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The LWKD Surface Boundary Layer Model
Version 8.10

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Canada

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Abstract

The objective of this document is to bring readers up to date on the present state of DRDC Valcartier's LWKD model. Many important changes have been made to the previously reported version (V7.09) and need to be documented. Apart from changes to the physical equations and the inputs to and outputs from the program, it is also necessary to document changes to the program's development structure. As of version 7.51, the program is now being developed using Microsoft's Visual C/C++ (version 6) environment and the code has been reformulated as object oriented code and documented using Rational Rose's Computer Assisted Software Engineering (CASE) tool.

The first chapter of the document highlights some of the important changes made since version 7.09. Chapter 2 discusses the set of scaling equations that are used in the LWKD model and how they have been modified, and the method used by LWKD to solve for the parameters of the scaling equations. Chapter 3 discusses how LWKD calculates the index of refractivity from the visible to the far infrared and for radio frequencies. Chapter 4 shows how LWKD determines various structure parameters, including the refractivity structure parameter. Chapter 5 describes the additions and changes to the program's modes of operation and its new options, outputs and compilation modes, and Chapter 6 provides some conclusions.

Résumé

Ce document a pour objectif de présenter les mises à jour récentes du modèle LWWKD de RDDC Valcartier. Puisque plusieurs changements importants ont été apportés depuis la dernière version publiée (V7.09), il faut les documenter. À part les changements aux équations physique et aux entrées et sorties de programme, il faut aussi documenter les changements aux structures de programme. Depuis la version 7.51, le programme est maintenant développé avec l'environnement Visual C/C++ de Microsoft (Version 6), et il était documenté avec l'outil d'ingénierie logiciel assiste pas ordinateur (ILAO) de Rational Rose.

La première partie du document met en évidence les plus importants changements qui ont été faits depuis la version 7.09. Dans la deuxième partie, on présente les équations d'échelle employées par le modèle LWKD et comment elles one été modifiées, et la méthode utilisée par LWKD pour déterminer les paramètres de ces équations. Dans la troisième, on présente comment l'indice de réfraction, du visible à l'infrarouge lointain et pour les fréquences radio, sont calculées. Dans la quatrième partie, on montre comment les paramètres de structure, incluant le paramètre structure pour la réfraction, sont déterminés. Dans la cinquième partie on décrit les changements aux modes d'opération, les nouvelles entrées et sorties, et les modes de compilation, et dans la sixième partie on forme quelques conclusions.

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Executive summary

Given the development of new electro-optic (EO) sensors, such as the SIRIUS infrared search and track system that will soon be installed on various naval ships, and the need for tactical decision aids (TDAs) for such systems, the question of how electromagnetic radiation propagates through the atmosphere is of foremost importance and relevance. As the atmosphere's refractive index varies with pressure, temperature, water vapour content and height above the surface, all radiation follows a curved path. Straight line propagation is only possible in non-refractive atmospheres, where the index of refraction is absolutely uniform. This means that, in general, the apparent elevation angle of a target as seen by an observer is not that given by the straight line from the observer to the target. This leads to two phenomena. The first is the phenomenon called sub-refraction, which occurs when electromagnetic radiation is bent away from the surface of the earth. This can lead to mirage effects, where an observer can detect a single source at two different elevation angles. The second phenomenon is called super-refraction, which occurs when electromagnetic radiation is bent towards the surface of the earth, such that an observer can detect a source beyond the geometrically defined horizon. The magnitude of these phenomena is dependent upon both meteorological conditions and radiation wavelength. In the maritime environment, this means that under some conditions the distance from an observer to the visible horizon can be shorter than the distance to the geometric horizon (sub-refraction), while under other conditions the visible horizon can be farther than the geometric horizon (super-refraction or ducting). From the results of many trials, it has been found that the distance to the visible horizon can vary by as much as 10 km for a geometric horizon of 30 km. Consequently, knowledge of the distance to the visible horizon is very important for determining the maximum distance at which an object can be detected or tracked, and for determining the maximum amount of time available for making decisions.

For the past 20 years, DRDC Valcartier has been developing the LWKD model for predicting the effect of atmospheric refraction on image distortion, target detection range, ducting and mirage formation in marine and terrestrial environments. Continuing changes to the model and its computer program have made a revision of the version 7.09 document a necessity. All changes to the model and the software program are thoroughly discussed and a number of conclusions are given at the end.

Sommaire

Le développement de nouveaux capteurs électro-optiques (EO), comme le système de surveillance et de pistage infrarouge SIRIUS, qui sera bientôt installé sur plusieurs navires, et le besoin d'aides décision tactique (ADT) pour de tels systèmes, fait que la propagation de la radiation électromagnétique à travers l'atmosphère est une question très importante. Comme l'indice de réfraction de l'atmosphère varie avec la pression, la température, la quantité de vapeur d'eau et la hauteur au-dessus de la surface, toute radiation suit une trajectoire courbe. Des trajectoires droites sont seulement possibles dans une atmosphère non-réfractive ou l'indice de réfraction est absolument uniforme. Cela signifie qu'en général l'élévation apparente d'une cible vue par un observateur n'est pas celle donnée par une ligne droite entre la cible et l'observateur. Ceci entraine deux phénomènes. Le premier est un phénomène appelé sous-réfraction. Il se présente quand la radiation électromagnétique d'une source est courbée au delà de la surface terrestre. Le résultat peut donner des effets de mirage, ou un observateur pourrait voir une source unique à deux angles d'élévations différentes. Le deuxième phénomène est appelé super-réfraction. Il se manifeste quand la radiation électromagnétique d'une source est courbée vers la surface terrestre, pour qu'un observateur puisse détecter une source au delà de l'horizon défini par la géométrie. La puissance de ces phénomènes dépend des conditions météorologiques et de la longueur d'onde de la radiation. Dans un environnement maritime, cela veut dire que, dans certains conditions, la distance à l'horizon vue par un observateur peut être plus courte que la distance à l'horizon géométrique (sous-réfraction), tandis que dans d'autres conditions, il peut être plus loin que l'horizon géométrique (super-réfraction ou propagation transhorizon). Résumant les données de plusieurs essaie, on a remarqué que la distance a l'horizon visible pouvait varier jusqu'à 10 km pour un horizon visible de 30 km. Par conséquent, la connaissance de la vraie distance à l'horizon visible est très importante pour la détermination de la distance maximale à laquelle un objet peut être détecté ou suivi, et pour déterminer le temps maximum disponible pour prendre les décisions.

RDDC Valcartier développe le modèle LWKD pour prédire les effets de réfraction atmosphériques sur la distorsion d'image, distance de détection de cible, la propagation transhorizon, et la création de mirages dans l'environnement maritime et terrestre depuis 20 ans. Les changements continus de modèle et de son programme informatique ont entamé la nécessité de réviser le document fait pour la version 7.09. Tous les changements apportés depuis la version 7.09 dans le modèle est son programme informatique sont discutés en profondeur et certaines conclusions sont données à la fin.

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1.0   Introduction

At DRDC Valcartier we have been developing marine boundary layer (MBL) models and programs for the past 20 years. One such model is the Luc (Wavy) Walmsley KEL DREV model, or L(W)WKD (Ref. 1, 2), now known simply as the LWKD model. It was designed to produce vertical profiles of the refractivity, the air temperature, the refractivity structure parameter and other profiles given a specific set of meteorological parameters. These profiles can then be used by other programs to predict the optical, infrared or radio-frequency characteristics of the marine boundary layer. For example, refractivity profiles produced by LWKD were used in 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.

DGA (France) has also developed an MBL model called "Profils d'Indice de Réfraction en Atmosphère Marine" or PIRAM (Ref. 3, 27), whose outputs have been compared with those from LWKD. As a result of several technical exchanges between Canada and France, agreements have been established regarding certain calculations, such that the two models now produce very similar results for most calculations.

As a result of the many experimental trials that the Sensor Performance Group has been involved in over the past eight years, in particular, POLLEX (POint targets at Low eLevation EXperiment) in Livorno, Italy (2001) (Ref. 28), VAMPIRA in Surendorf, Germany (2004) (Ref. 29), and the TG40 Land Trial in White Sands, New Mexico (2005) (Ref. 30). Comparison of the LWKD calculations with experimental measurements obtained during these and other trials is left to a later report, whereas this report describes the equations and options coded within the program and comments on the changes introduced since the document describing version 7.09 was produced (Ref. 2).

Some of the principal changes that have been made to LWKD and its program are that it:

- is now object oriented and developed within Microsoft's Visual C/C++ environment (version 6);

- is now documented using Rational Rose's Computer Assisted Software Engineering (CASE) tool;

- is now compiled as a single executable code that uses command line parameters to change its functionality;

- no longer produces on-screen graphics when used interactively. All results are now sent to a text output file for graphing by the user;

- provides a choice of two gradient functions for temperature and specific humidity under unstable cases using the "scale_mode" parameter defined in file LWKD.ini;

- has three new parameters to take into account the interfacial layer at the land or sea surface;

- is now able to determine profiles over a land surface;

- no longer calculates band-averaged values for the A and B coefficients, but determines these parameters using the wavelength provided by the user;

- uses a universal form of the structure parameter function that is defined by eight parameters;

- can now determine and output a parameter called "characteristic height";

- no longer produces the files IRCOND or RFCOND, as they have been replaced by the CONDxxx file, whose format is similar that of TDP_***;

- has more parameters in the LWKD.ini file so that the user can modify certain program constants without having to recompile the code;

- has a modified input parameter checking routine having the same bounds as those defined by DRDC Valcartier's IRBLEM (Infrared Boundary Layer Environment Model) code (Ref. 8).

- corrects an error in the calculation of refractivity for RF

Chapter 2 of the report discusses the basic scaling equations that are derived from the similarity theory of Monin and Obukhov (Ref. 4, 5) for the near-surface atmosphere, and the method used by LWKD to obtain a solution for this set of equations. Chapter 3 discusses the calculation of refractive index profiles from the visible to the far infrared and for radio frequencies (Ref. 1, 2, 6, 7), and Chapter 4 presents a method to calculate various structure parameters that are useful for determining the amount of turbulence within the MBL. In addition, Appendix A presents basic meteorological relationships that are used within LWKD, Appendix B presents the algorithm that is used by LWKD, Appendix C describes the LWKD Wavy model, Appendix D shows a fit of an LWKD function to one provided by Edson (Ref. 21), and Appendix E provides a complete list of all the modifications made to LWKD since version 7.09.

Chapter 5 of the report describes in detail the structure and operation of the LWKD program and highlights some of the principal changes that have been made. The program is now compiled as a single executable file that uses a command line parameter to change its functionality. The command line parameters allow for one interactive mode and three batch modes of operation. The batch modes of operation have been designed to be easily integrated as separate modules into modular programs such as IRBLEM (Ref. 8).

Finally, in Chapter 6, the document presents some conclusions and discusses various ways in which the LWKD model may be changed in the future.

This work was carried out at DRDC Valcartier between July 1999 and February 2007 under various work units within Thrust 1A.

2.0   LWKD Marine Boundary Layer Model

The L(W)WKD model (Ref. 1,2), or as it is now referred to, the LWKD model, is based on the WKD model developed for DRDC Valcartier by Low and Hudak (Ref. 9) and the Wavy WKD (WWKD) model developed at DRDC Valcartier by Beaulieu (Ref. 10). The objective in developing this model was to provide a simple and effective technique for predicting the atmosphere's refractivity profile in the Marine Surface Layer (MSL) at several wavelength bands using a limited set of meteorological measurements. This set includes a measurement of the sea temperature, and the wind speed at a known height, z_2, above the water level, and measurements of the air pressure, air temperature, and relative humidity at another known, but not necessarily different height, z_1. The model is based on the earlier work of Monin and Obukhov (Refs. 4& 5) using similarity theory and on more recent work by Walmsley (Ref. 11). The following sections describe the model and the recent changes that have been incorporated since version 7.09; in particular, its applicability to flat land surfaces with the addition of air temperature and relative humidity measurements taken at a second height. It is strongly suggested that the reader refer to Appendix A for definitions of various meteorological parameters and for references to equations relating many of these parameters, to Appendix B for the Iteration Algorithm, and to Appendix C for a discussion about the Wavy Model. Similarly, the reader should refer to the List of Symbols for the definitions of all constants and variables used in this report as, due to the large number of parameters; the nomenclature is not always standard.

2.1   Basic Scaling Equations

As with all surface boundary layer (SBL) models, LWKD assumes that the gradient of an adiabatically conservative quantity, ω, is proportional to $(1/z)\varphi_\omega(z/L)$ where z is the height above the water level and $\varphi_\omega(z/L)$ is a dimensionless function. LWKD uses the three conservative quantities; wind speed (u), virtual potential temperature (θ_v), and specific humidity (q), with the following dimensionless gradient functions for the wind speed (φ_u), virtual potential temperature (φ_{θ_v}), and specific humidity (φ_q):

$$\varphi_u(\zeta) = \varphi_u(z/L) \ = \frac{\kappa z}{u_*}\frac{\partial u}{\partial z}$$

$$\varphi_{\theta_v}\zeta) \ = \varphi_{\theta_v}(z/L) = \frac{\kappa z}{\theta_{v*}}\frac{\partial \theta_v}{\partial z} \tag{1}$$

$$\varphi_q(\zeta) = \varphi_q(z/L) \ = \frac{\kappa z}{q_*}\frac{\partial q}{\partial z}.$$

u_*, θ_{v*}, and q_* are the respective scaling constants for the wind speed, virtual potential temperature and specific humidity, κ (= 0.41) is now the default value used for von Karman's constant, and ζ (= z/L) is a normalized height. L is called the Monin-Obukhov length and is defined by:

$$L = (u_*^2 T_{vm})/(\kappa\, g\, \theta_{v*}), \tag{2}$$

where g is the acceleration due to gravity, and T_{vm} (K) is the average virtual air temperature within the boundary layer. As required, L is positive (stable atmosphere) when θ_{v*} is positive and negative (unstable atmosphere) when θ_{v*} is negative. Furthermore, L goes to zero as u* goes to zero, or as θ_{v*} goes to infinity.

To solve Eq. 1, the following gradient functions are used by LWKD for the wind speed, virtual potential temperature, and specific humidity. The functions are empirically derived from actual measurements and assume that both the wind scaling constant (u_*) and the Monin-Obukhov length are non-zero.

$$\varphi_u(\zeta) = \begin{cases} 1 + \eta_1 \zeta / (1+\zeta) & , \zeta \geq 0 \, ; KONDO \\ 1 + \alpha_1 \zeta & , \zeta \geq 0 \, ; WKD \\ (1 - \beta_1 \zeta)^{-1/4} & , \zeta < 0 \end{cases} \tag{3a}$$

$$\varphi_{\theta_v}(\zeta) = \begin{cases} 1 + \eta_2 \zeta / (1+\zeta) & , \zeta \geq 0 \, ; KONDO \\ 1 + \alpha_2 \zeta & , \zeta \geq 0 \, ; WKD \\ (1 - \beta_2 \zeta)^{-1/2} & , \zeta < 0 \end{cases} \tag{3b}$$

$$\varphi_q(\zeta) = \begin{cases} 1 + \eta_3 \zeta / (1+\zeta) & , \zeta \geq 0 \, ; KONDO \\ 1 + \alpha_3 \zeta & , \zeta \geq 0 \, ; WKD \\ (1 - \beta_3 \zeta)^{-1/2} & , \zeta < 0 \end{cases} \tag{3c}$$

where the coefficients, α_i, β_i, and γ_i (i = 1, 2 ,3), are constants. ζ (or L) greater than zero gives the appropriate functions for a stable atmosphere, and ζ (or L) less than zero gives the functions for an unstable atmosphere. Following Beaulieu (Ref. 10), and Kondo (Ref. 12), Eq. 3 is used with the following values for the coefficients: $\alpha = \alpha_1 = \alpha_2 = \alpha_3 = 5$, $\beta = \beta_1 = \beta_2 = \beta_3 = 16$, and $\eta = \eta_1 = \eta_2 = \eta_3 = 6$. Two equations (KONDO & WKD) are given for the stable case. The first formulation is that originally proposed by Kondo (Ref. 12) and is now the default form used in both PIRAM and LWKD. The experienced user can change the three parameters and choose between functions by modifying certain parameters within the LWKD initialization file, LWKD.INI (see Section 5.2). In fact it is also possible to choose to use the same function for the temperature and humidity profiles as that used for the wind profile.

Combining Eqs. 1 and 3, and performing the integration gives the following solutions for u(z), $\theta_v(z)$ and q(z):

$$u(z) = u_o + (u_*/\kappa)[\ln(z/z_{ou}) + \Psi_u(z; L) - \Psi_u(z_{ou}; L)]$$

$$\theta_v(z) = \theta_{vo} + (\theta_{v*}/\kappa)[\ln(z/z_{o\theta_v}) + \Psi_{\theta_v}(z; L) - \Psi_{\theta_v}(z_{o\theta_v}; L)] \tag{4}$$

$$q(z) = q_o + (q_*/\kappa)[\ln(z/z_{oq}) + \Psi_q(z; L) - \Psi_q(z_{oq}; L)]$$

where the integrated gradient functions, Ψ, are given by

$$\Psi_u(z;L) = \begin{cases} \eta \ln(1+\zeta) & , \zeta \geq 0 \,; KONDO \\ \alpha \zeta & , \zeta \geq 0 \,; WKD \\ 2 \tan^{-1} x - 2 \ln(1+x) - \ln(1+x^2) & , \zeta < 0 \end{cases} \qquad (5)$$

$$\Psi_{\theta_v}(z;L) = \Psi_q(z;L) = \begin{cases} \eta \ln(1+\zeta) & , \zeta \geq 0 \,; KONDO \\ \alpha \zeta & , \zeta \geq 0 \,; WKD \\ -2 \ln(1+x^2) & , \zeta < 0 \end{cases} \qquad (6)$$

and

$$x = (1 - \beta \zeta)^{1/4}. \qquad (7)$$

z_{ou}, $z_{o\theta v}$, and z_{oq} are the respective roughness lengths for the wind speed, virtual potential temperature and specific humidity, u_o, θ_{vo}, and q_o are the respective constants of integration evaluated at their respective roughness length, and u_*, θ_{v*}, and q_* are the respective scaling parameters.

Additional flexibility can be added to the constants of integration, if we consider the interfacial sublayer, or the layer of air adjacent to the surface where our theory is no longer applicable and which corresponds to the values given by the roughness heights. Using Eq. 1, the following relations hold at the roughness heights:

$$\left. \frac{\partial u}{\partial z} \right|_{z=z_{0u}} = \frac{u_*}{\kappa z_0} \varphi_u(z_{0u}/L) \simeq \frac{u_*}{\kappa z_{0u}} \quad ; z_{0u} \ll L$$

$$\left. \frac{\partial \theta_v}{\partial z} \right|_{z=z_{0\theta_v}} = \frac{\theta_{v*}}{\kappa z_{0\theta_v}} \varphi_{\theta_v}(z_{0\theta_v}/L) \simeq \frac{\theta_{v*}}{\kappa z_{0\theta_v}} \quad ; z_{0\theta_v} \ll L \qquad (8)$$

$$\left. \frac{\partial q}{\partial z} \right|_{z=z_{0q}} = \frac{q_*}{\kappa z_{0q}} \varphi_q(z_{0q}/L) \simeq \frac{q_*}{\kappa z_{0q}} \quad ; z_{0q} \ll L$$

Equation 8 shows that the gradients at the roughness heights are proportional to the scaling constants and inversely proportional to the roughness heights. Furthermore, as the heat flux is given by

$$H/\tau_\theta = \frac{\rho c_p u_* \theta_{v*}}{\tau_\theta} = \left. \frac{\partial \theta_v}{\partial z} \right|_{z=z_{0\theta_v}} = \frac{\theta_{v*}}{\kappa z_{0\theta_v}} \,; \qquad (9)$$

where ρ is the density of air, τ_θ is the surface thermal conductivity, and c_p is the specific heat capacity at constant pressure, this implies that

$$z_{0\theta_v} = \frac{\tau_\theta}{\kappa \rho c_p u_*} \qquad (10)$$

and

$$\theta_{v0} = \theta_v(z_{0\theta_v}) = \theta_v(0) + h_\theta \frac{\theta_{v*}}{\kappa} \ ; \qquad (11)$$

where we have integrated Eq. 9 under the assumption that the heat flux is constant all the way to the surface ($z = 0$). The parameter h_θ is nominally equal to unity; however, to add flexibility, other values can be used within LWKD. In a similar fashion, using the humidity flux, it can also be shown that

$$z_{0q} = \frac{\tau_q}{\kappa \rho u_*} \qquad (12)$$

and

$$q_0 = q(z_{0q}) = q(0) + h_q \frac{q_*}{\kappa} \ ; \qquad (13)$$

where again, h_q is a parameter that is nominally equal to unity, and τ_q is the surface moisture diffusion coefficient (conductivity). Finally, using the momentum flux

$$z_{0u} = \frac{\tau_u}{\kappa \rho u_*} \qquad (14)$$

and

$$u_0 = u(z_{0u}) = u(0) + h_u \frac{u_*}{\kappa} \ ; \qquad (15)$$

where h_u is a parameter that is nominally equal to zero, τ_u is the surface mass diffusion coefficient (conductivity), and $u(0)$ is equal to zero.

Substituting Equations 11, 13 and 15 into Eq. 4 provides us with the following set of equations

$$u(z) = u(0) + (u_*/\kappa)[h_u + \ln(z/z_{ou}) + \Psi_u(z;L) - \Psi_u(z_{ou};L)]$$
$$\theta_v(z) = \theta_v(0) + (\theta_{v*}/\kappa)[h_\theta + \ln(z/z_{o\theta_v}) + \Psi_{\theta_v}(z;L) - \Psi_{\theta_v}(z_{o\theta_v};L)] \ ; \qquad (16)$$
$$q(z) = q(0) + (q_*/\kappa)[h_q + \ln(z/z_{oq}) + \Psi_q(z;L) - \Psi_q(z_{oq};L)]$$

Excluding the *h* parameters, whose default values are set to zero so as to agree with earlier versions of LWKD, but which can now be modified within the LWKD.INI file (discussed later), the above equations provide us with a set of three equations with ten unknowns (including L). However, it is interesting to note that if values for the various conductivities (τ) are known, then the number of unknowns can be reduced to eight as the various roughness heights are simply related to one another. This topic will be brought forward in a following section when the method used by LWKD to determine these unknowns is discussed.

2.2   Solving the Basic Scaling Equations

To solve Eq. 16 requires the determination of ten unknown parameters. Six of these parameters can be determined using boundary conditions, while the other four need to be determined using other techniques. These techniques are discusses in the following sections.

2.2.1 Boundary Conditions

Since version 7.51 of the LWKD model, it is now possible to determine solutions within the SBL for circumstances where measurements are taken at two heights (lower and upper) above either the ground or the sea level and not just at one height (upper) above the sea level. The following two subsections describe the boundary conditions that are required depending upon which of the two situations is being considered.

2.2.1.1 Upper Level Boundary Condition

Three boundary conditions are given using measurements of the wind speed $u(z_2)$ at the height z_2, and measurements of the air temperature, $T(z_1)$, total atmospheric pressure, $P(z_1)$, and relative humidity, $H_r(z_1)$ at the height, z_1. Note that the height of the wind speed doesn't have to be made at a different height. Applying these conditions to Eq. 16 gives:

$$u(z_2) = u(0) + (u_*/\kappa)[h_u + \ln(z_2 / z_{ou}) + \Psi_u(z_2; L) - \Psi_u(z_{ou}; L)]$$

$$\theta_v(z_1) = \theta_v(0) + (\theta_{v*}/\kappa)[h_\theta + \ln(z_1 / z_{o\theta_v}) + \Psi_{\theta_v}(z_1; L) - \Psi_{\theta_v}(z_{o\theta_v}; L)] \; ; \tag{17}$$

$$q(z_1) = q(0) + (q_*/\kappa)[h_q + \ln(z_1 / z_{oq}) + \Psi_q(z_1; L) - \Psi_q(z_{oq}; L)]$$

where

$$q(z_1) = \mu \, H_r(z_1) \, P_w^s(T(z_1)) / [P_a(z_1) + \mu \, H_r(z_1) \, P_w^s(T(z_1))]$$

$$\theta_v(z_1) = T(z_1) [1 + (1 - \mu) \, q(z_1) / \mu][P_{ref} / P(z_1)]^{(\gamma-1)/\gamma}. \tag{18}$$

$q(z_1)$ is the specific humidity, $\theta_v(z_1)$ is the virtual potential temperature, $P_w^s(T(z_1))$ is the saturated water vapour pressure at height z_1, and P_{ref} is a reference pressure with a default value of 1000 hPa.

2.2.1.2 Sea Level Condition

For cases where only the sea temperature is provided, the following boundary condition is also present:

$$u(0) = 0$$

$$q(0) = \mu \, H_r(T_s) \, P_w^s(T_s) / [P_a(0) + \mu \, H_r(T_s) \, P_w^s(T_s)] \tag{19}$$

$$\theta_v(0) = T_s [1 + (1 - \mu) \, q(0) / \mu][P_{ref} / P(0)]^{(\gamma-1)/\gamma}$$

where $P_a(z=0)$ is the dry-air atmospheric in millibars, $P(z=0)$ is the total atmospheric pressure, $H_r(T_s)$ is the relative humidity, and $P_w^s(T_s)$ is the saturated water vapour pressure at the water level for water at temperature, T_s. Then

$$\Delta u = u(z_2) - u(0) = (u_*/\kappa)[h_u + \ln(z_2/z_{ou}) + \Psi_u(z_2; L) - \Psi_u(z_{ou}; L)]$$

$$\Delta\theta_v = \theta_v(z_1) - \theta_v(0) = (\theta_{v*}/\kappa)[h_\theta + \ln(z_1/z_{o\theta_v}) + \Psi_{\theta_v}(z_1; L) - \Psi_{\theta_v}(z_{o\theta_v}; L)] \quad ; \quad (20)$$

$$\Delta q = q(z_1) - q(0) = (q_*/\kappa)[h_q + \ln(z_1/z_{oq}) + \Psi_q(z_1; L) - \Psi_q(z_{oq}; L)]$$

where Δq is commonly referred to as the Air-Sea Specific Humidity Difference (ASSHD) and $\Delta\theta_v$ as the Virtual Potential Air-Sea Temperature Difference (VPASTD). A related quantity that is often referenced is the Air-Sea Temperature Difference (ASTD).

2.2.1.3 Land (Lower Level) Condition

For cases where measurements of relative humidity and air temperature are made over land at a lower height, z_o, we have

$$\Delta u = u(z_2) - u(0) = (u_*/\kappa)[h_u + \ln(z_2/z_{ou}) + \Psi_u(z_2; L) - \Psi_u(z_{ou}; L)]$$

$$\Delta\theta_v = \theta_v(z_1) - \theta_v(z_0) = (\theta_{v*}/\kappa)[\ln(z_1/z_0) + \Psi_{\theta_v}(z_1; L) - \Psi_{\theta_v}(z_0; L)] \quad ; \quad (21)$$

$$\Delta q = q(z_1) - q(z_0) = (q_*/\kappa)[\ln(z_1/z_0) + \Psi_q(z_1; L) - \Psi_q(z_0; L)]$$

where

$$u(0) = 0$$

$$q(z_0) = \mu\, H_r(z_0)\, P_w^s(z_0) / [P_a(z_0) + \mu\, H_r(z_0)\, P_w^s(z_0)]\ , \qquad (22)$$

$$\theta_v(z_0) = T(z_0)\,[1 + (1 - \mu)\, q(z_0)/\mu]\,[P_{ref}/P(z_0)]^{(\gamma-1)/\gamma}$$

$P_a(z=z_o)$ is the dry-air atmospheric pressure, $P(z=z_o)$ is the total atmospheric pressure, $H_r(z_o)$ is the relative humidity, and $P_w^s(z_o)$ is the saturated water vapour pressure for the temperature, $T(z_o)$. Furthermore, Δq is commonly referred to as the Specific Humidity Difference (SHD) and $\Delta\theta_v$ as the Virtual Potential Temperature Difference (VPTD). A related quantity that is often referenced is the Temperature Difference (TD).

2.2.2 Roughness Heights

With the six boundary equations, only four unknowns remain; the three roughness heights and the Monin-Obukhov length. This section provides three of the remaining four equations. While Eqs. 10, 12 and 14 could be used to relate the three roughness heights, the following empirical relationships developed by Businger et. al. (Ref. 14) and Smith (Ref. 15) are currently used within LWKD. They relate $z_{o\theta v}$ to z_{ou}, and z_{oq} to z_{ou} by;

$$\ln(z_{o\theta_v}/10) = -\kappa^2/[C_{TN} \ln(10/z_{ou})]$$

$$\ln(z_{oq}/10) = -\kappa^2/[C_{EN} \ln(10/z_{ou})] \qquad (23)$$

where C_{TN} is the 10 m neutral heat flux coefficient and C_{EN} is the 10 m moisture flux coefficient.

2.2.2.1   Water Surface

Over water C_{TN} has been established to be 1.0 x 10^{-3} for wind speeds ranging from 6 to 22 m/s, and C_{EN} to be 1.2 x 10^{-3} (Ref. 15). For the marine environment (over sea), the following wind dependent relation (Ref. 1,9,10 & 15) is used to represent the wind speed roughness length as a function of the friction velocity;

$$z_{ou} = \left[(\alpha_c / g) u_*^3 + v_d e^{-C\kappa} \right] / u_*$$
$$= \left[(\alpha_c / g) u_*^3 + a_d \theta_v + b_d e^{-C\kappa} \right] / u_* \tag{24}$$

where the part in brackets is essentially the surface mass diffusion coefficient of, κ is von Karmen's constant, C is a constant equal to 5.5, g is the acceleration due to gravity, α_c (= 0.011) is Charnock's constant, and v_d is the dynamic viscosity of dry air. These values have been chosen according to Walmsley (Ref. 11) with the difference that the dynamic viscosity is taken to be a function of the virtual potential temperature (K), where a_d is 9.267 x 10^{-8} and b_d is 1.346 x 10^{-5}. These values are obtained from a linear fit of the data given in Table A3 of Ref. 16 for temperatures from 0 to 40°C at a pressure of 1000 mb. Both LWKD and PIRAM use this functional form; however, LWKD uses the average virtual potential temperature, given by

$$\theta_{vm} = [\theta_{vs} + \theta_v(z_1)] / 2 , \tag{25}$$

where θ_{vs} is the virtual potential temperature at the sea surface, and $\theta_v(z_1)$ is the virtual potential temperatures at height z_1, in place of the virtual potential temperature given in Eq. 24.

2.2.2.2   Land Surface

For land surfaces it is assumed that the following ratios $z_{o\theta}/z_{ou}$ equal to 2 and z_{oq}/z_{ou} equal to 3.3 (Garrat pg. 92) are valid such that for known values of z_{ou}, values of C_{TN} and C_{EN} can be determined using the following variant of Eq. 23:

$$C_{TN} = \kappa^2/[\ln(2z_{ou}/10) \ln(z_{ou}/10)]$$
$$C_{EN} = \kappa^2/[\ln(3.3z_{ou}/10) \ln(z_{ou}/10)] \tag{26}$$

Using a default value of 0.012 for z_{ou} (Garrat pg. 290) instead of an equation like Eq. 24, C_{TN} and C_{EN} are given by 3.9 x 10^{-3} and 4.3 x 10^{-3} respectively. The default value of z_{ou} can be changed by editing the LWKD.INI file discussed later; however, C_{TN} and C_{EN} can not be modified.

2.2.3 Monin-Obukhov Length

With the addition of Equations 23 thru 26, only one unknown remains, the Monin-Obukhov length (L). Equation 2 provides the required 10th equation provided a definition is given for the average virtual temperature, T_{vm}. As in previous versions of LWKD, this average is taken to be the average between the respective virtual

$$T_{vm} = [T_{vs} + T_v(z_1)] / 2 \ \text{ or } \ T_{vm} = [T_v(z_o) + T_v(z_1)] / 2 \tag{27}$$

temperature at the sea surface, or the lower height, z_o, and that measured at the height z_1.

3.0   Refractive Index

Discussion of the functional form for the index of refraction or refractivity will be relatively brief as it is fully discussed in Ref. 1. While the functional form used by LWKD and PIRAM is the same, the same is not true for the various coefficients and this has not been part of any agreement.

Following Ref. 2, the refractivity ($Z = (n-1) \times 10^6$, where n is the refractive index), of the atmosphere at a wavelength, λ, can be approximated by

$$
\begin{aligned}
Z(\lambda) \, x \, 10^6 &= \left[D_a(\lambda,T) \frac{P_a}{kT} + D_w(\lambda,T) \frac{P_w}{kT} \right] (100 \, Pa/hPa) \\
&= \left[A(\lambda,T) \frac{P_a}{T} + B(\lambda,T) \frac{P_w}{T} \right] x \, 10^{-6}
\end{aligned}
\tag{28}
$$

where k is Boltzmann's constant, Z is the refractivity, P_a is the dry-air pressure, P_w is the water vapour pressure, T is the temperature, D_a is the dry-air molecular refractivity, D_w is the water vapour molecular refractivity, A is the dry-air coefficient, and B is the water vapour coefficient. In all future discussions it will be assumed that all pressures are in millibars (or hPa), all temperatures are in Kelvin, all densities are in grams per cubic metre, and all wavelengths are in micrometers. This leads to various transformation constants in many of the equations, including the factor of 100 Pascal/hPa given in Eq. 28.

3.1   Dry-Air Refractivity

Using measured refractivities for standard air (defined as containing 0.03% CO2 per volume at 101.3 mb and 15 ^{o}C), many authors have determined the A coefficient of Eq. 28. As discussed in Ref. 2, LWKD uses the following Sellmeier function (Ref. 17) developed by Edlén in 1953 (Ref. 18) for A:

$$
\begin{aligned}
A(\lambda) &= \left[64.328 + \frac{29498.10}{146 - 1/\lambda^2} + \frac{255.40}{41 - 1/\lambda^2} \right] \frac{288.2}{1013} \\
&= a(\lambda) \frac{288.2}{1013}
\end{aligned}
\tag{29a}
$$

where

$$
a(\lambda) = \left[64.328 + \frac{29498.10}{146 - 1/\lambda^2} + \frac{255.40}{41 - 1/\lambda^2} \right].
\tag{29b}
$$

λ is the wavelength in vacuum in µm and k is Boltzmann's constant. It has simple poles at 0.083 µm ($=[1/146]^{1/2}$) and 0.156 µm ($=[1/41]^{1/2}$) which simulate the effects of resonances due

to bound states, states near the ionization limit, and dissociative states. Edlén has shown that this fit is good to within 0.04 units (~ .05%) down to 0.2 μm.

3.2 Water Vapour Refractivity

For water vapour, LWKD uses the results of Hill and Lawrence (Ref. 7), which separates the molecular refractivity into the following sums over the IR and UV resonances (λ_i);

$$
\begin{aligned}
D_w(\lambda,T) &= \sum_{IR} S_i(T)/(1/\lambda_i^2 - 1/\lambda^2) + \sum_{UV} S_i(T)/(1/\lambda_i^2 - 1/\lambda^2) \\
&= D_w^{IR}(\lambda,T) + D_w^{UV}(\lambda,T) \ ,
\end{aligned}
\tag{30}
$$

where Sellmeier's dispersion function (Ref. 17) is used, and the S_i's are the line strengths. Using dispersion data from Erickson (Ref. 19) for eight visible wavelengths between 0.644 and 0.361 μm, they give the UV molecular refractivity to be

$$
D_w^{UV}(\lambda,T) = \frac{37.47}{124.40 - 1/\lambda^2} \frac{k}{R_w} = \frac{k}{R_w} b^{UV}(\lambda) \ ,
\tag{31a}
$$

where

$$
b^{UV}(\lambda) = \frac{37.47}{124.40 - 1/\lambda^2} \ ,
\tag{31b}
$$

and R_w (=R/M_w=0.4619) is the gas constant for water vapour. There is a simple pole at 0.090 μm which simulates the resonances from bound states, states near the ionization limit, and dissociation states. As for dry air, this implies that Eq. 31 should be good down to 0.2 μm. The claimed accuracy is less than 0.5%.

To determine the refractivity due to the IR resonances, Hill and Lawrence (Ref. 7) calculated $D_w^{IR}(\lambda,T)$ by performing the summation over more than 40,000 water vapour resonances extending from radio frequencies to the visible for nine wavelengths and temperatures from -40 to 40 0C in 10 °C steps. The wavelengths were 18.83, 17.82, 15.43, 13.11, 11.60, 10.37, 9.341, 8.562 and 7.837 μm. After fitting the calculations and scaling the results to agree with measurements near 10.6 μm, the following IR refractivity function was found,

$$
D_w^{IR}(\lambda,T) = \left[\frac{0.957 - 0.928\,\delta^{0.4}\,(x-1)}{1.03\,\delta^{0.17} - 19.8\,x^2 + 8.1\,x^4 - 1.7\,x^8} \right] \frac{k}{R_w} = \frac{k}{R_w} b^{IR}(\lambda,T)
\tag{32a}
$$

where

$$
b^{IR}(\lambda,T) = \left[\frac{0.957 - 0.928\,\delta^{0.4}\,(x-1)}{1.03\,\delta^{0.17} - 19.8\,x^2 + 8.1\,x^4 - 1.7\,x^8} \right] ,
\tag{32b}
$$

δ = T/273.15, and x = 10/λ. It should be noted that the effect of changing the temperature is not very important, so that using δ = 1 does not significantly affect the output of Eq. 32. Adding the UV and IR contributions together, we get the following result for the refractivity of water vapour;

$$
Z_w(\lambda,T) = [D_w^{UV}(\lambda) + D_w^{IR}(\lambda,T)] \frac{1x10^8 P_w}{kT} = B(\lambda,T)\frac{P_w}{T},
\tag{33a}
$$

where

$$B(\lambda,T)\,x\,10^{-8} = [D_w^{UV}(\lambda) + D_w^{IR}(\lambda,T)]\,/\,k$$
$$= [b^{UV}(\lambda) + b^{IR}(\lambda,T)]\,/\,R_w = b(\lambda)\,/\,R_w\,,$$

<div align="right">(33b)</div>

and

$$b(\lambda) = [b^{UV}(\lambda) + b^{IR}(\lambda,T)].$$

<div align="right">(33c)</div>

Equation 33 is applicable for wavelengths between 0.2 and 19 μm when they are sufficiently far from any significant resonances. In particular, this means that Eq. 33 should work very well in the visible, the 3-5 μm and the 8-12 μm windows.

3.3   The A and B Coefficients

Since Version 7.50, LWKD computes the A and B coefficients for any desired wavelength between 0.4 and 15 μm instead of using precomputed averages for the four bands as in earlier versions (Ref. 1,2). However, constants continue to be used for the microwave/radar band. The values used in the RF band are taken from Ref. 20 (A = 77.6 K/hPa; B = 3.75×10^5/T K/hPa). Finally, a problem was discovered in the calculation of the refractivity (index of refraction or modified refractivity) such that the actual value of B included an additional term of BP_w/T corresponding to an IR wavelength. Thus, the actual B that was used in previous versions was B = $(3.75 \times 10^5$/T + 72), which for a temperature of 300K amounts to an increase in the value of B of about 6%. This error has now been corrected.

4.0   Structure Parameters

The LWKD model is also capable of determining profiles for the refractive index structure parameter, C_n^2, the refractivity index structure parameter, C_Z^2, and other structure parameters. Differences with PIRAM continue to exist in this area as it has not been part of any agreement.

As shown in Ref. 2, the refractive index structure parameter at an elevation, z, can be given by

$$C_{n^2}(z) = h^{-2/3} < [n(z) - n(z+h)]^2 >_{avg}$$
$$= 1x10^{12} h^{-2/3} < [Z(z) - Z(z+h)]^2 >_{avg} = 1x10^{12} C_{Z^2}(z)$$

<div align="right">(34)</div>

where h is some incremental height, Z is the refractivity, and C_Z^2 is the refractivity structure parameter. Using Eq. 28, the refractivity structure parameter can be expressed as

$$h^{2/3} C_{Z^2}(z) = < [(K_A(z,\lambda,T)(T(z) - T(z+h)) + K_B(\lambda,T)(\rho_w(z) - \rho_w(z+h))]^2 >_{avg} \quad (35a)$$

where

$$K_A(z,\lambda,T) = \frac{A(\lambda)\,P_a(z)}{T^2(z)};\ \ K_B(z,\lambda,T) = B(\lambda,T)\frac{R_w}{100\ Pa/hPa}.$$

<div align="right">(35b)</div>

Carrying out the square in Eq. 35, gives

$$h^{2/3}C_{z^2}(z) = < K_A^2 [T(z)-T(z+h)]^2 + K_B^2 [\rho_w(z)-\rho_w(z+h)]^2$$
$$+ 2K_A K_B [T(z)-T(z+h)][\rho_w(z)-\rho_w(z+h)] >_{avg} \tag{36}$$

and finally

$$C_{z^2}(z) = h^{-2/3} \left[K_A^2 C_{T^2}(z) + K_B^2 C_{\rho_w^2}(z) + 2K_A K_B C_{T\rho_w}(z) \right], \tag{37}$$

where C_T^2 is the temperature structure parameter, $C_{\rho w}^2$ is the water vapour density structure parameter, and $C_{T\rho w}$ is the temperature-water vapour density structure parameter.

Following the parameterization of Monin Obukhov, the virtual potential temperature structure parameter, the specific humidity structure parameter, and the virtual potential temperature specific humidity structure parameter can be expressed in terms of the scaling parameters, θ_{v*} and q_*, such that

$$C_{\theta_v^2}(z) = \theta_{v*}^2 z^{-2/3} f_1(z/L)$$
$$C_{q^2}(z) = q_*^2 z^{-2/3} f_2(z/L) \tag{38}$$
$$C_{\theta,q}(z) = r_{\theta,q} \theta_{v*} q_* z^{-2/3} f_3(z/L)$$

where $r_{\theta vq}$ is the virtual potential temperature-specific humidity correlation coefficient, and the f_i's are experimentally determined functions. As the water vapour density is related to the specific humidity by $\rho_w = \rho q$, where ρ is the total air density, we can express the water vapour density structure parameter, and the virtual potential temperature-water vapour density structure parameter by

$$C_{\rho_w^2}(z) = \rho^2(z) C_{q^2}(z)$$
$$C_{\theta_v \rho_w}(z) = \rho(z) C_{\theta,q}(z) , \tag{39}$$

where we have assumed that the total density changes very little between z and z+h. Similarly, using Eqs. A1 and A3, and assuming that the specific humidity and the pressure change very little between z and z+h, the temperature structure parameter and the virtual temperature structure parameter are given by

$$C_{T^2}(z) = C_{T_v^2}(z)/[1 + (1 - \mu)q(z)/\mu]^2$$
$$C_{T_v^2}(z) = [P(z)/P_{ref}]^{2(\gamma-1)/\gamma} C_{\theta_v^2}(z) . \tag{40}$$

These results also imply the following three relations:

$$C_{Tq}(z) = C_{T_v q}(z)/[1 + (1 - \mu)q(z)/\mu]$$
$$C_{T_v q}(z) = [P(z)/P_{ref}]^{(\gamma-1)/\gamma} C_{\theta,q}(z) \tag{41}$$
$$C_{T\rho_w}(z) = \rho(z) C_{T_q}(z)$$

Subsequent substitution of the results from Equations 39 thru 41 into Eq. 38 allows one to easily calculate either the refractive index structure parameter, or the refractivity structure parameter once we have some knowledge about the correlation coefficient, $r_{\theta vq}$, and the structure parameter functions.

4.1 Structure Parameter Functions

Several expressions for the structure parameter function, f_1, have been proposed. Edson et al. (Ref. 21) proposed a modified version of that given by Wyngaard et al. (Ref. 22), while F.F.O.[1] (see Ref. 23) has proposed an independent function. These three functions are given by

$$(Wyngaard)\ f_1(z/L) = \begin{cases} 4.9[1 - 7(z/L)]^{-2/3} & ; z/L < 0 \\ 4.9[1 + 2.75(z/L)] & ; z/L \geq 0 \end{cases} \tag{42a}$$

$$(F.F.O.)\ f_1(z/L) = \begin{cases} 6.3[1 - 7(z/L) + 75(z/L)^2]^{-1/3} & ; z/L < 0 \\ 6.3[1 + 2.4(z/L) + 20(z/L)^2]^{1/3} & ; z/L \geq 0 \end{cases} \tag{42b}$$

$$(Edson)\ f_1(z/L) = \begin{cases} 5.8[1 - 7(z/L)]^{-2/3} & ; z/L < 0 \\ 5.8[1 + 2.4(z/L)^{2/3}] & ; z/L \geq 0 \ . \end{cases} \tag{42c}$$

LWKD uses the following functional

$$(LWKD)\ f_1(z/L) = \begin{cases} E_0[1 + E_1(z/L) + E_2(z/L)^2]^{E_3/3} & ; z/L < 0 \\ F_0[1 + F_1(z/L) + F_2(z/L)^2]^{F_3/3} & ; z/L \geq 0 \end{cases}, \tag{42d}$$

that is capable of emulating each of the functional forms. By default, LWKD uses the functional form due to Edson et al. with the following parameters for E_3, E_0, E_1 and E_2 of -2, 5.8, -7 and 0, respectively, and F_3, F_0, F_1, and F_2 of 1, 6.1, 19.8 and 12.7, respectively. The reader is referred to Appendix D for the fit to the Edson form for $z/L \geq 0$. The user may modify these six parameters by making changes to the initialization file, LWKD.ini. The PIRAM model uses the F.F.O.[1] functional form as there is no convincing evidence to definitely choose one functional form over another.

As it is difficult to determine the function f_2, most authors have worked under the assumption that it is proportional to f_1. This hypothesis implies that

$$\frac{C_{q^2}}{C_{\theta_v^2}} = A_{21} \frac{q_*^2}{\theta_{v*}^2} \tag{43}$$

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[1] Forschuninstitut Für Optik (Germany)

where the structure parameter ratio, A21(=f_2/f_1), is the proportionality constant to be determined. If one also uses the following definition for $r_{\theta_v q}$:

$$r_{\theta_v q} = \frac{C_{\theta_v q}}{\sqrt{C_{\theta_v^2} C_{q^2}}},$$ (44)

then, it follows that

$$f_1(z/L) = f_2(z/L)/A_{21} = f_3(z/L)/A_{21}^{1/2}.$$ (45)

The correlation coefficient can be either positive or negative depending upon whether the atmosphere is unstable or stable, respectively. Generally, it is accepted to have an absolute value between 0.6 and 1. Following Claverie et al. (Ref. 3), LWKD uses an absolute value of 0.8 as the exact value does not seem to influence the final result. Claverie et al. (Ref. 3) state that the constant of proportionality, A_{21}, can vary from 1 to 104 in the case of strong vapour pressure fluctuations. Neglecting the strong fluctuations, they assume it has a value of 1, even though this may not be entirely realistic. Davidson et al. (Ref. 24) suggest a value for A_{21} of 0.6. For the moment LWKD follows the recommendations of Claverie et al. and uses a default value of 1. In this respect, A_{21} can be thought of as another experimental parameter that still needs to be determined.

4.2   LWKD Structure Parameters

Finally, combining the results of the discussion about structure parameters and structure parameter functions, LWKD can calculates all structure parameters given in Eqs. 37 to 41. However, LWKD adds some flexibility to Eq. 37 by using the following form for the refractivity structure parameter;

$$C_{Z^2}(z) = E_z[K_A^2 C_{T^2}(z) + A_z^2 \; K_B^2 C_{\rho_w^2}(z) + 2A_z \; K_A K_B C_{T\rho_w}(z)].$$ (46)

Equation 46 is slightly different from Eq. 37 in that two parameters, the refractivity scaling parameter, E_z, and the refractivity ratio, A_z, have been introduced to allow the user to test changes that could later be applied to either the parameter E_0, F_0, or A_{21}. The user can modify these parameters by making the appropriate changes to the LWKD initialization file. The current default value for both parameters is 1.

5.0   The LWKD Program

Version 8.10 of the LWKD program has seen a number of important changes since Version 7.09 was discussed in DRDC Valcartier's earlier report (Ref. 2). The principal changes to the program are that it:

- is now object oriented and developed within Microsoft's Visual C/C++ Environment (Version 6);

- is now documented using Rational Rose's Computer Assisted Software Engineering (CASE) tool;

- is now compiled as a single executable code that uses command line parameters to change its functionality;

- no longer produces on-screen graphics when used interactively as all results are now sent to a text output file for graphing by the user;

- provides a choice between two gradient functions for the temperature and specific humidity under unstable cases using the "scale_mode" parameter in the LWKD.ini file. The choice is between the previously used function and that used by the wind speed;

- has introduced three new parameters to take into account the interfacial layer at the land or sea surface. These three parameters have the most effect over the sea surface as they essentially allow the user to take into account a possible difference between the bulk water temperature and its skin temperature. The default value for all three parameters is zero; however, they can all be modified using the LWKD.ini file.

- is now able to determine profiles over a surface using measurements at a second height instead of using measurements at the sea surface. These new parameters can be entered either interactively or through several parameters within the METDATA input file that have been redefined. This allows LWKD to be able to determine profiles over land;

- uses a constant roughness height over land instead of being variable as for conditions over the water. The default value of this parameter can be modified within the LWKD.ini file;

- no longer calculates band averaged values for the A and B coefficients, but determines these parameters using the wavelength provided by the user;

- uses a universal form of the structure parameter function that is defined by eight parameters. These parameters have been added to the initialization file LWKD.ini so that they can be modified without having to recompile the program;

- includes the two new parameters defined by the refractivity structure parameter function (Eq. 42d). These parameters can be modified using the LWKD.ini file;

- can now determine and output a parameter called the "characteristic height". This parameter can be positive or negative and is equal to the duct height when it is positive;

- the MP_H_*** file now as the same type of format as other output files;

- the files IRCOND or RFCOND are no longer produced. They have been replaced by the CONDxxx file that follows a similar output format as that for TDP_***;

- the default value of the van Karman constant is now 0.41;

- more parameters have been added to the LWKD.ini file so that the user can modify certain program constants without having to recompile the code;

- has a modified input parameter checking routine having the same bounds as those defined by DRDC Valcartier's IRBLEM (Infrared Boundary Layer Environment Model) code (Ref. 8)

- corrects an error in the calculation of refractivity for RF

- allows the output of vertical profiles up to 500 meters.

Apart from these changes, which are discussed in more detail below, a detailed list of all changes that have been made since Version 7.09 is given in Appendix E. Since Version 7.51 all modifications are now listed in the LWKD information file, LWKD.INF.

Version 8.10 is written to run on both WINDOWS and UNIX based systems using a command line interface. As a result all the graphics abilities were removed from LWKD starting with version 7.50. The software is now being developed using Microsoft Visual C/C++ (Ver. 6.0) and the code has been modified such that it is object oriented and can be documented using Rational Rose's Computer Assisted Software Engineering (CASE) tool or other similar tools. The program is now composed of eight C++ modules and sixteen user defined header files containing approximately 340 kb of text code and 128 kb of executable code. The names of the modules are mainlwkd.cpp, ErrorLib.cxx, LwkdInteractLib.cxx, LwkdModuleClass.cxx, ProfileLib.cxx, RunModeLib.cxx, ValuexLib.cxx, and WeatherLib.cxx. The header files are CDEF.H, deferror.h, deflwkd.h¬, defvaluex.h, global.h, IBMKEYS.H, varglobal.h, ErrorLib.hxx, GlobalLib.hxx, LwkdInteractLib.hxx, LwkdModuleClass.hxx, MathLib.hxx, ProfileLib.hxx, RunModeLib.hxx, ValuexLib.hxx, and WeatherLib.hxx. mainlwkd.cpp is the entrance module to the code and simply directs execution to the function LwkdModuleClass::FctMain.

5.1 Command Line Options

Starting with version 7.42, only one executable code is produced, instead of the several executable codes that were produced earlier. Instead, these different possibilities are now selected by including a parameter on the command line. The possibilities are LWKD -i (or just LWKD), the LWKDINT (Interactive) mode, LWKD -m, the LWKDMET (Meteorological) mode, LWKD -r, the LWKDMPH (Modified refractivity) mode, and LWKD -c, the LWKDCN2 (Refractivity structure parameter) mode. Apart from the LWKDINT mode, the three other modes only operate in BATCH mode. That is they require the existence of an input file called METDATA that contains all the meteorological data to be studied. The LWKDINT mode can also use files of type METDATA; however, the user may use any name that is less than 12 characters long (including any extension).

Several other parameters can also be included on the command line and are included so as to ease its integration with IRBLEM. These options control how information that would normally be sent to the screen is sent to the log file, LogFile.txt, and the message file, MsgList.txt. To set the desired options, add the selected option letters to the command line. The possible options are:

L : Log: Information normally sent to the output screen will be sent to the log file instead. Also, a copy of the warning and error messages will be sent to the message file. The message file will not be created if there is no warning or error.

A : Append: If the "log" option is also selected, this option will cause new information to be appended to both the log and message files. If this option is not given, both files will be erased regardless of the other options. This is the case when the program is called in normal mode (without any options).

C : Conditional: If the "append" option is also selected, this mode will cause the program to stop if a message indicating that a previous run of the program ran into an error message.

P : Path: Specifies the path to which the log file and message file are to be written.

M : Mute: This option may be use to prevent displaying some information. For example, it may block certain information from being sent to the log and message files.

If the -LAC option is used with one of the BATCH modes, it is suggested that the previous log and message files be deleted before executing LWKD.

When using one of the BATCH modes, the user may also want to provide a response (text) file. This file provides the program with additional parameters that are not included within the METDATA file. For the -r and -c options, the response file must have two lines, and for the -m option, it must contain a single line. For the -r and -c options the first line requires an answer to the following question:

Give value of wavelength [μm] for calculations in the visible/IR domain: 0.4 to 5 μm or 8 to 15 μm, or in the RF domain (0):

where acceptable values are 0, 0.4 to 5, or 8 to 15, and all options require a response to the question:

[w]avy or [n]on-wavy model?

where acceptable values are *w* or *n*. As stated earlier, it is strongly suggested that the wavy model not be used for calculations; thus, the *n* option should always be chosen. For the -m option, a response is only required to the final question as its outputs are wavelength independent.

Thus, a typical example of a command line would look like "lwkd -r -LAC < input.txt" where **input.txt** would be the redirected response file. More details about these modes and options, and the format of the METDATA file are given in later sections.

5.2   Initialization File: LWKD.INI

To provide the program with increased flexibility, the user is able to use the initialization file, LWKD.INI to modify certain default parameters within the program. If the file doesn't exist the program will use the default values contained within the program. Furthermore, only

those parameters defined within the file will have their related parameters modified within the program. Table 1 shows all the parameters that can currently be modified, the program's default parameter, the range of permissible values, and an example of how it should be written within the file. Any improper values cause the program to display a warning message and to use the default values instead of those contained within the initialization file. The number of parameters has been increased to 30 from 12 in Version 7.09. The changes include the addition of parameters used to define the gradient functions (see Eq. 3), parameters to define the universal structure parameter function (see Eq. 42d), and others.

Table 1: General format for the LWKD.INI file

#	Variables	Default	Min.	Max.	Comment/Example
1	Comment				- all comment lines must be at the beginning of the file, and they must start with a #. - for example: # This is a comment.
2	kel_cel	273.15	273	274	- variable to go between Celsius and Kelvin - for example: kel_cel 273.1
3	Mair	28.9	28	30	- variable giving the mass of dry air - for example: Mair 28.8
4	Mwater	18	17	20	- variable giving the mass of water - for example: Mwater 18.1
5	R	8.3145	8	9	- variable giving the Gas Constant - for example: R 8.31
6	g	9.806	9.5	10	-variable giving the acceleration due to gravity - for example: g 9.8
7	gamm	1.4	1.35	1.45	- variable giving the ratio of specific heat at constant pressure to that at constant volume for dry air -for example: gamm 1.41
8	cp	1004	1000	1010	- variable giving the specific heat at constant pressure - for example: cp 1004.1
9	Kconst	0.4	0.35	0.45	- variable giving von Karman's constant - for example: Kconst 0.41
10	p_adiab	1000	950	1050	- variable giving the adiabatic reference pressure (P_{ref}) - for example: p_adiab 1010.0
11	LandZ0	0.012	0.0001	1	- variable giving the value to be used for the roughness height for propagation over land - for example: LandZ0 0.01
12	WindH	0	-10	10	- variable giving the value to be used to include an interfacial layer for the wind speed. - for example: WindH 0.1

13	TempH	0	-10	10	- variable giving the value to be used to include an interfacial layer for the air temperature. - for example: TempH 0.1
14	HumidH	0	-10	10	- variable giving the value to be used to include an interfacial layer for the specific humidity. - for example: HumidH 0.1
15	max_height	50	5	500	- variable giving the maximum output height for vertical profiles - for example: max_height 20.0
16	pot_mode	1	0	1	- variable giving the potential temperature mode (0 - use dry air pressure; 1 - use total air pressure) - for example: pot_mode 0
17	scale_mode	3	0	3	- variable giving the scaling function mode to be used: 0: LWKD for stable & wind profile for unstable 1: Kondo for stable & wind profile for unstable 2: LWKD for stable & temp profile for unstable 3: Kondo for stable & temp profile for unstable Note: the wind profile is always used to determine the wind's profile for unstable conditions. - for example: scale_mode 3
18	gf_stableW	5	1	10	- variable giving the α parameter for the WKD gradient function for stable conditions - for example: gf_stableW 5
19	gf_stableK	6	1	10	- variable giving the γ parameter for the KONDO gradient function for stable conditions - for example: gf_stableK 6
20	gf_unstable	16	10	40	- variable giving the β parameter for the gradient function for unstable conditions - for example: gf_unstable 16
21	sf_scale0	5.8	1	10	- variable giving the E_0 parameter for the structure parameter function (unstable) - for example: sf_scale0 6.1
22	sf_unstble1	-7	-9	-5	- variable giving the E_1 parameter for the structure parameter function (unstable) - for example: sf_unstble1 -7
23	sf_unstble2	0	-100	100	- variable giving the E_2 parameter for the structure parameter function (unstable) - for example: sf_unstble2 0
24	sf_power0	-2	-3	-1	- variable giving the e_0 parameter for the structure parameter function (unstable) - for example: sf_power0 -2
25	sf_scale1	6.1	1	10	- variable giving the F_0 parameter for the structure

					parameter function (stable) - for example: sf_scale0 6.1
26	sf_stable1	19.8	-100	100	- variable giving the F_1 parameter for the structure parameter function (stable) - for example: sf_stable1 19.8
27	sf_stable2	12.7	-100	100	- variable giving the F_2 parameter for the structure parameter function (stable) - for example: sf_stable2 12.7
28	sf_power1	1	1	3	- variable giving the f_0 parameter for the structure parameter function (stable) - for example: sf_power1 1
29	corr_coef	0.8	0	1	- variable giving the correlation coefficient, $r_{\theta q}$, parameter used to calculate the refractivity structure parameter - for example: corr_coef 0.8
30	cn2_coef	1	.1	5	- variable giving the E_z parameter used to calculate the refractivity structure parameter - for example: corr_coef 0.2
31	cn2_ratio	1	-2	2	- variable giving the A_z parameter used to calculate the refractivity structure parameter - for example: cn2_ratop 1.0
Note: all 30 variables do not have to be listed and they do not have to be listed in the above order. The user only has to include those variables for which he does not want to use the default values.					

5.3   Interactive (-i) Mode

If the interactive mode of operation is chosen by the user, the user can interactively control and monitor the program's operation. This interactivity is achieved through the use of menus whose options are selected using the keyboard, and textual displays that request input or provide feedback (screens) to the user. The only limitation with this mode is that it is not necessarily fully compatible with UNIX systems. Furthermore, since version 7.50, no graphical displays are supported; thus, the user must use other graphing software to see the results of their studies. Apart from this, the structure of the program is very similar to that previously documented for version 7.09.

5.3.1 The Main Screen

Upon starting LWKD in interactive mode (using either LWKD or LWKD -i), a copyright page informs the user of the owner's proprietary rights, the program's version and creation date for several seconds before disappearing. Subsequently it performs various initialization functions, and finally presents the user with the program's **Main** screen. The initialization process includes initializing the system's parameters, reading the LWKD.ini initialization file

if necessary, initializing other default structures within the program and calculating a default profile for the default meteorological parameters (see Table 2).

The **Main** screen is composed of three text windows and a menu bar at the bottom. At the top are two windows that show the "Meteorological Parameters". The top-left "Weather Parameters - 1" window shows the default weather parameters used by LWKD to calculate the profile parameters that are shown in the top-right "Profile Parameters - 1" window. The 1 indicates that the user is looking at the 1st meteorological parameter data set. Table 2 shows the default weather parameters and their bounds. At the bottom of the figure, the three default modes for the options Scaling (Scaling Equations), Pot. Temp. (Potential Temperature), and Pressure (Reference Adiabatic Pressure) are also shown. By default, the **K**ONDO version of the scaling equations is used under **S**table conditions and the **T**emperature form of the scaling equations is used under **U**nstable conditions. The wind speed form of the scaling equations is always used for the wind speed. The total atmospheric pressure (**Total Pressure**) with a reference pressure of 1000 hPa (or mb) is used in Eq. A3 to determine the potential temperature.

Table 2: Parameter bounds and default values in Interactive Mode

Parameter/Units	Minimum Bound	Maximum Bound	Default
Horizontal Range (km)	0	100	0
Wave Height ($H_{1/3}$) (m)	0	10	0.25
Wind Sensor Height (m)	1	40	19.5
Mean Wind Speed (m/s)	0.1	30	15
P/T/RH Sensor Height (m)	1	40	12
Mean Air Temperature (^{o}C)	-40	40	10
Mean Relative Humidity	0	1	0.8
Mean Atmospheric Pressure (mb)	800	1200	1000
T/RH Surface Height (m)	0	1	0
Mean Surface Temperature (^{o}C)	-40	40	10
Mean Surface Relative Humidity	0	1	0.982

The LWKD profile parameters calculated using these initial values are displayed in the right hand side window. It shows the calculated roughness heights and scaling constants used for the wind speed, virtual potential temperature and the specific humidity profiles. It also shows the wind speed, air temperature and relative humidity calculated using these profiles for the input sensor heights, along with the Monin-Obukhov length and the number of iterations that were required for LWKD to obtain the solution.

The third window, which is initially empty, is the "Other Measured Parameters" window. The purpose of the window is to display any other weather measurements that the user wishes to

have included with the meteorological outputs. More details pertaining to this window are described later in this chapter.

The **Program** menu is the point of entry into the LWKD program and can be executed by hitting the appropriate function key. The choices are **F1-Interactive**, **F2-Batch** and **F5-EXIT**. Pressing the F5 key opens a message line that requires the user to respond to the following question: "Quit program (y/n)?". A no (or N) response returns the user to the **Main** screen, while a yes (or Y) response closes the program and returns the user to the operating system. Using the F1-Interactive function key opens a **Message** line that displays "Use the Arrow keys to cycle between data sets" for several seconds before the user is presented with the **Main** menu and finds themself in the Interactive mode of operation. Likewise, pressing the F2 function key puts the user in the Batch mode of operation. The details of using either operational mode are fully described in the following two sections. At this point it should be noted that the left and right Arrow keys on the keyboard can be used to change the meteorological data set displayed by the "Meteorological Parameters" and "Profile Parameters" windows (assuming more than one has been entered).

5.3.2 Interactive Mode

After the F1-Interactive function key of the **Program** menu has been selected, the **Program** menu is replaced by the **Main** menu. Details related to the four function keys; **F1-Modify**, **F2-Load Data**, **F3-Save Data**, and **F4-Output Data**, of the **Main** menu are given in the following subsections. The **F5-RETURN** key returns the user to the **Program** menu.

5.3.2.1 F1-Modify

The **F1-Modify** function key allows the user to modify the measured parameters so as to produce new profile parameters, to modify the three options, and to add/delete/modify values displayed in the "Other Measured Parameters" window. Upon pushing the key a new menu, the **Modify** menu, appears. It is composed of the four function keys **F1-Weather**, **F2-Options**, **F3-Other;Wind**, **F4-Other;Meteo** and **F5-RETURN**. Pressing the F5-RETURN key returns the user to the **Main** menu. The F1 key allows the user to modify the weather parameters, the F2 key allows the user to modify the various options, while the F3 and F4 keys allow the user to modify the wind parameters or the temperature/relative humidity parameters belonging to the "Other Measured Parameters" window.

5.3.2.2 F1-Weather

Pressing the **F1-Weather** key presents the user with the **Weather** menu. It is composed of the following four function keys: **F1-Edit**, **F2-Add**, **F3-Delete**, **F4-RESET**, **F5-ABORT**, and **F6-RETURN**. The F2 key is only displayed when the number of data sets is less than 10 as LWKD can not currently handle more than 10 data sets, and the F3 key is only displayed when there is more than 1 data set. The F4-RESET and F5-ABORT keys are only present

after a weather set has been edited. Pressing the F6-RETURN key returns the user to the **Modify** menu.

Pushing the **F1-Edit** key opens a series of **Message** lines through which the user can modify the horizontal range for the measurements, the $H_{1/3}$ wave height, the wind sensor height and the mean wind speed, the P/T/RH sensor height and the mean air temperature, mean relative humidity and mean atmospheric pressure, the T/RH surface height and the mean surface temperature and surface relative humidity. After the user has either accepted or modified each parameter, the program verifies that they are within the accepted bounds given by Table 2. Any parameters outside these limits are not modified, new profile parameters are calculated, and the updated weather and profile parameters are displayed on the **Main** screen. If new profile parameters cannot be calculated, the following **Message**, "Could not fit new weather parameters!!", is displayed for two seconds, and the newly edited weather parameters are reset to their previous values.

After accepting the modifications and being returned to the **Weather** menu, the F4-RESET and F5-ABORT keys will be available. The F4-RESET key opens the message line: "Reset parameters (Y/N):" A **No** response returns the user to the Weather menu, while a **Yes** response resets the weather parameters to their previous values and returns the user to the **Weather** menu. The F5-ABORT key opens a message line: "Reset parameters and RETURN? (Y/N):". Again, a **No** response returns the user to the **Weather** menu; however, a **Yes** response resets the weather parameters to their previous values and returns the user to the **Modify** menu (i.e., it does a RESET and a RETURN).

Pushing the F2-Add key, when it is available, displays the message, "New weather parameter set added!!", for two seconds. The new data set is created using the default weather parameters at a horizontal range of 0 km. To edit or delete any data set, use the left/right arrow keys to select the correct data set and hit either the F1-Edit or F3-Delete key. In general, the operator has to select the proper weather parameter set as the program automatically reorders the sets by increasing horizontal range.

Pushing the F3-Delete key, when it is available, displays the message, "Delete current weather parameter set? (Y/N):". If the correct set has not been chosen, make a **No** response, choose the correct data set using the left/right arrow keys, and push the F3-Delete key again. Choosing the **Yes** response automatically deletes the current data set, reorders the data sets, and displays one of the remaining data sets on the screen. This process can not be undone.

5.3.2.3   F2-Options

Pressing this function key presents the user with a series of message lines that allow the user to modify the three modes for the **Scaling Equations**, the

Potential Temperature, and the **Reference Pressure**. By default the Scaling Equations parameter is set to 3, which corresponds to the Kondo version of the gradient (scaling) equations used under stable conditions, and the use of the standard temperature scaling equation for unstable conditions (see Eq. 3). The default value of the Potential Temperature parameter is set to 1, which corresponds to using the total atmospheric pressure in Eq. A3, with the current Reference Pressure (default of 1000 mb). Changing these parameters changes the calculations as described in Table 1. Any parameters outside the limits shown in Table 1 are reset to their previously held values, new profile parameters are calculated, and the new weather and profile parameters are displayed on the **Main** screen. On the other hand, if the profile parameters cannot be calculated, the following message, "Could not fit using new options!!", is displayed for two seconds and the newly edited option parameters are reset to their previous values.

After accepting the modifications and returning to the **Options** menu, the F2-RESET and F3-ABORT keys are available. The F4-RESET key opens the message line: "Reset options (Y/N):". A **No** response returns the user to the **Options** menu, while a **Yes** response resets the option parameters to their previous values and returns the user to the **Options** menu. The F5-ABORT key shows the message line: "Reset options and RETURN? (Y/N):". Again, a **No** response returns the user to the **Options** menu; however, a **Yes** response resets the option parameters to their previous values and returns the user to the **Modify** menu (i.e., it does a RESET and a RETURN).

5.3.2.4   F3-Other;Wind & F4-Other;Meteo

Selecting either of these two function keys presents the user with either the **Wind** menu or the **Meteo** menu. Both menus are identical and are composed of the following four function keys: **F1-Edit**, **F2-Add**, **F3-Delete** and **F6-RETURN**. The F1, F2 and F3 keys are only displayed when they are available to be used. Pressing the F4-RETURN key returns the user to the **Modify** menu. The functions of the other keys are given in the following subsections.

F2-Add

The F2-Add key is only displayed when there is still space for another data set (the maximum number is 8). If there is, pushing the key shows a message line through which the user can modify the parameters belonging to the appropriate default data set. If the Other;Wind function key had previously been selected, the user can add a new wind speed and wind sensor height, while if the Other;Meteo function key had previously been selected, the user can add a new air temperature, relative humidity and meteo sensor height. After the user has accepted the new data set, the program verifies that they are within the limits given by Table 2, and displays them on the **Main** screen. The data sets are listed in increasing ordered with respect to each sensor's height.

F1-Edit

The F1-Edit key is only displayed when there is data that can be edited. Pushing the key opens an **Edit** message which requests the user to enter the number (1 to 8) associated with the data set to be modified. An illegal entry produces the following two second message: "Input out of range!!", and then allows the user to enter a new number. Once the data set has been selected, a message line is displayed requesting the user to modify the associated data. If the Other;Wind function key had previously been selected, the user can modify the wind speed and the wind sensor height, while if the Other;Meteo function key had previously been selected, the user can modify the air temperature, relative humidity, and the sensor height. After the user has changed the parameters, the program verifies that they are within the same bounds given by Table 2, before accepting them and displaying them on the main screen. The data sets are always displayed in increasing order with respect to their sensor heights.

F3-Delete

The F3-Delete key is only displayed when there is data that can be deleted. Pushing the key displays a message line that requests the user to enter a number, from 1 to 8, of the data set to be deleted. An illegal entry produces the following two second message, "Input out of range!!", and then allows the user to enter a new number. Once the data set is selected, the following message line is displayed: "Delete data set (Y/N)?". A **No** response aborts the delete and returns the user to the preceding menu (Wind or Meteo) while a **Yes** response deletes the data set before returning the user to the preceding menu. The data sets are then reordered with respect to the sensor heights before they are redisplayed on the main screen.

5.3.2.5 F3-Save Data

The F3-Save Data function key allows the user to save certain information to a special LWKD binary file having the extension "lwd". The file's most recent structure is shown in Table 3 where the first column gives the data type (integer, float, etc.), the second gives the number of bytes it requires, and the third column describes the data type's significance. This file is a general purpose file that includes each set of measured weather parameters, and their associated profile parameters and refractivity profiles. The refractivity profiles are designed for use as input into ray tracing algorithms. The file can be extended to contain other data while remaining backward compatible by changing the file identification number. In this way each file identification number can be uniquely associated with a specific version of LWKD.

Upon pressing the key, the user is presented with the following message to choose the wavelength: "GIVE VALUE OF WAVELENGTH [um] IN THE VISIBLE/IR DOMAIN: 0.4 to 5 [um] OR 8 to 12 [um] OR IN THE RF DOMAIN (0):". After entering the desired wavelength, the user is presented

with a second message: "[w]AVY or [n]ON-WAVY MODEL?". It is suggested that the user choose the Non-Wavy model for calculating the refractivity profiles. Once this is done, a file named "Profile.lwd" is automatically created and saved to the current directory. To save more than one profile, the user must rename this file before creating the next profile; otherwise, it will be overwritten. Each file requires at least 4.5 kb.

Table 3: Format for the LWKD binary file

Data Type	Bytes	Comments
1. Integer	2	File identification number = 4. Previous versions used 0, 1,2, & 3.
2. Integer	2	# of bytes in the file header including the null character = N.
3. String	N	N characters belonging to the file header.
4. Integer	2	# of bytes in the wavelength band's name including the null character = M.
5. String	M	M characters belonging to the wavelength band's name - VISIBLE, NEAR-INFRARED, MID-INFRARED, FAR-INFRARED or RADAR.
6. Integer	2	# of weather sets (maximum is 10)
7. Character	1	Scaling Equation Option (default is 1)
8. Character	1	Potential Temperature Option (default is 1)
9. Double	8	Reference Pressure Option (default is 1000 mb)
The following 4 outputs (10 to 13) are written for each weather set.		
10. Integer	2	# of bytes in the weather parameter structure (PARAM).
11. PARAM (11 floats)	32	PARAM contains the following 11 weather parameters - horizontal range, $H_{1/3}$ wave height, wind sensor height, wind speed, meteo sensor height, air temperature, sea temperature, air pressure, relative humidity, sea surface rel. humidity, and the sea surface wind speed (= 0).
12. Integer	2	# of bytes in the weather profile structure (W_STRUCT).

13. W_STRUCT
    (1 unsigned)
    (10 double)
	81	W_STRUCT contains the following profile parameters
		 - number of iterations (unsigned int), Monin-Obukhov length, wind speed scale and roughness height, wind speed, virtual potential temperature scale and roughness height, air temperature, water vapour density scale and roughness height, and relative humidity.

14. Float	4	Minimum height = $H_{1/3}/2$.
15. Float	4	Maximum height = 50.
16. Integer	2	# of bytes in the Other Wind weather structure (W_PARAM).

17. Integer	2	# of Other Wind weather structure data sets.
Output 18 is done for each Other Wind data set.		
18. W_PARAM	8	W_PARAM contains a wind sensor height and a wind speed.
19. Integer	2	# of bytes in the Other Meteo weather structure (M_PARAM).
20. Integer	2	# of Other Meteo weather structure data sets.
Output 21 is done for each Other Wind data set.		
21. M_PARAM	12	M_PARAM contains a meteo sensor height, an air temperature and a relative humidity.
The following outputs are written for each weather set.		
22. Data Record (2 float) (3 double)	32	Each data record contains the range (L = 0 km), the height (m) above the MWL (h), the refractivity (Z), and two derivatives (dZ/dh and dZ/dL(=0)) at the height h. The height (h) is calculated iteratively as follows: h = h + 0.05 + 0.025*h and records are written until h = max. height. The refractivities are calculated for the chosen wave band.

5.3.2.6   F2-Load Data

The F2-Load Data function key allows the user to load the meteorological parameters previously saved in an LWKD binary file from the current directory. When the key is pressed, the user is presented with the following message: "Input LWKD file (*.lwd):". After enter the name of the file, including its extension, the file is loaded, and displays several messages, including the wavelength that was used to create the file. If the file doesn't exist the following message is displayed: "Problems opening the LWKD file!!". It should be noted, that all previous binary file formats can be read, and that the refractivity profile data records are neither read nor required by the program, as the program calculates this profile itself.

5.3.2.7   F4-Output Data

Pressing the F4-Output Data key of the Main menu presents the user with the **Output** menu. This menu consists of the five function keys: **F1-Meteo Screen**, **F2-Meteo Profile**, **F3-Ref. Profile**, **F4-Other Graphs**, and **F5-RETURN**. Pressing the F5-RETURN key returns the user to the **Main** menu while use of the other keys allows the user to produce various ASCII output files. These outputs are discussed in the following subsections. It is important to note that if the user wishes to save additional files of the same type, the user must change the name of the previously saved file or it will be overwritten.

F1-Meteo Screen

Choosing the F1-Meteo Screen key allows the user to output the data displayed on the **Main** screen to a file in ASCII format. Upon pressing the key, the user is presented with the following message line: "Output Parameters (Y/N)?". Choosing **No** returns the user to the **Output** menu, while choosing **Yes,** creates and saves the information to a file named "weather.asc" in the current directory, and displays the message: "File Written.....", before returning to the **Output** menu. The file is 1.5 kb.

F2-Meteo Profile

Choosing the F2-Meteo Profile key allows the user to output various vertical profiles, for six different meteorological parameters to an ASCII file. Upon pressing the key, the user is asked to select between the wavy and non-wavy model, and to enter the maximum height for the data (< maximum Max. Height as defined in Table 1). Once this is done, an ASCII file named "Met_Ht.asc" is created with vertical profiles for the following parameters: Wind Speed, Air Temp., Virt. Pot. Temp., Total Pressure, Vapour Pressure, Rel. Humidity, Spec. Humidity, and Vapour Density, and the message "File Written…" is displayed before returning to the **Output** menu. The file's general format is given in Table 4 and is normally less than 16 kb in size.

Table 4: General format for all ASCII files

Line #	Variable (Format)	Comment
1.	File identification number (integer)	Identifies the file's origins (= 10)
2.	File description (string)	States the type of file and LWKD version
3.	Wavelength (real or string)	This line is not always present.
4.	Min. & Max. heights (reals)	Minimum and maximum heights for vertical profile. This line is not always present.
5.	Fixed profile height (real)	Height at which a calculation is performed. This line is not always present.
6.	Range of profile (real)	Range at which the profile is calculated. Depends on which dataset is currently being viewed. This line is not always present.
4.	Headers for each column (string)	The headers describe the structure of each data record
5.	Underline for each header (string)	
6.	Data record (all real)	Currently, the file contains 9 consecutive real parameters, including the height.
7.	Wind speed and height record (real)	Wind speed & height for the current weather set. Not always included.
8.	T/P/RH and height record (real)	Temp., RH, pressure & & height for the current weather set. Not always included

9.	Other wind speeds & heights (real)	Output the wind speeds & heights that are present in the Other Measured Parameters window. Not always included.
10.	Other T/P/RH & heights (real)	Output the temp., RH, pressure & heights that are present in the Other Measured Parameters window. Not always included.

F3-Ref. Profile

Choosing the F3-Ref. Profile key allows the user to output plots of the refractivity (Z), the derivative of the refractivity with height (dZ/dh), and the second derivative of the refractivity with height (d^2Z/dh^2) for any allowed wavelength as functions of height, the ASTD (sea temperature fixed), the wind speed, or the relative humidity. All plots can also be done with or without the Wavy model.

Upon pressing the key, the user is first asked to choose between **height (HT)**, **ASTD (SE)**, **wind speed (WS)** or **relative humidity (RH)**, then the wavelength, and between the wavy and non-wavy models. If **height** was chosen, the user is also requested to enter the maximum height (< maximum Max. Height as defined in Table 1); otherwise, the height at which the calculations are to be performed is required (< maximum Max. Height as defined in Table 1).

Once the above choices have been made, the appropriate "REF_**.ASC" file is created and the message: "File Written....." is displayed before returning to the **Output** menu. The ASCII file is usually less than 10 kb and follows the format described in Table 4.

F4-Other Graphs

Choosing the F4-Other Graphs key allows the user to output various XY data as ASCII files. The ASCII files follow the same general format given in Table 4. Upon pressing the key, the user is presented with the **Graphic Selection** menu having two choices **F1-Structure Parameters** and **F2-Profile Parameters**.

Choosing F1-Structure Parameters allows the user to create XY plots for four structure parameters as functions of six different parameters for any valid wavelength. The structure parameters are the refractivity structure parameter, the temperature structure parameter, the vapour density structure parameter, the temperature-vapour density structure parameter, virtual temperature potential structure parameter, and specific humidity structure parameter. It also outputs the three terms that make up the refractivity structure parameter (see Eq. 46). The possible dependent X-axis parameters are the height (**HT**), the ASTD (sea temperature fixed) (**SE**), the ASTD (air temperature fixed)

(**AR**), the wind speed (**WS**), the relative humidity (**RH**), and the H1/3 wave height (**WH**).

Choosing F2-Profile Parameters allows the user to create XY plots of various weather profile parameters versus the ASTD (sea temperature fixed) (**SE**), the ASTD (air temperature fixed) (**AR**), the wind speed (**WS**), the relative humidity (**RH**), the reference pressure (adiabatic pressure) (**AP**), or von Karmen's constant (**VK**). The parameter profiles are the the Monin-Obukhov length, the wind scale parameter, the wind roughness height, the temperature scale parameter, the temperature roughness height, the humidity scale parameter, and the humidity roughness height. As the process involved in creating these files are nearly identical to that for creating the files for refractivity profiles, only their differences will be described.

If the user chooses to create files of the structure parameters, the user will discover that the process is nearly identical to that for files of the refractivity profiles. The differences are only with respect to the available choices for the X-axis parameters. On the other hand, if the user chooses to create files of a profile parameter, the user will notice the following differences. The user will not be asked to select a wavelength nor to use the Wavy model. This is because these parameters are independent of these two options. Once the above choices have been made, the appropriate "SPR_**.ASC" files are created for the structure parameters and the appropriate "FPR_**.ASC" are created for the profile parameters, and the message: "File Written....." is displayed before returning to the **Output** menu. These ASCII files are normally less than 10 kb.

5.3.3 Batch Mode

Pressing the F2-Batch function key of the **Program** menu allows the user to produce weather, structure parameter, and refractivity output files from a METDATA input file containing up to 999 sets (records) of weather measurements. Upon selecting this mode, the user is requested to enter the name of the METDATA. The format of this file is given in Table 5. If a valid METDATA file is not entered, the user is returned to the **Program** menu; otherwise, the user is presented with the number of cases to be processed and prompted to select a valid wavelength and to use the Wavy model or not. After this, the program starts processing one entry at a time, indicates to the user which entry is being processed, shows the results on the **Menu** screen, indicates when the entire process has been completed, and returns the user to the **Program** menu. This batch mode operates in much the same way as the other batch modes to be discussed later, except that it produces all output files. That is it produces CONDXXX, TDPXXX, MP_H_XXX and CN2_XXX files (XXX = record #). The contents of these files are discussed in a later subsection, after the METDATA parameters have been discussed.

5.3.3.1   Metdata File

Since Version 7.09, the use of four parameters in the METDAT file that were not used by LWKD have been modified while remaining backward compatible as much as possible. The parameters *neutral drag coefficient (A)*, *neutral drag coefficient (B)*, *neutral Stanton number*, and *neutral Dalton number* are now the parameters *salinity (g/kg)*, *lower air temperature height (m)*, *relative humidity at lower height (%)*, and *tide height(m)*. As the *tide height (m)* is not required by LWKD it will not be discussed. The *lower air temperature height (m)* and *relative humidity at lower height (%)* were added for Version 7.51 so that LWKD could be used to determine vertical profiles over relatively flat land surfaces. In this case, LWKD requires a second measurement of relative humidity and air temperature at a second (lower) measurement height. This height is given by the *lower air temperature height (m)*, the relative humidity by the *relative humidity at lower height (%)*, and the lower air temperature is given by the *water temperature (^{o}C)*. Starting with Version 8.10, LWKD now has a salinity parameter. This parameter is only used if the *lower air temperature height (m)* is less than 0.001 m (normally set to zero), such that LWKD assumes that the lower surface is a sea surface. If the *salinity (g/kg)* is less than zero, the default value of 98.2% is used for the relative humidity at the sea surface (salinity ~ 34 g/kg); otherwise the relative humidity at the sea surface is given by Eq. A7 and uses the salinity. The default values and limits for the METDATA parameters used by LWKD are given in Table 6.

Table 5: General format for a METDATA ASCII file – a space separates each item

Line #	Variables	Comment/Example
1	String comment line	-each comment line must start with a # - for example: #This is a comment.
2	5 integers	-day, month, hour, minute, and measurement interval (min.) - for example: 20 2 8 20 5 (they are often set to zero)
3	Integer (N_w)	-number of weather conditions in the file - for example: 10
4...	Read weather condition (read 1 line at a time)	-each line contains 23 variables in the following order: air temperature measurement height (m), atmospheric pressure (mbar), air temperature (^{o} C), relative humidity (%), solar radiation*, wind speed, wind direction*, water temperature (^{o}C), wind speed measurement height (m), $H_{1/3}$ wave height (m), visibility (km)*, humidity measurement height (m)*, salinity (g/kg), lower air temperature height (m), relative humidity at lower height (%), tide height (m)*, wavelength (μm)*, pressure measurement height (m)*, air mass parameter*, and 24hr wind speed*, precipitation rate (mm/hr)*, and precipitation type (0-4)*, and liquid water content (g/m^3)*. * parameter is not required by LWKD

| | | - for example
15.0 1010.0 10.0 80.0 500.0 5.0 270 12.0 20.0 1.5 9.0, 0, 0,
0, 0, 0, 0, 0, 10, 3.0 0 0 0 |

Table 6: Parameter bounds and defaults

Parameter/Units	Minimum Bound	Maximum Bound	Default
Air temp. measurement height (m)	1	40	12
Atmospheric Pressure (hPa)	800	1200	1000
Air Temperature (^{o}C)	-40	40	10
Relative Humidity (%)	0	100	80
Wind Speed (m/s)	0.1	30	15
Water (lower) Temperature (^{o}C)	-10	40	10
Wind Speed Measurement Height (m)	1	40	19.5
$H_{1/3}$ Wave Height (m)	0	10	0.25
Salinity (g/kg)*	none	0	34
Lower Air Temp. Height (m)	0	1	0
RH at Lower (Sea) Height (%)	0	100	98.2

* The salinity is not directly tested; instead, it is the RH at the sea surface that is tested. A salinity of 0 g/kg corresponds to 100% and 34 g/kg to 98.2%.

5.3.3.2   The CONDxxx File

The purpose of the COND file is to present the user with the 'xxx' meteorological condition, where 'xxx' denotes the line of meteorological data from the METDATA file, for which a solution was determined by LWKD. The file also provides the user with the basic micrometeorological parameters determined by LWKD. Table 7 describes the new general format of this file (Version 2.0) and the information that it provides. This file format has been used since Version 7.41; with the addition of several minor changes.

Table 7: Format of the CONDxxx file

Variables	Comment/Example
Comment line	##
File type	## File Type : COND
Version	## Version : 2.0

LWKD Version	## Generated by : LWKD Ver. 8.10
Wind Sensor Height	## Wind sensor height : 19.5 m
Wind speed, temp. sensor height, air temp., relative humidity, air pressure	## Wind speed : 5.0 m/s etc.
Lower measurement height	This parameter is only present when a lower measurement height is used. ## Lower sensor height : 0.20 m
Sea or lower temperature and relative humidity	## Water temperature : 10.0 C ## Sea relative humidity : 98.2 %
Stability/error code	This parameter provides information as to the reliability of the LWKD solution (see 3.3.3.2). ## Stability code : 0.20
Monin-Obukhov length	## Monin-Obukhov length : 10.0 m
Scaling parameters u_*, θ_{v*} and q_*	## Wind scaling parameter : 1.000E-001 m/s etc.
Roughness lengths z_{0u}, $z_{0\theta v}$ and z_{0q}	## Wind roughness length : 1.000E-002 m etc.
Offset values (or integration constants) u_0, θ_{v0} and q_0	## Wind offset : 0.000E+000 m/s etc.
H coefficients h_u, $h_{\theta v}$ and h_q	## Wind H coefficient : 0.000E+000 etc.

All of the parameters have been discussed earlier except the *stability/error code* so only it is discussed here. The *stability/error code* provides the user with an indicator as to the reliability of the results. The format of this code is *IJ.K*, where *J* can have a value between 0 and 10 depending upon how many of the entered parameters are tested (not all parameters are tested) and found to be outside their respective minimum and maximum bounds (see Table 6). Thus *J* equal to 5 would indicate that five of the parameters were found to be outside their bounds. Those found to be outside their bounds are set to their respective default values. *I* equal to 2 indicates that a solution was found by incrementing the wind speed in steps of 0.1 m/s, *I* equal to 1 that no solution could be found up to a maximum wind speed of 25 m/s, and *I* equal to 0 that a solution was found without having to change the wind speed. If a solution is found, *K* equal to 1 indicates that the weather condition was stable, and a value of *2* that the weather condition was unstable. Thus, the ideal values for *IJ.K* would be either 0.1 or 0.2 for a stable or unstable condition, respectively.

5.3.3.3 The TDPxxx, MP_Hxxx and CN2_xxx Files

The TDPxxx files contain vertical profiles of meteorological parameters as described earlier in Section 5.3.2.7 (F2 - Meteo Profile), and the CN2_xxx files contain vertical profiles for the same structure parameters as described in Section 5.3.2.7 (F4 - Other Graphs). The MP_H_xxx files contain vertical for the refractivity as described in Section 5.3.2.7 (F3 - Ref. Profile), except that it provided the modified refractivity (M):

$$M(z) = Z(z) + 0.157z\,; \qquad\qquad (50)$$

where Z is the refractivity and z is the height in meters above the sea. All the profiles go up to the maximum height as given in Table 1 (row 11). Table 8 gives the general format used by these three files.

The MP_H files also provide the user with the characteristic refractive height (h_c) or duct height. This height is determined using the following algorithm:

1. Set the characteristic refractive height, $h_c = 0$

2. If a height, h, exists at which dM/dz = 0 (dN/dz = -0.157), then set the characteristic refractive height, h_c = h. This is what is normally called the duct height, and corresponds to rays that will follow the Earth's curvature.

3. Else if a height, h, exists at which dN/dz = 0, then set the characteristic refractive height, h_c = -h.

Table 8: General format for the TDP, MP_H and CN2 output files

Variables	Comment/Example
Comment line	##
File type	## File Type : TDP, MP_H or CN2
Version	## Version : 2.1
LWKD Version	## Generated by : LWKD Ver. 8.10
Wavelength	Only given for CN2 & MP_H ## Wavelength : 0.50 um
Model	## Model : Non-Wavy or Wavy
Duct height	Only given for MP_H. Provides the characteristic refractive height (or duct height) for the specified wavelength (see text). ## Duct Height : 4.60E001 m
Met Data	Provides a listing of all the meteorological parameters from the METDAT file

	## Wind sensor height : 5.0 m
	## Wind speed : 5.0 m/s
	etc.
Column Headings	- MP_H_xxx files
	# h[m], M(h), M(h), M'(h)
	- TDPxxx files
	# HEIGHT TEMPERATURE Rel. Hum. PRESSURE ...
	# [m] [Deg] [%] [mbar] ...
	# ======== ========== ======== ======== ...
	- CN2_xxx files
	# HEIGHT INDEX TEMP. VAP. DEN. ...
	# [m] [m-2/3] [m-2/3] [m-2/3] ...
	# ====== ======== ========== ========== ...
Vertical profile data	- MP_H files
	height, modified refractivity, 1st and 2nd derivatives
	- TDPxxx files
	height, and various meteorological parameters
	- CN2_xxx files
	height, and various structure parameters

5.4   Batch (–r, -m & -c) Modes

As mentioned earlier in Section 5.1, there are three batch modes available with LWKD. These modes were developed for integration into DRDC Valcartier's IRBLEM model; however, this does not preclude there use with other models. All three modes require an input file called METDATA and should also be used with a redirected input file from the keyboard. If a redirected file isn't provided, the user will be prompted for one or two responses. For example, excluding the use of the possible options mentioned in Section 5.1, the following commands could be used:

LWKD –m < input1.txt

LWKD –r < input2.txt

LWKD –c < input2.txt

where "input1.txt" consists of one line and "input2.txt" contains two lines (Note: any names can be used for these two files.) The first line in "input2.txt" must be the chosen wavelength and represents the users answer to the following request:

"GIVE VALUE OF WAVELENGTH [um] IN THE VISIBLE/IR DOMAIN: 0.4 to 5 [um] OR 8 to 12 [um] OR IN THE RF DOMAIN (0):";

whereas, the sole line in "input1.txt" and the second line in "input2.txt" is the user's answer to:

"[w]AVY or [n]ON-WAVY MODEL?".

The output files produced from the first case (-m) are the COND and TDP files for each meteorological case found in the METDATA file (maximum of 999). For the 2nd case (-r), MP_H files are produced for each meteorological case, and for the 3rd case (-c), CN2 files are produced for each meteorological case.

6.0   Conclusions

This report has described in detail both the physics and the mathematical structures contained within the most recent version (version 8.10) of the LWKD model and offered some comparisons with previously published versions (Ref. 1, 2) and the PIRAM model (Ref. 3). It has also given a complete description of the operational procedures required to operate the associated LWKD computer program.

Many of the improvements suggested in the previous report have now been implemented, including options to modify the functional forms for the gradient functions, and structure parameter functions, to extend the number of variables defined in the initialization file "LWWKD.INI", and to output more meteorological profiles and structure profiles.

Future changes to LWKD will largely depend on more detailed analysis against measurements obtained during past trials such as POLLEX, VAMPIRA and the TG40 Land Trial, and on how it performs against data obtained from future measurements.

7.0   References

1. Forand, J.L., "The L(W)WKD Marine Boundary Layer Model", DREV-R-9618, March 1997, UNCLASSIFIED

2. Forand, J.L., "The L(W)WKD Marine Boundary Layer Model Version 7.09", DREV-TR-1999-099, September 1999, UNCLASSIFIED

3. Claverie, J., Hurtaud, Y., de Fromont, Y. and Junchat, A., "Modelisation des Profils Verticaux d'Indice de Réfraction et de C2n en Atmosphère Marine", Propagation Assessment in Coastal Environments, AGARD Conference Proceed¬ings 567, p. 29-1, 1994.

4. Monin, A.S. and Obukhov, A.M., "Basic Regularity in Turbulent Mixing in the Surface Layer of the Atmosphere", Trad. Geophys. Inst. ANSSSR, No. 24, p. 163, 1954.

5. Lumley, J.L. and Panofsky, H.A., "The Structure of Atmospheric Turbulence", Interscience Monographs and Texts in Physics and Astronomy, Vol. XII, p. 99, Edited by R.E. Marshak, University of Rochester, Rochester, New York, 1964.

6. Hill, R.J., Clifford, S.F. and Lawrence, R.S., "Refractive-Index and Absorption Fluctuations in the Infrared caused by Temperature, Humidity and Pressure Fluctuations", J. Opt. Soc. Am., Vol. 70, No. 10, pp. 1192-1205, 1980.

7. Hill, R.J. and Lawrence, R.S., "Refractive Index of Water Vapor in Infrared Windows", Infrared Phys., Vol. 26, No. 6, pp. 371-376, 1986.

8. Dion, D. and Schwering, P., AOn the Analysis of Atmospheric Effects on Electro-Optical Sensors in the Marine Surface Layer@, IRIS Conference, UK, June 1996

9. Low, T.B. and Hudak, D.R., AFinal Report on the Development and Testing of a Marine Boundary Layer Model@, KelResearch Corp. Report under DSS contract #W7701-8-2419/01-XSK, September 1990

10. Beaulieu, A.J., "Atmospheric Refraction Model and the Effects of Surface Waves", DREV R-4661/92, May 1992, UNCLASSIFIED

11. Walmsley, J.L., "On Theoretical Wind Speed and Temperature Profiles over the Sea with Applications to Data from Sable Island, Nova Scotia", Atmosphere Ocean, Vol. 26, pp. 203-233, 1988.

12. Kondo, J., "Air-Sea Bulk Transfer Coefficients in Diabetic Conditions", Bound. Layer Meteo., 9, 1975, pp 91-112.

13. Claverie, J., "Private communication", July 1998.

14. Businger, J.A., Wyngaard, J.C., Isumi, Y. and Bradley, E.F., "Flux-Profile Relationships in the Atmospheric Surface Layer", J. Atmos. Sci., 28, pp. 181-189, March 1971.

15. Smith, S.D., "Water Vapour Flux at the Sea Surface", Boundary Layer Meteorology, 47, pp. 277-293, 1989.

16. Garratt, J.R., "The Atmospheric Boundary Layer", Cambridge University Press, Cambridge, p. 286, 1992.

17. Born, M., and Wolf, E., "Principles of Optics", 6th (Corrected) Ed., Pergamon Press, Toron¬to, pp. 87-98, 1980.

18. Edlén, B., "The Dispersion of Standard Air", J. Opt. Soc. Am., 43, pp. 339-344, 1953.

19. Erickson, K.E., "Investigation of the Invariance of Atmospheric Dispersion with a Long Path Refractometer", J. Opt. Soc. Am., 52, pp. 777-780, 1962.

20. Bean, B.R. and Dutton, E.J., "Radio Meteorology", National Bureau of Standards Monograph 92, p. 1-22, 1966.

21. Edson, J.B., Fairall, C.W., Mestayer, P.G. and Larsen, S.E., "A Study of the Inertial-Dissipation Method for Computing Air Sea Fluxes", J. of Geoph. Res., 96, pp. 10689-10711, 1991.

22. Wyngaard, J.C., Izumi, Y. and Stuart Jr., A.S., "Behavior of the Refractive Index Structure Parameter Near the Ground", J. Opt. Soc. Am., 61, pp. 1646-1650, 1971.

23. Bataille, P., "Analyse du comportement d'un système de télécommunication optique fonctionnant à 0.83 μm dans la basse troposphère", thèse de doctorat de l'Université de Rennes, Nov. 1, 1992.

24. Davidson, K.L., Schacher, G.E., Fairall, C.W., and Goroch, A.K., "Verification of the Bulk Method of Calculating Overwater Optical Turbulence", Applied Optics, 20, pp. 2919-2924, 1981.

25. Forand, J.L., "Horizontal Non-homogeneous Effects in the Marine Boundary Layer", Propagation and Imaging through the Atmosphere, SPIE Meeting, Denver CO, pp. 180-191, 1997.

26. Dion, D. and Gardenal, L., "On the accuracy of bulk methods for predicting path losses in the marine surface layer", 1999 IEEE AP-S/URSI International Symposium, Orlando, USA, July 11-16, 1999.

27. Hurtaud, Y., Dion, D., Claverie, J. and Forand, L., "Coopérations Franco-canadienne: Arrangement Spécifiques no7 sur la propagation électromagnétique au-dessus de la mer, Rapport Final", DGA GEOS/99.49/SOP/80832, le 13 avril 1999.

28. de Jong, A.N., Winkel, H., Moerman, M., Stein, K., Weiss-Wrana, K., Forand, J.L., Potvin, G., Buss, J., Cini, A., Vogel, H., & Stark, E., "TG16 Point Target Detection Experiment (POLLEX), Livorno 2001", Proc. SPIE Vol. 4820, Infrared Technology and Applications XXVIII, Seattle, July 2002.

29. Heemskerk, E., "Vampira – Radar and Infrared propagation synergism trial", European Conference on Propagation and Systems (ECPS) 2005, Invited Paper, Brest, France, 15-18 March 2005.

30. Tofsted, D., Quintis, D., O'Brien, S., Yarbrough, J., Bustillos, M., and Tirrell Vaucher, G., "Test Report on the November 2005 NATO RTG-40 Active Imager Land Field Trials", Army Research Laboratory, White Sands Missile Range, New Mexico, ARL-TR-4010, December 2006.

APPENDIX A: Meteorological Equations

This Appendix presents definitions of potential temperature, virtual temperature, water vapour pressure, etc., as it is important to comment on the conceptual processes used to define the atmosphere. In our case, we consider a system that is at a given temperature, specific humidity, and total atmospheric pressure, such that the virtual temperature is calculated for an equivalent dry-air system at the same total atmospheric pressure. This equivalent dry-air system is then adiabatically moved to a new system at a uniform pressure of, say 1000 hPa, at a new temperature defined as the virtual potential temperature.

A.1 Virtual Temperature and Specific Humidity

The virtual temperature, T_v, is the temperature at which a volume of dry air has the same density, ρ, as moist air with specific humidity, q, at the same total atmospheric pressure (P). Equation A1 shows the relationship between the virtual temperature and the temperature moist air (T), and how this is applied to the ideal gas law:

$$T_v = [1 + (1 - \mu)q/\mu]T$$
$$\mu = M_w/M_a = 0.622 \tag{A1}$$
$$P = \rho R_a T_v = \rho R_m T .$$

In these equations, M_w is the molecular mass of water, M_a is the molecular mass of dry air, R_m is the gas constant for moist air, R_a (= R/M_a) is the gas constant for dry air, and R is the universal gas constant. In turn, the specific humidity can be expressed in terms of the total atmospheric pressure ($P = P_a + P_w$), the dry air pressure (P_a), and the water vapour pressure (P_w) by

$$q = \mu P_w/[P \ (1 - \mu) \ P_w]$$
$$= \mu P_w/[P_a + \mu P_w] \tag{A2}$$
$$= \omega/(1 + \omega) \ ; \omega = \mu P_w/P_a ,$$

where ω is called the mixing ratio. The PIRAM model also follows these definitions.

A.2 Virtual Potential Temperature

The virtual potential temperature of dry air (θ_v) is defined as the temperature that a volume of dry air at virtual temperature, T_v, assumes when brought adiabatically from its existing pressure, P, to a standard reference pressure, P_{ref}. The resultant virtual potential temperature is related to the virtual temperature by

$$\theta_v = T_v (P_{ref}/P)^{(\gamma - 1)/\gamma} \tag{A3}$$

where γ (= c_p/c_v =1.40 for dry air at room temperature) is the ratio of the specific heat at constant pressure (c_p) and the specific heat at constant volume (c_v) for dry air. By default and by convention P_{ref} is taken to be 1000 hPa, although LWKD does allow it to be modified. In versions of LWKD before 7.09, the dry-air pressure was used by default in Eq. A3 instead of

the total air pressure. While LWKD still provides this as an option, the total air pressure continues to be the default option.

A.3 Water Vapour Pressure

As the water vapour pressure is not generally available from meteorological measurements, LWKD calculates it using the following empirical relationship for the saturated water vapour pressure obtained from a variation of the Clausius-Clapeyron equation:

$$\ln(P_w^s(T)) = 19.32 - 4223/(T - 32) \tag{A4}$$

Thus, Eq. A4 provides a relationship between either the saturated water vapour pressure (P_w^s) in hPa and the air temperature (T) in Kelvin. Equations other than Eq. A4 can be used for the saturated water vapour pressure and give very similar results. One of the advantages of Eq. A4 is that its derivative is much simpler than these other formulations. The actual humidity in the atmosphere can also be given using the dew-point temperature (T_d). The dew-point temperature is obtained using

$$P_w(T) = P_w^s(T_d) \tag{A5}$$

where P_w is the atmosphere's water vapour pressure. However, as the relative humidity (H_r) is more commonly quoted than the dew point temperature, use must be made of Eq. A6, which relates the water vapour pressure to the relative humidity, and the saturated water vapour pressure:

$$P_w(T) = H_r(T) P_w^s(T). \tag{A6}$$

The PIRAM model uses a different formulation from Eq. A4 (see Ref. 27) for the saturated water vapour pressure; however, no significant difference has ever been remarked due to the use of two different functions.

At the surface of a sea with salinity, S, and at temperature T_s, the relative humidity continues to be given by

$$H_r(T_s, S) = \frac{P_{sw}^s(T_s, S)}{P_w^s(T_s)} \approx \frac{P_w^s(T_s)(1 - \varepsilon S)}{P_w^s(T_s)} = (1 - \varepsilon S) \tag{A7}$$

where P_{sw}^s is the saturated water vapour pressure above salt water (sw), P_w^s is the saturated water vapour pressure above fresh water, and ε is taken to be 5.37 x 10^{-4} (Ref. 13). Thus, for a standard salinity of 34g of salt per kilogram of water, the relative humidity at the surface is 98.2 %. This is the default value used for the relative humidity at the sea surface for both LWKD and PIRAM.

A.4 Vertical Atmospheric Pressure Profile

The final required equation is that relating the total air pressure ($P = P_a + P_w$) to the height above the ground. Assuming that the forces on an equivalent slab of dry-air are balanced, and using the perfect gas law in Eq. A1, gives the hydrostatic equation:

$$\frac{dP}{P} = \frac{g}{R_a T_v} dz, \tag{A8}$$

where dP is the pressure differential across the slab, dz is the width of the slab, g is the acceleration due to gravity near the surface, T_v is the virtual temperature of the slab, and R_a is the gas constant for dry-air. Assuming that g and R_a do not vary much near the surface, integrating Eq. A8 gives;

$$P(z)/P(z_1) = e^{-g/R_a \int_{z_1}^{z} \frac{d'z}{T_v(z')}} \approx e^{\frac{-g(z-z_1)}{R_a T_v(z_1)}} \approx 1 - \frac{g(z-z_1)}{R_a T_v(z_1)} \tag{A9}$$

where $P(z_1)$ is the total atmospheric pressure, and $T_v(z_1)$ is the virtual air temperature at the height z_1. The first approximation in Eq. A9, is used by LWKD, and is obtained by assuming that the temperature profile is uniform (constant temperature within the SBL). The last simplification in Eq. A9 is obtained by using the first term of the Taylor series expansion of the exponential and is used in PIRAM; however, no significant differences have been observed due to these choices. The air density profile can be obtained from Eq. A9 and Eq. A1, such that

$$\rho(z) = \frac{P(z_1)}{R_a T_v(z_1)} e^{-\frac{g(z-z_1)}{R_a T_v(z_1)}}. \tag{A10}$$

Again PIRAM expands the exponential and only uses the first term in z.

APPENDIX B: Iterative Algorithm

Using the above developed equations, the algorithm described below is used to provide a solution for a given set of atmospheric parameters. The algorithm is enumerated as a series of steps, with each step accompanied by a descriptive comment. For simplicity the algorithm is divided into three parts. The first part describes the steps required to determine the boundary conditions from the measurements, the second part describes the steps used to initialize the variables used during the iteration algorithm that is described in the third section.

B.1 Part 1 - Measurements

1) Calculate the water vapour pressure, $P_w(z_1)$, using the measured relative humidity and air temperature at height z_1 (Eqs. A4-A6).
2) Calculate the specific humidity, $q(z_1)$, using the measured air pressure at height z_1, and the water vapour pressure from Step 1 (Eq. A2).
3) Calculate the virtual temperature, $T_v(z_1)$ using the measured air temperature at height z_1, and the specific humidity from Step 2 (Eq. A1).
4) Calculate the virtual potential temperature, $\theta_v(z_1)$ using the measured air pressure at height z_1, $P(z_1)$, and the virtual temperature from Step 3. If the dry-air option has been chosen then the air pressure is replaced by $P(z_1)$ - $P_w(z_1)$, where $P_w(z_1)$ is obtained from Step 1 (Eq. A3).
5) Calculate the total atmospheric pressure at sea level or for the lower level, $P(z=0)$ or $P(z=z_o)$ using the total air pressure at height z_1, and the virtual temperature from Step 3 (Eq. A9).
6) Calculate the water vapour pressure at sea level or for the lower level, $P_w(z=0)$ or $Pw(\tilde{z}=z_o)$ using the sea surface relative humidity and sea surface temperature or the relative humidity and air temperature for the lower level (Eqs. A4-A7).
7) Calculate the specific humidity at sea level or for the lower level, $q(\tilde{z}=0)$ or $q(z=z0)$ using the air pressure from Step 5 and the water vapour pressure from Step 6 (Eq. A2).
8) Calculate the virtual temperature at sea level or for the lower level, $T_v(\tilde{z}=0)$ or $T_v(z=z0)$ using the measured temperature and the specific humidity from Step 7 (Eq. A1).
9) Calculate the virtual potential temperature at sea level or for the lower level, $\theta v(\tilde{z}=0)$ or $\theta v(z=\tilde{z}_o)$ using the air pressure from Step 5, and the virtual temperature from Step 8. If the dry-air option has been chosen then the air pressure is replaced by $P(z)$ - $P_w(z)$, where $P_w(z)$ is the result from Step 6 ($z=0$ or $z=z_o$) (Eq. A3).
10) Calculate the average virtual temperature in the layer, T_{vm}, using the results from Steps 3 and 8 (Eq. 27).
11) If the lower surface is water, calculate the average virtual potential temperature in the layer, θ_{vm}, using the results from Steps 4 and 9 (Eq. 25).

B.2 Part 2 - Initialization

1) Set the number of iterations parameter, N, equal to zero. This parameter keeps track of the number of iterations required to obtain a stable solution.

2) Set the iteration precision parameter, ε, equal to 0.001. This is one of two arbitrarily set parameters that can stop the iteration procedure. Its significance is discussed further in Step 10 of Part 3.

3) Set the maximum number of iterations parameter, MAXN, equal to 100. This is the second arbitrarily set parameter that can stop the iteration procedure.

4) Set the following parameter, S(0), equal to a large number. It is currently set arbitrarily to 1 x 10^{10}. The significance of this parameter is discussed in Step 10 of Part 3.

5) Calculate the specific humidity difference (SHD) using $q(z_1) - q(0)$ over water or $q(z_1) - q(z_0)$ over land using the results from Steps 2 and 7 of Part 1.

6) Calculate the virt. pot. temperature difference (VPTD) using $\theta_v(z_1) - \theta_v(0)$ over water or $\theta_v(z_1) - \theta_v(z_0)$ over land using the results from Steps 4 and 9 of Part 1.

7) Set the wind speed measured at the height z_2 to $u(z_2)$.

8) Set the initial wind roughness height, $z_{ou}(0)$ equal to 1.5 x 10^{-4} m over water or to 0.01 m over land.

9) Set the initial virtual potential temperature roughness height, $z_{o\theta v}(0)$, using Eq. 23 and an appropriate value for C_{TN}.

10) Set the initial specific humidity roughness height, $z_{oq}(0)$, using Eq. 23 and an appropriate value for C_{EN}.

11) Set the initial wind scaling constant, $u_*(0)$, using only the first term in Eq. 17, the measured wind speed at height z_2, and $z_{ou}(0)$ from Step 8:

$$u_*(0) = \kappa u(z_2) / \ln[z_2 / z_{ou}(0)] . \qquad (B1)$$

12) Set the initial virtual potential temperature scaling constant, $\theta_{v*}(0)$, using only the first term in Eq. 20 or 21, VPTD from Step 6, and $z_{o\theta v}(0)$ from step 9:

$$\theta_{v*}(0) = \kappa (VPTD) / \ln[z_1 / z_{o\theta_v}(0)] . \qquad (B2)$$

13) Set the initial specific humidity scaling constant, $q_*(0)$, using only the first term in Eq. 20 or 21, SHD from Step 5, and $z_{oq}(0)$ from step 10:

$$q_*(0) = \kappa (SHD) / \ln[z_1 / z_{oq}(0)] . \qquad (B3)$$

14) Set the initial Monin Obukhov length, L(0), using Eq. 2 and the results from Steps 11 and 12, and Step 10 from Part 1.

B.3 Part 3 - Iteration

1) Using the wind speed roughness height, $z_{ou}(0)$, the Monin-Obukhov length, L(0), and u(0), solve Eq. 20 (sea) or Eq. 21 (land) for a new value of the scaling constant, $u_*(1)$.

2) Using the virtual potential temperature roughness height, $z_{o\theta v}(0)$, the Monin-Obukhov length, L(0), and VPTD, solve Eq. 20 (sea) or Eq. 21 (land) for a new value of the scaling constant, $\theta_{v*}(1)$.

3) Using the specific humidity roughness height, $z_{oq}(0)$, the Monin-Obukhov length, L(0), and SHD, solve Eq. 20 (sea) or Eq. 21 (land) for a new value of the scaling constant, $q_*(1)$.

4) Calculate a new value for the wind speed roughness height, $z_{ou}(1)$. For the sea, use Eq. 24, $u_*(1)$ from Step 1, and θ_{vm} from Step 11 of Part 1, while for the land set it equal its default value (nominally 0.01 m).

5) Calculate a new value for the virtual potential temperature roughness height, $z_{o\theta v}(1)$, using Eq. 23 and $z_{ou}(1)$ from Step 4.

6) Calculate a new value for the specific humidity roughness height, $z_{oq}(1)$, using Eq. 23 and $z_{ou}(1)$ from Step 4.

7) Calculate a new value for the Monin Obukhov length, $L(1)$, using Eq. 2, T_{vm} from Step 10 of Part 1, and the new scaling constants $u_*(1)$ and $\theta_{v*}(1)$ calculated from Steps 1 and 2.

8) Calculate the absolute relative differences for the three scaling constants and the three roughness heights. The absolute relative difference for each parameter is defined to be:

$$D_A = \begin{cases} |[A(1)\ A(0)]/A(0)|\,; A(0) \neq 0 \\ |[A(1)\ A(0)]/A(1)|\,; A(0) = 0, A(1) \neq 0 \\ 0 \qquad\qquad\quad\,; A(0) = A(1) = 0 \end{cases} \qquad (B4)$$

where A represents any of the six parameters.

9) Calculate the sum, $S(1)$, of the six absolute relative differences calculated in Step 8. S is the measure used to describe the goodness of the solution.

10) The final step in the iteration loop is the following IF block which decides whether to continue or stop the iterative procedure. The procedure is stopped and the solution is valid if $S(1)$ is less than ε and N is less than MAXN. The significance of $S(1)$ being less than ε is that the sum of the relative differences is less than $100*\varepsilon$ % (i.e. the maximum possible value that any of the individual relative differences can have is $100*\varepsilon$ %). Thus, a value of 0.001 translates into a maximum difference of 0.1% for any of the parameters. The IF block used by LWKD is constructed as follows:

    IF $(S(1) < \varepsilon)$ THEN
        - solution found; stop the iteration procedure and return the results
    ELSE IF $(N > MAXN)$ THEN
        - no solution found within MAXN iterations; stop the iteration
        procedure and return an error flag
    ELSE IF $((N\ 5)$ OR $(S(1) < S(0)))$ THEN
        - solution not yet found; continue the iteration procedure as either less than 6 iterations have been performed $(N\ 5)$ or the goodness of the solution is improving $(S(1) < S(0))$
        - increment N to N+1
        - set $z_{ou}(0) = z_{ou}(1)$; $z_{o\theta v}(0) = z_{o\theta v}(1)$; $z_{oq}(0) = z_{oq}(1)$
        - set $u_*(0) = u_*(1)$; $\theta_{v*}(0) = \theta_{v*}(1)$; $q_*(0) = q_*(1)$
        - set $L(0) = L(1)$
        - GOTO Step 1
    ELSE
        - no solution found because $N > 5$ and $S(1)\ S(0)$
        IF (mode is INTERACTIVE[1]) THEN
            - stop the iteration procedure and return an error message
        ELSE (mode is BATCH[12])
            IF (wind speed < 30 m/s) THEN

---

[2] The Interactive and Batch modes of operation are discussed in Section 3.

- increase the wind speed by 0.5 m/s and return to Step 1

ELSE

- stop the iteration procedure, return an error flag, and output uniform profiles

APPENDIX C: Wavy Model

The Wavy WKD model developed at DREV by Beaulieu (Ref. 10) was an attempt to mimic the effect that water waves would have on the vertical profiles generated by the WKD model (flat sea). The LWKD model also incorporates this effect on the profiles it generates; however, its use is not recommended as results using this feature have not agreed with any of our measurements. This is because it tends to create stronger vertical gradients near the sea surface than those that are observed. Nevertheless, the option is still available for those who would like to play with it and to keep a place holder within the program for any future changes to this option.

Thus, for the current model, if one assumes that the action of the waves is to turn a flat surface into a sinusoidal surface with a wave height (trough to peak) of H_w and a wavelength of λ_w, then the height of any part of the wave (H) above the mean sea level is given by
where x is between 0 and λ_w. Thus, assuming that the instantaneous vertical profile, Φ_α, for

$$H(x) = (H_w/2)\cos(2\pi x/\lambda_w) , \qquad (C1)$$

parameter α, above every point of the wave is that given by LWKD for a flat sea, the average effect of this wave action can be calculated by averaging the vertical profile over one wavelength. This gives

$$\Phi_\alpha^w(z) = \begin{cases} (1/H_w) \displaystyle\int_{z-H_w/2}^{z+H_w/2} \Phi_\alpha(z')\,d'z \; ; z \geq z_{max} + H_w/2 \\[2em] (1/H_w) \displaystyle\int_{z_{max}}^{z+H_w/2} \Phi_\alpha(z')\,d'z \; ; z_{max} \leq z < z_{max} + H_w/2 \end{cases} \qquad (C2)$$

where Φ_α^w is the averaged vertical α-profile, z is the height above the mean sea level or flat sea, z´ is the instantaneous height above a point on the wave, and z_{max} (= max(z_{ou}, $z_{o\theta v}$, z_{oq})) is the maximum of the wind speed, virtual potential temperature, and specific humidity roughness heights. The first function in Eq. C2 is used for heights above the peak of the wave, while the second function is used for heights between the mean sea level and the wave's peak. The function is not calculated for heights below the mean sea level.

Equation C2 can easily be calculated using the rectangular integration rule such that
and

$$\Phi_\alpha^w(z) = \begin{cases} \displaystyle\sum_{i=0}^{n_1} \Phi_\alpha(z_i')/n \qquad ; z \geq z_{max} + H_w/2; i = 0,1,..n_1 \\[2em] \displaystyle\sum_{i=m}^{n_1} \Phi_\alpha(z_i')/(nm) \; ; z_{max} \leq z < z_{max} + H_w/2; i = 0,1,..n_1 \end{cases} \qquad (C3a)$$

$$z_i' = z - (H_w/2)\cos(2\pi i/n) \qquad (C3b)$$

$$m = (n/\pi) \cos^{-1}[2\,(z - z_{max})/H_w].\qquad\qquad\text{(C3c)}$$

The above procedure is only valid for profiles that are linear combinations of the four fundamental vertical profiles given by Equations 4 and A9 for the wind, virtual potential temperature, specific humidity, and total atmospheric pressure, respectively. Any nonlinear combinations of these profiles must first calculate the wavy profile for each of these four profiles before combining their results. This is an extremely important point (see Ref. 1), as many of the desired quantities involve nonlinear combinations of these profiles.

APPENDIX D: Structure Function Fit to Edson

The fit of the functional form used by LWKD (see Eq. 42d) to emulate various forms of the structure functions described in Section 4.1 provided by Edson (Ref. 21) was obtained by determining the least squares of

$$Sum = 100 \sum_i \left[\frac{LWKD_i - Edson_i}{Edson_i} \right]^2 . \qquad (D1)$$

Table D1 shows the final results of this process and the resultant parameters (F_0, F_1, F_2) where for $F_3 = 1$, and Fig. D1 shows the graph of Edson's form, the fit, and the least squares.

Table D1: Table providing parameters obtained for the least squares fit between the Edson form and the LWKD form.

	F0	6.1	
	F1	19.8	
	F2	12.7	
	Stable Case (z/L >= 0)		
z/L	Edson	LWKD	
0.01	6.45	6.48	0.0029
0.02	6.83	6.83	0.0000
0.04	7.43	7.44	0.0001
0.07	8.16	8.22	0.0048
0.1	8.80	8.90	0.0132
0.2	10.56	10.75	0.0300
0.4	13.36	13.55	0.0196
0.7	16.77	16.85	0.0021
1	19.72	19.66	0.0008
2	27.90	27.48	0.0233
4	40.88	40.07	0.0407
7	56.74	55.71	0.0338
10	70.41	69.34	0.0237
20	108.36	107.53	0.0061
40	168.61	168.60	0.0000
70	242.23	243.51	0.0028
100	305.70	308.20	0.0066
200	481.86	487.99	0.0158
400	761.49	773.63	0.0246
700	1103.22	1122.84	0.0306
1000	1397.80	1423.93	0.0337
		Sum	0.3150

Least Squares Fit of Edson & LWKD
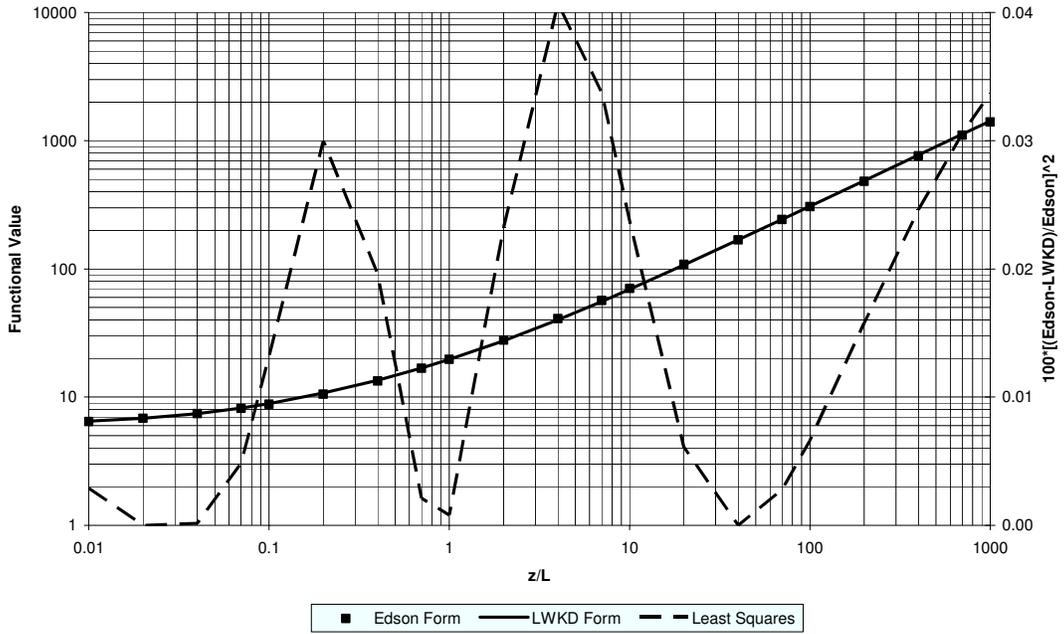**(Stable Case)**

Figure D1: Least squares fit of the LWKD form to the Edson form.

APPENDIX E: List of of LWKD Modifications

This Appendix gives a short list of some of the major changes made to LWKD since Version 7.09. Comments are not provided with respect to all changes; however, it is believed that all major changes are noted.

Version 7.10 – Sept. 17, 1999
Only minor changes, that don't greatly affect its operation, were made. These included:
1. changing 'DREV copyright' to 'proprietary to DREV';
2. references to programs are always to 'LWKD' instead of 'LWWKD' and 'LWKDCN2' instead of 'WKDCN2';
3. changing the 'LWWKD.INI' file to the 'LWKD.INI' file. For backward compatibility the program will use a 'LWWKD.INI' file if a 'LWKD.INI' file isn't found;
4. changing output headers for the structure parameters so that the appropriate units are shown. T is deg. C and Q is g/m3.

Version 7.20 – March 23, 2000
1. Modified the minimum, maximum and default values for the meteorological parameters, and the wavelength so that all the modules used within IRBLEM have the same parameter checks. Please note: that while both the relative humidity and the wave heights can be set to zero, even though they are actually set to 1×10^{-10} internally. This required the creation of three PARAM variables, "w_minimum, w_maximum and w_default".
2. Changed the display screen so that the Monin-Obukhov length is expressed in scientific notation.
3. Choice of adiabatic pressure also has the same limits as the atmospheric pressure (i.e. 800 to 1200 mbars).
4. Change MaxWspd; used to modify the wind speed to obtain a solution from 25 m/s to the maximum allowed wind speed. Also change the wind speed step size so that it is 1/6th the maximum allowed wind speed.
5. In the IRCOND or RFCOND file, save the wind speed that was used and not the originally read wind speed in the first data line.
6. Removed the wind speed that was used from the 2nd data line of the IRCOND or RFCOND file.
7. Output the wavelength in the RFCOND or IRCOND file with 2 digits after the decimal.
8. Change the heading section of the TDP*** files such that all parameters read from the METDATA file are shown. This will be Ver. 2.0. To do this a new METDATA structure was created in LWWKDBAT.H.
9. Added a new parameter, "liquid water content", to the METDATA structure.
10. Changed the calculation of the refractivity structure parameter to take account of a recent empirical correction. The correction is to multiply the previous value by 0.2.
11. Height step size used to produce the TDP*** and CN2*** output files are now the same as for the MP_H*** file. This means that it is variable.
12. Default settings are used for the wavelength and wavy model when using the batch version of LWKD.

13. Corrected error display problems during batch execution when using the interactive version.
14. Corrected minor errors (unit for RH, etc.) present in the postscript output of the meteorological parameters.
15. Corrected an error when using the batch programs that caused the program to fail if it didn't find an lwwkd.ini or lwkd.ini file.

Version 7.21 – May 5, 2000
An error in the maximum allowed horizontal range corrected. It is now set to 100 instead of the previous value of zero.

Version 7.30 – May 8, 2000
1. Changed error message in LWWKDBAT that is shown when the wind measurement height is out of bounds.
2. Changed the calculation of the refractivity structure parameter back to what it had been before Version 7.20. In other words, the correction of 0.2 has been removed.

Version 7.31 – October 1, 2000
1. LIBERROR.C and LIBERROR.H have been modified and RUNMODE.C and RUNMODE.H have been added. These routines control the error messages and the run mode of the program in batch mode. These changes have been made such that IRBLEM and PRIME write these messages to appropriate sub-directories.
2. Changed the calculation of the refractivity structure parameter back to what it had been in Version 7.20. In other words, reintroduce the correction factor. This time the correction factor is being put into the "lwkd.ini" file as well with a default value of 0.20.

Version 7.32 – October 23, 2000
Certain modifications were made to the files so that the BATCH versions of the program will compile in UNIX.

Version 7.33 – January 18, 2001
1. Minor changes were made by NURUN to the files "liberror.c", "runmode.c", and "runmode.h". Some of the changes involved the log file.
2. Changes to the log file require changes to LWWKD.C as well.

Version 7.34 – February 12, 2001
Returned to Ver. 7.08 for the equation that calculates C_N^2 as it appears to work much better. I.e. the +2 has been changed back to -2. Also, the scaling factor of 0.2 has been replaced by 1.0.

Version 7.40 – June 28, 2001
1. Placed the following parameters into the LWKD.INI file so that they can be more easily modified:
   a. the specific humidity-virtual potential temperature correlation coefficient. It's default value is 0.8 and it can be set from 0 to 1;

b. the three coefficients that belong to the structure parameter function. The present coefficients are those due to Edson and they will continue to be the default values;

c. the three coefficients that are used by the three functions that can be used for the gradient functions for both the stable or unstable cases.

2. Add the virtual potential temperature, specific humidity and virtual potential temperature-specific humdity structure parameters to the CN2 output file.

3. Add the three terms that make up the refractivity structure parameter to the C_N^2 output file. The sum of the three terms will add up to the refractivity structure parameter.

4. Include the ability to plot the 6 additional structure parameters.

5. Change the von Karman constant's default value to 0.41.

Version 7.41 – June 14, 2002

1. The previous files IRCOND and RFCOND are no longer produced. Instead, a CONDxxx file is produced that follows the same kind of output format as TDPxxx & MP_H_xxx. It contains a list of the input parameters used by LWKD to obtain a solution and the resultant parameters obtained from the Monin-Obukhov fit.

2. Changes were made to the batch modes such that it always uses the value of the wavelength obtained from the METDATA file. Also, the non-wavy model is now used for both batch versions of the program. Thus, the program no longer requires any inputs from the user.

3. The far-infrared band has been extended to accept values from 8 to 15 microns. The A & B coefficients have not been changed although this may become a future issue.

4. Added a third compilation flag LWKDMPH and changed the earlier flag, WKDCN2, to LWKDCN2. The new flag controls the output of the MP_H_xxx file. Now if LWKDCN2 = 1 only the CN2 profile is output, if LWKDMPH = 1 only the modified refractivity is output, and if both are not defined then only the CONDxxx and TDPxxx files are output.

Version 7.42 – August 15, 2002

The compilation flags are removed and instead the mode of operation will be decided by a parameter on the command line such that:

-g : graphics based interactive mode
-m : batch mode where only the met files CONDxxx & TDPxxx are output)
-r : batch mode where only the refractivity file MP_H_xxx is output
-c : batch mode where only the CN2 file CN2xxx is output.

Note 1: if no command line parameters are present, then the interactive mode is run. All other cases require that the command parameter be given.

Note 2: to use the other command line parameters L, A, etc., you can enter them as lwwkd -m -LA or lwwkd -m -L -A. Either method will work as long as the desired operating mode is the first command line parameter and is separate from all other parameters.

Note 3: the -g command does not make use of any other command line parameters.

Version 7.50 – Aug 15, 2002

1. Created a new interactive operating mode that uses no graphics dependent functions at all. This mode will be denoted by -i. It will also make use of the other command line parameters.

2. The -g command will also no longer exist as an option.

3. Change wavelength input so that it is no longer done by band but by wavelength with limits between 0.4 & 15 microns.
4. The met output file for the interactive mode puts out the met data provided to LWKD at the end of the file.
5. LWKD fitting routine has been modified so that it can be used when there is a second (surface) met measurement (temperature & relative humidity) taken near the surface (<= 1 m). Thus, a value of zero corresponds to a measurement at the surface. This allows the code to now be used with land measurements.
6. There is a new restriction in the minimum height allowed for the upper level met measurement. This is now set to 2 meters,   such that there is always at least a 1 meter difference between the heights of the upper level measurements and the lower (surface) level measurements.

Version 7.51 – September 11, 2002
Starting with this version the file structure has been changed. This has been done with the use of Rational Rose.
1. The tide height above the mean water level (MWL) has replaced the neutral Dalton number in the METDATA file. While this value is not used by LWKD it is passed on to the TDP*** file when operated in BATCH mode. Please note that the sensor measurement heights given to LWKD must already take any tide effects into consideration and must already be given relative to the MWL (or the ground level for a land scenario).
2. The H1/3 wave height is now only output to the TDP*** file and not to the COND*** file. Thus, the COND*** file only contains information pertinent to the Monin-Obukhov solution.
3. The neutral drag coefficient B, and the Stanton number have also been replaced in the METDATA file by the height at which a second (surface) met measurement has been made, and the measured RH at this height. The temperature at this height must replace the sea temperature. A height of zero will indicate that no second met measurement has been made and that the surface is assumed to be water.
4. The file MP_H_*** now has the same format as the other output files.
5. Introduced a new term "ctq_coef" into the "lwkd.ini" file so that the coefficient, whose default value is -2 can be modified.

Version 7.52 – November 22, 2002
1. As the new METDATA format has three new parameters, it is not necessarily backward compatible. To handle this any METDATA file that contains a version line "## Version : xx.x", where the version is 4.1 or greater will handle the new parameters; otherwise it will assume that it is an older version of the file and the new parameters are not defined.

Version 7.53 – April 28, 2005
The duct height that is output in the COND file is now defined using the following algorithm:
    duct height = 0;
    if a height exists such that dN/dz = -0.157 then
        duct height = height
    else if a height exists such that dN/dz = 0 then
        duct height = -height

The negative duct height is a new introduction that follows a development by CELAR where the negative height is known as the characteristic height.

Version 7.54 – July 6, 2005
The met parameters in the TDP*** output file now contain 3 digits after the decimal point instead of 2.

Version 7.55 – July 11, 2005
Corrected a problem with the humidity not being put to its default value of 98.2% after changing from a case where there is a lower measurement height to a case where the lower measurement height is the sea surface.

Version 7.56 – July 14, 2005
Modified LWKD.ini slightly to take into account a change in the expression used to calculate the refractivity structure parameter. The parameter ctq_coef in LWKD.ini is now given by cn2_ratio.

Version 8.00 – July 15, 2005
Corrections were made to several minor problems having to do with the screen displays. They had no effect on the calculations! Version 8.00 will also mark a change to a different file system as a result of a reorganization of the Sensor Performance Group's many software packages.

Version 8.10 – December 21, 2007
Note: the new file system has not yet been integrated; however, it is expected to be integrated for future versions. For this version
1. minor changes were made to the output files and to the user interface;
2. the salinity was added to the METDATA file;
3. the wind speed roughness height for land measurements is fixed at 0.05 m;
4. 3 height parameters were introduced to parameterize the interfacial (air-sea interface) region;
5. a universal form of the structure parameter function that is defined by eight parameters. These parameters have been added to the initialization file LWKD.ini so that they can be modified without having to recompile the program.
6. corrects an error in the calculation of the index of refraction, refractivity and modified refractivity for radio frequencies (RF)
7. can output vertical profiles for heights up to 500 meters

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
Height above mean water level	z		m
Monin-Obukhov length	L		m
Wind speed	u		m/s
Virtual potential air temperature	θ_v		K
Specific humidity	q		g/g
Wind speed gradient function	φ_u		
Virtual potential temperature gradient function	$\varphi_{\theta v}$		
Specific humidity gradient function	φ_q		
Normalized height (=z/L)	ζ		
Von Karman's constant	κ	0.41	
Wind speed scaling constant	u_*		m/s
Virtual potential temperature scaling constant	θ_v^*		K
Specific humidity scaling constant	q_*		g/g
Mean virtual temperature in MBL	T_{vm}		K
Acceleration due to gravity	g	9.81	m/s^2
Kondo stable wind speed gradient function coefficient	η_1	6	
Kondo stable virt. pot. temp. gradient function coef.	η_2	6	
Kondo stable specific humidity gradient function coef.	η_3	6	
WKD stable wind speed gradient function coefficient	α_1	5	
WKD stable virt. pot. temp. gradient function coef.	α_2	5	

WKD stable specific humidity gradient function coef.	α_3	5	
Unstable wind speed gradient function coefficient	β_1	16	
Unstable virt. pot. temp. gradient function coef.	β_2	16	
Unstable specific humidity gradient function coef.	β_3	16	
WKD stable gradient function coefficient ($\zeta \geq 0$)	α	5	
Unstable gradient function coefficient ($\zeta < 0$)	β	16	
Kondo stable gradient function coefficient ($\zeta \geq 0$)	η	6	
Wind speed constant of integration	u_0		m/s
Virtual potential temperature constant of integration	θ_{v0}		K
Specific humidity constant of integration	q_0		g/g
Wind speed roughness length	z_{0u}		m
Virtual potential temperature roughness length	$z_{0\theta v}$		m
Specific humidity roughness length	z_{0q}		m
Integrated wind speed gradient function	Ψ_u		
Integrated virt. pot. temperature gradient function	$\Psi_{\theta v}$		
Integrated specific humidity gradient function	Ψ_q		
Heat flux	H		J/m^2
Surface thermal conductivity	τ_θ		J/m/K
Total atmospheric density	ρ		g/m^3
Spec. heat capacity of dry air at constant pressure	c_p	1.004	J/g/K
Temperature profile *h* parameter	h_θ	0	
Surface moisture diffusion coefficient	τ_q		g/m/s
Humidity profile *h* parameter	h_q	0	
Surface mass diffusion coefficient	τ_u		g/m/s

Wind profile h parameter	h_q	0	
Temp., RH & pressure upper measurement height	z_1		m
Wind speed measurement height	z_2		m
Ratio of mol. Masses of water and dry air (= M_w/M_a)	μ	0.622	
Air temperature	T		K
Ratio of heat capacities for dry air (= c_p/c_v)	γ	1.40	
Relative humidity	H_r		%
Saturated water vapour pressure over water	P_w^s		hPa
Dry air atmospheric pressure	P_a		hPa
Total atmospheric pressure	P		hPa
Total atmospheric reference pressure	P_{ref}	1000	hPa
Sea temperature	T_s		K
Virtual potential Temperature Difference (VPTD)	$\Delta\theta_v$		K
Specific humidity difference	Δq		g/g
Temp. and RH lower measurement height	z_0		m
10-m neutral heat flux coefficient	C_{TN}	1.0×10^{-3}	
10-m neutral moisture flux coefficient	C_{EN}	1.2×10^{-3}	
Charnock's constant	α_c	0.011	
Dynamic viscosity	v_d		m^2/s
C wind coefficient	C	-5.5	
a_d wind coefficient	a_d	9.267×10^{-8}	$m^2/s/K$
b_d wind coefficient	b_d	1.346×10^{-5}	m^2/s
Mean virtual potential temperature in MBL	θ_{vm}		K
Virtual potential sea temperature	θ_{vs}		K

Virtual air temperature	T_v		K
Virtual sea temperature	T_{vs}		K
Refractivity	Z		
Boltzmann's constant	k	1.381×10^{-23}	J/K
Wavelength	λ		μm
Water vapour pressure	P_w		hPa
Molecular refractivity for dry air	D_a		
Molecular refractivity for water vapour	D_w		
Refractivity coefficient for dry air	A		K/hPa
Refractivity coefficient for water vapour	B		K/hPa
i^{th} wavelength resonance	λ_i		μm
i^{th} line strength	S_i		
IR molecular refractivity for water vapour	D_w^{IR}		
UV molecular refractivity for water vapour	D_w^{UV}		
Water vapour gas constant (= R/M_w)	R_w	0.462	J/g/K
Universal gas constant	R	8.31	J/mol/K
Molecular mass of water	M_w	18.0	g
Refractive index	n		
Refractive index structure parameter	C_n^2		$m^{-2/3}$
Refractivity structure parameter	C_Z^2		$m^{-2/3}$
Dry-air refractivity structure parameter coefficient	K_A		
Water vapour refractivity structure parameter coef.	K_B		
Temperature structure parameter	C_T^2		$K^2\text{-}m^{-2/3}$
Water vapour density structure parameter	$C_{\rho w}^2$		$g^2\text{-}m^{-20/3}$

Temperature-water vap. density structure parameter	$C_{T\rho w}$	$K\text{-}g\text{-}m^{-11/3}$
i^{th} structure parameter function	f_i	
Virt. potential temperature structure parameter	$C_{\theta v}^2$	$K^2\text{-}m^{-2/3}$
Specific humidity structure parameter	C_q^2	$m^{-2/3}$
Virt. pot. temp.-specific humidity structure parameter	$C_{\theta vq}$	$K\text{-}m^{-2/3}$
Virt. pot. temp.-specific hum. correlation coefficient	$r_{\theta vq}$	± 0.8	
Virt. pot. temp.-vapour density structure parameter	$C_{\theta v\rho w}$	$K\text{-}g\text{-}m^{-11/3}$
Virtual temperature structure parameter	C_{Tv}^2	$K^2\text{-}m^{-2/3}$
Temperature-specific humidity structure parameter	C_{Tq}	$K\text{-}m^{-2/3}$
Virtual temp.-spec. humidity structure parameter	C_{Tvq}	$K\text{-}m^{-2/3}$
LWKD structure parameter function – unstable exponent parameter	E_3	-2	
LWKD structure parameter function – 0th unstable parameter	E_0	5.8	
LWKD structure parameter function – 1st unstable parameter	E_1	-7	
LWKD structure parameter function – 2nd unstable parameter	E_2	0	
LWKD structure parameter function – stable exponent parameter	F_3	1	
LWKD structure parameter function – 0th stable parameter	F_0	6.1	
LWKD structure parameter function – 1st stable parameter	F_1	19.8	
LWKD structure parameter function – 2nd stable parameter	F_2	12.7	
Structure parameter function ratio	A_{21}	1	
Refractivity structure parameter scaling parameter	E_z	1	

Refractivity ratio parameter	A_z	1	
Modified refractivity	M		
Characteristic refractive height	h_c		m
Molecular mass of dry air	M_a	28.9	g
Dry air gas constant (= R/M_a)	R_a	0.288	J/g/K
Moist air gas constant	R_m		J/g/K
Mixing ratio	ω		g/g
Spec. heat capacity of dry air at constant volume	c_v	0.717	J/g/K
Dew-point temperature	T_d		K
Saturated water vapour pressure over salt water	P_{sw}^{s}		hPa
Salinity	S		g/kg
Salinity coefficient	ε	5.37×10^{-4}	
Average of the 1/3 highest wave heights	$H_{1/3}$		m
Water wave height	H_w		m
Wavelength of water wave	λ_w		m
Instantaneous vertical profile function	Φ_α		
Wave averaged vertical profile function	Φ^w_α		

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 General 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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(U) The objective of this report is to bring up to date the present state of DRDC Valcartier's LWKD model. Many important changes have been to the previous reported version (V7.09) and need to be documented. Apart from changes to the physical equations, and the inputs to and outputs from the program, it is also necessary to document changes to the program's development structure. As of version 7.51, the program is now being developed using Microsoft's Visual C/C++ (Version 6) environment, the code has been reformulated as object oriented code, and it has been documented using Rational Rose's Computer Assisted Software Engineering (CASE) tool.

(U) The first section of the report highlights some of the important changes made since version 7.09. The second section discusses the set of scaling equations that are used in the LWKD model and how they have been modified, and the method used by LWKD to solve for the parameters of the scaling equations. Section three discusses how LWKD calculates the index of refractivity from the visible to the far infrared and for radio frequencies. Section four shows how LWKD determines various structure parameters, including the refractivity structure parameter. Section five describes the additions and changes to the program's modes of operation, and its new options, outputs, and compilation modes and section six provides some conclusions.

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LWKD, surface boundary layer, marine boundary layer, Monin-Obukhov similarity theory, refractivity profile, index of refractivity structure parameter

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