Walmsley, KEL & DREV
DREV	Defence Research Establishment Valcartier (now DRDC Valcartier)
DRDC	Defence Research and Development Canada
CASE	Computer Assisted Software Engineering
EO	Electro-Optical
IRST	Infrared Search and Track
TDA	Tactical Decision Aid
NATO	North Atlantic Treaty Organization
RF	Radio-frequency
DGA	Directeur Général d'Armement
MBL	Marine Boundary Layer
PIRAM	Profils d'Indice de Réfraction en Atmosphère Marine
IRBLEM	Infrared Boundary Layer Environment Model
MSL	Marine Surface Layer
SBL	Surface Boundary Layer
WKD	Walmsley, KEL & DREV
ASSHD	Air-Sea Specific Humidity Difference
ASVPTD	Air-Sea Virtual Potential Temperature Difference
ASTD	Air-Sea Temperature Difference
SHD	Specific Humidity Difference
VPTD	Virtual Potential Temperature Difference
TD	Temperature Difference
F.F.O.	Forschuninstitut Für Optik

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The objective of this report is to demonstrate how DRDC Valcartier's surface boundary layer model LWKD may be used to predict the vertical profile for the index of refraction or the refractivity, and the refractivity structure parameter for the propagation of sound waves through the air and over relatively flat land, ice or water.

DRDC Valcartier's LWKD model was originally developed to produce vertical profiles of air temperature, relative humidity, atmospheric pressure, and wind speed over water using Monin-Obukhov similarity theory. Using the fundamental parameters obtained from its solution of the Monin-Obukhov similarity equations, the model determines structure parameters for temperature and humidity. From these parameters, it can also predict vertical profiles for the refractivity and the refractivity structure parameter, two of the most important parameters required to predict the propagation of electromagnetic radiation through the atmosphere. In its current version, it produces these values for optical, near infrared, mid-infrared and far-infrared wavelengths, and radio frequencies, but not for acoustical wavelengths.

The report gives a brief introduction of LWKD with particular attention to details of importance to acoustic propagation in the atmosphere, discusses the speed of sound in moist air, the determination of the vertical refractivity profile for sound, and the determination of the refractivity structure parameter for sound. It discusses how to use the most recent version of LWKD (Ver. 8.10) to obtain the required vertical profiles to determine the refractivity and the refractivity structure parameter, and how this version could be modified to produce these parameters by the addition of a new acoustic mode. Finally, it discusses the work that will remain to validate the acoustic mode using past and future experimental results.

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LWKD, acoustic propagation, index of refraction, refractivity structure parameter

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