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An Algorithm for the Vertical Structure of Aerosol Extinction in the Lowest Kilometer of the Atmosphere: Rev. 1

by Melvin G Heaps and Robert D Johnson

Contributing Editor: Alan E Wetmore

NOTICES

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14. ABSTRACT

This is a revision of the original 1983 technical report by Melvin G Heaps and Robert D Johnson (ASL-TR-0142). This report has been reprinted to allow wider distribution than the original limited distribution report and to allow users of the Air Force's LOWTRAN and MODTRAN models more complete documentation of the Army Vertical Structure Algorithm (VSA) used in those models.

A previously developed algorithm describes the vertical structure of visibility for low visibility/low stratus conditions. The mathematical formalism of this earlier algorithm has been retained, and based upon additional data and reasonable physical assumptions, extended to more general cases. Tabular values and guidelines are now provided that allow estimations of the vertical structure of visibility within the planetary boundary layer (nominally up to 1 km in altitude) for low to high surface visibilities and under conditions ranging from low cloud ceilings to clear skies.

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Editor's Note

This is a revision of the original 1983 technical report by Melvin G Heaps and Robert D Johnson (ASL-TR-0142). This report has been revised to allow wider distribution than the original limited distribution report and to allow users of the Air Force's LOWTRAN and MODTRAN models more complete documentation of the algorithms used in those models. The equations and other mathematics have been reset in an appropriate font. The footnote references have been moved to their own section. The document is suitable for electronic distribution allowing hyperlinks to be added. A few typos have been corrected and clarifications have been made as follows:

Page 3 : Figure 1 has been redrawn with color and improved labels.

Page 7 : A more complete description of Table 1's contents has been added to the text.

Page 8 : Table 1 has been slightly rearranged.

Page 9 : Annotated outline ↦ annotated listing.

Page 10 : The FORTRAN source code variable `ZINVHT` has been spelled correctly in Table 2.

Page 17 : The source code listing has syntax highlighting and should now be legible.

Extracting the Source Code Files

The FORTRAN source code for the Vertical Structure Algorithm (VSA) program is included within the electronic document. The FORTRAN source shown in Appendix B can be extracted when viewing the electronic version of this document by right clicking on this 📎 paperclip icon and selecting the "`Save Embedded File to Disk...`" menu option.

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1. Introduction

The concept of visibility has acquired new emphasis on the modern battlefield due to the introduction of precision-guided munitions and sophisticated electro-optical sensors. Traditionally, visibility has referred to estimates of the visual range for which targets are discernable against a background or horizon, and where the line of sight is frequently horizontal and within a few meters of the ground. Today, military forces are relying increasingly on new surveillance and weapon systems whose sensors must function over slant paths within the lowest kilometer of the atmosphere, where variations of visibility in the vertical now assume an increased importance.

In low visibility situations, due to haze or fog, a number of observations have shown that surface visibility is not representative of conditions at tens or even hundreds of meters above the surface. Thus "slant path visibility" can be significantly different from "horizontal visibility". Based on several sets of data[1,2] which show that visibility degrades with increasing altitude, an empirical representation of this type of behavior was developed.[3] In turn, this representation has been used to develop an algorithm of simple analytical form which describes the vertical structure in visibility for low visibility/low stratus conditions, and which uses as input quantities only the observed surface visibility and cloud ceiling height.[4]

In extending the algorithm to cover all general cases of atmospheric extinction due to aerosols, four types of vertical profiles are now considered. The first two types of profiles are for cases where the visibility decreases with increasing height (that is, the atmospheric volume extinction coefficient increases with increasing altitude). These profiles are used to characterize thick fogs of considerable vertical extent, clear to foggy conditions underneath low-lying stratus, and low-lying stratus clouds themselves. These two types of profiles have been previously discussed for low visibility/low stratus conditions.[4] Two new profiles are now developed for the cases where the atmospheric visibility improves with increasing altitude. This is generally true for a shallow radiation fog, the hazy atmosphere underneath an inversion layer, or the well-mixed boundary layer. In such cases a low cloud ceiling is not present. In all instances the atmospheric extinction profiles calculated here are due to the aerosol component of the atmosphere. Molecular extinction, where appropriate, should be calculated independently.

The report is structured in two sections—outline and discussion of the algorithm, and application of the algorithm. Appendices address the definition of visibility as applied in this text and define the computer program used to compute extinction coefficient as a function of altitude.

2. Outline of the Algorithm

If the extinction coefficient, σ_{e}, at 0.55 μm is used as the metric for visibility, the vertical structure of visibility can be written as[4]

$$\sigma_{\mathrm{e}} = A \exp[B \exp(Cz)] \tag{1}$$

where z is the altitude and the coefficients A, B, and C are functions of the boundary conditions for three different visibility regions. In some cases the coefficient C is also a function of the cloud ceiling height, radiation fog depth, or the inversion layer height. The visibility regions and several representative vertical profiles of extinction are depicted in figure 1.

In the initial development of the vertical structure algorithm,[4] two visibility regions were uniquely defined on the basis of the data taken from vertical profiles of droplet size spectra. The boundary values of the extinction coefficient in the first region, thick fog or low stratus cloud have physical interpretations. The upper bound represents the average upper limit to extinction one would find in a stratus cloud or in a very thick fog at the surface. (The two are taken as synonymous in this context.) The lower bound to this region represents the dividing line between extinction caused by droplet growth in subsaturated/saturated environments and that caused by droplet growth in saturated/supersaturated environments. The lower bound to the thick fog/-cloud region thus represents either the cloud bottom or that stage of a fog where the droplet growth begins to take place in a supersaturated environment. Implicit in the definition of this first region is the concept that convective motions exist in both the cloud and fog, which produce a saturated to supersaturated environment. The special case of a radiation fog is treated in a later section.

The second visibility region has a range of extinction coefficients suitable to describe the transition from haze to fog. The upper bound to the extinction coefficient in the haze/fog visibility region is the same as the lower bound in the thick fog/cloud region and implies a transition from a subsaturated to a supersaturated environment.

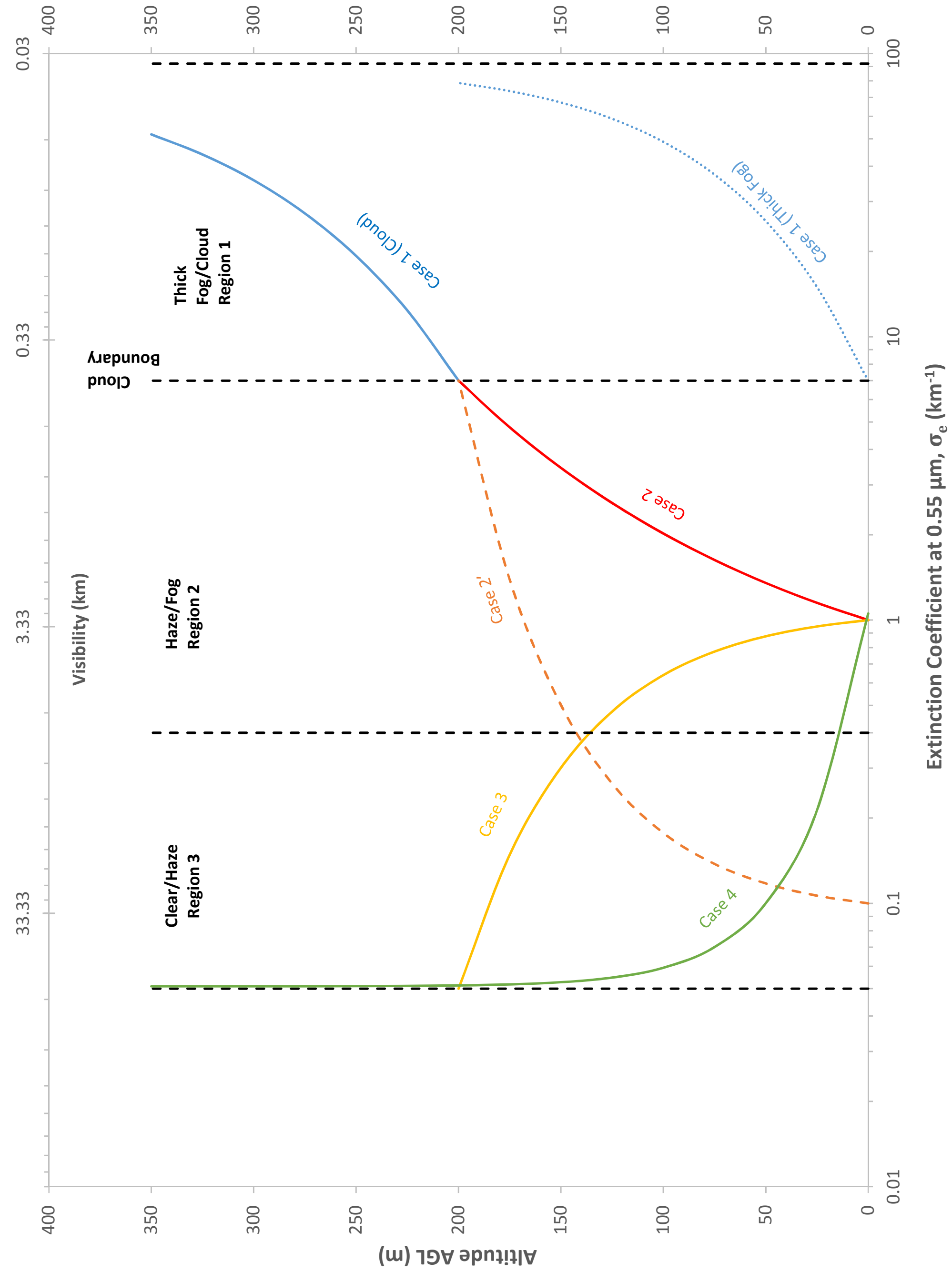

Fig. 1 Graphical representation of the vertical structure algorithm showing various cases (examples) in each of the regions of applicability. The boundary values for each region are represented by the vertical dashed lines.

The lower bound in this second visibility region represents both a transition from a dry haze to a wet haze as well as limitations in the instrumentation used to gather the data. Many of the aerosols which cause haze begin to grow in size once the relative humidity reaches approximately 80 percent. (This is greatly influenced by aerosol composition, size distribution, and number density.) At lower humidities most aerosol particles and droplets are in the sub-micrometer range. Unfortunately, the particle measuring devices used to gather the data are increasingly inefficient in this same sub-micrometer range; visibilities calculated from such devices tend to overestimate the visibility (that is, give values too large) as the visibility improves.[5] Thus the value of the extinction coefficient (0.4 km^{-1}) used as the lower bound in the haze/fog visibility region may be subject to some uncertainties, but will be taken to represent the transition from a dry haze to a wet haze, at least until more definitive data become available.

A third visibility region is now defined which represents the clear to hazy atmosphere. The upper bound to the extinction coefficient is identical to the lower bound of the hazy/foggy region. The lower bound can be chosen to fit the observed clear visibility conditions; for the purposes of the algorithm a default value of 0.5 km^{-1} is suggested unless otherwise input. The coefficient A in equation 1 is chosen on the basis of the observed surface visibility (see appendix A) and the visibility region into which it falls. The method for this selection is explained below.

If the extinction coefficient associated with the observed surface visibility is called D then the coefficient B can be found by

$$B = \ln(D/A) \quad . \tag{2}$$

The coefficient B is sometimes a function of the cloud ceiling height, the inversion layer height, or the radiation fog depth, and a boundary value of the visibility region into which the observed surface visibility falls. In such cases the coefficient C can be found by

$$C = \frac{1}{Z_\mathrm{c}} \ln \left[\frac{\ln(E/A)}{\ln(D/A)} \right] \tag{3}$$

where Z_c is the cloud ceiling height, inversion layer height, or radiation fog depth. E is a boundary value extinction coefficient selected on the basis of the visibility region into which the surface visibility falls, and A and D are defined as above. The methodology for determining the use of C is given in the following sections.

Depending on the signs of the coefficients B and C, the vertical structure of visibility can be represented by four different types of curves as illustrated in figure1. Note that more than one example is given for some profile types. Cases 1 and 2 are represented by the profiles where the extinction coefficient increases (that is, visibility decreases) with increasing altitude; these profiles are representative of the vertical structure of visibility for thick fogs or for low visibility/low stratus conditions and have been discussed in greater detail in an earlier report.[4] Cases 3 and 4 are represented by the profiles where the extinction coefficient decreases (that is, visibility improves) with increasing altitude.

2.1 Case 1: $(B < 0, C < 0)$

Coefficient A is the upper limit for the extinction coefficient in the thick fog/cloud region. This curve is to be used for dense fogs at ground level and when one is at the cloud base or in the cloud. Physically this curve represents the increase in liquid water content, and consequently the increase in extinction coefficient and decrease in visibility, of a saturated parcel of air rising (or descending) at the wet adiabatic lapse rate. This curve should be used only when the initial extinction coefficient (that is, visibility) is in the thick fog/cloud region shown between the two dashed lines representing boundary values on the right hand side of figure 1.

2.2 Case 2: $(B > 0, C > O)$

Coefficient A is the lower limit for the extinction coefficient in the haze/fog region. This curve is to be used when the observed surface visibility matches the low visibility conditions in the haze/fog region and there is a low cloud ceiling (< 1 km) present.

2.3 Case 3: $(B < 0, C > 0)$

Coefficient A is taken as 1.1 times the extinction coefficient for the observed surface visibility in whichever region it falls. This curve is to be used when there is a shallow radiation fog present or when a haze layer is capped by a distinct (low-lying) temperature inversion. A cloud ceiling is usually not present.

2.4 Case 4: $(B > 0, C < O)$

Coefficient A is the lower limit for the extinction coefficient which is taken as a nominal background value within the planetary boundary layer. This profile is to be used for cases where there is reasonable vertical homogeneity for visibility in a clear to hazy atmosphere which may have a shallow haze layer near the surface. A cloud ceiling is usually not present.

Profiles of the 0.55 μm extinction coefficient are shown in figure1 for the different cases. Two examples of representative profiles are shown for case 1. The first example is for a thick fog at the surface, which is represented by an extinction coefficient profile that increases with height. When the depth of the fog is not known (which is usually the case because the sky is obscured), a default depth of 200 m is recommended. The second example is for a low-lying stratus cloud; in this instance the cloud ceiling height is taken to be 200 m. This profile should only be used from the cloud base to the cloud top. Again cloud thickness is usually not a measured quantity, and a default value of 200 m is recommended. The two examples shown here are actually the same type of profile, one starting at the surface for the thick fog and the other starting at the cloud base of a low-lying stratus cloud. Within visibility region 1, thick fog/cloud, only profiles of the case 1 type should be used unless a shallow radiation fog has been specifically identified.

A representative profile for the structure beneath a stratus cloud is shown for case 2. In this instance the visibility conditions at the surface are representative of region 2, haze/fog; the illustrated cloud ceiling height is 200 m. The slope and shape of the vertical structure profile beneath the cloud deck are a function of the initial value of the surface visibility and the cloud ceiling height. For haze/fog conditions when a cloud ceiling with height $<$ 1 km is present, a profile of the case 2 type should always be used.

Often a low-lying cloud cover is present when the surface visibility is clear to only slightly hazy, that is, surface conditions are representative of visibility region 3. In this instance a vertical structure profile similar to case 2 is appropriate. This profile is denoted as case $2'$ and is shown in figure1 as an alternate profile for the instance of a 200 m cloud ceiling height. The only difference between the cases 2 and $2'$ is the manner in which the coefficient A is selected, based upon the surface visibility.

A shallow radiation fog or a haze layer bounded by a temperature inversion can be represented by a vertical structure profile as shown in figure 1 for case 3. The inversion layer heights or fog depths for such occurrences are often difficult to estimate. Temperature inversion heights can be obtained from acoustic sounders or radiosonde observations; often visual sightings can be used to estimate depths of shallow fogs or haze layers. A nominal inversion layer height of 200 m has been selected for illustrative purposes in figure 1 for a haze layer underneath a temperature inversion.

Case 4 shows a representative profile for the condition where the vertical structure is essentially constant with altitude, with the exception of the lowest few hundred meters of the boundary layer. A default value of 0.05 km^{-1} has been chosen as the nominal background value for the 0.55 μm extinction coefficient for the fair weather case. Numerous observations[6,7] have shown that the extinction coefficient is essentially constant within the planetary layer for well mixed conditions. Setting the coefficient C equal to zero in equation 1 will cause the algorithm to default to the observed surface value while providing a constant vertical profile.

Table 1 gives the tabular values of the 0.55 μm extinction coefficients, which are to be used as boundary values for the different cases in their respective regions of applicability. It also includes the values for the parameters $A, B, C, D,$ and E used in the calculation of σ_e. The relationship between visibility and the 0.55 μm extinction coefficient is defined briefly in appendix A.

3. Use of the Algorithm

The Vertical Structure Algorithm (VSA) operates with only two basic inputs: the surface visibility (kilometers) and a statement of sky conditions. The algorithm converts the visibility into an extinction coefficient and then determines into which visibility region the input surface visibility falls; this is done for later selection of the type of vertical structure profile (cases l through 4) to be used.

The statement of sky conditions can contain three pieces of information: the cloud ceiling height (or absence of a cloud ceiling), the actual cloud thickness or fog depth, and the inversion height (or absence of an inversion). The use of these pieces of information will allow one to choose the appropriate type of vertical profile and select the boundary conditions; default options are also provided if this information is lacking.

Table 2 provides a definition of variables that are used to program the algorithm and outline the decision tree. Also shown are default options utilized to define the

Table 1 Input and boundary values for the vertical structure algorithm

$$\sigma_{\mathrm{e}}(0.55\mu\mathrm{m}) = A\exp[B\exp(Cz)]$$

	Case 1	Case2	Case $2'$	Case3	Case 4
	$B < 0$; $C < 0$; $D < A$	$B > 0$; $C > 0$; $D > A$	$B < 0$; $C > 0$; $D < 0.04$	$B < 0$; $C > 0$; $D < A$	$B > 0$; $C < 0$; $D > A$
Range of σ_{e} (km^{-1})	7.0–92.0	0.4–7.0	0.05–7.0	0.05–92.0	0.05–7.0
Region of Applicability	thick fog/ clouds (ceiling obscured)	haze/fog ceiling < 1000 m	clear/haze ceiling < 1000 m	no ceiling or ceiling < 1000 m, distinct low-lying inversion layer or radiation fog	no ceiling or ceiling < 1000 m, no inversion or boundary layer
Surface Visibility (km)	< 0.4	0.4–7.5	> 7.5	Any	> 0.4
A (km^{-1})	92.0	0.4	0.9 × D	1.1 × D	0.05 [a]
B	$\ln(D/A)$				
C (m^{-1})	-0.014	$\frac{1}{Z_{\mathrm{c}}}\ln\left[\frac{\ln(E/A)}{B}\right]$			-0.03
D (km^{-1})	initial value at surface or at cloud boundary	initial value at surface			
E (km^{-1})	(not used)	7.0	7.0	0.05	(not used)
Z_{c} (m)	(not used)[b]	ceiling height[c]	ceiling height[d]	inversion or boundary layer height[e]	(not used)

---

[a] A nominal background value for the lower troposphere.

[b] When fog or cloud depth is not known (usually the case), the algorithm should be used only up to 200 m above the surface or cloud boundary (a default value for stratus cloud thickness).

[c] If the ceiling height is not explicitily specified, a default value will be chosen based upon the surface visibility.

[d] If the ceiling height is not explicitly specified, a default value of 500 m is chosen.

[e] If the inversion layer height is not explicitly specified, a default value of 500 m is chosen; if the radiation fog depth is not explicitly specified, a default value of 50 m is chosen.

vertical structure profiles used. Following is a description of the material in table 2.

First, the observed surface visibility, `VIS`, is entered and converted into an extinction coefficient, `D`. The visibility region into which the surface visibility falls, `IVR`, is determined.

Next a statement about the cloud ceiling height, `CHT`, is entered. If the cloud ceiling height is known it should be entered as a positive number (units of meters). A negative number indicates there is no cloud ceiling present (that is, the sky is clear, or at least there are no clouds within the lowest kilometer). If no value is entered, the algorithm will select a default value of 500 m if the initial surface visibility is in visibility region 3 (clear/haze); if the initial surface visibility is in region 2 (haze/-fog), then the VSA program will internally calculate a default cloud ceiling height. If the initial surface visibility is in region 1, surface conditions are thick fog and a cloud ceiling is not used.

For surface visibilities in visibility range 1 (thick fog/cloud), a fog depth, `DEPTH`, should be entered as the next statement of sky conditions. When a cloud ceiling has been specified this same entry can serve as the cloud thickness. (Note that both conditions do not simultaneously occur; if a surface visibility falls into region 1 then a cloud ceiling height is not explicitly used.) If the fog depth or cloud thickness is known it is entered as a positive number (units of meters). No entry means that a default value of 200 m will be selected. A negative entry for the fog depth means that a radiation fog is present; if its depth is known this value can be entered explicitly as the negative entry.

The final entry is the inversion layer height or radiation fog depth, `ZINVHT`. If this is known it should be entered explicitly as a positive number (units of meters). No entry means that a 500-m default value will be chosen for the inversion layer height, or a 50-m default value will be chosen for the radiation fog depth. A negative entry means there is no inversion layer or radiation fog present and implies that skies are clear and the boundary layer is well mixed.

Once the visibility region has been identified for the input surface visibility, the statements of the sky condition identify the vertical structure profiles to be used and subsequently define the values of the coefficients needed for their generation. Appendix B contains an annotated listing for a computer program that accomplishes

Table 2 Definition of variables and selection of vertical structure profiles for the vertical structure algorithm

`VIS`= observed surface visibility (km)
`D`= 3.0/`VIS`, extinction coefficient (km^{-1})
`IVR`= identifier for visibility region

`D`> 7	`IVR=1`	thick fog/cloud
$7 \geq$`D`> 0.4	`IVR=2`	haze/fog
$0.4 \geq$`D`> 0.05	`IVR=3`	clear/haze (0.05 is a default value and can be changed)

`CHT`= cloud ceiling height (m)
`DEPTH`= the cloud thickness or fog depth (m)
= positive value (the actual observed or estimated cloud ceiling height)
= 0.0 (cloud ceiling height not known, or thick surface fog is present and sky obscured; default value is 500 m if `IVR=3` and is calculated internally if `IVR=2`)
= negative value (no cloud ceiling present, i.e., clear skies
`DEPTH`= the cloud thickness or fog depth (m)
= positive value (actual or estimated value given for cloud thickness or fog depth)
= 0.0 (value not known, usually the case, a default value of 200 m will be used later)
= negative value (this means a radiation fog is present and implies there is no cloud ceiling; the actual depth need not be given here if it is not known)
`ZINVHT`= the height of the inversion layer or the depth of the raditation fog
= positive value (the actual or estimated value is explicitly input)
= 0.0 (the values are unknown; default values are 500 m for an inversion layer and 50 m for a radiation fog)
= negative value (there is no radiation fog or inversion present, i.e., skies are clear and the boundary layer is well mixed)

`ICASE`= identifier for the type of vertical profile to be used
If `(IVR = 1)` and `(DEPTH` ≥ 0.0 `)` `ICASE = 1`
If `(IVR = 1)` and `(DEPTH` < 0.0 `)` `ICASE = 3`
If `( (IVR = 2)` or `(IVR = 3) )`and `(CHT` ≥ 0.0 `)` `ICASE = 2`
If `( (IVR = 2)` or `(IVR = 3) )`and `(CHT` < 0.0 `)` `ICASE = 3`
If `(ICASE = 3)` and `(DEPTH` ≥ 0.0`)` and `(ZINVHT` ≤ 0.0 `)` `ICASE = 4`

the above tasks. The vertical profile of extinction, or visibility, is then calculated as a function of altitude.

4. Summary

An empirical algorithm has been developed for the vertical structure of visibility within the planetary boundary layer. The altitude range of validity is from the surface to approximately 1 km in altitude. The algorithm applies to conditions of thick fog/low stratus clouds, shallow radiation fogs, haze layers trapped under low-lying temperature inversions, and well-mixed conditions within the planetary boundary layer. For these latter cases there are clear skies or only clouds at higher levels present.

The algorithm is designed to operate with only two basic inputs: the observed surface visibility and a statement of sky conditions. The algorithm converts the input surface visibility to an extinction coefficient (units of km^{-1}); the output is the extinction coefficient as a function of altitude. The statement of sky conditions can contain the following pieces of information: cloud ceiling height (or lack of a cloud ceiling), fog depth or cloud thickness, and inversion layer height or radiation fog thickness. Default values and default options are provided if any or all of these latter items are unknown.

The algorithm is able to retain its simplified form by preselecting values for its coefficients based upon the input surface visibility. This is done by selecting three contiguous visibility regions and defining four values of the extinction coefficient to bound these regions. The three visibility regions are for thick fog/cloud, haze/fog, and clear/haze. The four boundary values represent the upper and lower bounds for, as well as divisions between, these regions. Physically the four boundary values given as extinction coefficients represent the (average) upper limit to extinction in a thick fog or low-lying stratus cloud, the transition from a subsaturated to a supersaturated environment or the extinction at the cloud base, the transition from a dry haze to a wet haze or the beginning droplet growth, and finally a representative extinction for the clear atmosphere.

Based upon the above inputs and determinations, the algorithm selects one of four basic profiles to represent the vertical structure of visibility (output as the extinction coefficient as a function of altitude). Two profiles can be appended one to the other to give a more complete representation of the vertical structure. The four profiles or cases are given as follows: Case 1 is for thick fog or clouds where the visibility decreases with increasing altitude. Case 2 is to be used beneath low-lying stratus clouds; the visibility decreases with altitudes up to the cloud base (Case 1 may be appended to Case 2 in order to represent the vertical structure in the cloud). Case 3 is for shallow radiation fogs and haze layers beneath inversions where the visibility improves with altitude; there is no cloud cover present in this case (at least at lower levels). Case 4 is for the well-mixed atmosphere which may have a shallow haze layer at the surface; the visibility is essentially constant with altitude (except possibly near the surface) and usually no low-level clouds are present.

The algorithm with its current data base should not be used to determine the vertical structure beneath or in cumulus clouds, should not be extended much beyond the altitude range of 1 km, or be used to judge the structure of altostratus or cirrus clouds.

The algorithm thus gives reasonable, physically based representations of the vertical structure of visibility in approximately the lowest kilometer of the atmosphere. Its simplified inputs allow the use of field inputs from meteorological observers or airfield observations. Extinction along vertical or slant path line of sight can be calculated for assessments of system performance or generation of system performance indicators.

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6. Johnson RW. Winter and summer measurements of European very low altitude volume scattering coefficients. Hanscom Air Force Base, MA: Air Force Geophysics Laboratory; 1981. Report No.: AFGL-TR-91-0154.

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Appendix A. Visibility Definition

A brief statement on the use of the term "visibility" is in order. Three terms are commonly used: visibility, visual range, and meteorological range. The latter two have precise definitions[1], although all three are often used interchangeably. The visual range, R_{v}, may be defined as

$$R_{\mathrm{v}} = \frac{1}{\sigma_{\mathrm{e}}} \ln \frac{C}{\varepsilon} \tag{A-1}$$

where σ_{e} is the extinction coefficient in the visual wavelength band, C is the inherent contrast of the target against the background, and ε is the threshold contrast of the observer. The meteorological range R_{m} is defined as above for the case where a black target is against the background, so that $C = 1$, and where the visual contrast threshold is taken as $\varepsilon = 0.02$, a near optimum value for daylight conditions. Thus

$$R_{\mathrm{m}} = \frac{1}{\sigma_{\mathrm{e}}} \ln \frac{1}{0.02} = \frac{3.912}{\sigma_{\mathrm{e}}} \tag{A-2}$$

The meteorological range is often taken as the "visibility", but it should be clear that this is an optimum visibility. In practice the visual range is a more useful quantity because it allows for a target/background contrast of less than unity and/or a threshold contrast of more than 2 percent. Many visibility meters are calibrated on the basis of an assumed "observer" threshold contrast of 5 percent (or a combination of target contrast and perceptual threshold contrast so that $C/\varepsilon = 1/0.05$). The visual range in this instance would be

$$R_{\mathrm{v}} = \frac{1}{\sigma_{\mathrm{e}}} \ln \frac{1}{0.05} = \frac{3.00}{\sigma_{\mathrm{e}}} \tag{A-3}$$

The visual range defined in this manner is a slightly more conservative estimate than the meteorological range ($R_{\mathrm{v}} = 0.766 R_{\mathrm{m}}$), but it correlates better with the visibility reported in meteorological observations[2] The term "visibility" in the text is used in this sense of visual range. Conversions from 0.55μm extinction coefficient to visibility were made using equation A-3.

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[1] McCartney EJ. Optics of the atmosphere: Scattering by molecules and particles. New York: John Wiley and Sons, Inc.Wiley; 1976.

[2] Gordon JI. Daytime visibility: A conceptual study. Hanscom Air Force Base, MA: Air Force Geophysis Laboratory; 1979. Report No.: AFGL-TR-79-0257.

Appendix B. Vertical Structure Algorithm Source Code Listing

```
C     FILE NAME: VSA.FOR
        PROGRAM VSA
C
C       VIS     VISIBILITY (KILOMETERS);DEFAULT 10 KILOMETERS
C
C       D       CALCULATED EXTINCTION VIA D=3.0/VIS     INVERSE KILOMETERS
C
C       CHT     THE CLOUD CEILING HEIGHT (METERS)
C               + VALUE - EXPLICIT CLOUD CEILING HEIGHT
C               0 VALUE - CLOUD CEILING PRESENT BUT HEIGHT UNKNOWN OR OBSCURED
C               - VALUE - NO CLOUD CEILING PRESENT AT LEAST IN LOWER LEVELS
C                         I.E. CLEAR SKIES
C
C       DEPTH   THE CLOUD THICKNESS OR FOG DEPTH (METERS)
C               + VALUE - EXPLICIT VALUE GIVEN
C               0 VALUE - VALUE UNKNOWN; DEFAULT 2000 METERS
C               - VALUE - THIS KEYS A RADIATION FOG
C
C       ZINVHT  THE HEIGHT OF THE INVERSION OR BOUNDAARY LAYER (METERS)
C               + VALUE - EXPLICIT VALUE GIVEN
C               0 VALUE - VALUE UNKNOWN; DEFAULT 500 METERS FOR INVERSION
C                                                 50 METERS FOR RADITAION FOG
C               - VALUE - THERE IS NO INVERSION LAYER OR RADIATONI FOG PRESENT
C
C       DELZ    THE HEIGHT INTERVAL FOR CALCULATIONS (METERS);
C               DEFAULT 5 METERS
C
        NDATA=0
    1   READ(5,500,END=190)VIS,CHT,DEPTH,ZINVHT,DELZ
500     FORMAT(5E10.4)
        NDATA=NDATA+1
        WRITE(6,598)NDATA
598     FORMAT(/10X,16HDATA SET NUMBER ,I5)
        IDELZ=IFIX(DELZ)
        IF(IDLEZ.LE.0)IDELZ=5
        IF(VIS.LE.0.0)VIS=10.0
        D=3.0/VIS
C
        IVR=1
        IF(D.LT.7.0)IVR=2
        IF(D.GT.92.0)WRITE(6,600)
600     FORMAT(/5X,41HTHE INPUT VISIBILITY WAS LESS THAN THE BOUNDARY ,
     1          5HVALUE,/5X,41HIT HAS BEEN CHANGED TO THE BOUNDARY VALUE/)
        IF(D.GT.92.0)D=92.0
        IF(D.LT.0.4)IVR=3
        IF(D.LT.0.014)WRITE(6,601)
601     FORMAT(/5X,41HTHE INPUT VISIBILITY WAS GREATER THAN THE RAYLEIGH ,
     1          5HVALUE,/5X,41HIT HAS BEEN CHANGED TO THE CLEAR ATMOSPHERE BACK,
     2          12HGROUND VALUE,/)
        IF(D.LT.0.014)D=0.05
C
        IF(IVR.EQ.1.AND.DEPTH.GE.0.0)ICASE=1
        IF(IVR.EQ.1.AND.DEPTH.LT.0.0)ICASE=3
        IF((IVR.EQ.2.OR.IVR.EQ3).AND.CHT.GE.0.0)ICASE=2
```

```
        IF((IVR.EQ.2.OR.IVR.EQ3).AND.CHT.LT.0.0)ICASE=3
        IF(ICASE.EQ.3.AND.DEPTH.GE.0.0.AND.ZINVHT.LT.0.0)ICASE=4
C
        IF(ICASE.GT.1)GO TO 2
        A=92.0
        B=ALOG(D/A)
        C=-0.014
        Z=DEPTH
        IF(Z.LE.0.0)Z=200
        GO TO 5
C
    2   IF(ICASE.GT.2)GO TO 3
        A=0.4
        IF(D.LE.0.0)A=0.9*D
        B=ALOG(D/A)
        E=7.0
        Z=CHT
        IF(CHT.EQ.0.0.AND.D.GT.0.4)GO TO 21
        IF(CHT.EQ.0.0.AND.D.LE.0.4)Z=500.0
        C=1.0/Z*ALOG(ALOG(E/A)/B)
        GO TO 5
C
C       METHOD FOR COMPUTING Z AND C
   21   C=0.0125
        Z=1.0/C*ALOG(ALOG(E/A)/B)
        GO TO 5
C
    3   IF(ICASE.GT.3)GO TO 4
        A=1.1*D
        B=ALOG(D/A)
        E=0.05
        IF(D.LT.0.05)E=0.014
        Z=ZINVHT
        IF(ZINHT.EQ.0.0)Z=500.0
        IF(DEPTH.LT.0.0)Z=-1.0*DEPTH
        IF(DEPTH.LT.0.0.AND.ZINVHT.EQ.0.0)Z=50.0
        C=1.0/Z*ALOG((ALOG(E/A)/B)
        GO TO 5
C
    4   A=0.05
        B=ALOG(D/A)
        C=-0.015
        Z=1000.0
C
    5   ZZ=0.0
        DELZ=REAL(IDELZ)
        IZ=IFIX(Z)/IDELZ+2
        WRITE(6,597)VIS,CHT,DEPTH,ZINVHT,DELZ,D,IVR,ICASE
597     FORMAT7X,52HVIS           CHT         DEPTH       ZINVHT
     1     9X,20HD         IVR   ICASE,/,6F12.3,2I7)
        WRITE(6,599)
599     FORMAT(/15X,27HHEIGHT (M)     SIGMA (KM-1)/15X,10(H1-),
     1      5X,12(1H-)/)
C
```

```
      DO 51 I=1,IZ
        IF(ZZ.GE.Z.AND.ICASE.EQ.2)GO TO 51
        IF(ZZ.GE.Z)ZZ=Z
        SIGMA=A*EXP(B*EXP(C*ZZ))
        HEIGHT=ZZ
        WRITE(6,603)HEIGHT,SIGMA
        IF(ZZ.GE.Z)GO TO 52
        ZZ=ZZ+DELZ
   51 CONTINUE
  603 FORMAT(10X,2F15.4)
C
   52 IF(ICASE.NE.2)GO TO 1
      A=92.0
      B=ALOG(7.0/A)
      C=-0.014
      Z2=DEPTH
      IF(Z2.EQ.0.0)Z2=200.0
      IZ=IFIX(Z2)/IDELZ+1
      ZZ=Z
      ZC=0.0
C
      DO 53 IJ=1,IZ
        SIGMA=A*EXP(B*EXP(C*ZC))
        HEIGHT=ZZ+ZC
        WRITE(6,603)HEIGHT,SIGMA
        ZC=ZC+DELZ
   53 CONTINUE
      GO TO 1
C
  190 WRITE(6,200)
  200 FORMAT(1H1)
      STOP
      END
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