
MODTRAN4 USER'S MANUAL

**A. Berk^{*}, G.P. Anderson[#], P.K. Acharya^{*}, J.H. Chetwynd[#], L.S. Bernstein^{*},
E.P. Shettle[^], M.W. Matthew^{*}, and S.M. Adler-Golden^{*}**

*** Spectral Sciences, Inc.
99 South Bedford Street, #7
Burlington, MA 01803-5169
(lex@spectral.com)**

**# Air Force Research Laboratory
Space Vehicles Directorate
Air Force Materiel Command
Hanscom AFB, MA 01731-3010
(ganderson@plh.af.mil)**

**^ Naval Research Laboratory
Remote Sensing Division
Washington, DC, 20375-5351**

1 June 1999



**AIR FORCE RESEARCH LABORATORY
Space Vehicles Directorate
AIR FORCE MATERIEL COMMAND
HANSCOM AFB, MA 01731-3010**

TABLE OF CONTENTS

<u>Section</u>	<u>Page</u>
1. INTRODUCTION	1
1.1 Summary of Features and Options	1
1.1.1 Versions through MODTRAN3.5	1
1.1.2 MODTRAN3.7.....	3
1.1.3 MODTRAN4.....	4
1.2 Radiation Transport Upgrades.....	5
2. OVERVIEW OF INPUT DATA FORMAT	6
2.1 Listing of CARDS and Their Format.....	7
3. CARD 1 (REQUIRED) – MAIN RADIATION TRANSPORT DRIVER.....	11
4. CARD 1A (REQUIRED) – RADIATIVE TRANSPORT DRIVER CONT'D	17
5. OPTIONAL CARDS 1A1, 1A2, 1A3 (SPECTRAL DATA AND SENSOR RESPONSE FUNCTION FILES)	20
6. CARD 2 (REQUIRED) – MAIN AEROSOL AND CLOUD OPTIONS	23
7. OPTIONAL CARD 2A+ (FLEXIBLE AEROSOL MODEL).....	30
8. OPTIONAL CARD 2A (CLOUD MODELS)	32
8.1 CARD 2A Standard Form (CIRRUS CLOUD MODELS, ICLD = 18 or 19).....	32
8.2 CARD 2A Alternate Form (WATER/ICE CLOUD MODELS, ICLD = 1 - 10)	32
9. OPTIONAL CARD 2B (ARMY VERTICAL STRUCTURE ALGORITHM).....	37
10. OPTIONAL CARDS 2C, 2C1, 2C2, 2C2X, 2C3 (USER-DEFINED ATMOSPHERIC PROFILES).....	38
10.1 CARD 2C	38
10.2 CARDS 2C1, 2C2, 2C2X.....	39
10.3 CARD 2C3.....	41
11. OPTIONAL CARDS 2D, 2D1, 2D2 (USER-DEFINED AEROSOL AND CLOUD PARAMETERS)	43
11.1 CARD 2D	43
11.2 CARD 2D1	44
11.3 CARD 2D2	44
12. OPTIONAL CARDS 2E1 AND 2E2 (USER-DEFINED CLOUD PARAMETERS)	46
12.1 CARD 2E1.....	46
12.2 CARD 2E2.....	47

TABLE OF CONTENTS

<u>Section</u>	<u>Page</u>
13. CARD 3 (REQUIRED) – LINE-OF-SIGHT GEOMETRY	50
13.1 Standard CARD 3	50
13.2 Alternate CARD 3 (TRANSMITTED SOLAR/LUNAR IRRADIANCE, IEMSCT=3).53	
14. OPTIONAL CARDS 3A1 AND 3A2 (SOLAR/LUNAR SCATTERING GEOMETRY)....	54
14.1 CARD 3A1	54
14.2 CARD 3A2	54
15. OPTIONAL CARDS 3B1, 3B2, 3C1-3C6 (USER-DEFINED SCATTERING PHASE FUNCTIONS)	57
15.1 CARD 3B1.....	57
15.2 CARD 3B2.....	57
15.3 CARDS 3C1-3C6	57
16. CARD 4 (REQUIRED) – SPECTRAL RANGE AND RESOLUTION	58
17. OPTIONAL CARDS 4A, 4B1, 4B2, 4B3, 4L1 AND 4L2 (GROUND SURFACE CHARACTERIZATION)	61
17.1 CARD 4A	61
17.2 CARD 4B1.....	62
17.3 CARD 4B2.....	67
17.4 CARD 4B3.....	67
17.5 CARD 4L1.....	68
17.6 CARD 4L2.....	68
18. CARD 5 (REQUIRED) – REPEAT RUN OPTION	69
19. DEDICATION AND ACKNOWLEDGEMENTS.....	71
20. REFERENCES	72
APPENDIX A: MODTRAN3.7 / MODTRAN4 USER-SUPPLIED AEROSOL UPGRADES.	75
APPENDIX B: NOVAM IN MODTRAN.....	81
APPENDIX C: MODTRAN INSTALLATION AND I/O FILES.....	91

LIST OF TABLES

Table 1.	MODTRAN CARD 1: Columns List Allowed Values of Input Parameters: MODTRN, <i>SPEED</i> , MODEL ITYPE, IEMSCT, IMULT, MDEF, NOPRNT and <i>SURREF</i>	16
Table 2.	Shows the Value of IVULCN Corresponding to the Different Choices of Extinction Coefficient Model and the Vertical Distribution Profile	25
Table 3.	Default Wind Speeds for Different Model Atmospheres Used with the Navy Maritime Model (IHAZE = 3)	28
Table 4.	MODTRAN CARD 1 Input Parameters: IHAZE, ISEASN, IVULCN, VIS.....	29
Table 5.	MODTRAN CARD 2 Input Parameter: ICLD.....	29
Table 6.	Default Aerosol Region Boundaries.....	31
Table 7.	Properties of the MODTRAN Cumulus and Stratus Type Model Clouds	33
Table 8.	The Association of the JCHAR(J) Index (J = 1, 14) with the Variables P, T and WMOL	40
Table 9.	Various Names for the Heavy Molecular Gases, (WMOLX(J), J = 1, 13)	40
Table 10.	VARSPC Array of Fixed (Required) Wavelengths for the Multiply Read CARD 2D2.....	45
Table 11.	Default Values of the Earth Radius for Different Model Atmospheres.....	51
Table 12.	Allowed Combinations of Slant Path Parameters.....	52
Table 13.	CARD 3A2: Options for Different Choices of IPARM.....	56
Table 14.	MODTRAN CARD 5 Input Parameter: IRPT	70

1. INTRODUCTION

This documentation provides complete user instructions for MODTRAN4 and brief descriptions of recently added features. These instructions describe each input in the MODTRAN input file, tape5 [*rootname.tp5*].

The original MODTRAN 2 code and many of the MODTRAN3 upgrades are covered in the 1996 report "MODTRAN 2/3 Report and LOWTRAN 7 Model" (Abreu and Anderson, 1996). The current documentation incorporates material from that report, from Section 3 of the 1988 Users Guide to LOWTRAN 7 (Kneizys *et al.*, 1988), from the 1989 Air Force Research Laboratory (AFRL) report on the MODTRAN band model (Berk *et al.*, 1989), and from the 1996 Spectral Sciences, Inc. report on the cloud and rain model upgrades (Berk and Anderson, 1995). Descriptions of the MODTRAN3.7 and MODTRAN4 upgrades are also included here.

Articles (Bernstein *et al.*, 1995; Berk *et al.*, 1998) discuss recent improvements to the band model. For questions and / or comments about MODTRAN, please send email to Gail P. Anderson (ganderson@plh.af.mil; ganderson@cmdl.noaa.gov), Jim H. Chetwynd (chetwynd@plh.af.mil) and / or Alexander Berk (lex@spectral.com).

1.1 Summary of Features and Options

1.1.1 Versions through MODTRAN3.5

Many new features were introduced between MODTRAN 2 (1992) (Acharya *et al.*, 1993) and MODTRAN3.5 (1996). These include:

- A second multiple scattering option based on the multiple stream discrete ordinate DISORT algorithm (Stamnes *et al.*, 1988);
- A new CO₂ mixing ratio input option for scaling the profile;
- "Heavy" molecule (e.g., CFCs) cross-section spectra and profiles;
- A set of surface reflectivity (albedo) options;
- Upgrades to the cloud and rain models;
- New solar TOA (top of the atmosphere) irradiance databases;
- Wavelength / frequency inputs in cm⁻¹, μm and nm;
- Convolution with an instrument slit function in any of the above units; and
- New plot output files 'pltout', 'pltout.scn', and 'tape7.scn'.

Introduction

For runs not involving clouds, backward compatibility of the 'tape5' input file has been maintained through MODTRAN3.5. In MODTRAN3.5 the cloud/rain models were made easier to modify and more flexible. Clouds may be placed anywhere within the defined atmosphere, can coexist with aerosols, and can have a mixed phase composition.

The addition of new parameters necessitated the addition of new input cards and minor modifications to other cards. A **CARD** in this context refers to a 'card image' based on fixed-format input lines of up to 80 characters.

Two changes were made to **CARD 1** for MODTRAN3.5. First, the SALB parameter (replaced by character string SURREF in MODTRAN4) was generalized to permit input of spectral surface reflectivity from a selection of default curves. Negative integer values specify any of an assortment of rudimentary surface types including snow, forest, farm, desert, ocean, cloud deck and four sample grass models. Second, the MDEF value on **CARD 1** was previously either 0 or 1. The value 1 was used with MODEL = 0 or 7 to select a single set of pre-stored molecular profiles for O₂, NO, SO₂, NO₂, NH₃ and HNO₃. Now, when MDEF = 2 and MODEL = 0 or 7, user-specified profiles for the thirteen 'heavy' molecules consisting of nine chlorofluorocarbons (CFCs) plus ClONO₂, HNO₄, CCl₄, and N₂O₅ are input. When MDEF = 1, defaults based on 1990 photochemical predictions (M. Allen, 1990) are provided for the heavy molecules. Under MODEL = 0 or 7, CFCs are zeroed out if MDEF is zero.

CARD 1A was introduced to govern the DISORT multiple scattering option, the TOA solar irradiances scanning function, and the CO₂ mixing ratio update. The CO₂ option is offered because, for historic calibration studies, the mixing ratio of 330 ppmv has been preserved in the code even though the current value is closer to 365 ppmv (Dutton, 1999). Additional inputs were appended to **CARD 1A** for MODTRAN3.7 and MODTRAN4 (Section 4).

New cards govern the cloud parameters. The older form of **CARD 2A** still applies to cirrus clouds, but the format has been condensed. The new, alternate form, which is mandatory with ICLD = 1 through 10, supplies water/ice vertical column densities, humidity, and Henyey-Greenstein scattering phase function asymmetry factors. It also triggers the reading of the **CARDs 2E1** and **2E2**; **CARD 2E1** defines cloud and rain profiles, and **CARD 2E2** defines spectral properties.

Introduction

A new **CARD 4** format allows spectral range inputs to be specified as floating point numbers in cm^{-1} , nm or μm . **CARD 4** is also used to select from a set of instrument slit functions. The code internally converts wavelength inputs [nm or μm] to the nearest integer wavenumbers.

Changes have also been made to the output files. Incremental (path within a single layer) column densities for each extinction source are now written to 'tape6', and the multiple scattering contribution to the thermal radiance is printed. There are three additional output files. The file 'pltout' is a two-column file containing frequency or wavelength in column one, and transmittance, radiance, or irradiance in column two. Using the slit function, as defined by **CARD 4**, results in the creation of the files 'tape7.scn' and 'pltout.scn'. These are simply the convolved outputs for the specified instrument slit function and are analogous to the 'tape7' and 'pltout' output files.

1.1.2 MODTRAN3.7

MODTRAN3.7 includes a number of upgrades to the aerosol models. The built-in aerosol models are no longer confined to fixed regions, but can be independently moved to any region and can be stretched, compressed, overlapped and scaled. The user-supplied spectral parameter input schemes for aerosols have also been improved. These options are invoked using a new input card, **CARD 2A+**. In addition, extensive modifications now allow MODTRAN to incorporate NOVAM, the Navy Oceanic Vertical Aerosol Model (Gathman and Davidson, 1993). Here, NOVAM is used as a stand-alone code, which is first executed to produce an output file consisting of spectral- and altitude-dependent aerosol extinction, absorption, and asymmetry parameters. MODTRAN, if the NOVAM option is enabled on **CARD 2**, can then read this output file and incorporate the aerosols in subsequent calculations. The stand-alone NOVAM package, courtesy of SPAWAR (S. G. Gathman, Naval Command, Control and Ocean Surveillance Center, RDT&E Division), is delivered with MODTRAN3.7 and MODTRAN4. The user's manual for NOVAM (Gathman and Davidson, 1993) should be obtained directly from SPAWAR.

1.1.3 MODTRAN4

MODTRAN4 adds the following features:

- Two Correlated- k (CK) options: the standard option which uses 17 k values (absorption coefficients) per spectral bin and a slower, 33 k value option primarily for upper-altitude (>40 km) cooling rate and weighting function calculations (**CARD 1**);
- An option to include azimuth dependencies in the calculation of DISORT solar scattering contributions (**CARD 1A**);
- Upgraded ground surface modeling including parameterized forms for spectral BRDFs (Bidirectional Reflectance Distribution Functions) and an option to define a ground image pixel (H2) different from its surrounding surface.
- A high-speed option, most appropriate in short-wave and UV spectral regions, that uses 15 cm^{-1} band model parameters (**CARD 1A**);
- Scaling options for water vapor and ozone column amounts (**CARD 1A**);
- Improved, higher spectral resolution, cloud parameter database (not aerosols); and
- More accurate Rayleigh scattering and indices of refraction.

Both Correlated- k options permit more accurate calculation of molecular absorption in the presence of multiple scattering (MS). Without the azimuth dependent DISORT option, the multiple (not single) scatter solar contributions included in MODTRAN line-of-sight calculations are averaged over azimuth. The BRDFs are fully interfaced into the atmospheric radiative transport (distribution of DISORT coupled to the BRDF surface for the MS contributions is being delayed until the DISORT BRDF option is publicly released). The dual surface option enables modeling of adjacency effects. (Adjacency is defined here as the scattered radiance arising from the contrast between the reflectance of the image pixel and its surrounding large-area average reflectance; in other context, adjacency refers to the scattered radiance arising from nearby localized bright pixels.) The updated Rayleigh scattering algorithm models the spectral dependence of the depolarization factor, and the refractivity (equal to one minus the real part of the index of refraction) now varies not only with water density but also with CO_2 partial pressure (Bodhaine *et al.*, 1999).

All MODTRAN3.5 input files are fully compatible with MODTRAN4.

Minimally, six input cards (1, 1A, 2, 3, 4, and 5) are required to run MODTRAN. For specific problems, combinations of several additional optional control cards are possible.

1.2 Radiation Transport Upgrades

In addition to adding the above features, many improvements have been made to MODTRAN's radiation transport algorithms. These include:

- Using the new HITRAN96 database (Rothman *et al.*, 1992; Rothman *et al.*, 1998) to generate the band model parameters;
- Reformulating the absorption coefficient and line spacing band model parameters, and the temperature dependence of the Lorentz half-widths (Bernstein *et al.*, 1995) (MODTRAN3.5);
- Lowering the minimum of the band model parameter temperature grid to 180 K for linear interpolation modeling of the Antarctic tropopause (MODTRAN3.5);
- Improving the band model line tail treatment by more carefully accounting for the line center locations (MODTRAN3.5) and increasing the line tail calculation resolution to 0.25 cm^{-1} (MODTRAN3.7);
- Applying the "linear-in-tau" method to thermal radiance multiple scattering terms (MODTRAN3.5).

2. OVERVIEW OF INPUT DATA FORMAT

An attempt has been made in MODTRAN4 to make it easier for the users to keep track of input and output (I/O) files. The need for easier file handling is evident to anyone who runs MODTRAN using different `tape5` input files and who wants to save the corresponding output files (the `tape6`, `pltout`, `tape7`, and so on). In the past, every MODTRAN input file had to have the name 'tape5' and previously generated I/O files had to be renamed to avoid overwriting them with newer files. The need for renaming is now avoided by creating a new MODTRAN input file (referred to as the root name file) called either '**modroot.in**' or '**MODROOT.IN**'. If 'modroot.in' does not exist, MODTRAN checks for the existence of a 'MODROOT.IN' file. If neither of these files exists, MODTRAN I/O files are the traditional ones: 'tape5', 'tape6', 'tape7', 'tape8', etc. If a root name file exists and its very first line contains a non-null string (maximum length is 80 characters), this string is treated as a prefix. If the string consists of all blanks or is a null string, the traditional I/O file names are assumed. The root name should contain no embedded blanks; leading and trailing blanks are properly ignored. This string is used as a prefix for the I/O files whose names have mnemonic suffixes. As an example, if the string is **case1**, the MODTRAN I/O files will have these names:

case1.tp5	(corresponding to tape5)
case1.tp6	(corresponding to tape6)
case1.tp7	(corresponding to tape7)
case1.tp8	(corresponding to tape8)
case1.7sc	(corresponding to tape7.scn)
case1.7sr	(corresponding to tape7.scr)
case1.plt	(corresponding to pltout)
case1.psc	(corresponding to pltout.scn)
case1.clr	(corresponding to clrates)
case1.chn	(corresponding to channels.out)
case1.flx	(corresponding to specflux)

MODTRAN is controlled by a single input file, 'tape5' or '*rootname*.tp5', which consists of a sequence of six or more **CARDS** (inputs lines). The input file format is summarized below. Except when specifying file names, character inputs are case insensitive. Also, blanks are read as zeroes for

Overview of Input Data Format

numerical inputs, and as default values otherwise. Detailed descriptions of the card formats and parameters are given in the following sections.

2.1 Listing of CARDS and Their Format

In the following, optional cards are indented. *Inputs that are new to MODTRAN4 are in Italics.*

CARD 1: MODTRN, *SPEED*, MODEL, ITYPE, IEMSCT, IMULT, M1, M2, M3, M4, M5, M6, MDEF, IM, NOPRNT, *TPTEMP*, *SURREF*
FORMAT (2A1, I3, 12I5, F8.3, A7)

CARD 1A: DIS, *DISAZM*, NSTR, LSUN, ISUN, CO2MX, H2OSTR, O3STR, LSUNFL, *LBMNAM*, *LFLTNM*, *H2OAER*, SOLCON
FORMAT (2L1, I3, L1, I4, F10.5, 2A10, 4(1X, A1), 2X, F10.3)

CARD 1A1: SUNFL2
FORMAT (A80) (If LSUNFL = True)

CARD 1A2: *BMNAME*
FORMAT (A80) (If *LBMNAM* = True)

CARD 1A3: *FILTNM*
FORMAT (A80) (If *LFLTNM* = True)

CARD 2: APLUS, IHAZE, CNOVAM, ISEASN, ARUSS, IVULCN, ICSTL, ICLD, IVSA, VIS, WSS, WHH, RAINRT, GNDALT
FORMAT (A2, I3, A1, I4, A3, I2, 3I5, 5F10.5)

CARD 2A+: ZAER11, ZAER12, SCALE1, ZAER21, ZAER22, SCALE2, ZAER31, ZAER32, SCALE3, ZAER41, ZAER42, SCALE4
FORMAT ((3(1X, F9.0), 20X, 3(1X, F9.0))) (If APLUS = 'A+')

CARD 2A: CTHIK, CALT, CEXT
FORMAT (3F8.3) (If ICLD = 18 or 19)

Alternate **CARD 2A:** CTHIK, CALT, CEXT, NCRALT, NCRSPC, CWAVLN, CCOLWD, CCOLIP, CHUMID, ASYMWD, ASYMIP
FORMAT (3F8.3, 2I4, 6F8.3) (If ICLD = 1-10)

CARD 2B: ZCVSA, ZTVSA, ZINVSA
FORMAT (3F10.3) (If IVSA = 1)

Overview of Input Data Format

CARD 2C: ML, IRD1, IRD2, HMODEL
FORMAT (3I5, A65) (If MODEL = 0 or 7, and IM = 1)

CARDS 2C1, 2C2, 2C2X, and 2C3 (as required) are each repeated ML times.

CARD 2C1: ZM, P, T, WMOL(1), WMOL(2), WMOL(3), (JCHAR(J), J = 1, 14),
JCHARX
FORMAT (F10.3, 5E10.3, 14A1, 1X, A1)

CARD 2C2: (WMOL(J), J = 4, 12)
FORMAT (8E10.3, /E10.3) (If IRD1 = 1)

CARD 2C2X: (WMOLX(J), J = 1, 13)
FORMAT (8E10.3, /5E10.3) (If MDEF = 2 & IRD1 = 1)

CARD 2C3: AHAZE, EQLWCZ, RRATZ, IHA1, ICLD1, IVUL1, ISEA1, ICHR
FORMAT (10X, 3F10.3, 5I5) (If IRD2 = 1)

CARD 2D: (IREG(N), N = 1, 2, 3, 4)
FORMAT (4I5) (If IHAZE = 7 or ICLD = 11)

CARD 2D1: AWCCON, TITLE
FORMAT (E10.3, A70)

CARD 2D2: (VARSPC(N, I), EXTC(N, I), ABSC(N, I), ASYM(N, I), I = 1, 2, ...,
 I_{\max})
If ARUSS = 'USS' and IREG(N) > 1, then $I_{\max} = \text{IREG}(N)$; Else $I_{\max} = 47$
FORMAT ((3(F6.2, 2F7.5, F6.4)))

CARD 2E1: (ZCLD(I, 0), CLD(I, 0), CLDICE(I, 0), RR(I, 0), I = 1, NCRALT)
FORMAT((4F10.5)) (If ICLD = 1 - 10, NCRALT ≤ 3)

CARD 2E2: (WAVLEN(I), EXTC(6, I), ABSC(6, I), ASYM(6, I), EXTC(7, I),
ABSC(7, I), ASYM(7, I), I = 1, NCRSPC)
FORMAT((7F10.5)) (If ICLD = 1 - 10, NCRSPC ≤ 2)

Overview of Input Data Format

CARD 3: H1, H2, ANGLE, RANGE, BETA, RO, LENN, PHI
FORMAT (6F10.3, I5, 5X, F10.3)

Alternate **CARD 3:** H1, H2, ANGLE, IDAY, RO, ISOURC, ANGLEM
FORMAT (3F10.3, I5, 5X, F10.3, I5, F10.3) (If IEMSCT = 3)

CARD 3A1: IPARM, IPH, IDAY, ISOURC
FORMAT (4I5) (If IEMSCT = 2)

CARD 3A2: PARM1, PARM2, PARM3, PARM4, TIME, PSIPO, ANGLEM, G
FORMAT (8F10.3) (If IEMSCT = 2)

CARD 3B1: NANGLS, NWLF
FORMAT (2I5) (If IPH = 1)

CARD 3B2: (ANGF(I), F(1, I, 1), F(2, I, 1), F(3, I, 1), F(4, I, 1), I = 1, NANGLS)
FORMAT (8(1X, F9.0)) (If IPH = 1 and NWLF = 0)

CARD 3C1: (ANGF(I), I = 1, NANGLS)
FORMAT (8(1X, F9.0)) (If IPH = 1 and NWLF > 0)

CARD 3C2: (WLF(J), J = 1, NWLF)
FORMAT (8(1X, F9.0)) (If IPH = 1 and NWLF > 0)

In **CARDs 3C3-3C6**, 'I' is angle index as in **CARD 3C1** and 'J' is the wavelength index as in **CARD 3C2**.

CARD 3C3: (F(1, I, J), J = 1, NWLF)
FORMAT (8(1X, E9.3)) (If IPH = 1 and NWLF > 0)

CARD 3C4: (F(2, I, J), J = 1, NWLF)
FORMAT (8(1X, E9.3)) (If IPH = 1 and NWLF > 0)

CARD 3C5: (F(3, I, J), J = 1, NWLF)
FORMAT (8(1X, E9.3)) (If IPH = 1 and NWLF > 0)

CARD 3C6: (F(4, I, J), J = 1, NWLF)
FORMAT (8(1X, E9.3)) (If IPH = 1 and NWLF > 0)

Overview of Input Data Format

CARD 4: V1, V2, DV, FWHM, YFLAG, XFLAG, DLIMIT, FLAGS
FORMAT (4F10.0, 2A1, A8, A7)

CARD 4A: NSURF, AATEMP
FORMAT (I1, F9.0) (If *SURREF* = 'BRDF' or 'LAMBER')

CARDS 4B1, 4B2, 4B3, 4L1, and 4L2 (as required) are each repeated *NSURF* times.

CARD 4B1: CBRDF
FORMAT (A80) (If *SURREF* = 'BRDF')

CARD 4B2: NWVSRF, SURFZN, SURFAZ
FORMAT (*) (If *SURREF* = 'BRDF')

CARD 4B3 is repeated *NWVSRF* times.

CARD 4B3: WVSRF, (PARAMS(I), I = 1, NPARAM)
FORMAT (*) (If *SURREF* = 'BRDF')

CARD 4L1: SALBFL
FORMAT (A80) (If *SURREF* = 'LAMBER')

CARD 4L2: CSALB
FORMAT (A80) (If *SURREF* = 'LAMBER')

CARD 5: IRPT
FORMAT (I5)

3. CARD 1 (REQUIRED) – MAIN RADIATION TRANSPORT DRIVER

The **CARD 1** format has been modified in MODTRAN4 by the replacement of the logical variable MODTRN with two new CHARACTER*1 variables, MODTRN and *SPEED*, which control the band model choice and the Correlated-*k* options. In addition, the inputs TBOUND and SALB from earlier versions of MODTRAN and LOWTRAN have been replaced by TPTEMP and SURREF to accommodate the updated MODTRAN surface treatment. The new format is fully backward compatible. *Italicized features are exclusive to MODTRAN4.*

CARD 1: MODTRN, *SPEED*, MODEL, ITYPE, IEMSCT, IMULT, M1, M2, M3, M4, M5, M6, MDEF, IM, NOPRNT, TPTEMP, SURREF
FORMAT (2A1, I3, 12I5, F8.3, A7)

MODTRN selects the band model algorithm used for the radiative transport, either the moderate spectral resolution MODTRAN band model or the low spectral resolution LOWTRAN band model. **LOWTRAN spectroscopy is obsolete** and is retained only for backward compatibility. The MODTRAN band model may be selected either with or without the Correlated-*k* treatment.

MODTRN = 'T', 'M' or blank	MODTRAN band model.
= 'C' or 'K'	<i>MODTRAN correlated-k option (IEMSCT radiance modes only; most accurate but slower run time).</i>
= 'F' or 'L'	20 cm ⁻¹ LOWTRAN band model (not recommended except for quick historic comparisons).
<i>SPEED</i> = 'S' or blank	<i>'slow' speed Correlated-k option using 33 absorption coefficients (k values) per spectral bin (1 cm⁻¹ or 15 cm⁻¹). This option is recommended for upper altitude (> 40 km) cooling-rate and weighting-function calculations only.</i>
= 'M'	<i>'medium' speed Correlated-k option (17 k values).</i>

CARD 1 (Required)

MODEL selects one of the six geographical-seasonal model atmospheres or specifies that user-defined meteorological or radiosonde data are to be used.

- MODEL = 0 If single-altitude meteorological data are specified (constant pressure, horizontal path only; see instructions for **CARDs 2C, 2C1, 2C2, 2C2X, and 2C3**).
- 1 Tropical Atmosphere (15° North Latitude).
 - 2 Mid-Latitude Summer (45° North Latitude).
 - 3 Mid-Latitude Winter (45° North Latitude).
 - 4 Sub-Arctic Summer (60° North Latitude).
 - 5 Sub-Arctic Winter (60° North Latitude).
 - 6 1976 US Standard Atmosphere.
 - 7 If a user-specified model atmosphere (e.g. radiosonde data) is to be read in; see instructions for **CARDs 2C, 2C1, 2C2, 2C2X, and 2C3**.

ITYPE indicates the type of atmospheric line-of-sight (LOS) path.

- ITYPE = 1 Horizontal (constant-pressure) path, i.e., single layer, no refraction calculation.
- 2 Vertical or slant path between two altitudes.
 - 3 Vertical or slant path to space or ground.

IEMSCT determines the mode of execution of the program.

- IEMSCT = 0 Program executes in spectral transmittance mode.
- 1 Program executes in spectral thermal radiance (no sun / moon) mode.
 - 2 Program executes in spectral thermal plus solar / lunar radiance mode (if IMULT = 0, only single scatter solar radiance is included).
 - 3 Program calculates directly transmitted spectral solar / lunar irradiance.

IMULT determines inclusion of multiple scattering (MS).

- IMULT = 0 Program executes without multiple scattering.
- ±1 Program executes with multiple scattering.

IEMSCT must equal 1 or 2 to execute with multiple scattering. MS contributions are calculated using plane parallel geometry (the solar illumination on each layer is determined with spherical refractive geometry, important for low sun angles, when the ISAACS MS model is selected, **CARD 1A**). If IMULT = 1, the solar geometry at the location of H1 (latitude and longitude) is used in the MS calculation; if IMULT = -1, the MS calculation is instead referenced to H2. The quantity H2 is the final path altitude unless ITYPE = 3 and H2 ≥ 0; in that case, the MS plane parallel atmosphere is defined *near* the tangent point of the limb path. (The path zenith of 90° *at* the tangent point is a

CARD 1 (Required)

forbidden input to the plane-parallel MS models because it leads to a mathematical singularity.) For simulation of sensors on satellite platforms, IMULT should generally be set to -1 since MS will only be significant nearer to H2 (the surface or tangent height).

M1, M2, M3, M4, M5, M6, and MDEF are used to modify or supplement user-specified altitude profiles for temperature, pressure, and molecular gases: H₂O, O₃, CH₄, N₂O, CO, O₂, NO, SO₂, NO₂, NH₃, HNO₃, and 13 "heavy molecules." For normal operation of the program using the standard model atmospheres (MODEL 1 to 6), one may set M1 = M2 = M3 = M4 = M5 = M6 = MDEF = 0. MODTRAN then resets M1 through M6 to the value MODEL and MDEF to 1.

If MODEL = 0 or 7 and M1 through M6 and MDEF are zero, then the JCHAR parameter on **CARD 2C1** must be utilized to supply the necessary profiles. If M1 through M6 and MDEF are non-zero, then the chosen default profiles will be utilized whenever the specific JCHAR input is blank:

M1	=	1 to 6	Default temperature and pressure to specified model atmosphere.
M2	=	1 to 6	Default H ₂ O to specified model atmosphere.
M3	=	1 to 6	Default O ₃ to specified model atmosphere.
M4	=	1 to 6	Default CH ₄ to specified model atmosphere.
M5	=	1 to 6	Default N ₂ O to specified model atmosphere.
M6	=	1 to 6	Default CO to specified model atmosphere.
MDEF	=	1	Default O ₂ , NO, SO ₂ , NO ₂ , NH ₃ , and HNO ₃ species profiles.

If MDEF = 1, default heavy species profiles are used. If MDEF = 2, the user must input the profiles for the heavy species, which include nine chlorofluorocarbons (CFCs) plus ClONO₂, HNO₄, CCl₄, and N₂O₅. The 1 cm⁻¹ absorption cross-sections are stored in "DATA/CFCBMP96.ASC"; "DATA/CFC96_15.ASC" is the 15 cm⁻¹ version of the file. The specification of user-defined profiles is modeled after the MODEL = 7 option in LOWTRAN, but only one unit definition (see JCHARX definition in **CARD 2C1**) can be used for the whole set of heavy species. The "default" profiles for these species are stored in BLOCK DATA /XMLATM/ and are based on 1990 photochemical predictions (after M. Allen, JPL). Since some of the CFCs have increased by as much as 8% per year, the user might well wish to redefine these values. Note that both CFC11 and CFC12 are now as much as 80% larger than the default profiles.

CARD 1 (Required)

If MODEL = 0 or 7, MODTRAN expects to read user-supplied atmospheric profiles. Set IM = 1 for the first run. To sequentially rerun the same atmosphere for a series of cases, set IM to 0 in subsequent runs; MODTRAN will then reuse the previously read data.

IM	= 0	For normal operation of program or when calculations are to be run with the atmosphere MODEL last read in.
	= 1	When user input data are to be read.
NOPRNT	= 0	For normal operation of program; controls tape6 output.
	= 1	To minimize printing of transmittance or radiance table and atmospheric profiles in tape6.
	= -1	Create additional tape8 output, including either weighting functions in transmission mode (IEMSCT = 0) or fluxes in radiation modes with multiple scattering on (IMULT = ± 1 and IEMSCT = 1 or 2).
	= -2	Generates spectral cooling rate data in addition to the tape8 output; spectral cooling rates are written to the 'clrates' or 'rootname.clr' file.

If NOPRNT is set to -1 for multiple scattering calculations, spectral diffuse and total flux values along the lines of sight will be written to tape8. These values are 1 cm^{-1} spectral resolution results (15 cm^{-1} results if the 15 cm^{-1} band model data file is used). Spectral flux values convolved with the instrument slit function are output to the 'specflux' or 'rootname.flx' file if FLAGS(7:7) is not left blank (**CARD 4**). Be warned that setting NOPRNT to -1 for long paths (e.g., ground to space) over a large spectral range (e.g., 0.4 to $0.7 \mu\text{m}$) will generate large tape8 files.

- TPTEMP* > 0. *Boundary temperature [K] of 'image pixel' (i.e., at H2), used in the radiation mode (if IEMSCT = 1 or 2) for slant paths that intersect the earth OR terminate at a gray boundary (for example, cloud, target). If the 'area-average' temperature (AATEMP, CARD 4A) is not entered and the line-of-sight intersects the earth, TPTEMP is also used as the lower boundary temperature in the multiple scattering models.*
- £ 0. *No surface emission if H2 is above ground. If the path intersects the Earth and TPTEMP is either not positive or left blank, MODTRAN uses the temperature of the first atmospheric level as the boundary temperature. If the 'area-average' temperature (AATEMP, CARD 4A) is not entered and the line-of-sight intersects the earth, the temperature of the first atmospheric level is also used as the lower boundary temperature in the multiple scattering models.*

CARD 1 (Required)

SURREF = 'BRDF' (or the first non-blank character is 'B' or 'b') Surface spectral BRDFs (Bidirectional Reflectance Distribution Functions) are specified by **CARD 4A, 4B1, 4B2 and 4B3** inputs.

= 'LAMBER' (or the first non-blank character is 'L' or 'l') Spectral Lambertian surface(s) is (are) specified by **CARD 4A, 4L1 and 4L2** inputs.

≥ 0. or blank Albedo of the earth (and at H2 if *TPTEMP* > 0), equal to one minus the surface emissivity and spectrally independent (constant). If the value exceeds one, the albedo is set to 1; if *SURREF* is blank, the albedo is set to 0.

< 0 Negative integer values allow the user to access pre-stored spectrally variable surface albedos from the 'DATA/spec_alb.dat' file.

The file 'DATA/spec_alb.dat' is a replacement for the 'DATA/refbkg' file used in MODTRAN3.7 and earlier versions of the model. It is delivered with 13 surface choices: *SURREF* equals '-1' for fresh snow, '-2' for forest, '-3' for farm, '-4' for desert, '-5' for ocean, '-6' for cloud deck, '-7' for old grass, '-8' for decayed grass, '-9' for maple leaf (only default vegetation that includes a strong chlorophyll edge), '-10' for burnt grass, '-21' for constant 5% reflectivity, '-22' for constant 50% reflectivity, and '-31' for the CCM3 (Kiehl *et al.*, 1996) sea ice description. These are only meant to be representative of the types of options available; the user is encouraged to add to the set or replace the existing ones. Instructions for adding surfaces to the 'spec_alb.dat' file are provided directly within the file. It is recommended that the wavelength limits on the surface properties match or exceed the spectral range specified for the MODTRAN run. MODTRAN will use the endpoint values at any wavelength outside this range (no extrapolations). Table 1 summarizes the use of selected **CARD 1** parameters: *MODTRN*, *SPEED*, *MODEL*, *ITYPE*, *IEMSCT*, *IMULT*, *MDEF*, *NOPRNT* and *SURREF*.

CARD 1 (Required)

Table 1. MODTRAN CARD 1: Columns List Allowed Values of Input Parameters: MODTRN, SPEED, MODEL ITYPE, IEMSCT, IMULT, MDEF, NOPRNT and SURREF.

CARD 1 FORMAT (2A1, I3, I2I5, F8.3, A7)		MODTRN, SPEED, MODEL, ITYPE, IEMSCT, IMULT, M1, M2, M3, M4, M5, M6, MDEF, IM, NOPRNT, TPTEMP, SURREF							
MODTRN (COL. 1)	S P E E D *	MODEL (COL. 3-5)	ITYPE (COL. 6-10)	IEMSCT (COL. 11-15)	IMULT (COL. 16-20)	MDEF (COL. 51-55)	NOPRNT (COL. 61-65)	SURREF (COL. 74-80)	
T or M MODTRAN Run		0 User- Defined [%]	1 Horizontal Path	0 Transmittance	0 No Multiple Scattering	0 For MODEL = 1-6 Default for Minor Species**	-1 tape Short Output	-1 snow	
F, L or blank LOWTRAN Run		1 Tropical	2 Slant Path H1 to H2	1 Thermal Radiance	1 Multiple Scattering Based at H1	1 For MODEL = 0,7 Default for Minor Species**	0 tape6 Normal Output	-2 forest	
C or K Correlated-K with MODTRAN	S o r M	2 Mid- Latitude Summer	3 Slant Path to Space	2 Thermal and Solar/Lunar Radiance	- Multiple 1 Scattering Based at H2	2 For MODEL = 0,7 User Control of Heavy Molecules [§]	-1 tape8 Output	-3 farm	
		3 Mid- Latitude Winter						3 Transmitted Solar/Lunar Irradiance	-2 tape8 Plus Spectral Cooling Rates
		4 Sub-Arctic Summer							-5 ocean
		5 Sub-Arctic Winter							-6 cloud deck
		6 1976 U.S. Standard							-7 old grass
		7 User- Defined [%]							-8 decayed grass
									-9 maple leaf
									-10 burnt grass
							-21 Constant 5%		
							-22 Constant 50%		
							-31 CCM3 sea ice		

M1, M2, M3, M4, M5, M6, MDEF, IM TPTEMP, and SURREF are left blank for standard cases.
[%] Options for non-standard models.
^{**}CO₂, O₂, NO, SO₂, NO₂, NH₃, HNO₃
[§] CFC's plus ClONO₂, NHO₄, CCl₄, and N₂O₅.
^{*} S stands for slow and M stands for medium speed of execution of the code.

4. CARD 1A (REQUIRED) – RADIATIVE TRANSPORT DRIVER CONT'D

The **CARD 1A** format was appended with new inputs in MODTRAN3.7 and MODTRAN4. The older **CARD 1A** parameters are used to govern the multiple stream DISORT algorithm, the solar irradiance, and the CO₂ mixing ratio. New parameters define water vapor and ozone column amounts, trigger specification of data files, and enable scaling of the solar constant.

Italicized features are exclusive to MODTRAN4.

CARD 1A: DIS, DISAZM, NSTR, LSUN, ISUN, CO2MX, H2OSTR, O3STR, LSUNFL, LBMNAM, LFLTNM, H2OAER, SOLCON
FORMAT (2L1, I3, L1, I4, F10.5, 2A10, 4(1X, A1), 2X, F10.3)

DIS	= t, f or blank	Used if IMULT = ±1 in CARD 1 . Set DIS to TRUE (T or t) to activate the DISORT discrete ordinate multiple scattering algorithm. If DIS is FALSE (F, f or blank), the less accurate but faster Isaac's two-stream algorithm is used.
DISAZM	= t, f or blank	<i>Azimuth dependence flag used with DISORT. Set DISAZM to TRUE (T or t) to include azimuth dependence in the line-of-sight multiple scatter solar. Since this option increases computation time, DISAZM should be set to FALSE (F, f or blank) if only vertical fluxes are needed, if solar or viewing zenith angle is near vertical, or if solar multiple scattering is a small radiance component (e.g. for LWIR calculations).</i>
NSTR	= 2, 4, 8 or 16	Number of streams to be used by DISORT. Using high NSTR values generally improves accuracy but slows computation. NSTR = 8 is recommended for most application, although more streams are desirable if modeling highly forward peaked scatterers. DISORT has been optimized for NSTR = 4, 8 and 16 only (for further details, see the DISORT documentation: Stamnes <i>et al.</i> , 1988 or the DISORT ftp site. ftp://climate.gsfc.nasa.gov/pub/wiscombe/Discr_ord/)
LSUN	= t, f or blank	Set to FALSE (F, f or blank) to use the default solar 5 cm ⁻¹ spectral resolution irradiances (block data routine sunbd.f); set to TRUE (T or t) to read 1 cm ⁻¹ binned solar irradiance from a file (see input LSUNFL below) - this requires input of ISUN.
ISUN		The FWHM (Full Width at Half Maximum) of the triangular scanning function used to smooth the TOA solar irradiance (wavenumbers).
CO2MX		CO ₂ mixing ratio in ppmv. The default value (used when CO2MX = blank or 0.) is 330 ppmv; the current (1999) recommended value is closer to 365 ppmv (Dutton, 1999).

CARD 1A (Required)

- H2OSTR** Vertical water vapor column character string. If blank or 0., the default water vapor column is used. If the first non-blank character is 'g', the water vapor column in gm / cm² follows 'g' (e.g., g 2.0). If the first non-blank character is an 'a', the water column in ATM-cm follows 'a' (e.g., a 3000.). Otherwise, a positive value is interpreted as a scaling factor for the water column (e.g. 2.0 doubles the default water vapor column). H2OSTR should not be used with a constant pressure path, i.e., MODEL = 0 on **CARD 1**. The water density within water clouds (ICLD = 1-10) is not scaled. Also, the water number density at each profile altitude will not be increased above 100% RH (relative humidity) or by more than 5 times the original value. When the 100% RH limit is reached, the water is distributed to other levels to the extent possible to achieve the input water column.
- O3STR** Vertical ozone column character string. If blank or 0., the default ozone column is used. If the first non-blank character is 'g', the ozone column in gm / cm² follows 'g' (e.g., g 0.0001). If the first non-blank character is an 'a' the ozone column in ATM-cm follows 'a' (e.g., a 0.2). Otherwise, a positive value is interpreted as a scaling factor for the ozone column (e.g. 2.0 doubles the default ozone column). One Dobson unit equals 10⁻³ ATM-cm at 273.15 K. O3STR should not be used with a constant pressure path, i.e., MODEL = 0 on **CARD 1**.
- LSUNFL** = t, f or blank. If TRUE (T or t), read solar radiance data file name from **CARD 1A1**. The file is only used if LSUN is also TRUE. If LSUNFL is FALSE (F, f or blank) and LSUN is TRUE, the file name 'DATA/newkur.dat' is used. LSUNFL can also be set to 1, 2, 3, or 4; see **CARD 1A1**.
- LBMNAM** = t, f or blank. If TRUE (T or t), read band model parameter data file name from **CARD 1A2**. Otherwise, the default (1 cm⁻¹ bin) band model database ('DATA/BMP98_01.BIN') is used.
- LFLTNM** = t, f or blank. If TRUE (T or t), read file name for user-defined instrument filter function from **CARD 1A3**.
- H2OAER** = t, f or blank *If t, aerosol optical properties are modified to reflect the changes from the original relative humidity profile arising from the scaling of the water column (see H2OSTR on this CARD). Otherwise, the H₂O properties are fixed even though water amount has changed.*

- SOLCON < 0. The absolute value of SOLCON, likely close to +1, is used as a scale factor for the TOA (Top-Of-Atmosphere) solar irradiance. The built-in data files (in the DATA/ directory) integrate to 1368.00 W/m² for newkur.dat, 1362.12 W/m² for cebchkur.dat, 1359.75 W/m² for chkur.dat and 1376.73 W/m² for thkur.dat. An additional scaling of the solar irradiance value to account for earth-to-sun distance (based on day of year, **CARD 3A1**) is applied within MODTRAN, and this earth-to-sun correction factor is written to 'tape6' or 'rootname.tp6'.
- = 0. or blank. Do not scale the TOA solar irradiance.
- > 0. The solar constant is assigned the input value [W/m²]. As with SOLCON < 0., an additional scaling of the solar irradiance value to account for earth-to-sun distance (based on day of year, **CARD 3A1**) is applied within MODTRAN, and this earth-to-sun correction factor is written to 'tape6' or 'rootname.tp6'.

5. OPTIONAL CARDS 1A1, 1A2, 1A3 (SPECTRAL DATA AND SENSOR RESPONSE FUNCTION FILES)

CARD 1A1: *SUNFL2*
FORMAT(A80)

CARD 1A1 is used to select the TOA solar irradiance database. It is read only if LSUNFL = T in **CARD 1A**.

SUNFL2 = 1 or blank	The corrected Kurucz database is used (DATA/newkur.dat).
= 2	The Chance database is used (DATA/chkur.dat).
= 3	The Cebula plus Chance data are used (DATA/cebchkur.dat).
= 4	The Thuillier plus corrected Kurucz are used (DATA/thkur.dat)
= a file name	A user-defined database residing in the file.

The solar databases are obtained from various sources (Anderson and Hall, 1989; Cebula *et al.*, 1996; Chance and Spurr, 1997; Kurucz, 1993; Kurucz, 1995; McElroy, 1995; McElroy *et al.*, 1995; Thuillier *et al.*, 1997; Thuillier *et al.*, 1998; Woods *et al.*, 1996).

The user-defined file must be in a special form. The first line must contain a pair of integers. The first integer designates the spectral unit [1 for frequency in wavenumbers (cm^{-1}); 2 for wavelength in nanometers (nm); and 3 for wavelength in microns (μm). The second integer denotes the irradiance unit [1 for Watts $\text{cm}^{-2} / \text{cm}^{-1}$; 2 for photons $\text{sec}^{-1} \text{cm}^{-2} / \text{nm}$; and 3 for Watts $\text{m}^{-2} / \mu\text{m}$ or equivalently milli-watts $\text{m}^{-2} / \text{nm}$]. The subsequent lines contain one pair of frequency and irradiance entry per line. There is no restriction on frequency or wavelength increments. However, data beyond 50,000 wavenumbers are ignored. If needed, data in the user-supplied file are padded with numbers from newkur.dat so that the data encompasses the range of 50 to 50,000 wavenumbers. Note that the user-defined file has a form that is different from DATA/cebchkur.dat, DATA/thkur.dat, DATA/newkur.dat, and DATA/chkur.dat.

Optional CARDS 1A1, 1A2, 1A3

CARD 1A2: BMNAME
FORMAT(A80)

CARD 1A2 is used to select the name of the binary, direct-access version of the band model parameter data file. It is read only if LBMNAM = T in CARD 1A.

BMNAME = Name of binary, direct-access version of the band model parameter data file. The default name for the 1 cm^{-1} band model file is 'DATA/BMP98_01.BIN'. There is also a 15 cm^{-1} band model file available for faster short-wave calculations: 'DATA/BMP98_15.BIN'. If the 1 cm^{-1} (15 cm^{-1}) band model file is selected, MODTRAN will also open the 1 cm^{-1} (15 cm^{-1}) Correlated-k data file when input variable MODTRN (**CARD 1**) equals 'C' or 'K'. The name of the CK data file is hardwired to 'DATA/CORK01.BIN' (The name for the 15 cm^{-1} band model version of the CK data file is 'DATA/CORK15.BIN').

CARD 1A3: FILTNM
FORMAT(A80)

CARD 1A3 is used to select a user-supplied instrument filter (channel) response function file. It is read only if LFLTNM = T in CARD 1A.

FILTNM = User-supplied instrument filter response function file name. A **sample** AVIRIS filter response function is supplied with the model ('DATA/aviris.flt').

Whenever this option is used, the include file CHANNELS.h should be reviewed to insure consistency between the CHANNELS.h PARAMETERS and the input response function file.

CHANNELS.h defines 4 parameters:

MXCHAN	The maximum number of channels in the response function file.
MNBIN	The minimum frequency bin used in the channel function integrations (cm^{-1}).
MXBIN	The maximum frequency bin used in the channel function integrations (cm^{-1}).
MXNCHN	The maximum number of channels to which a single band model spectral bin will contribute.

The CHANNELS.h MNBIN and MXBIN parameters must be defined in frequency (cm^{-1}) units even though the filter function file data may be entered in frequency or wavelength (nm or microns) units.

Optional CARDS 1A1, 1A2, 1A3

If the filter function file is used, it must be in the following form:

```
UNITS_HEADER  
HEADER(1)  
w11   r11  
w12   r12  
w13   r13  
...  
HEADER(2)  
w21   r21  
w22   r22  
w23   r23  
...  
etc.
```

Here, UNITS_HEADER is a string whose first character is 'N' (for nm), 'W' (for wavenumber), or 'M' (for microns), denoting the wavelength or frequency unit.

HEADER(i) is a string, whose first character is non-numeric and not a decimal point, denotes the start of a list of (wavelength, response) pairs for the ith channel.

(w_{ij} r_{ij}) are the jth wavelength and response values for the ith channel.

6. CARD 2 (REQUIRED) – MAIN AEROSOL AND CLOUD OPTIONS

**CARD 2: APLUS, IHAZE, CNOVAM, ISEASN, ARUSS, IVULCN, ICSTL, ICLD, IVSA, VIS, WSS, WHH, RAINRT, GNDALT
FORMAT (A2, I3, A1, I4, A3, I2, 3I5, 5F10.5)**

IHAZE, ISEASN, IVULCN, and VIS select the altitude and seasonal-dependent aerosol profiles and aerosol extinction coefficients. IHAZE specifies the aerosol model used for the boundary-layer (0 to 2 km) and a default, surface-meteorological range. The relative humidity dependence of the boundary-layer aerosol extinction coefficients is based on the water vapor content of the model atmosphere selected by MODEL. ISEASN selects the seasonal dependence of the profiles for both the tropospheric (2 to 10 km) and stratospheric (10 to 30 km) aerosols. IVULCN is used to select both the profile and extinction type for the stratospheric aerosols and to determine transition profiles through the stratosphere to 100 km. VIS, the meteorological range, when specified, will supersede the default meteorological range in the boundary-layer aerosol profile set by IHAZE.

IHAZE selects the type of extinction and a default meteorological range for the boundary-layer aerosol models only. If VIS is also specified, it will override the default IHAZE value. Interpolation of the extinction coefficients based on relative humidity is performed only for the RURAL, MARITIME, URBAN, and TROPOSPHERIC coefficients used in the boundary layer (0 to 2 km altitude).

The character string inputs APLUS, CNOVAM, and ARUSS (for AeRosol User Supplied Spectra) were introduced in MODTRAN3.7 to give greater flexibility in defining aerosols. APLUS was introduced to modify aerosol profiles, NOVAM introduced to allow selection of NOVAM, and ARUSS introduced to give greater flexibility in defining aerosol optical properties.

APLUS = *Blank Default*
= *'A+' Use "Aerosol Plus" option (triggers reading of CARD 2A+) to characterize user-defined aerosols optical properties.*

CARD 2 (Required)

IHAZE	=	-1	No aerosol attenuation, but the model clouds may be included (i.e., ICLD = 1, 2, ..., 10).
	=	0	No aerosol or cloud attenuation included in the calculation.
	=	1	RURAL extinction, default VIS = 23 km.
	=	2	RURAL extinction, default VIS = 5 km.
	=	3	NAVY MARITIME extinction, sets VIS based on wind speed and relative humidity.
	=	4	MARITIME extinction, default VIS = 23 km (LOWTRAN model).
	=	5	URBAN extinction, default VIS = 5 km.
	=	6	TROPOSPHERIC extinction, default VIS = 50 km.
	=	7	User-defined aerosol extinction coefficients. Triggers reading CARDs 2D, 2DI and 2D2 for up to 4 altitude regions of user-defined extinction, absorption and asymmetry parameters. (This option is kept for backward compatibility; the ARUSS = 'USS' option affords greater flexibility in specifying user-defined aerosols).
	=	8	FOG1 (Advection Fog) extinction, 0.2 km VIS.
	=	9	FOG2 (Radiative Fog) extinction, 0.5 km VIS.
	=	10	DESERT extinction, sets visibility from wind speed (WSS).
CNOVAM	=	Blank	Default
	=	'N'	Use Navy Oceanic Vertical Aerosol Model (NOVAM) output (see Appendix B).

ISEASN selects the appropriate seasonal aerosol profile for both the tropospheric and stratospheric aerosols. Only the tropospheric aerosol extinction coefficients are used with the 2 to 10 km profiles.

ISEASN	=	0	Season determined by the value of MODEL; SPRING-SUMMER for MODEL = 0, 1, 2, 4, 6, 7 FALL-WINTER for MODEL = 3, 5
	=	1	SPRING-SUMMER
	=	2	FALL-WINTER
ARUSS	=	Blank	Default

CARD 2 (Required)

= 'USS' User-supplied aerosol optical properties (see instructions in Appendix A)

The parameter IVULCN controls both the selection of the aerosol profile as well as the type of extinction for the stratospheric aerosols. It also selects appropriate transition profiles above the stratosphere to 100 km. Meteoric dust extinction coefficients are always used for altitudes from 30 to 100 km.

- IVULCN = 0,1 BACKGROUND STRATOSPHERIC profile and extinction
- = 2 MODERATE VOLCANIC profile and AGED VOLCANIC extinction
- = 3 HIGH VOLCANIC profile and FRESH VOLCANIC extinction
- = 4 HIGH VOLCANIC profile and AGED VOLCANIC extinction
- = 5 MODERATE VOLCANIC profile and FRESH VOLCANIC extinction
- = 6 MODERATE VOLCANIC profile and BACKGROUND STRATOSPHERIC extinction
- = 7 HIGH VOLCANIC profile and BACKGROUND STRATOSPHERIC extinction
- = 8 EXTREME VOLCANIC profile and FRESH VOLCANIC extinction

Table 2. Shows the Value of IVULCN Corresponding to the Different Choices of Extinction Coefficient Model and the Vertical Distribution Profile.

EXTINCTION MODEL		VERTICAL DISTRIBUTION			
		BACKGROUND STRATOSPHERIC	MODERATE VOLCANIC	HIGH VOLCANIC	EXTREME VOLCANIC
	BACKGROUND STRATOSPHERIC	0,1	6	7	-
	AGED VOLCANIC	-	2	4	-
	FRESH VOLCANIC	-	5	3	8

ICSTL is the air mass character (1 to 10), used with the precursor to NOVAM, i.e., the Navy-maritime Aerosol Model NAM (**IHAZE = 3**). Default value is 3. ICSTL is not used with NOVAM.

CARD 2 (Required)

ICSTL = 1 Open ocean
.
.
.
10 Strong continental influence

ICLD specifies the cloud and rain models used. The rain profiles decrease linearly from the ground to the top of the associated cloud model. The program cuts off the rain at the cloud top.

ICLD = 0 No clouds or rain.
= 1 Cumulus cloud layer: base 0.66 km, top 3.0 km.
= 2 Altostratus cloud layer: base 2.4 km, top 3.0 km.
= 3 Stratus cloud layer: base 0.33 km, top 1.0 km.
= 4 Stratus/stratocumulus layer: base 0.66 km, top 2.0 km.
= 5 Nimbostratus cloud layer: base 0.16 km, top 0.66 km.
= 6 2.0 mm/hr ground Drizzle
(modeled with cloud 3 and 0.86 mm / hr at 1.0 km).
= 7 5.0 mm/hr ground Light rain
(modeled with cloud 5 and 2.6 mm / hr at 0.66 km).
= 8 12.5 mm/hr ground Moderate rain
(modeled with cloud 5 and 6.0 mm / hr at 0.66 km).
= 9 25.0 mm/hr ground Heavy rain
(modeled with cloud 1 and to 0.2 mm / hr at 3.0 km).
= 10 75.0 mm/hr ground Extreme rain
(modeled with cloud 1 and 1.0 mm / hr at 3.0 km).
= 11 Read in user defined cloud extinction and absorption. Triggers reading **CARDs 2D, 2D1 and 2D2** for up to 4 altitude regions of user defined extinction, absorption, and asymmetry parameters (This option is kept for backward compatibility; **CARD 2A** inputs afford greater flexibility in specifying user-defined clouds).
= 18 Standard Cirrus model (64 μm mode radius for ice particles).
= 19 Sub-visual Cirrus model (4 μm mode radius for ice particles).

CARD 2 (Required)

IVSA selects the use of the Army Vertical Structure Algorithm (VSA) for aerosols in the boundary layer.

IVSA = 0 Not used.
= 1 Vertical Structure Algorithm.

VIS specifies the surface meteorological range (km) overriding the default value associated with the boundary layer chosen by IHAZE. If set to zero, VIS is the default value specified by IHAZE. Visibility is related to surface aerosol extinction at 550 nm ($EXT550$ in km^{-1}) by the equation

$$VIS [km] = \frac{\ln(50)}{EXT550[km^{-1}] + 0.01159 km^{-1}}$$

where $0.01159 km^{-1}$ is the surface Rayleigh Scattering Coefficient at 550nm.

VIS > 0. User specified surface meteorological range (km).
= 0. Uses the default meteorological range set by IHAZE; (See Table 3).

WSS specifies the current wind speed for use with the Navy maritime and desert aerosol models.

WSS = Current wind speed (m/s). Used with the Navy Aerosol Maritime (NAM) model (IHAZE = 3) or the DESERT model (IHAZE = 10).

WHH specifies the 24-hour average wind speed for use with the Navy maritime model.

WHH = 24-hour average wind speed (m/s). Used with the Navy Aerosol Maritime (NAM) model (IHAZE = 3)

For the Navy Aerosol Maritime model, if $WSS = WHH = 0$, default wind speeds are set according to the value of MODEL, Table 3. For the Desert aerosol model (IHAZE = 10), if $WSS < 0$, the default wind speed is 10 m/s.

Table 3. Default Wind Speeds for Different Model Atmospheres Used with the Navy Maritime Model (IHAZE = 3).

Model	Model Atmosphere	WSS and WHH Default Wind Speed (m/s)
0	User-defined (Horizontal Path)	6.9
1	Tropical	4.1
2	Mid-latitude summer	4.1
3	Mid-latitude winter	10.29
4	Sub-arctic summer	6.69
5	Sub-arctic winter	12.35
6	U.S. Standard	7.2
7	User-define	6.9

RAINRT specifies the rain rate and GNDALT specifies the altitude of the surface relative to sea level.

RAINRT = Rain rate (mm/hr) default value is zero. Used to top of cloud when cloud is present; when no clouds, rain rate used to 6km.

GNDALT = Altitude of surface relative to sea level (km). GNDALT may be negative but may not exceed 6 km. The baseline 0 to 6 km aerosol profiles are compressed (or stretched) based on input GNDALT.

Table 4 summarizes the use of the input control parameters IHAZE, ISEASN, IVULCN, and VIS on **CARD 2**. Table 5 summarizes the use of the parameter ICLD.

CARD 2 (Required)

Table 4. MODTRAN CARD 1 Input Parameters: IHAZE, ISEASN, IVULCN, VIS.

CARD2 APLUS, IHAZE, CNOVAM, ISEASN, ARUSS, IVULCN, ICSTL, ICLD, IVSA, VIS, WSS, WHH, RAINRT, GNDALT FORMAT (A2, I3, A1, I4, A3, I2, 3I5, 5F10.5)									
IHAZE			ISEASN		IVULCN				
In COL. 3-5	VIS* (KM)	EXTINCTION	In COL. 7-10	SEASON	In COL. 14-15	SEASON	PROFILE	EXTINCTION	PROFILE/EXTINCTION
0 No Aerosols									
1	23	RURAL	0	Set by model		Set by model			Meteoric dust extinction
2	5		1	Spring-Summer		Spring-summer			
3	**		Navy maritime	2	Fall-winter		Fall-winter		
4	23	LOWTRAN maritime	Tropospheric profile/ tropospheric extinction	0			Background stratospheric	Background stratospheric	Normal atmospheric profile
5	5	URBAN		1			Moderate volcanic	Aged volcanic	Transition profiles - volcanic to normal
6	50	Tropospheric		2			High volcanic	Fresh volcanic	
7	23	User-defined		3			High volcanic	Aged volcanic	
8	0.2	Fog 1		4			Moderate volcanic	Fresh volcanic	
9	0.5	Fog 2		5			Moderate volcanic	Background stratospheric	
10	**	Desert		6			High volcanic	Background stratospheric	
				7			Extreme volcanic	Fresh volcanic	
			8						
0 to 2 km			2 to 10 km		10 to 30 km				30 to 100 km
* Default VIS, can be overridden by VIS > 0 on CARD 2									
** Sets own default VIS									

Table 5. MODTRAN CARD 2 Input Parameter: ICLD.

ICLD	Cloud and/or Rain Option		
0	NO CLOUDS OR RAIN		
1	CUMULUS CLOUD		
2	ALTOSTRATUS CLOUD		
3	STRATUS CLOUD		
4	STRATUS / STRATOCUMULUS		
5	NIMBOSTRATUS CLOUD		
6	2.0 MM/HR	DRIZZLE	(MODELED WITH CLOUD 3)
7	2.0 MM/HR	LIGHT RAIN	(MODELED WITH CLOUD 5)
8	12.5 MM/HR	MODERATE RAIN	(MODELED WITH CLOUD 5)
9	25.0 MM/HR	HEAVY RAIN	(MODELED WITH CLOUD 1)
10	75.0 MM/HR	EXTREME RAIN	(MODELED WITH CLOUD 1)
11	USER DEFINED CLOUD EXTINCTION AND ABSORPTION		
18	STANDARD CIRRUS MODEL		
19	SUB VISUAL CIRRUS MODEL		

7. OPTIONAL CARD 2A+ (FLEXIBLE AEROSOL MODEL)

CARD 2A+, which is read if APLUS = 'A+' in **CARD 2**, allows the user to move MODTRAN's built-in aerosols from their original positions to arbitrary altitude regions (which may overlap) and to compress and stretch them using only two input lines. If the **CARD 2** input GNDALT is non-zero, the aerosol densities below 6 km will undergo an additional compression or stretching, as described in Section 6. An important benefit is the ability to move the tropopause height. The **CARD 2A+** options cannot be used in conjunction with NOVAM.

CARD 2A+: **ZAER11, ZAER12, SCALE1, ZAER21, ZAER22, SCALE2, ZAER31, ZAER32, SCALE3, ZAER41, ZAER42, SCALE4** (If APLUS = 'A+')
FORMAT((3(1X, F9.0), 20X, 3(1X, F9.0)))

There are 12 variables in the two lines of **CARD 2A+** as enumerated above. The first set of three is for aerosol number 1; the second set of three, for aerosol 2; the third set, for aerosol 3 and the fourth set, for aerosol 4. The meanings of the numerical values for ZAERi1, ZAERi2 and SCALEi, i = 1, 2, 3 and 4, are as follows:

ZAERi1		The base/bottom of aerosol i
ZAERi2	> ZAERi1	The top of aerosol i
	< ZAERi1	Translate original profile to new base, ZAERi1
	= ZAERi1	Set values to default, ignore SCALEi
		(Also set to default when both ZAERi1 and ZAERi2 are blank)
SCALEi	> 0.0	Multiply vertical profile by SCALEi
	= 0 or blank	Multiply vertical profile by 1.0 (i.e., preserves column density)

The aerosols are linearly mapped into the new region and the column densities are preserved if SCALEi is unity. Note that since the cards are read using fixed formats, blanks are interpreted as zeros. By default, SCALEi is set to unity if blanks or 0.0 are input. Note that if the APLUS option is used, the two lines of **CARD 2A+** must be present even if any of these lines are intended to consist of all blanks.

The MODTRAN/LOWTRAN definition of an aerosol region leads to some confusion. Possibly a preferred definition of the aerosol region would be the contiguous altitudes over which the aerosol

Optional CARD 2A+

concentration is positive. By this definition, the region of aerosol 1, for example, is from 0 to 3 km; the profile linearly decreases from a positive value at 2 km to zero at 3 km. Instead, in previous MODTRAN documentation this region is said to be from 0-2 km. In the MODTRAN upgrade, the ZAERi1 and ZAERi2 values refer to the bounding altitudes, which sandwich the entire region where the aerosol concentration is positive. Table 6 lists the default values of these bounding altitudes along with the commonly referred to region boundaries for each aerosol.

One caveat with regard to the **CARD2+** inputs should be noted. For the Tropospheric aerosol model (**IHAZE = 6**), MODTRAN combines the boundary layer (Aerosol 1) and tropospheric (Aerosol 2) regions; therefore, these region may not be scaled independently. Thus, the parameters used to scale the tropospheric aerosol model are min (ZAER11, ZAER21), max (ZAER12, ZAER22) and max (SCALE1, SCALE2).

Table 6. Default Aerosol Region Boundaries.

Aerosol	Common Region Definition	Actual ZAERi1	Actual ZAERi2
1	0-2 km	0 km	3 km
2	2-10	2	11
3	10-30	10	35
4	30-100	30	100

8. OPTIONAL CARD 2A (CLOUD MODELS)

CARD 2A is required for all cloud models ($ICLD > 0$) except $ICLD = 11$. Note that the original MODTRAN3.0 format has been changed. To run a default cloud case with $ICLD = 1-10$, the alternative **CARD 2A** should read:

```
-9.000 -9.000 -9.000 -9 -9 -9.000 -9.000 -9.000 -9.000 -9.000 -9.000
```

The standard and alternate forms are discussed in Subsections 8.1 and 8.2, respectively.

8.1 CARD 2A Standard Form (CIRRUS CLOUD MODELS, ICLD = 18 or 19)

CARD 2A: **CTHIK, CALT, CEXT**
 FORMAT (3F8.3) (FORMAT changed in MODTRAN3.5)

CTHIK is the cirrus thickness (km):

CTHIK = 0. use thickness statistics.
 > 0. user-defined thickness.

CALT is the cirrus base altitude (km):

CALT = 0. use calculated value.
 > 0. user-defined base altitude.

CEXT is the extinction coefficient (km^{-1}) at 0.55 micron:

CEXT = 0. use $0.14 * CTHIK$.
 > 0. user-defined extinction coefficient.

8.2 CARD 2A Alternate Form (WATER/ICE CLOUD MODELS, ICLD = 1 - 10)

CARD 2A: **CTHIK, CALT, CEXT, NCRALT, NCRSPC, CWAVLN, CCOLWD,**
 CCOLIP, CHUMID, ASYMWD, ASYMIP
 FORMAT(3F8.3, 2I4, 6F8.3)

This form of **CARD 2A** is for modifying parameters for clouds other than cirrus. Use of this CARD triggers the reading of **CARDs 2E1** and **2E2**, described below in their respective sections. See Berk and Anderson, SSI-TR-267, for a more extensive discussion.

Default values can be assigned to any of the **CARD 2A** variables by setting them equal to negative nine. An actual computer card image is shown below (2 leading spaces and two spaces between each number). All **CARD 2A** variables are set to their default value with this input line:

Optional CARD 2A

-9.000 -9.000 -9.000 -9 -9 -9.000 -9.000 -9.000 -9.000 -9.000 -9.000

A blank line will not generate the default values. In fact, setting all **CARD 2A** inputs to zero would produce an isotropic scattering ground-level cloud.

C_{THIK} is the cloud vertical thickness:

C_{THIK} > 0. Cloud vertical thickness [km].
 C_{THIK} ≥ 0. Use default cloud thickness.

The cloud vertical thickness is defined as the altitude difference between the highest and lowest cloud profile boundary altitude for which either water droplet or ice particle density is positive. The ten MODTRAN cloud/rain models are derived from five distinct clouds. The default thicknesses for these clouds are listed in Table 7. This will not only scale default clouds but also user-specified cloud profiles (**CARD 2E1**).

Table 7. Properties of the MODTRAN Cumulus and Stratus Type Model Clouds.

ICLD	Cloud Type	Thickness (km)	Base (km)	.55mm Ext. (km ⁻¹)	Column Amt. (km gm / m ³)
1	Cumulus	2.34	0.66	92.6	1.6640
2	Altostratus	0.60	2.40	128.1	0.3450
3	Stratus	0.67	0.33	56.9	0.2010
4	Stratus/Stratocumulus	1.34	0.66	38.7	0.2165
5	Nimbostratus	0.50	0.16	92.0	0.3460

C_{ALT} is the cloud base altitude relative to ground level:

C_{ALT} ≥ 0. Cloud base altitude relative to ground level [km].
 C_{ALT} < 0. Use default cloud base altitude.

This differs from the meaning of C_{ALT} in the cirrus cloud models (ICLD = 18 or 19) which define base altitude relative to sea level. Note that a value of zero translates the cloud down to the ground; the user must enter a negative altitude to have the cloud automatically placed at the default altitude. If there is a non-constant rain profile below a cloud, that profile is stretched or compressed depending upon whether the base altitude is increased or decreased.

Optional CARD 2A

CEXT is the cloud liquid water droplet and ice particle vertical extinction:

CEXT	> 0.	Cloud water particle vertical extinction [km^{-1}].
	≥ 0 .	Do not scale extinction coefficients.

CEXT is defined for wavelength CWAVLN (see below). Within the code, CEXT is used to scale the extinction (and absorption) coefficient curves. The ratio of the input optical depth (CEXT * CTHIK) to the calculated optical depth (the product of column density and extinction coefficient at CWAVLN, summed for both liquid water droplets and ice particles) is determined. The extinction and absorption coefficients at all frequencies are multiplied by this ratio. The default cloud extinction at $0.55 \mu\text{m}$ for each of the five MODTRAN liquid water droplet model clouds is listed in Table 6.

NCRALT is the number of layer boundary altitudes if a user-defined cloud/rain profile is being input:

NCRALT	≥ 3	Number of layer boundary altitudes (from CARD 2E1) in user-defined cloud/rain profile.
	< 3	Use default cloud profile for ICLD.

The maximum allowed value for NCRALT is 16, parameter NZCLD in PARAM.LST; this value can be increased, but this change requires some modification of block data /MDTA/. NCRALT must be at least 3 to define the cloud base, the cloud top, and the highest boundary altitude for which the water droplet and ice particle densities must be zero. It is generally recommended that the altitude below which cloud densities are zero also be included in the cloud profile. If this altitude is not entered, MODTRAN assumes that the cloud densities drop to zero 1 meter below the cloud base.

Optional CARD 2A

NCRSPC is the number of wavelength entries:

- NCRSPC \geq 2 Number of wavelength at which cloud spectral data is being entered (on **CARD 2E2**).
- < 2 Use default spectral data for ICLD.

NCRSPC must be at least 2 so the minimum and maximum wavelengths do not coincide. A maximum of 788 wavelengths (parameter MXWVLN in PARAM.LST) may be input.

CWAVLN is the reference wavelength used in defining cloud vertical extinction:

- CWAVLN ≥ 0.2 & ≤ 200.0 Reference wavelength for defining cloud vertical extinction [μm]

CWAVLN outside this range specifies the default, 0.55 μm . The variable CWAVLN is only used if a user-selected value for CEXT is input. Furthermore, if CWAVLN is outside the spectral range of user-defined cloud spectral data (**CARD 2E2**), a fatal error message is logged and execution terminated.

CCOLWD is the water droplet (WD) cloud vertical column density:

- CCOLWD \geq 0. Cloud liquid water droplet vertical column density [$\text{km gm} / \text{m}^3$].
- < 0. Do not scale the water droplet densities.

MODTRAN determines the ratio of this input water droplet vertical column density to the column density calculated from the input cloud base, thickness, and the default water droplet densities. Then all the water droplet densities are scaled by this ratio so that the desired column amount results.

It should be noted that if the cloud being modeled only has liquid water and a positive cloud vertical extinction, CEXT, is input, MODTRAN will change spectral extinction and absorption coefficients so that predicted path transmittances and radiances are independent of CCOLWD. However, if the spectral data are not being scaled to give a particular vertical extinction, increasing column density will increase extinction. Furthermore, if the cloud consists of both liquid water droplets and ice particles, CCOLWD can be used to customize the relative contribution from the two particle types. The default cloud water droplet column densities for the five MODTRAN liquid water clouds are listed in Table 6.

CCOLIP is the ice particle (IP) cloud vertical column density:

- CCOLIP \geq 0. Cloud ice particle vertical column density or amount [$\text{km gm} / \text{m}^3$].
- < 0. Do not scale the ice particle densities.

Optional CARD 2A

Generally, CCOLIP is used to scale ice particle density the same way CCOLWD is used to scale water droplet density. However, two points should be noted: (1) The MODTRAN cumulus and stratus type clouds (ICLD = 1 - 10) treated by this alternate **CARD 2A** do not contain ice particles. Thus, only user-defined cloud profiles (see **CARD 2E1** below) can be scaled using CCOLIP; (2) If both CCOLWD and CCOLIP are zero, scaling is turned off for both; it does not make sense to define a cloud with no liquid water droplets or ice particles.

CHUMID is the relative humidity at all layer boundaries with either a positive rain rate or a positive cloud density:

CHUMID	>0. & ≤105.	Cloud / rain relative humidity [%].
CHUMID	≤0. or >105.	Assume 100% relative humidity at cloud/rain layer boundaries.

As much as 5% super saturation is permitted, and clouds with 0% relative humidity throughout the entire cloud region are forbidden.

ASYMWD is the Henyey-Greenstein phase function asymmetry factor for scattering by cloud liquid water droplets:

ASYMWD	< 1.	Water droplet Henyey-Greenstein scattering phase function asymmetry factor at all wavelengths.
	≥ 1.	Use user-defined or model spectral asymmetry factors for scattering by cloud liquid water droplets.

Even if the spectral asymmetry factors are input using **CARDs 2E2**, MODTRAN uses the ASYMWD value if its absolute value is less than one.

ASYMIP is the Henyey-Greenstein phase function asymmetry factor for scattering by cloud ice particles:

ASYMIP	< 1.	Ice particle Henyey-Greenstein scattering phase function asymmetry factor at all wavelengths.
	≥ 1.	Use user-defined or model (standard cirrus) spectral asymmetry factors for scattering by cloud ice particles.

9. OPTIONAL CARD 2B (ARMY VERTICAL STRUCTURE ALGORITHM)

CARD 2B is the input card for the Army VSA (Vertical Structure Algorithm) subroutine (required when IVSA = 1 on **CARD 2**).

CARD 2B: **ZCVSA, ZTVSA, ZINVSA**
 FORMAT (3F10.3)

The case is determined by the parameters VIS, ZCVSA, ZTVSA, and ZINVSA.

CASE 1: cloud/fog at the surface; increasing extinction with height from cloud/fog base to cloud/fog top. Selected by $VIS \leq 0.5$ km and $ZCVSA \geq 0$.

Use case 2 or 2' below the cloud and case 1 inside it.

CASE 2: hazy/light fog; increasing extinction with height up to the cloud base. Selected by $0.5 < VIS \leq 10$ km, $ZCVSA \geq 0$.

CASE 2': clear/hazy; increasing extinction with height, but less so than case 2, up to the cloud base. Selected by $VIS > 10$ km, $ZCVSA \geq 0$.

CASE 3: no cloud ceiling but a radiation fog or an inversion or boundary layer present; decreasing extinction with height up to the height of the fog or layer. Selected by $ZCVSA < 0$ $ZINVSA \geq 0$.

CASE 4: no cloud ceiling or inversion layer; constant extinction with height. Selected by $ZCVSA < 0$ and $ZINVSA < 0$.

ZCVSA is the cloud ceiling height [km]:

ZCVSA	>	0.0	sets the known cloud ceiling height;
	=	0.0	height unknown: the program will calculate one for case 2, and default is 1.8 km for case 2'; or
	<	0.0	no cloud ceiling (cases 3 and 4).

ZTVSA is the thickness of the cloud (case 2) or the thickness of the fog at the surface (case 1) [km]:

ZTVSA	>	0.0	the known value of the cloud thickness;
	=	0.0	thickness unknown; default is 0.2 km.

ZINVSA is the height of the inversion or boundary layer [km]:

ZINVSA	>	0.0	the known height of the inversion layer;
	=	0.0	height unknown: default is 2 km, 0.2 km for fog;
	<	0.0	no inversion layer (case 4, if $ZCVSA < 0.0$ also).

10. OPTIONAL CARDS 2C, 2C1, 2C2, 2C2X, 2C3 (USER-DEFINED ATMOSPHERIC PROFILES)

User-supplied profile data are read in when the parameter MODEL is 7 (or 0 for a constant pressure path) and IM is 1 on **CARD 1**. In this case, **CARDS 2C** and **2C1** are required.

Using **CARDS 2C, 2C1, and 2C2**, the user has the choice of entering gas concentration data in any of several different sets of units or defaulting to a model atmosphere concentration at the specified altitude. The concentrations are entered on **CARDS 2C1** and **2C2** in the units specified by JCHAR on **CARD 2C1**. If MDEF (**CARD 1**) is set to 2, concentrations of the heavy molecular gases are read from **CARD 2C2X** in the units specified by JCHARX on **CARD 2C1**.

Aerosol vertical distributions, cloud liquid water contents, and rain rates can be input at specified altitudes using **CARD 2C3**. The default altitudes for the four aerosol regions may be modified using the parameters IHA1, ICLD1 or IVUL1.

CARDS 2C1 through **2C3** are repeated ML times, where ML (in **CARD 2C**) is the number of atmospheric levels (ML = 1 for a horizontal path).

10.1 CARD 2C

CARD 2C: **ML, IRD1, IRD2, HMODEL** **(MODEL = 0/7, IM = 1)**
 FORMAT (315, A20)

ML = Number of atmospheric levels to be inserted (maximum of NLayer, see PARAM.LST file).

IRD1 Controls reading of WMOL(4-12) as described in Table 8 (**CARD 2C2**)

IRD1 = 0 No read.

IRD1 = 1 Read **CARD 2C2**.

IRD2 Controls reading AHAZE, EQLWCZ, ... (**CARD 2C3**)

IRD2 = 0 No read.

IRD2 = 1 Read **CARD 2C3**.

IRD2 = 2 Read new version of **CARD 2C3**; see Appendix A.

HMODEL = Identification of new model atmosphere.

10.2 CARDS 2C1, 2C2, 2C2X

CARD 2C1: ZM, P, T, (WMOL(J), J = 1, 3), (JCHAR(J), J = 1, 14), JCHARX
FORMAT (F10.3, 5E10.3, 14A1, 1X, A1)

CARD 2C2: (WMOL(J), J = 4, 12) (If IRD1 = 1)
FORMAT (8E10.3, /E10.3)

CARD 2C2X: (WMOLX(J), J = 1, 13) (If IRD1 = 1 and MDEF = 2)
FORMAT (8E10.3, /5E10.3)

ZM = Altitude of layer boundary (km).

P = Pressure of layer boundary.

T = Temperature of layer boundary.

WMOL(1-12) = Individual molecular species densities (see Table 8 for species).

WMOLX(1-13) = Heavy molecular species densities (see Table 9 for species).

JCHAR(1-14) = Control variables for selection of units for primary profile inputs (P, T and molecular constituents, see Table 8).

JCHARX = Single control variable for selection of units for entire set of CFCs and other heavy molecules. (See Table 9 for order and identification of these species).

By utilizing a choice of values for the JCHAR(J) control variable (where J = 1, 14) the user can designate specific units or accept defaults for the various molecular species and for the temperature and pressure. If JCHAR(J) is left blank the program will default to the values chosen by M1, M2, M3, M4, M5, M6 and MDEF when the given amount is zero. If the amount is non-zero and the JCHAR(J) is blank, the code assumes the first option on units: mb for pressure, K for temperature, and ppmv on constituents. The single unit option, JCHARX, follows the same rules, and for each altitude specified on **CARD 2C1**, the code will expect to find a full set (2 card images) containing values for the 13 species in the order specified by Table 8. These values are required only if MDEF=2.

Optional CARDS 2C, 2C1, 2C2, 2C2X, 2C3

For JCHAR(1),

- A indicates Pressure in (mb)
- B indicates Pressure in (atm)
- C indicates Pressure in (torr)
- 1-6 default to specified atmospheric MODEL value
- blank default to M1 (**CARD 1**) model atmosphere value

Table 8. The Association of the JCHAR(J) Index (J = 1, 14) with the Variables P, T and WMOL.

J	Variable	Species
1	P	pressure
2	T	temperature
3	WMOL(1)	water vapor (H ₂ O)
4	WMOL(2)	carbon dioxide (CO ₂)
5	WMOL(3)	ozone (O ₃)
6	WMOL(4)	nitrous oxide (N ₂ O)
7	WMOL(5)	carbon monoxide (CO)
8	WMOL(6)	methane (CH ₄)
9	WMOL(7)	oxygen (O ₂)
10	WMOL(8)	nitric oxide (NO)
11	WMOL(9)	sulfur dioxide (SO ₂)
12	WMOL(10)	nitrogen dioxide(NO ₂)
13	WMOL(11)	ammonia (NH ₃)
14	WMOL(12)	nitric acid (HNO ₃)

Table 9. Various Names for the Heavy Molecular Gases, (WMOLX(J), J = 1, 13).

1	CCl ₃ F	F11	CFC-11
2	CCl ₂ F ₂	F12	CFC-12
3	CClF ₃	F14	CFC-13
4	CF ₄	F14	CFC-14
5	CHClF ₂	F22	CFC-22
6	C ₂ Cl ₃ F ₃	F113	CFC-113
7	C ₂ Cl ₂ F ₄	F114	CFC-114
8	C ₂ ClF ₅	F115	CFC-115
9	ClONO ₂		
10	HNO ₄		
11	CHCl ₂ F		
12	CCl ₄		
13	N ₂ O ₅		

For JCHAR(2),

Optional CARDS 2C, 2C1, 2C2, 2C2X, 2C3

- A indicates ambient temperature in degrees K
- B indicates ambient temperature in degrees C
- 1-6 will default to specified atmospheric MODEL value
- blank default to M1 (**CARD 1**) model atmosphere value

For JCHAR(3-14),

- A indicates Volume mixing ratio (ppmv)
- B indicates Number density (molecules/cm³)
- C indicates Mass mixing ratio (gm/kg)
- D indicates Mass density (gm/m³)
- E indicates Partial pressure (mb)
- F indicates Dew point temperature (TD in T[K]) - H₂O only
- G indicates Dew point temperature (TD in T[C]) - H₂O only
- H indicates Relative humidity (RH in percent) - H₂O only
- 1-6 will default to specified model atmosphere
- blank default to **CARD 1** model atmosphere values
(M2 for H₂O; M3 for O₃; M4 for CH₄; M5 for N₂O; M6 for CO; otherwise, MDEF).

10.3 CARD 2C3

**CARD 2C3: AHAZE, EQLWCZ, RRATZ, IHA1, ICLD1, IVUL1, ISEA1, ICHR
FORMAT (10X, 3F10.3, 5I5)**

CARD 2C3 (for user-specified aerosol/cloud/rain models) is read when IRD2 is set to 1 on **CARD 2C**. The following instructions apply to MODTRAN3.5, as well as to more recent versions when IRD2 = 1. Instructions for IRD2 = 2 are given in Appendix A.

If AHAZE is positive, EQLWCZ is ignored.

- AHAZE Aerosol or cloud scaling factor (equal to the visible [wavelength of 0.55 μm] extinction coefficient [km^{-1}] at altitude ZM)
- EQLWCZ Equivalent liquid water content (GM / m^3) at altitude ZM for the aerosol, cloud or fog models
- RRATZ Rain rate (mm / hr) at altitude ZM

Optional CARDS 2C, 2C1, 2C2, 2C2X, 2C3

Only one of IHA1, ICLD1 or IVUL1 is allowed:

- IHA1 Aerosol model extinction and meteorological range control for the altitude, ZM. See IHAZE (**CARD 2**) for options.
- ICLD1 Cloud extinction control for the altitude, ZM; see ICLD (**CARD 2**) for options. When using ICLD1 it is necessary to set ICLD to the same value as the initial input of ICLD1.
- IVUL1 Stratospheric aerosol profile and extinction control for the altitude ZM; see IVULCN (**CARD 2**) for options.

The precedent order of these parameters (IHA1, ICLD1 and IVUL1) is as follows:

- If (IHA1 > 0) then others ignored
- If (IHA1 = 0) and (ICLD1 > 0) then use ICLD1
- If (IHA1 = 0) and (ICLD1 = 0) then use IVUL1

If AHAZE and EQLWCZ are both zero, the default profile is loaded from IHA1, ICLD1, IVUL1.

- ISEA1 Aerosol season control for the altitude, ZM, see ISEASN (**CARD 2**) for options.
- ICHR Used to indicate a boundary change between 2 or more adjacent user defined aerosol or cloud regions at altitude ZM (required for IHAZE = 7 or ICLD = 11).
- ICHR = 0 no boundary change in user defined aerosol or cloud regions (regions are not adjacent).
- = 1 signifies the boundary change in adjacent user defined aerosol or cloud regions.

NOTE: ICHR internally defaults to 0 if (IHA1 ≠ 7) or (ICLD1 ≠ 11).

11. OPTIONAL CARDS 2D, 2D1, 2D2 (USER-DEFINED AEROSOL AND CLOUD PARAMETERS)

These cards allow the user to specify the aerosol and cloud parameters (extinction and absorption coefficients and asymmetry parameter) for any or all four of the aerosol altitude regions. They are only read if IHAZE = 7 or ICLD = 11 are specified on **CARD 2**.

THE FOLLOWING INSTRUCTIONS ONLY APPLY WHEN PARAMETER ARUSS (CARD 2) IS NOT SET TO 'USS'. WHEN ARUSS EQUALS 'USS', SEE APPENDIX A FOR INSTRUCTIONS.

11.1 CARD 2D

CARD 2D: **(IREG(N), N = 1, 4)** (If IHAZE = 7 or ICLD = 11)
 FORMAT (415)

IREG specifies in which of the four altitude regions a user-defined aerosol or cloud model is used (IHAZE = 7 / ICLD = 11). It controls the number of pairs of **CARDs 2D1** and **2D2** read in (1 pair for each region for which IREG(N) = 1).

The region boundary altitudes default to 0-2, 3-10, 11-30, 35-100 km but can be overridden with 'IHA1' (**CARD 2C3**) with MODEL = 7 (See Section 7 for a more complete description of the default aerosol regions).

IREG(N)	=	0	Use default values for the region N, N = 1, 2, 3 and 4.
	=	1	Read extinction, absorption, and asymmetry parameter for the region.

11.2 CARD 2D1

CARD 2D1 and **CARD 2D2** are read sequentially once for each of the four aerosol regions for which $I_{REG}(N) = 1$.

CARD 2D1: **AWCCON, TITLE**
 FORMAT (E10.3, 18A4)

AWCCON is a conversion factor from extinction coefficient (km^{-1}) to equivalent liquid water content (gm/m^3). It is numerically equal to the equivalent liquid water content corresponding to an extinction coefficient of 1.0 km^{-1} , at a wavelength of $0.55 \mu\text{m}$. **AWCCON** has units of (km gm m^{-3}).

TITLE for an aerosol or cloud region (up to 72 characters)

11.3 CARD 2D2

CARD 2D2: **(VARSPC(I), EXTC(N, I), ABSC(N, I), ASYM(N, I), I = 1, 47)**
 FORMAT (3(F6.2, 2F7.5, F6.4))

CARD 2D2 consists of 47 sets of 4 numbers (3 sets or 12 numbers per line) in each aerosol region N for which $I_{REG}(N)$ is 1 (See Appendix A for the meaning of $I_{REG}(N) > 1$. There are no corresponding **CARDs 2D1** and **2D2** if $I_{REG}(N) = 0$.

This card is for input of user-defined aerosol or cloud extinction and absorption coefficients when $I_{HAZE} = 7$ or $I_{CLD} = 11$.

VARSPC(I) = Wavelengths for the aerosol or cloud coefficients. If $I_{REG}(N)$ is 1, the wavelengths from Table 10 must be entered (actually, the input values are not used and the Table 10 entries are assumed). For $I_{REG}(N) > 1$, see Appendix A.

EXTC(N, I) = Aerosol or cloud extinction coefficients, normalized so that **EXTC** for a wavelength of $0.55 \mu\text{m}$ is 1.0 km^{-1} .

ABSC(N, I) = Aerosol or cloud absorption coefficient, normalized so that **EXTC** for a wavelength of $0.55 \mu\text{m}$ is 1.0 km^{-1} .

ASYM(N, I) = Aerosol or cloud asymmetry parameter.

Table 10. VARSPC Array of Fixed (Required) Wavelengths for the Multiply Read CARD 2D2.

Index	Wavelength	Index	Wavelength
1	.2000	25	9.0000
2	.3000	26	9.2000
3	.3371	27	10.0000
4	.5500	28	10.5910
5	.6943	29	11.0000
6	1.0600	30	11.5000
7	1.5360	31	12.5000
8	2.0000	32	14.8000
9	2.2500	33	15.0000
10	2.5000	34	16.4000
11	2.7000	35	17.2000
12	3.0000	36	18.5000
13	3.3923	37	21.3000
14	3.7500	38	25.0000
15	4.5000	39	30.0000
16	5.0000	40	40.0000
17	5.5000	41	50.0000
18	6.0000	42	60.0000
19	6.2000	43	80.0000
20	6.5000	44	100.0000
21	7.2000	45	150.0000
22	7.9000	46	200.0000
23	8.2000	47	300.0000
24	8.7000		

Note: In MODTRAN4, this array contains the wavelengths at which the spectral data are read in when IREG(N) = 1. The spectral grid of built-in cloud data is now much finer with 788 points. The aerosol optical properties are also tabulated at the 788 grid points, but the data is simply an interpolation of the lower resolution data. This array is retained for backward compatibility with earlier tape5's.

12. OPTIONAL CARDS 2E1 AND 2E2 (USER-DEFINED CLOUD PARAMETERS)

The following cards, used with the alternate **CARD 2A**, permit the user to control parameters for non-cirrus clouds. **CARD 2E1** is read if $\text{NCRALT} \geq 3$, and **CARD 2E2** is read if $\text{NCRSPC} \geq 2$ on **CARD 2A**.

12.1 CARD 2E1

CARD 2E1: (ZCLD(I, 0), CLD(I, 0), CLDICE(I, 0), RR(I, 0), I = 1, NCRALT)
FORMAT ((4F10.5)) (If ICLD = 1 - 10, NCRALT ≥ 3)

A series of these **CARD 2E1** inputs is used to set up user-defined cloud/rain profiles, one card per layer boundary. The profile parameters being set are all arrays. If the alternate **CARD 2A** inputs CTHIK, CALT, CCOLWD and CCOLIP are all assigned negative values, MODTRAN calculations are performed using the user-defined cloud/rain profiles exactly as input. However, the **CARD 2A** variables can be used to study the effect of changing the input cloud's thickness, altitude or column amounts.

ZCLD(I, 0) Altitude above ground level of layer boundary I for the user-defined cloud/rain profile [KM].

ZCLD(1, 0) can be 0., and this is necessary if it is raining on the ground. The model also allows the cloud to actually sit on the ground. The ZCLD must monotonically increase. Also, a fatal error will result if the highest cloud altitude, ZCLD(NCRALT, 0), is above the top of the MODTRAN atmosphere (100 km above sea level for the model atmospheres).

CLD(I, 0) Liquid water droplet density at altitude ZCLD(I, 0) [g/m^3].

The liquid water droplet densities cannot be negative. MODTRAN models the densities as varying linearly between altitudes. The entire CLD array is scaled if the **CARD 2A** variable CCOLWD is assigned a non-negative value.

CLDICE(I,0) Ice particle density at altitude ZCLD(I, 0) [g/m^3]

Optional CARDS 2E1 and 2E2

The ice particle densities cannot be negative. MODTRAN models the densities as varying linearly between altitudes. The entire CLDICE array is scaled if the **CARD 2A** variable CCOLIP is assigned a non-negative value.

RR(I, 0) Rain rate at altitude ZCLD(I, 0) [mm/hr]

The rain rates can not be negative. If a rain rate is entered through **CARD 2** (variable RAINRT), that constant rain rate supersedes this parameter. Thus, if a user-defined rain rate profile is desired, variable RAINRT must not be positive.

12.2 CARD 2E2

CARD 2E2: (WAVLEN(I), EXTC(6, I), ABSC(6, I), ASYM(6, I),
 EXTC(7, I), ABSC(7, I), ASYM(7, I), I = 1, NCRSPC)
 FORMAT(7F10.5) (If ICLD = 1 - 10, NCRSPC ≥ 2)

The **CARD 2E2** variables are used to input user-defined cloud spectral data arrays. If the **CARD 2A** inputs CEXT, ASYMWD and ASYMIP all specify the use of defaults, MODTRAN uses these spectral data exactly as input. However, if a positive vertical cloud extinction, CEXT, is input, the extinction and absorption coefficients curves are scaled. Similarly, if the **CARD 2A** asymmetry factors ASYMWD and ASYMIP have magnitude less than one, they supersede the ASYM(6, I) and ASYM(7, I) values, respectively.

WAVLEN(I) Wavelength [μm] I in the spectral grid.

The first wavelength, WAVLEN(1), can be as low as 0.0 μm , and the wavelengths must be entered in increasing order. If a positive vertical cloud extinction (CEXT) is input on **CARD 2A**, the reference wavelength (CWAVLN or 0.55 μm) must be between WAVLEN(1) and WAVLEN(NCRSPC) inclusive, or else MODTRAN execution will be terminated with an error message.

EXTC(6, I) Liquid water droplet extinction coefficient at wavelength WAVLEN(I)
 [$\text{km}^{-1} \text{m}^3 / \text{g}$]

If a negative value is input, EXTC(6, I) is assigned the wavelength-interpolated extinction coefficient from the default data for cloud model ICLD.

Optional CARDS 2E1 and 2E2

ABSC(6, I) If positive: liquid water droplet absorption coefficient at wavelength WAVLEN(I) [$\text{km}^{-1} \text{m}^3 / \text{g}$]
If negative: liquid water droplet scattering albedo, minus 1, at wavelength WAVLEN(I)

If the input value for ABSC(6, I) is less than -1 or if it exceeds the extinction coefficient at WAVLEN(I), ABSC(6, I) is calculated by first determining the default absorption to extinction ratio for cloud model ICLD, and then multiplying EXTC(6, I) by this ratio. This is equivalent to assuming that the liquid water model cloud single scatter albedo (T) should be used to determine the absorption coefficient. A negative value for ABSC(6, I) not less than -1 is taken to be the negative of one minus the liquid water droplet scattering albedo, $-(1-T)$.

ASYM(6, I) Liquid water droplet Henyey-Greenstein scattering phase function asymmetry factor at wavelength WAVLEN(I)

These inputs are ignored if the magnitude of the **CARD 2A** input ASYMWD is less than one. If ASYM(6, I) is also not between -1. and 1., ASYM(6, I) is assigned the wavelength interpolated value from cloud model ICLD.

EXTC(7, I) Ice particle extinction coefficient at WAVLEN(I) [$\text{km}^{-1} \text{m}^3 / \text{g}$]

If a negative value is input, EXTC(7, I) is assigned the wavelength interpolated extinction coefficient from the standard cirrus cloud model (ICLD = 18).

ABSC(7, I) If positive: Ice particle absorption coefficient at wavelength WAVLEN(I) [$\text{km}^{-1} \text{m}^3 / \text{g}$]
If negative: Ice particle scattering albedo minus 1 at WAVLEN(I)

If the input value for ABSC(7, I) is less than -1 or if it exceeds the extinction coefficient at WAVLEN(I), ABSC(7, I) is calculated by first determining the default absorption to extinction ratio for the standard cirrus cloud model (ICLD = 18), and then multiplying EXTC(7, I) by this ratio. This is equivalent to assuming that the standard cirrus cloud model single scatter albedo (T) should be used to determine the absorption coefficient. A negative value for ABSC(7, I) not less than -1 is taken to be the negative of one minus the ice particle scattering albedo, $-(1-T)$.

ASYM(7, I) Ice particle Henyey-Greenstein scattering phase function asymmetry factor at wavelength WAVLEN(I)

Optional CARDS 2E1 and 2E2

These inputs are ignored if the magnitude of the **CARD 2A** input ASYMIP is less than one. If ASYM(7, I) is also not between -1. and 1., ASYM(7, I) is assigned the wavelength interpolated value from the standard cirrus cloud model (ICLD = 18).

13. CARD 3 (REQUIRED) – LINE-OF-SIGHT GEOMETRY

13.1 Standard CARD 3

CARD 3: H1, H2, ANGLE, RANGE, BETA, RO, LENN, PHI
FORMAT (6F10.3, I5, 5X, F10.3)

CARD 3 is used to define the geometrical path parameters for a given problem.

H1 = initial altitude (km)
H2 = final altitude (km) (for ITYPE = 2)
 = tangent height (km) (for ITYPE = 3)

It is important to emphasize here that in the radiance mode of program execution (IEMSCT = 1 or 2) H1, the initial altitude, always defines the position of the observer (or sensor). H1 and H2 cannot be used interchangeably as in the transmittance mode.

ANGLE = initial zenith angle (degrees) as measured from H1
RANGE = path length (km)
BETA = earth center angle subtended by H1 and H2 (degrees)
RO = radius of the earth (km) at the particular latitude at which the calculation is to be performed.

If RO is left blank, the program will use the mid-latitude value of 6371.23 km if MODEL is set equal to 7. Otherwise, the earth radius for the appropriate standard model atmosphere (specified by MODEL) will be used as shown in Table 11.

LENN = switch to determine short and long paths for cases 2a and 2e as described below.

If LENN = 1, path will be "long", extending through the tangent height.

If LENN = 0 (default), path will be "short".

PHI = zenith angle at H2 (target or final altitude) towards H1 (sensor or initial altitude)

Table 11. Default Values of the Earth Radius for Different Model Atmospheres.

Model	Model Atmosphere	Earth Radius, RO (km)
0	User-defined (Horizontal Path)	Not used
1	Tropical	6378.39
2	Mid-latitude summer	6371.23
3	Mid-latitude winter	6371.23
4	Sub-arctic summer	6356.91
5	Sub-arctic winter	6356.91
6	U. S. Standard	6371.23
7	User-defined	6371.23

It is not necessary to specify every variable on **CARD 3**; only those that adequately describe the problem according to the parameter ITYPE, as described below (also see Table 12).

(1) Horizontal Paths (ITYPE = 1)

(a) specify H1, RANGE

(b) If non-standard meteorological data are to be used, that is, if MODEL = 0 on **CARD 1**, then refer to the instructions for **CARD 2C** for a detailed explanation.

(2) Slant Paths Between Two Arbitrary Altitudes (ITYPE = 2)

(a) specify H1, H2, ANGLE, and LENN (LENN only if H2 < H1)

(b) specify H1, ANGLE, and RANGE

(c) specify H1, H2, and RANGE

(d) specify H1, H2, and BETA

(e) specify H2, H1, PHI, and LENN (LENN only if H1 < H2)

(f) specify H2, PHI, and RANGE

(3) Slant Paths to Space (ITYPE = 3)

(a) specify H1 and ANGLE

(b) specify H1 and H2 (for limb-viewing problem where H2 is the tangent height or minimum altitude of the path trajectory).

(c) specify H2 and PHI (here H1 = space)

CARD 3 (Required)

For ITYPE = 2, the following scheme is used to classify geometry inputs:

```

If (PHI>0 and RANGE>0) THEN
  CASE 2f
ELSE IF (PHI>0) THEN
  CASE 2e
ELSE IF (BETA>0) THEN
  CASE 2d
ELSE IF (RANGE>0 AND ANGLE>0) THEN
  CASE 2b
ELSE IF (RANGE>0) THEN
  CASE 2c
ELSE
  CASE 2a
END IF
  
```

For ITYPE = 3, a similar scheme is used:

```

IF (PHI>0) THEN
  CASE 3c
ELSE IF (H2 = 0) THEN
  CASE 3a
ELSE
  CASE 3b
END IF
  
```

Table 12 lists the **CARD 3** options provided to the user for the different types of atmospheric paths.

Table 12. Allowed Combinations of Slant Path Parameters.

Case	H1	H2	Angle	Range	BETA	LENN (Optional)	PHI
2a	*	*	*			(*)	
2b	*		*	*			
2c	*	*		*			
2d	*	*			*		
2e	*	*				(*)	*
2f		*		*			*
3a	*		*				
3b	*	*					
3c	*	*					*

LENN is used only when H1 > H2 and Case 2a, or H2 > H1 and Case 2e. Otherwise, LENN is automatically set in the program.
 * Required Inputs.

13.2 Alternate CARD 3 (TRANSMITTED SOLAR / LUNAR IRRADIANCE, IEMSCT = 3)

For calculating directly transmitted solar or lunar irradiance, an ITYPE = 3 path is assumed and CARD 3 has the following form:

**ALT CARD 3: H1, H2, ANGLE, IDAY, RO, ISOURC, ANGLEM
FORMAT (3F10.3, 15, 5X, F10.3, 15, F10.3)**

H1	=	altitude of the observer
H2	=	tangent height of path to sun or moon
ANGLE	=	apparent solar or lunar zenith angle at H1
IDAY	=	day of the year, used to correct for variation in the earth-to-sun distance
RO	=	radius of earth (default according to MODEL)
ISOURC	=	0 extraterrestrial source is the sun
	=	1 extraterrestrial source is the moon
ANGLEM	=	phase angle of the moon, that is, the angle formed by the sun, moon, and earth (required if ISOURC = 1; note that ISOURC = 0 refers to the sun as described by CARD 3A1)

Either H2 or ANGLE should be specified. If both are given as zero, then a vertical path (ANGLE = 0) is assumed. If both are greater than zero, the scheme for ITYPE = 3 is invoked. If IDAY is not specified, then the mean earth to sun distance is assumed.

If the apparent solar zenith angle is not known for a particular case, then the solar scattering option (IEMSCT = 2) may be used along with, for instance, the observer's location, day of the year and time of day to determine the solar zenith angle (see instructions for CARDS 3A1 and 3A2). Note that the apparent solar zenith angle is zenith angle at H1 of the refracted path to the sun and is less than the astronomical solar zenith angle. The difference between the two angles is small for angles less than 80°.

Optional CARDS 3A1 and 3A2

For IPARM = 1:

The parameters IDAY (**CARD 3**) and TIME must be specified. This option cannot be used with ISOURC = 1, which refers to the moon as the source.

- PARM1 = observer latitude (-90° to $+90^{\circ}$)
- PARM2 = observer longitude (0° to 360° , west of Greenwich)
- PARM3, PARM4 are not required

For IPARM = 2:

- PARM1 = azimuth angle between the observers line-of-sight and the observer-to-sun path, measured from the line of sight, positive east of north, between -180° and 180°
- PARM2 = the solar zenith angle at H1 (the observer)
- PARM3, PARM4 are not required

Note that the calculated apparent solar zenith angle is the zenith angle at H1 of the refracted path to the sun and is less than the astronomical solar zenith angle. The difference between the two angles is negligible for angles less than 80 degrees.

For IPARM = 10:

- PARM1 = latitude at H2
- PARM2 = longitude at H2
- PARM3 = source (sun or moon) latitude
- PARM4 = source (sun or moon) longitude
- PSIPO = true path azimuth from H2 to H1

For IPARM = 11:

- PARM1 = latitude at H2
- PARM2 = longitude at H2
- TIME = Greenwich time
- PSIPO = true path azimuth from H2 to H1

For IPARM = 12:

- PARM1 = relative solar azimuth (degrees East of North) at H2
- PARM2 = solar zenith (degrees) at H2

Table 13. CARD 3A2: Options for Different Choices of IPARM.

IPARM	0	1	2	10	11	12
PARM1	Observer Latitude (-90° to +90°)	Observer Latitude (-90° to +90°)	Azimuth Angle Between Observer LOS & Observer to Sun Path	Latitude at H2 (-90° to +90°)	Latitude at H2 (-90° to +90°)	Relative Solar Azimuth at H2 (Degrees East of North)
PARM2	Observer Longitude (0° to 360° West of Greenwich)	Observer Longitude (0° to 360° West of Greenwich)	Solar Zenith Angle	Longitude at H2 (Degrees West of Greenwich)	Longitude at H2 (Degrees West of Greenwich)	Solar Zenith at H2 (Degrees)
PARM3	Source Latitude	-	-	Source Latitude	-	-
PARM4	Source Longitude	-	-	Source Longitude	-	-
TIME	-	Greenwich Time (Decimal Hours)	-	-	Greenwich Time (Decimal Hours)	-
PSIPO	True Path Azimuth Angle from H1 to H2 (Degrees East of Due North)	True Path Azimuth Angle from H1 to H2 (Degrees East of Due North)	-	True Path Azimuth Angle from H2 to H1 (Degrees East of Due North)	True Path Azimuth Angle from H2 to H1 (Degrees East of Due North)	-
ANGLEM (only if ISOURC = 1)	Lunar Phase Angle	-	Lunar Phase Angle	Lunar Phase Angle	-	Lunar Phase Angle
G (only if IPH = 0)	Asymmetry Parameter (-1 to +1) for use with Henyey-Greenstein Phase Function	Asymmetry Parameter (-1 to +1) for use with Henyey-Greenstein Phase Function	Asymmetry Parameter (-1 to +1) for use with Henyey-Greenstein Phase Function	Asymmetry Parameter (-1 to +1) for use with Henyey-Greenstein Phase Function	Asymmetry Parameter (-1 to +1) for use with Henyey-Greenstein Phase Function	Asymmetry Parameter (-1 to +1) for use with Henyey-Greenstein Phase Function

The remaining control parameters are:

- TIME = Greenwich time in decimal hours, that is, 8:45 a.m. is 8.75, 5:20 p.m. is 17.33 etc. (used with IPARM = 1 or 11)
- PSIPO = Path azimuth (degrees east of north, that is, due north is 0.0° due east is 90.0° etc. (used with IPARM = 0, 1, 10, or 11)
- ANGLEM = Phase angle of the moon, that is, the angle formed by the sun, moon, and earth (required only if ISOURC = 1)
- G = asymmetry factor for use with Henyey-Greenstein phase function (only used with IPH = 0); +1 for complete forward scattering, 0 for isotropic or symmetric scattering, and -1 for complete back scattering.

15. OPTIONAL CARDS 3B1, 3B2, 3C1-3C6 (USER-DEFINED SCATTERING PHASE FUNCTIONS)

These input cards are for entering user-defined phase functions when IPH = 1 (**CARD 3A1**). The following instructions apply when the ARUSS (**CARD 2**) is not set to 'USS'. Instructions for the MODTRAN3.7 / MODTRAN4 upgrade (ARUSS = 'USS') are provided in Appendix A.

15.1 CARD 3B1

CARD 3B1: **NANGLS** (If IPH = 1 on **CARD 3A1**)
 FORMAT (I5)

NANGLS = number of angles for the user-defined phase functions (maximum of 50).

15.2 CARD 3B2

This card is repeated NANGLS times (1 to NANGLS).

CARD 3B2: (**ANGF(I), F(1, I, 1), F(2, I, 1), F(3, I, 1), F(4, I, 1), I = I, NANGLS**)
 FORMAT ((5E10.3))

ANGF(I) = scattering angle in decimal degrees (0.0° to 180.0°)

F(1, I, 1) = user-defined phase function at ANGF(I), boundary layer (0 to 2 km default altitude region)

F(2, I, 1) = user-defined phase function at ANGF(I), troposphere (2 to 10 km default altitude region)

F(3, I, 1) = user-defined phase function at ANGF(I), stratosphere (10 to 30 km default altitude region)

F(4, I, 1) = user-defined phase function at ANGF(I), mesosphere (30 to 100 km default altitude region)

The default altitude regions may be overridden by the parameters IHA1, ICLD1 or IVUL1 (**CARD 2C3**). The third index, which is 1 here, is introduced to make scattering phase functions wavelength dependent in MODTRAN3.7/4. There was no wavelength dependence prior to MODTRAN3.7.

15.3 CARDs 3C1-3C6

These cards are used only with the MODTRAN3.7 / MODTRAN4 upgrade; see Appendix A.

16. CARD 4 (REQUIRED) - SPECTRAL RANGE AND RESOLUTION

This card specifies the spectral range, frequency/wavelength increments, and spectral degradation of the outputs using a slit function. The default slit function, which is used when FLAGS(1:2) are blanks, is triangular and defined on a discrete wavenumber grid. Setting FLAGS(1:4) accesses a set of alternate, continuous slit functions, which may be defined in various frequency or wavelength units. The outputs from the alternate slit functions are written to the files 'tape7.scn' and 'pltout.scn'

CARD 4: V1, V2, DV, FWHM, YFLAG, XFLAG, DLIMIT, FLAGS FORMAT (4F10.0, 2A1, A8, A7)

- V1 Initial frequency in wavenumber [cm^{-1}] or, alternatively, wavelength in units defined via FLAGS(1:1)
- V2 Final frequency (or wavelength)
- DV Frequency (or wavelength) increment used for spectral outputs. DV applies to all output files when using the default slit function, i.e., FLAGS(1:4) is blank. Otherwise, DV is applied to tape7.scn and pltout.scn, and the frequency increment for the other files (tape6, tape7, tape8 and pltout) is set to the calculation bin size. **Unless only bandpass information is required, DV should not exceed FWHM for MODTRAN runs to avoid under sampling in the output spectra.** The recommended value for DV is $\text{FWHM} / 2$.
- FWHM Slit function Full Width at Half Maximum. FLAGS(1:1) is the unit specifier. For the MODTRAN band model, the maximum FWHM value is 50 times calculation bin size (1 cm^{-1} or 15 cm^{-1}). The type of slit function is defined in FLAGS. A minimum of twice the bin size (2 cm^{-1} for the standard 1 cm^{-1} bin size) will insure proper sampling. No convolution is performed if FWHM equals the bin size and the default slit function is selected.
- YFLAG = T Transmittances are output in pltout [*rootname.plt*] and pltout.scn [*rootname.psc*].
 = R Radiances (instead of transmittances) are output in pltout [*rootname.plt*] and pltout.scn [*rootname.psc*].
- XFLAG controls the units for output files pltout and pltout.scn:
- XFLAG = W Frequency in wavenumbers; radiances in $\text{W}/\text{sr}/\text{cm}^2/\text{cm}^{-1}$.
 = M Wavelength in microns; radiances in $\text{W}/\text{sr}/\text{cm}^2/\mu\text{m}$.
 = N Wavelength in nanometers; radiances in $\mu\text{W}/\text{sr}/\text{cm}^2/\text{nm}$.
- DLIMIT Character string, up to 8 characters long. Used in pltout [*rootname.plt*] and pltout.scn [*rootname.psc*] to separate output from repeat (sequential) MODTRAN runs.
- FLAGS: A string of seven characters, each defined below. If FLAGS(1:2) (the first two characters) are both blank, the default slit function is used and FLAGS(3:7) are

ignored. Otherwise, an alternative slit function is used and the results are written to `pltout.scn` [*rootname.psc*] and `tape7.scn` [*rootname.7sc*].

FLAGS(1:1) defines the spectral units for input parameters V1, V2, DV and FWHM and output files `pltout.scn` [*rootname.psc*] and `tape7.scn` [*rootname.7sc*].

FLAGS(1:1)	= blank	Default spectral units in wavenumbers.
	= W	Spectral units in wavenumbers.
	= M	Spectral units in microns.
	= N	Spectral units in nanometers.
FLAGS(2:2)	= blank	Default slit function (triangular).
	= 1 or T	Triangular slit function.
	= 2 or R	Rectangular slit function.
	= 3 or G	Gaussian slit function.
	= 4 or S	Sinc slit function.
	= 5 or C	Sinc ² slit function.
	= 6 or H	Hamming slit function.
	= 7 or U	User-supplied function.
FLAGS(3:3)	= blank or A	FWHM is absolute.
	= R	FWHM is percent relative, i.e., $FWHM = 100 dv/v = 100 d\lambda/\lambda$.
FLAGS(4:4)	= blank	Degrade only total radiance and transmittance.
	= A	Degrade all radiance and transmittance components.
FLAGS(5:5)	= s or S	Save non-degraded results for degrading later.
	= blank	Do not save current results.
FLAGS(6:6)	= r or R	Use saved results for degrading with the current slit function.
	= blank	Do not use saved results.
FLAGS(7:7)	= t or T	Use no more than 80 characters per line in spectral flux table (i.e., include line feeds for each spectral point). These files can be quite large since they include flux data at every atmospheric level (altitude) and spectrally gridded based on the input DV (CARD4) value.
	= f or F	For each spectral point, all flux values are on a single line (i.e., there are no line feeds). [A warning is warranted here: Some FORTRAN compilers limit the number of characters per line and setting FLAGS(7:7) to FALSE can cause this limit to be exceeded.]
	= blank	Do not write a spectral flux table.

CARD 4 (Required)

The scanning / slit functions as chosen by FLAGS(2:2) are defined below. All built-in scanning functions are symmetrical about the central spectral wavelength ($\delta_o = \lambda_o$) or frequency ($\delta_o = \nu_o$) [the unit is specified by FLAGS (1:1)]. Let Δ be the FWHM along the frequency-axis:

Triangular

$$F_{d_o, \Delta}(\mathbf{d}) = \frac{1}{\Delta} \left(1 - \frac{|\mathbf{d} - \mathbf{d}_o|}{\Delta} \right) ; \quad |\mathbf{d} - \mathbf{d}_o| < \Delta \quad (=0 \text{ elsewhere})$$

Square

$$F_{d_o, \Delta}(\mathbf{d}) = \frac{1}{\Delta} ; \quad |\mathbf{d} - \mathbf{d}_o| < \frac{\Delta}{2} \quad (=0 \text{ elsewhere})$$

Gaussian

$$F_{d_o, \Delta}(\mathbf{d}) = \frac{s}{\sqrt{p}} e^{-s^2(\mathbf{d} - \mathbf{d}_o)^2} ; \quad s = \frac{2\sqrt{\ln 2}}{\Delta}$$

Sinc [$Sinc(x) \circ sin(px) / (px)$]

$$F_{d_o, \Delta}(\mathbf{d}) = s Sinc[s(\mathbf{d} - \mathbf{d}_o)] ; \quad s = \frac{1.2067}{\Delta}$$

Sinc²

$$F_{d_o, \Delta}(\mathbf{d}) = s Sinc^2[s(\mathbf{d} - \mathbf{d}_o)] ; \quad s = \frac{0.88589}{\Delta}$$

Hamming

$$F_{d_o, \Delta}(\mathbf{d}) = 0.230822 s \{ 2.33235 Sinc[s(\mathbf{d} - \mathbf{d}_o)] + Sinc[s(\mathbf{d} - \mathbf{d}_o) - 1] + Sinc[s(\mathbf{d} - \mathbf{d}_o) + 1] \} ;$$

$$s = \frac{0.88589}{\Delta}$$

17.2 CARD 4B1

CARD 4B1: CBRDF

FORMAT (A80)

(If *SURREF* = 'BRDF')

Character string *CBRDF* defines the name of number associated with a BRDF parameterization. Model names are case insensitive and leading blanks are ignored. Currently, there are 7 BRDF model options. The symmetric Walthall (Walthall, 1985) and symmetric Sinusoidal-Walthall are empirical models; the Hapke (Hapke, 1981; Hapke 1986), Rahman (Rahman *et al.*, 1993), Roujean (Roujean *et al.*, 1992), and Ross-Li (Wanner *et al.*, 1995; Wanner *et al.*, 1997; Lucht *et al.*, 1999) are all semi-empirical models; and the Pinty-Verstraete (Pinty and Verstraete, 1991) is a physical model. Generally, the BRDFs are numerically integrated to define surface albedo, directional (hemispheric) reflectivities and emissivities, and azimuth moments (required for interfacing to the DISORT multiple scattering routines); negative values of the BRDF (which can result from angular extrapolation of the measurement-based parameterizations) are replaced by 0. For the simple empirical models, an option to use analytic representations of the reflectance quantities is also provided.

The model descriptions below are primarily intended just to define the BRDF parameters expected by MODTRAN; the user should consult the original references for further details.

CBRDF = '2' or 'Walthall'

$$r(\mathbf{q}_v, \mathbf{q}_s, \Delta \mathbf{j}) = P_1 + P_2 \mathbf{q}_v \mathbf{q}_s \cos(\Delta \mathbf{j}) + P_3 \mathbf{q}_v^2 \mathbf{q}_s^2 + P_4 (\mathbf{q}_v^2 + \mathbf{q}_s^2)$$

where \mathbf{q}_v is the view zenith angle from the surface to the sensor (H1);

\mathbf{q}_s is the source zenith angle at the surface; and

$\Delta \mathbf{j}$ is the view-to-source relative azimuth angle from the surface.

CBRDF = '51' or 'Walthall(a)'

Analytically evaluated Walthall reflectance integrals.

CBRDF = '11' or 'Sine-Walthall'

$$\begin{aligned} r(\mathbf{q}_v, \mathbf{q}_s, \Delta \mathbf{j}) &= P_1' + P_2' \sin \mathbf{q}_v \sin \mathbf{q}_s \cos(\Delta \mathbf{j}) \\ &+ P_3' \sin^2 \mathbf{q}_v \sin^2 \mathbf{q}_s + P_4' (\sin^2 \mathbf{q}_v + \sin^2 \mathbf{q}_s) \end{aligned}$$

The sinusoidal Walthall form was introduced to facilitate Monte-Carlo sampling of photon trajectories. The sinusoidal Walthall parameters can be approximated from the Walthall parameters by equating zenith integrations, term-by-term. This lead to the following relationships:

$$\begin{aligned} P_1' &= P_1 & P_2' &= 9 \mathbf{p}^2 P_2 / 64 \\ P_3' &= (\mathbf{p}^2 / 4 - 1)^2 P_3 & P_4' &= (\mathbf{p}^2 / 4 - 1) P_4 \end{aligned}$$

CBRDF = '52' or 'Sine-Walthall(a)'

Analytically evaluated sinusoidal Walthall reflectance integrals.

CBRDF = '4' or 'Hapke'

$$r(\mathbf{q}_v, \mathbf{q}_s, \Delta \mathbf{j}) =$$

$$\frac{P_1 / 4}{\cos \mathbf{q}_v + \cos \mathbf{q}_s} \left\{ \left[1 + \frac{P_4 / P_1}{B(\cos \mathbf{f}, P_2, P_3)} \right] P_{HG}(\cos \mathbf{f}, P_2) + H(\cos \mathbf{q}_v, P_1) H(\cos \mathbf{q}_s, P_1) - 1 \right\}$$

$$\text{where } \cos \mathbf{f} = \cos \mathbf{q}_v \cos \mathbf{q}_s + \sin \mathbf{q}_v \sin \mathbf{q}_s \cos \Delta \mathbf{j}$$

$$P_{HG}(\cos \mathbf{f}, g) = \frac{1 - g^2}{(1 + g^2 + 2 g \cos \mathbf{f})^{3/2}}$$

$$B(\cos \mathbf{f}, g, h) = \frac{1 - g}{(1 + g)^2} \left[1 + \frac{\sqrt{(1 + \cos \mathbf{f}) / (1 - \cos \mathbf{f})}}{h} \right]$$

$$H(x, \mathbf{w}) = \frac{1 + 2 x}{1 + 2 x \sqrt{1 - \mathbf{w}}}$$

Parameter $P_1 = \mathbf{w}$ is the average single scattering albedo of the particles making up the surface; parameter $P_2 = g$ is the Henyey-Greenstein asymmetry factor ranging from -1 (backward scattering) to +1 (forward scattering); parameter $P_3 = h$ controls the width of the opposition effect (hot spot); and parameter $P_4 = S_H$ controls the magnitude of the opposition effect. [Note that the atmospheric radiative transport convention for the Henyey-Greenstein

variables has been adopted in these equations. The BRDF community generally represents the asymmetry factor with the symbol Θ (instead of g) and represents the scattering angle with the symbol g (instead of ϕ) – a confusing state of affairs to say the least.]

CBRDF = '5' or 'Rahman'

$$r(\mathbf{q}_v, \mathbf{q}_s, \Delta \mathbf{j}) = P_1 [\cos \mathbf{q}_v \cos \mathbf{q}_s (\cos \mathbf{q}_v + \cos \mathbf{q}_s)]^{P_3 - 1} P_{HG}(\cos \mathbf{f}, P_2) \left[1 + \frac{1 - P_1}{1 + G(\mathbf{q}_v, \mathbf{q}_s, \Delta \mathbf{j})}\right]$$

$$\text{where } G(\mathbf{q}_v, \mathbf{q}_s, \Delta \mathbf{j}) = \sqrt{\tan^2 \mathbf{q}_v + \tan^2 \mathbf{q}_s - 2 \tan \mathbf{q}_v \tan \mathbf{q}_s \cos \Delta \mathbf{j}}$$

Parameter $P_1 = r_o \geq 0$ characterizes the reflectance of the surface cover; parameter $P_2 = g$ is the Henyey-Greenstein asymmetry factor ranging from -1 (backward scattering) to $+1$ (forward scattering); and parameter $P_3 = k$ indicates the level of anisotropy of the surface.

CBRDF = '6' or 'Roujean'

$$r(\mathbf{q}_v, \mathbf{q}_s, \Delta \mathbf{j}) = P_1 + P_2 K_{geo}(\mathbf{q}_v, \mathbf{q}_s, \Delta \mathbf{j}) + \frac{4}{3p} P_3 K_{RT}(\mathbf{q}_v, \mathbf{q}_s, \Delta \mathbf{j})$$

$$\text{where } K_{geo} = \frac{(\mathbf{p} - \Delta \mathbf{j}) \cos \Delta \mathbf{j} + \sin \Delta \mathbf{j}}{2\mathbf{p}} \tan \mathbf{q}_v \tan \mathbf{q}_s - \frac{\tan \mathbf{q}_v + \tan \mathbf{q}_s + G(\mathbf{q}_v, \mathbf{q}_s, \Delta \mathbf{j})}{\mathbf{p}}$$

$$K_{RT} = \frac{(\mathbf{p}/2 - \mathbf{f}) \cos \mathbf{f} + \sin \mathbf{f}}{\cos \mathbf{q}_v + \cos \mathbf{q}_s} - \frac{\mathbf{p}}{4}$$

Parameter $P_1 = k_{Lamb}$ is the Lambertian scattering component and equal to the bidirectional reflectance for $\mathbf{q}_v = 0$ and $\mathbf{q}_s = 0$. Parameter $P_2 = k_{geo}$ is the coefficient of the geometric scattering kernel K_{geo} , and parameter $P_3 = k_{vol}$ is the coefficient for the RossThick volume scattering kernel K_{RT} , so called for its assumption of a dense leaf canopy.

CBRDF = '10' or 'Pinty-Verstraete'

$$r(\mathbf{q}_v, \mathbf{q}_s, \Delta \mathbf{j}) = \frac{P_1 / 4}{\cos \mathbf{q}_v + \mathbf{k}_v(P_3) \left(\frac{\cos \mathbf{q}_s}{\mathbf{k}_s(P_3)} \right)} * \left\{ T(\mathbf{q}_v, \mathbf{q}_s, \Delta \mathbf{j}, P_3, P_4) P_{HG}(\cos \mathbf{f}, P_2) + H \left[\left(\frac{\cos \mathbf{q}_v}{\mathbf{k}_v(P_3)} \right), P_1 \right] H \left[\left(\frac{\cos \mathbf{q}_s}{\mathbf{k}_s(P_3)} \right), P_1 \right] - 1 \right\}$$

where $T(\mathbf{q}_v, \mathbf{q}_s, \Delta \mathbf{j}, \mathbf{c}_l, r\Lambda) = 1 + \frac{1}{1 + \left(4 - \frac{16}{3p} \right) \left(\frac{\cos \mathbf{q}_v}{\mathbf{k}_v(\mathbf{c}_l)} \right) \left(\frac{G(\mathbf{q}_v, \mathbf{q}_s, \Delta \mathbf{j})}{r\Lambda} \right)}$

$$\mathbf{k}_x(\mathbf{c}_l) = 1 - \Psi(\mathbf{c}_l) + 1.754 \Psi(\mathbf{c}_l) \cos \mathbf{q}_x$$

$$\Psi(\mathbf{c}_l) = (1.2666 + 0.66 \mathbf{c}_l) \mathbf{c}_l; \quad x = v \text{ or } s$$

Parameter $P_1 = \mathbf{w}$ is the average single scattering albedo of the particles making up the surface; parameter $P_2 = g$ is the Henyey-Greenstein asymmetry factor ranging from -1 (backward scattering) to $+1$ (forward scattering); parameter $P_3 = \mathbf{c}_l$ is most negative (-0.4) for an erectophile canopy (mostly vertical scatterers), 0 . for a canopy with a uniform distribution (equal probability for all scatterer orientations), and most positive (0.6) for a planophile canopy (mostly horizontal scatterers); and parameter $P_4 = r\mathbf{L}$ is the product of r , the radius of the Sun flecks on the inclined scatterers, and \mathbf{L} , the scatterer area density of the canopy (expressed as the scatterer surface per unit bulk area). Note that the functions describing the orientation distribution of the scatterers for the illumination and viewing angles, \mathbf{k}_v and \mathbf{k}_s , are defined here as twice their normal value to be consistent with the definition of multiple scattering functions, $H(x, \mathbf{w})$.

CBRDF = '12' or 'Ross-Li'

$$\mathbf{r}(\mathbf{q}_v, \mathbf{q}_s, \Delta \mathbf{j}) = P_1 + P_2 K_{LSR}(\mathbf{q}_v, \mathbf{q}_s, \Delta \mathbf{j}, P_4, P_5) + P_3 K_{RT}(\mathbf{q}_v, \mathbf{q}_s, \Delta \mathbf{j})$$

where

$$K_{LSR} = \frac{1 + \sec \mathbf{q}'_v \sec \mathbf{q}'_s + \tan \mathbf{q}'_v \tan \mathbf{q}'_s \cos \Delta \mathbf{j}}{2} + \left(\frac{t - \sin t \cos t}{p} - 1 \right) (\sec \mathbf{q}'_v + \sec \mathbf{q}'_s)$$

$$\cos^2 t = \min \left\{ \left(\frac{P_4}{\sec \mathbf{q}'_v + \sec \mathbf{q}'_s} \right)^2 \left[G(\mathbf{q}'_v, \mathbf{q}'_s, \Delta \mathbf{j})^2 + (\tan \mathbf{q}'_v \tan \mathbf{q}'_s \sin \Delta \mathbf{j})^2 \right], 1 \right\}$$

$$\tan \mathbf{q}'_x = P_5 \tan \mathbf{q}_x; \quad x = v \text{ or } s$$

Parameter $P_1 = k_{Lamb}$ is the Lambertian scattering component and equal to the bidirectional reflectance for $\mathbf{q}_v = 0$ and $\mathbf{q}_s = 0$. Parameter $P_2 = k_{geo}$ is the coefficient of the LiSparse-Reciprocal geometric scattering kernel K_{LSR} , derived for a sparse ensemble of surface objects casting shadows on a Lambertian background. Parameter $P_3 = k_{vol}$ is the coefficient for the RossThick volume scattering kernel K_{RT} , so called for its assumption of a dense leaf canopy. The two constants, dimensionless crown relative height ($P_4 = h/b$) and shape ($P_5 = b/r$) parameters have been empirically obtained and should not be interpreted too literally. **The LiSparse-Reciprocal kernel has only been validated for $h/b = 2$ and $b/r = 1$. These are the recommended constant input values for parameters P_4 and P_5 , and the values that will be used to invert the angular radiance data from NASA's Moderate Resolution Imaging Spectroradiometer - MODIS (Justice *et al.*, 1998).**

17.3 CARD 4B2

CARD 4B2: *NWVSRF, SURFZN, SURFAZ*
FORMAT (*) (If *SURREF* = 'BRDF')

CARD 4B2 defines the number of BRDF spectral grid points and the direction of the surface normal. Currently, the surface normal is required to point upward; the surface normal inputs are included in anticipation of a future upgrade allowing modeling of a graded ground surface and/or arbitrarily oriented image facets.

<i>NWVSRF</i>	<i>Number of BRDF spectral grid points. If NWVSRF is set to 1, the BRDF will be spectrally independent. The maximum allowed value for NWVSRF is defined by the parameter MWVSRF in the PARAM.LST file. If necessary, the user can increase MWVSRF and then recompile MODTRAN. Upon delivery of MODTRAN, MWVSRF is set to 50.</i>
<i>SURFZN</i>	<i>The zenith angle [degrees] of the surface normal. Currently, only a value of 0. is supported.</i>
<i>SURFAZ</i>	<i>The true azimuth angle of the image pixel surface normal [0 for North, 90 for East, 180 for South, and 270 for East. This value is currently not used.</i>

17.4 CARD 4B3

CARD 4B3: *WVSURF, (PARAMS(I), I = 1, NPARAM)*
FORMAT (*) (If *SURREF* = 'BRDF')

CARD 4B3 defines the BRDF parameters on the input spectral grid and is repeated *NWVSRF* times.

<i>WVSURF</i>	<i>BRDF spectral wavelength [nm]. The wavelength grid must be input in increasing wavelength order.</i>
<i>PARAMS(I)</i>	<i>BRDF parameters at wavelength WVSURF. The Rahman and Roujean BRDF models are 3-parameter models. Ross-Li is also a 3 parameter model, although an additional two constants [PARAMS(4) = 2. and PARAMS(5) = 1.] are required as inputs (See Section 17.2 for further details). All other current BRDF models require 4 parameters. The parameters must be entered in the order specified by the model equations of Section 17.2, i.e., P_1, P_2, \dots</i>

17.5 CARD 4L1

CARD 4L1: SALBFL
FORMAT (A80) (If *SURREF* = 'LAMBER')

CARD 4L1 defines the name of the input data file being used to define the spectral albedo. Leading blanks are ignored. As noted above, input of **CARD 4L1** (followed by **CARD 4L2**) is repeated *NSURF* times.

SALBFL Name of the spectral albedo data file. The default spectral albedo file, 'DATA/spec_alb.dat' may be used or a user-supplied file. If a user-supplied file is specified, it must conform to the format described in the default file.

17.6 CARD 4L2

CARD 4L1: CSALB
FORMAT (A80) (If *SURREF* = 'LAMBER')

CARD 4L2 defines the number or name associated with a spectral albedo curve from the *SALBFL* file.

CSALB Number **or** name of a spectral albedo curve in the *SALBFL* file. There are currently 13 spectral albedo curves available in the default spectral albedo file 'DATA/spec_alb.dat'. Leading blanks are ignored. The 13 (case-insensitive) *CSALB* inputs for 'DATA/spec_alb.dat' are:

'1'	or	'snow cover'
'2'	or	'forest'
'3'	or	'farm'
'4'	or	'desert'
'5'	or	'ocean'
'6'	or	'cloud deck'
'7'	or	'old grass'
'8'	or	'decayed grass'
'9'	or	'maple leaf'
'10'	or	'burnt grass'
'21'	or	'constant5%'
'22'	or	'constant50%'
'31'	or	'CCM3 Sea ice'

18. CARD 5 (REQUIRED) – REPEAT RUN OPTION

CARD 5: IRPT FORMAT (I5)

Non-zero values of the control parameter IRPT cause MODTRAN to repeat program execution, so that a series of problems can be run with a single submission of tape5. *A message is written to standard output indicating a repeat run is beginning if a negative value of IRPT is input.*

- IRPT = 0 or blank STOP program.
- = ±1 read full set of new data cards followed by an additional **CARD 5**.
- = ±3 read new geometry (**CARD 3, ...**) and surface (**CARD 4A, ...**) inputs followed by an additional **CARD 5**.
- = ±4 read new spectral and surface (**CARD 4, ...**) inputs followed by an additional **CARD 5**.

The atmospheric profiles from the previous calculation are reused when the IRPT = ±3 or IRPT = ±4 options are selected. In these cases, the specific sequences of CARD inputs are as follows:

If IRPT = ±3

- CARD 5:** IRPT = ±3
- CARD 3:** H1, H2, ANGLE, RANGE, BETA, RO, LENN, PHI (If IEMSCCT < 3)
- CARD 3:** H1, H2, ANGLE, IDAY, RO, ISOURC, ANGLEM (If IEMSCCT = 3)
- CARD 3A1:** IPARM, IPH, IDAY, ISOURC (If IEMSCCT = 2)
- CARD 3A2:** PARM1, PARM2, PARM3, PARM4,
TIME, PSIPO, ANGLEM, G (If IEMSCCT = 2)
- CARD 3B1:** NANGLS, NWLF (If IPH = 1)
- CARD 3B2:** (ANGF(I), F(1, I, 1), F(2, I, 1), F(3, I, 1),
F(4, I, 1), I = 1, NANGLS), (If IPH = 1 and NWLF = 0)
- CARD 3C1:** (ANGF(I), I = 1, NANGLS) (If IPH = 1 and NWLF > 0)
- CARD 3C2:** (WLF(J), J = 1, NWLF) (If IPH = 1 and NWLF > 0)
- CARD 3C3:** (F(1, I, J), J = 1, NWLF) (If IPH = 1 and NWLF > 0)
- CARD 3C4:** (F(2, I, J), J = 1, NWLF) (If IPH = 1 and NWLF > 0)
- CARD 3C5:** (F(3, I, J), J = 1, NWLF) (If IPH = 1 and NWLF > 0)
- CARD 3C6:** (F(4, I, J), J = 1, NWLF) (If IPH = 1 and NWLF > 0)
- CARD 4A:** NSURF, AATEMP (If SURREF = 'BRDF' or 'LAMBER')
- CARD 4B1:** CBRDF (If SURREF = 'BRDF')
- CARD 4B2:** NWVSRF, SURFZN, SURFAZ (If SURREF = 'BRDF')
- CARD 4B3:** WVSURF, (PARAMS(I), I = 1, NPARAM) (If SURREF = 'BRDF')
- CARD 4L1:** SALBFL (If SURREF = 'LAMBER')
- CARD 4L2:** CSALB (If SURREF = 'LAMBER')
- CARD 5** IRPT = 0

CARD 5 (Required)

If IRPT = ±4

- CARD 5:** IRPT = ±4
- CARD 4** V1, V2, DV, FWHM, YFLAG, XFLAG, DLIMIT, FLAGS
- CARD 4A:** NSURF, AATEMP (If *SURREF* = 'BRDF' or 'LAMBER')
- CARD 4B1:** CBRDF (If *SURREF* = 'BRDF')
- CARD 4B2:** NWVSRF, SURFZN, SURFAZ (If *SURREF* = 'BRDF')
- CARD 4B3:** WVSURF, (PARAMS(I), I=1, NPARAM) (If *SURREF* = 'BRDF')
- CARD 4L1:** SALBFL (If *SURREF* = 'LAMBER')
- CARD 4L2:** CSALB (If *SURREF* = 'LAMBER')
- CARD 5** IRPT = 0

The final IRPT card should always be blank or contain a value of zero. Table 14 summarizes the user-control parameters on **CARD 5**. IRPT can be -1, -3, or -4, which are same as 1, 3, or 4. respectively with the exception that a message is printed to the screen each time a repeat run begins. The user is thus able more easily to follow the progress of an extensive series of calculations.

Table 14. MODTRAN CARD 5 Input Parameter: IRPT.

CARD 5	IRPT
COLUMNS 1-5	Format (I5)
0	End of program.
±1	Read full set of new CARDs .
±2	Not used (same as 0).
±3	Read new CARDs 3 and 5 plus optional CARDs .
±4	Read new CARDs 4 and 5 plus optional CARDs .

19. DEDICATION AND ACKNOWLEDGEMENTS

We dedicate this report to John Selby and the late Frank Kneizys whose pioneering work led to the development of the original LOWTRAN programs and formed the basis for the MODTRAN model. MODTRAN4 is just the latest in the series of AFRL atmospheric radiative transport band models. We also acknowledge the contributions of other early developers, from the AF Geophysics Laboratory: S.A. Clough, L.W. Abreu, and W.O. Gallery; and from Spectral Sciences, Inc.: D.C. Robertson.

Specifically for MODTRAN4, significant contributions have been made by the developers of the DISORT model, K.H. Stamnes (University of Alaska, Fairbanks, AK), N.F. Larsen (Raytheon ITSS, Lanham, MD), W. Wiscombe (NASA Goddard Space Flight Center, Greenbelt, MD), and S.-C. Tsay (NASA Goddard Space Flight Center, Greenbelt, MD). J. Qi (Michigan State University, East Lansing, MI), C.B. Schaaf (Boston University, Boston, MA), and N. Goldstein (Spectral Sciences, Inc., Burlington, MA) provided assistance and direction in the development of the MODTRAN4 BRDF model. H. Dothe (Spectral Sciences, Inc., Burlington, MA) helped develop the 15 cm⁻¹ MODTRAN band model and data file.

Contributions to earlier versions of the MODTRAN model include the 2-stream multiple scattering algorithm (R.G. Isaacs and R.D. Worsham, Atmospheric and Environmental Research, Inc., Cambridge, MA) and the Navy Oceanic Vertical Aerosol Model (NOVAM) (led by S.G. Gathman Space and Naval Warfare Center, SPAWAR). Modifications to the solar irradiance options were suggested by R. Kurucz and K. Chance (Smithsonian Observatory, Harvard University), M.E. VanHoosier (Naval Research Laboratory), A. Hall (AFRL), and G. Thuillier (Service d'Aeronomie du CNRS, France), among others. K. Minschwaner (New Mexico State Technical College) provided suggestions for an enhanced integration for the single scattered radiance implementation.

This work was funded by AFRL under contracts F19628-91-C-0145 and F19628-98-0050.

20. REFERENCES

- Abreu, L.W. and G.P. Anderson, "The MODTRAN 2/3 Report and LOWTRAN 7 Model", Prepared by Ontar Corporation for PL/GPOS (1996).
- Acharya, P.K., D.C. Robertson, and A. Berk, "Upgraded Line-of-Sight Geometry Package and Band Model Parameters for MODTRAN," PL-TR-93-2127, Geophysics Directorate/GPOS, 29 Randolph Rd., Hanscom AFB, MA 01731-3010 (May 1993).
- M. Allen (private communication to Gail P. Anderson, 1990).
- Anderson, G.P. and L.A. Hall, Solar Irradiance between 2000-3100 Angstroms with Spectral Band Pass Of 1 Angstroms, *J. Geophys. Res.*, 94D, 6435-6441 (1989).
- Berk, A., L.S. Bernstein, G.P. Anderson, P.K. Acharya, D.C. Robertson, J.H. Chetwynd and S.M. Adler-Golden, MODTRAN Cloud and Multiple Scattering Upgrades with Application to AVIRIS, *Remote Sens. Environ.* 65, 367-375 (1998).
- Berk, A. and G.P. Anderson, "Upgrades to MODTRAN Layer Cloud/Rain Models", SSI-SR-69, Spectral Sciences, Inc., 99 S. Bedford Street, Burlington, MA 01803, (1995).
- Berk, A., L.S. Bernstein, and D.C. Robertson, MODTRAN: A Moderate Resolution Model for LOWTRAN 7, GL-TR-89-0122, Geophysics Directorate, Phillips Laboratory, Hanscom AFB, MA 01731 (April 1989) ADA214337.
- Bernstein, L.S., A. Berk, P.K. Acharya, D.C. Robertson, G.P. Anderson, J.H. Chetwynd and L.M. Kimball, Very Narrow Band Model Calculations of Atmospheric Fluxes and Cooling Rates, *Journal of Atmospheric Sciences*, Vol. 53, No. 19, pp. 2887-2904 (1996).
- Bodhaine, B.A., N.B. Wood, E.G. Dutton, and J.R. Slusser, Note on Rayleigh Optical Depth Calculations, Submitted to *Journal of Atmospheric and Oceanic Technology (JTECH)*, April 26, 1999.
- Cebula, R., Thuillier, G., Vanhousier, R.M., Hilsenrath, E., Herse, M., and Simon, P.C., 1996 Observation of the Solar Irradiance in the 200-350 nm Interval During the ATLAS I Mission: A Comparison of Three Sets of Measurements – SSBUV, SOLSPEC and SUSIM, *Geophys. Res. Lett.*, 23, 2289 (1996).
- K. Chance, K. and R.J.D. Spurr, Ring Effect Studies: Rayleigh Scattering, Including Molecular Parameters for Rotational Raman Scattering, and the Fraunhofer Spectrum, *Applied Optics* 36, 5224-5230, (1997).
- Dutton, E.G., Climate Monitoring & Diagnostics Laboratory, NOAA (private communication to Gail P. Anderson, 1999).
- Gathman, S.G. and Davidson, K.L., The Navy Oceanic Vertical Aerosol Model, TR-1634, Naval Command Control and Ocean Surveillance Center, RDT&E Division, San Diego CA (1993).
- Hapke, B.W., Bidirectional reflectance spectroscopy – 1. Theory, *J. Geophys. Res.*, 86, 3039-3054 (1981).
- Hapke, B.W., Bidirectional reflectance spectroscopy – 1. The extinction coefficient and opposition effect, *Icarus*, 67, 264-280 (1986).

References

- Justice, C.O., E. Vermote, J.R.G. Townshend, R. DeFries, D.P. Roy, D.K. Hall, V.V. Salomonson, J.L. Privette, G. Riggs, A. Strahler, W. Lucht, R.B. Myneni, Y. Knjazikhin, S.W. Running, R.R. Nemani, Z. Wan, A.R. Huete, W. van Leeuwen, R.E. Wolfe, L. Giglio, J.-P. Muller, P. Lewis, and M.J. Barnsley, The Moderate Resolution Imaging Spectroradiometer (MODIS): Land remote sensing for global change research, *IEEE Trans. Geosci. Remote Sens.*, 36, 1228-1249 (1998).
- Kiehl, J.T., *et al.*, Description of the NCAR Community Climate Model (CCM3), NCAR Tech. Note, NCAR/TN-420+STR, Natl. Cent. for Atmos. Res., Boulder, Colo., 1996.
- Kneizys, F.X., E.P. Shettle, L.W. Abreu, J.H. Chetwynd, G.P. Anderson, W.O. Gallery, J.E.A. Selby, and S.A. Clough, "Users Guide to LOWTRAN 7," AFGL-TR-88-0177 Geophysics Directorate/GPOS, 29 Randolph Rd., Hanscom AFB, MA 01731-3010, (August 1988) ADA206773.
- Kurucz, R.L., (1) Atomic and Molecular Data for Opacity Calculations; (2) Finding the Missing Solar Ultraviolet Opacity; and (3) Remaining Line Opacity Problems for the Solar Spectrum, all three papers in *Revista Mexicana de Astronomia y Astrofisica*, 23, 1992.
- Kurucz, R.L., The Solar Irradiance by Computation, "Proceedings of the 17th Annual Review Conference on Atmospheric Transmission Models", edited by Anderson, G.P., Picard, R.H., and Chetwynd, J.H., PL/-TR-95-2060, Special Reports, No. 274, Pl. 332, Phillips Laboratory / Geophysics Directorate, MA, May 1995.
- Lucht, W., C.B. Schaaf, and A.H. Strahler, An algorithm for the retrieval of albedo from space using semiempirical BRDF models, *IEEE Trans. Geosci. Remote Sens.*, in press, 1999.
- McElroy, C.T. , A spectroradiometer for the measurement of direct and scattered solar spectral irradiance from on-board the NASA ER-2 high-altitude research aircraft, *Geophys. Res. Lett.*, 22, 1361-1364 (1995).
- McElroy, C.T., C. Midwinter, D.V. Barton, and R.B. Hall, A Comparison of J-values estimated by the composition and photodissociative flux measurement with model calculations, *Geophys. Res. Lett.*, 22, 1365-1368 (1995).
- Pinty, B. and M.M. Verstraete, Extracting Information on surface properties from bidirectional reflectance measurements, *J. Geophys. Res.*, 96, 2865-2874, (1991).
- Rahman, H., B. Pinty, and M.M. Verstraete, Coupled Surface-Atmosphere Reflectance (CSAR) Model 2. Semiempirical Surface Model Usable With NOAA Advanced Very High Resolution Radiometer Data, *J. Geophys. Res.* 98D, 20,791-20,801 (1993).
- Rothman, L.S., R.R. Gamache, R.H. Tipping, C.P. Rinsland, M.A.H. Smith, D. Chris Benner, V. Malathy Devi, J.-M. Flaud, C. Camy-Peyret, A. Perrin, A. Goldman, S.T. Massie, L.R. Brown, and R.A. Toth, The HITRAN molecular database: editions of 1991 and 1992, *JQSRT*, 48, 469-507 (1992).
- Rothman, L.S., C.P. Rinsland, A. Goldman, S.T. Massie, D.P. Edwards, J.-M. Flaud, A. Perrin, V. Dana, J.-Y. Mandin, J. Schroeder, A. McCann, R.R. Gamache, R.B. Wattson, K. Yoshino, K. Chance, K.W. Jucks, L.R. Brown, V. Nemtchinov, and P. Varanasi, The HITRAN Molecular Spectroscopic Database and HAWKS (HITRAN Atmospheric Workstation): 1996 Edition, *JQSRT* 60, 665-710 (1998).
- Roujean, J.-L., M. Leroy, P.-Y. Dechamps, A Bidirectional Reflectance Model of the Earth's Surface for the Correction of Remote Sensing Data, *J. Geophys. Res.*, 97D, 20,455-20,468 (1992).

Stamnes, K., S.-C. Tsay, W. Wiscombe, and K. Jayaweera, Numerically Stable Algorithm for Discrete-Ordinate-Method Radiative Transfer in Multiple Scattering and Emitting Layered Media, *Applied Optics*, 27, 2502-2509 (1988).

Thuillier, G., Herse, M., Simon, P.C., Labs, D., Mandel, H., and Gillotay, D., 1996 Observation of the UV Solar Spectral Irradiance Between 200 and 350 nm During the ATLAS I Mission by the SOLSPEC Spectrometer, *Sol. Phys.*, 171, 283-302 (1997).

Thuillier, G., M. Herse, P.C. Simon, D. Labs, H. Mandel, and D. Gillotay, 1996 Observation of the Visible Solar Spectral Irradiance Between 350 and 850 nm During the ATLAS I Mission by the SOLSPEC Spectrometer, *Sol. Phys.*, 177, 41-61 (1998).

Walthall, C.L., J.M. Norman, J.M. Welles, G. Campbell, and B.L. Blad, Simple equation to approximate the bidirectional reflectance from vegetative canopies and bare soil surfaces, *Applied Optics*, 24, 383-387 (1985).

Wanner, W., X. Li, and A.H. Strahler, On the derivation of kernels for kernel-driven models of bidirectional reflectance, *J. Geophys. Res.*, 100D, 21,077-21,090 (1995).

Wanner, W., A.H. Strahler, B. Hu, X. Li, C.L. Barker Schaaf, P. Lewis, J.-P. Muller, and M.J. Barnsley, Global retrieval of bidirectional reflectance and albedo over land from EOS MODIS and MISR data: theory and algorithm, *J. Geophys. Res.*, 102D, 17,143-17,162 (1997).

Woods, T.N., D.K. Prinz, G.J. Rottman, J. London, P.C. Crane, R.P. Cebula, E. Hilsenrath, G.E. Brueckner, M.D. Andrews, O.R. White, M.E. VanHoosier, L.E. Floyd, L.C. Herring, B.G. Knapp, C.K. Pankratz and P.A. Reiser, Validation of the UARS Solar Ultraviolet Irradiances: Comparison with the ATLAS 1 and 2 Measurements, *J. Geophys. Res.*, 101D, 9841-9569 (1996).

APPENDIX A: MODTRAN3.7 / MODTRAN4 USER-SUPPLIED AEROSOL UPGRADES

This section contains instructions for the MODTRAN3.7/MODTRAN4 options that provide flexible wavelength-dependent specification of extinction, absorption, and asymmetry parameters and phase functions. These upgrades, used in conjunction with a stand-alone Mie code, allow aerosols to be modeled more realistically. The spectral grid can be arbitrary (i.e., not limited to the default 47 fixed spectral points of Table 10) and different for each aerosol. The scattering phase function can have wavelength dependence in addition to angular dependence. There can be up to four user-defined aerosol profiles. In addition, utility programs are provided which allow MODTRAN to be run with the Navy Oceanic Vertical Aerosol Model (NOVAM).

A.1 User-Supplied Aerosol Spectral Parameters (ARUSS Option)

Previous to this upgrade, the user could provide extinction, absorption and asymmetry parameters only for user-supplied aerosol profiles (IHAZE = 7 or ICLD = 11) which are in fact the extinction values at 0.55 μm . Furthermore, the spectral parameters were limited to the 47 wavelengths of Table 10. This was done using **CARDs 2D, 2D1 and 2D2** with IHAZE = 7 or ICLD = 11.

There have been two generalizations to user-supplied aerosol spectral data:

- Now the user can supply spectral data on an arbitrary grid for IHAZE = 7 or ICLD = 11. For this ARUSS (in **CARD 2**) needs to be set to the three-character string 'USS'. Additionally, the meaning of the IREG(N), N = 1, 2, 3 and 4, variables in **CARD 2D** has been generalized; when > 1, they now specify the number of wavelengths at which data is supplied.
- The user can also supply spectral data for the default aerosol profiles, as selected by IHAZE, ISEASN and IVULCN (IHAZE \neq 7 and ICLD \neq 11), instead of relying on the sparse built-in databases of MODTRAN. Setting ARUSS to the character string 'USS' also does this. The USS option can also be used in conjunction with the APLUS option.

The relevant **CARDs** for these upgrades are **CARD 2D, 2D1 and 2D2** as described below.

Note that the extinction and absorption coefficients in MODTRAN are dimensionless because they are defined by dividing the actual values by the extinction at 0.55 μm :

$$K_{\text{EXT}}(\lambda) = \text{EXT}(\lambda) / \text{EXT}(0.55 \mu\text{m})$$

$$K_{\text{ABS}}(\lambda) = \text{ABS}(\lambda) / \text{EXT}(0.55 \mu\text{m})$$

CARD 2D: IREG(1), IREG(2), IREG(3), IREG(4)
 FORMAT(4I5) (If IHAZE = 7 or ICLD = 11 or ARUSS = 'USS')

CARD 2D1: AWCCON, TITLE
 FORMAT(E10.3, 18A4) (CARDS 2D1 and 2D2 needed if IREG(1) > 0)

CARD 2D2: (VARSPC(1, I), EXTC(1, I), ABSC(1, I), ASYM(1, I), I = 1, IREG(1) or 47)
 FORMAT(3(F6.2, 2F7.5, F6.4)) (If ARUSS is not set)

CARD 2D1: AWCCON, TITLE
 FORMAT(E10.3, 18A4) (If IREG(2) > 0)

CARD 2D2: (VARSPC(2, I), EXTC(2, I), ABSC(2, I), ASYM(2, I), I = 1, IREG(2) or 47)
 FORMAT(3(F6.2, 2F7.5, F6.4)) (If ARUSS is not set)

CARD 2D1: AWCCON, TITLE
 FORMAT(E10.3, 18A4) (If IREG(3) > 0)

CARD 2D2: (VARSPC(3, I), EXTC(3, I), ABSC(3, I), ASYM(3, I), I = 1, IREG(3) or 47)
 FORMAT(3(F6.2, 2F7.5, F6.4)) (If ARUSS is not set)

CARD 2D1: AWCCON, TITLE
 FORMAT(E10.3, 18A4) (If IREG(4) > 0)

CARD 2D2: (VARSPC(4, I), EXTC(4, I), ABSC(4, I), ASYM(4, I), I = 1, IREG(4) or 47)
 FORMAT(3(F6.2, 2F7.5, F6.4)) (If ARUSS is not set)

CARDS 2D1 and 2D2 are repeated up to four times, one pair for each aerosol. However, the two cards for aerosol *i* are needed if and only if IREG(*N*) > 0. The only differences between the present and prior forms are in **CARD 2D** and **CARD 2D2**. Now **CARD 2D** has four integer values denoting the number of spectral grid points for each of the four aerosols; IREG(*N*) = number of spectral grid points for aerosol *N*. **CARD 2D2** is the list of the spectral parameters: VARSPC is the wavelength in microns, EXTC is the extinction coefficient, ABSC is the absorption coefficient and ASYM is the asymmetry parameter. Previously the IREG values were all 1 or 0. A value of 1 meant that spectral parameters had to be read using **CARD 2D2** and the number of spectral points were fixed at 47. (Actually the VARSPC array was not used at all because the 47 wavelengths were already fixed in the code at an earlier point.) Now, VARSPC is a 2D-array; the first dimension identifies the aerosol

and the second is the wavelength index. The user must input VARSPC values in microns and in increasing order; that is, the first VARSPC must be the lowest wavelength. The VARSPC array may differ for each aerosol.

Appendix A: User-Supplied Aerosol Parameters

The meaning of IREG is summarized and further clarified below:

<u>VALUE OF ARUSS</u>	<u>VALUE AND MEANING OF IREG(N)</u>
ARUSS = 'USS'	IREG(N) = 0 No user-supplied data. IREG(N) = M User-supplied data for M arbitrary wavelengths.
ARUSS = blank	IREG(N) = 0 No user-supplied spectral data. IREG(N) = 1 User-supplied data for the 47 fixed grid points of Table 10; Although VARSPC array is read, they are not used; instead Table 10 wavelengths are used.

A.2 User-Supplied Aerosol Phase Functions (CARDS 3B1, 3B2, 3C1-3C6)

The user-supplied phase function input scheme has also been upgraded. As before, the user-supplied phase functions are read in if IPH (**CARD 3A2**) is set to 1. Now, the user-supplied phase functions can vary with wavelength in addition to angle. This upgrade is actually independent of the A+ and USS upgrades, and it necessitates a "generalized" form of **CARD 3B1**:

CARD 3B1: NANGLS, NWLF
FORMAT(2(I5)) (If IPH = 1)

NWLF is the new variable which can be either 0 or a positive integer; 0 means that the phase function has no wavelength dependence whereas a positive integer means that the phase function will be specified on a wavelength grid with that many points. The phase function array, F, now has three indices: aerosol index, angle index and the wavelength index.

If NWLF = 0 or blank, **CARD 3B2** is used as before:

CARD 3B2: (ANGF(I), F(1, I, 1), F(2, I, 1), F(3, I, 1), F(4, I, 1), I = 1, NANGLS)
FORMAT(5E10.3) (If IPH = 1, NWLF = 0)

Appendix A: User-Supplied Aerosol Parameters

If $NWLF > 0$, **CARD 3B2** is replaced by **CARDS 3C1-3C6**:

CARD 3C1: (ANGF(I), I = 1, NANGLS) FORMAT(8(1X, F9.0))	(Read angles [degrees] if IPH = 1, $NWLF > 0$)
CARD 3C2: (WLF(J), J = 1, NWLF) FORMAT(8(1X, F9.0))	(Read wavelengths [μm] if IPH = 1, $NWLF > 0$)
CARD 3C3: (F(1, I, J), J = 1, NWLF) FORMAT(8(1X, E9.3))	(Read phase function for aerosol 1 if IPH = 1 and $NWLF > 0$; repeat NANGLS times)
CARD 3C4: (F(2, I, J), J = 1, NWLF) FORMAT(8(1X, E9.3))	(Read for aerosol 2; repeat NANGLS times)
CARD 3C5: (F(3, I, J), J = 1, NWLF) FORMAT(8(1X, E9.3))	(Read for aerosol 3; repeat NANGLS times)
CARD 3C6: (F(4, I, J), J = 1, NWLF) FORMAT(8(1X, E9.3))	(Read for aerosol 4; repeat NANGLS times)

In this upgrade, the wavelength grid and the angle grid is the same for each of the four aerosols. Furthermore, the phase function must be supplied either for all aerosols or no aerosol. For each, all **CARDS 3C3** are supplied first, then all **CARDS 3C4**, all **3C5**, and finally all **3C6**; the **CARDS** for the subsequent aerosol then follow.

A.3 User-Supplied Aerosol Profiles (CARD 2C3)

Prior to these upgrades, the user could only input one aerosol profile by using the user-selected profile option, $MODEL = 7$, $IRD2 = 1$. Now the user can have up to four user-defined aerosol profiles with $MODEL = 7$, $IRD2 = 2$. ($MODEL = 0$ is not allowed.)

This upgrade cannot be used with the A+ upgrade option; the APLUS option is ignored if $MODEL = 7$ and $IRD2 = 2$ or 1. The A+ option allows the built-in aerosols to be shifted around, whereas this upgrade allows the user to input aerosol profiles (up to all four) with greater control. The four profiles can only be input as altitude-dependent aerosol extinction coefficients at $0.55 \mu\text{m}$. Previously the single user-defined aerosol profile could be either the altitude-dependent extinction coefficient or the altitude-dependent liquid water content (in gm/m^3). For backward compatibility the previous option for the single aerosol profile is maintained.

Appendix A: User-Supplied Aerosol Parameters

This upgrade is achieved by a generalization of **CARD 2C3**. For this purpose AHAZE was changed from a scalar variable to an array, AHAZE(4). The two versions of **CARD 2C3** are shown below:

CARD 2C3: AHAZE(1), EQLWCZ, RRATZ, IHA1, ICLD1, IVUL1, ISEA1, ICHR
FORMAT(10X, 3F10.0, 5I5) (If IRD2 = 1)

CARD 2C3: AHAZE(1), RRATZ, AHAZE(2), AHAZE(3), AHAZE(4)
FORMAT(10X, F10.0, 10X, 4F10.0) (If IRD2 = 2)

The variables missing in the newer version of **CARD 2C3** (IRD2 = 2) are not needed for specifying aerosols. However, ICLD1 (IRD2 = 1) allows the user to specify cloud profiles in addition to aerosol profiles with the restriction that a cloud extinction and an aerosol extinction cannot be specified at the same altitude using **CARD 2C3**. The price of the current upgrade is the elimination of the cloud extinction at an altitude for having the luxury of inputting up to four aerosol extinctions. However, user-specified cloud profiles may be entered using **CARD 2E1**.

As mentioned, in lieu of extinction an aerosol profile could also be given as liquid water content in gm/m^3 . The conversion factor for converting liquid water content (gm/m^3) to extinction coefficient is given by AWCCON. AWCCON can also be user-specified by using **CARD 2D** (IHAZE = 7 or ICLD = 11). However, since in the present upgrade, the aerosol profiles cannot be stated in terms of liquid water content, AWCCON values in **CARD 2D1** are not used.

A.4 Example tape5 File

Here is an example of a tape5 that has both the A+ and ARUSS aerosol options. Notice the **CARD 2A+** following **CARD 2** (which contains 'A+' as its first two characters). Also note that user-supplied spectral data are used for a built-in aerosol profile.

Appendix A: User-Supplied Aerosol Parameters

```

M  4  3  0  1  0  0  0  0  0  0  1  0  -1      .0500
F  0F  0
A+ 1  1USS 0  0  0  0  0.000  0.000  0.000  0.000
      0.0      4.0      1.0 (CARD 2A+)
(This blank line must be here or this line should have zeros) (CARD 2A+)
  40  0  0  0 (CARD 2D)
0.000e+00region #1 desert summer aerosol
.20 1.0167 .43495 .8797 .30 1.0167 .43495 .8797 .34 1.0194 .44735 .8857
.55 1.0000 .21935 .7980 .69 1.0370 .16743 .7666 1.06 1.1149 .03721 .7143
1.54 1.2084 .04348 .7689 2.00 1.0471 .04212 .8557 2.25 .90502 .03577 .8936
2.50 .77022 .05025 .9116 2.70 .66704 .08621 .9281 3.00 .62886 .11468 .9247
3.39 .81244 .12218 .8623 3.75 .78888 .10013 .8493 4.50 .67765 .10404 .8524
5.00 .60842 .10488 .8551 5.50 .51168 .11551 .8706 6.00 .36239 .15033 .9038
6.20 .33716 .15081 .9065 6.50 .31172 .15288 .9079 7.20 .67035 .20663 .7748
7.90 .28524 .12992 .8881 8.20 .30108 .18832 .8855 8.70 .60029 .25834 .7717
9.00 .82965 .33903 .6736 9.20 .83153 .34675 .6684 10.00 .80838 .34487 .6558
10.59 .69210 .27596 .6814 11.00 .66931 .25000 .6748 11.50 .62531 .23290 .6805
12.50 .52648 .20100 .7023 14.80 .49395 .19037 .6708 15.00 .48791 .18807 .6700
16.40 .46622 .17702 .6539 17.20 .46122 .17202 .6408 18.50 .44203 .18161 .6366
21.30 .48520 .26897 .5959 25.00 .45705 .22352 .5460 30.00 .40179 .25847 .5494
40.00 .36801 .23947 .4688
4.90000      180.00000
      2500      2600      25      5
0

```

APPENDIX B: NOVAM IN MODTRAN

The most recent compilation of the NOVAM (Navy Oceanic Vertical Aerosol Model) profiles offers a new set of aerosol descriptions, providing both optical and size distributions appropriate from the shipboard surface to 6 km, covering the spectral range from 0.2 micron to 40 microns at relatively sparse spectral resolution. Since the ozone retrievals currently implemented in the UV encompass an accounting of the aerosol background, the addition of NOVAM profiles to MODTRAN was deemed critically important.

B.1 NOVAM Code

Spectral Sciences, Incorporated (SSI) obtained the NOVAM code from NRaD through S. Gathman (Gathman and Davidson, 1993). R. A. Paulis released this code under the authority of J. H. Richter, Oceanic and Atmospheric Sciences Division, Naval Command, Control and Ocean Surveillance Center, San Diego. The NOVAM code is an upgrade to NAM (Navy Aerosol Model) which is already in MODTRAN. NOVAM is based on extensive direct shipboard measurements carried out by several different agencies specializing in the marine environment. The inputs to the NOVAM code are radiosonde data consisting of altitude, temperature, pressure and relative humidity (RH), and other surface observation parameters such as optical visibility, wind speeds and surface IR extinction (1/km) at 10.6 microns; not all the inputs are required for implementation.

NOVAM recognizes three types of meteorological profiles characterized by existence or non-existence of temperature inversions. The cases are denoted numerically: 1 for no inversion; 2 for two inversions; and 3 for one inversion. The wavelength spectrum ranges from 0.2 to 40 microns. The actual spectral grid (in microns) is: 0.2, 0.3, 0.3371, 0.55, 0.6943, 1.06, 1.536, 2.0, 2.25, 2.5, 2.7, 3.0, 3.3923, 3.75, 4.5, 5.0, 5.5, 6.0, 6.2, 6.5, 7.2, 7.9, 8.2, 8.7, 9.0, 9.2, 10.0, 10.591, 11.0, 11.5, 12.5, 14.8, 15.0, 16.4, 17.2, 18.5, 21.3, 25.0, 30.0, 40.0. The model contains four classes of marine aerosols with three mode radii of 0.03, 0.24 and 2.0 microns, where the mode radius is the "size" of the most populous part (i.e., the peak) of the distribution at the RH of 80%. The 0.03-micron aerosol consists of two classes: soluble and insoluble. The other two sizes consist of soluble aerosols only.

The version of NOVAM from NRaD outputs surface layer altitudes, and the net extinction, absorption and asymmetry coefficients by combining the effect of all four aerosols. The output of NOVAM consists of aerosol size distribution parameters, and total extinction, absorption and

asymmetry values as a function of wavelength. In this study, NOVAM was modified to output this information as a function of wavelength for a series of altitude values beginning at the lowest “significant” radiosonde altitude (usually a few meters), extending into the lower troposphere. The NOVAM model is claimed to be valid up to 6 km. However, in consultation with Gathman (private communication), we have restricted the NOVAM aerosol profiles to reach no higher than 2 km.

The set of NOVAM routines consists of about 6000 lines of FORTRAN code written in non-standard FORTRAN 77. NOVAM, however, needs only minimal modification so as to be acceptable to most FORTRAN compilers. Extensive modification of the code was ruled out in order to maintain an easily discernible correspondence between the modified and original versions.

The user should familiarize herself/himself with the NOVAM input files of which there are three: (i) the **Surface Observation Data File**, (ii) the **Radiosonde Profile File**, and (iii) a file called **novam.in**. For purposes of familiarizing with NOVAM, it is highly recommended that the user consult the above referenced NOVAM manual. In this report only a very brief description of the inputs and output are given. Questions regarding the use of NOVAM within MODTRAN should be directed to the authors of this report.

Note that the NOVAM code supplied with this delivery has 13 inputs in the **Surface Observation File** as opposed to 9 as stated on page 9, Table 2, of the NOVAM manual. These inputs are the same as stated for positions 1 to 7. The revised Table 2 is described below. Values outside the stated range make the code use built-in default values. It is suggested that the user employ the default values when any of the specific data items are not available.

- 1 Sea Surface Temperature (°C)
- 2 Air Temperature (°C)
- 3 Relative Humidity (%)
- 4 Optical Visibility (km)
- 5 Current Real Wind Speed (m / s)
- 6 Averaged Wind Speed (24 hours, m / s)
- 7 Air Mass Parameter (1 to 30)
- 8 Cloud Cover Fraction (0 to 1)
- 9 Cloud Type (0 to 9)
- 10 Surface IR Extinction at 10.6 micron (1/km, 0.001 to 100.0)

Appendix B: NOVAM

- 11 Weather (0 to 11)
- 12 Height of Lowest Cloud (meters, negative value uses default)
- 13 Zonal/Seasonal Category (1 to 6)

The **Radiosonde Profile Data File** is in either of the formats described on page 15, Table 4 and Table 5, of the NOVAM manual. Table 4 contains data, each line of which consists of an altitude (m), potential temperature (°C) and aerosol mixing ratio (g/kg). The relationship between the potential temperature (2) and the usual air temperature (T) is given by the formula:

$$2 = T (P_0/P)^\kappa; \quad \kappa = (C_p - C_v) / C_p \approx 0.288$$

where the C's are heat capacities at constant pressure and constant volume, $P_0 = 1013.25$ mb and both temperatures are in Kelvin. [Potential temperature is the temperature attained by air at pressure P and temperature T where it is brought adiabatically (i.e., at constant entropy) to a standard pressure P_0 (Houghton, 1986).] Table 5 contains data, each line of which consists of a line number (an integer), log (base 10) of pressure in millibars multiplied by 10^4 , the air temperature in °C, RH in percent and pressure in millibars multiplied by 10. As stated above, one needs the profile data either in the format of Table 4 and Table 5. Table 4 is said to be in 'n' format whereas Table 5 is said to be in 'r' format, presuming that 'n' denotes 'number' defined by mixing ratio, while 'r' denotes 'relative humidity.'

In addition to these files, NOVAM needs another file called **novam.in**. An example of **novam.in** is reproduced below:

```
1905sops
1905prof.txt
n
```

Here, **1905sops** is the **Surface Observation File** and **1905prof.txt** is the **Profile File** in the 'n' format as indicated by the last line. This file then specifies for the program where the necessary data files can be found.

The output of NOVAM, **novam.out**, now in a form suitable for MODTRAN, typically looks as follows. The *italicized* text will not appear in the output. The first number is 40, which is the number of wavelengths (in microns) which are then individually listed. The number 10 is the number of altitudes (in meters) which are then individually listed. Then the temperatures (in K) for each altitude

are listed, followed by the pressures (in MB) and relative humidity (RH in %). Then for the first wavelength (0.2 micron), the extinction coefficients (in 1/km) for each altitude are listed. The absorption coefficients (in 1/km) for each altitude are followed by the asymmetry parameters for each altitude. Then the same set of information of the second wavelength (.3 micron) is listed. This pattern continues.

```

40 (number of wavelengths and wavelengths in microns)
  .2000   .3000   .3371   .5500   .6943   1.0600   1.5360   2.0000
  2.2500  2.5000  2.7000  3.0000  3.3923  3.7500  4.5000  5.0000
  5.5000  6.0000  6.2000  6.5000  7.2000  7.9000  8.2000  8.7000
  9.0000  9.2000 10.0000 10.5910 11.0000 11.5000 12.5000 14.8000
 15.0000 16.4000 17.2000 18.5000 21.3000 25.0000 30.0000 40.0000

10 (number of altitudes and altitudes in m )
 20.9 123.6 226.3 329.1 393.8 458.6 523.4 572.0 620.7 669.3
    (temperature in K)
287.65 286.49 285.57 284.85 285.37 285.95 285.65 287.65 288.91 288.45
    (pressures in mb)
1010.70 999.40 988.10 976.80 969.66 962.55 955.50 949.60 943.73 937.90
    (RH)
 88.80  91.41  95.39  95.60  81.88  66.69  65.60  50.08  37.44  35.80
    (spectral data for 0.2 microns)
.156E+00 .146E+00 .145E+00 .145E+00 .144E+00 .142E+00 .140E+00
.377E-01 .377E-01 .377E-01      (extinction)
.224E-03 .140E-03 .133E-03 .132E-03 .130E-03 .128E-03 .125E-03
.635E-06 .635E-06 .635E-06      (absorption)
.801E+00 .798E+00 .797E+00 .797E+00 .797E+00 .797E+00 .797E+00
.758E+00 .758E+00 .758E+00      (asymmetry)
    (spectral data for 0.3 microns)
.150E+00 .140E+00 .139E+00 .139E+00 .137E+00 .135E+00 .133E+00
.283E-01 .283E-01 .283E-01
.377E-05 .255E-05 .245E-05 .243E-05 .240E-05 .236E-05 .233E-05
.488E-06 .488E-06 .488E-06
.804E+00 .800E+00 .799E+00 .799E+00 .799E+00 .799E+00 .799E+00
.777E+00 .777E+00 .777E+00

```

B.2 Incorporation into MODTRAN

First all structure variables were eliminated and all non-standard system routines (such as **gettim**) were also eliminated from NOVAM. Several non-standard (i.e., non-FORTRAN 77) features were left intact. These include the DO ... ENDDO structure, longer than six character variable names and the use of the INCLUDE statement as these are acceptable by almost all modern compilers. The goal was to minimize changes to NOVAM and to use it almost "as is". The changes to the NOVAM code are briefly stated later.

Extensive changes were made to the MODTRAN code to accommodate the way NOVAM treats its four aerosols. The reason changes were extensive is that, unlike MODTRAN's current requirement, NOVAM does not output an aerosol profile (varying with altitude) and spectral extinction and absorption coefficients (varying with wavelength but not with altitude). Instead NOVAM outputs both altitude and spectrally varying quantities which are products of profile and spectral parameters. Changes to NOVAM code itself, however, were kept to a minimum. This meant that in order to use NOVAM in MODTRAN the user must supply the required radiosonde input data to NOVAM, separate from the MODTRAN inputs. NOVAM is executed off-line and creates a file called **novam.out** (lower case in UNIX) which is used as input to MODTRAN (uppercase filename in UNIX). Note that NOVAM input files are currently separate and in addition to MODTRAN's usual input file (which is named **tape5**). If the altitudes in **tape5** overlap with those in the NOVAM output file, the meteorological parameters, such as humidity, pressure and temperature, used by MODTRAN will be those provided by NOVAM.

In a future upgrade, the requirement for NOVAM to have a separate input file can be eliminated; both MODTRAN and NOVAM will then use the information contained in the MODTRAN input file, **tape5**. This process will be facilitated by the prior development of a sonde compression scheme. SSI and PL/GPO have collaborated to write a program, called **SNDTP5**, which can compress radiosonde measurements, consisting of hundreds of altitude layers (such as those used by NOVAM), into a form more suitable for the finite layering appropriate (and generally just as accurate for transmittance and radiance calculations) for a MODTRAN **tape5**.

As mentioned NOVAM actually can model altitudes as high as 6000 meters. However, in consultation with E.P. Shettle (Naval Research Laboratory, private communication) and S. G.

Appendix B: NOVAM

Gathman (NOSC, private communication), the maximum NOVAM altitude relevant for MODTRAN was determined to be 2 km. In reality, for most applications it will be less than 2 km. NOVAM distinguishes between three different temperature inversion cases. The code was modified to output these inversion layers explicitly which are then used in MODTRAN. This enables MODTRAN to use only a few layers and still accurately model the temperature effects. If the aerosol does not contain inversion layers, currently MODTRAN will introduce layers, which are at most 100 m apart. Although adequate, this scheme may be improved so those layers are more closely spaced nearer to the surface (where the scale height is smaller/steeper) and are farther apart towards the top of the boundary layer (where the scale height is generally larger). This may allow using fewer layers without loss of accuracy.

In summary, NOVAM is simply used to generate a database of marine aerosol profiles and spectral information for MODTRAN. NOVAM does not at present generate angular phase functions. Instead, it has a database of asymmetry parameters from which Henyey-Greenstein phase functions can be computed. In principle, a Mie code can be used to generate the phase functions for NOVAM.

B.3 Some Results

Three typical (as provided in the NOVAM package) profiles of aerosol extinction and coincident temperature are shown in Figures 1a and 1b. Figure 2a, b, and c shows the simulated backscattered UV signatures associated with these profiles, as might be measured by a potential ozone monitor staring down from a space platform. These calculations use all three types of temperature inversions modeled in NOVAM. The calculation with no aerosol includes only the Rayleigh scattering component and is used as the measure of change imparted to the backscattered signature by low-lying aerosols. No attempt was made to smoothly incorporate these profiles into a total profile. Rather, the "default" US Standard temperature, pressure, and constituent (primarily ozone) profiles and background rural (23 km visibility) aerosols were employed above 0 - 2 km, the acceptable vertical range for the NOVAM input. The spectral range presented is only that reaching the surface and near-surface, as wavelengths short of 300 nm will be absorbed (in general) at higher altitudes. MODTRAN will accommodate simulations from 200 nm to the far-IR, including the aerosol impact, so the short spectral range depicted in these calculations is not a restriction.

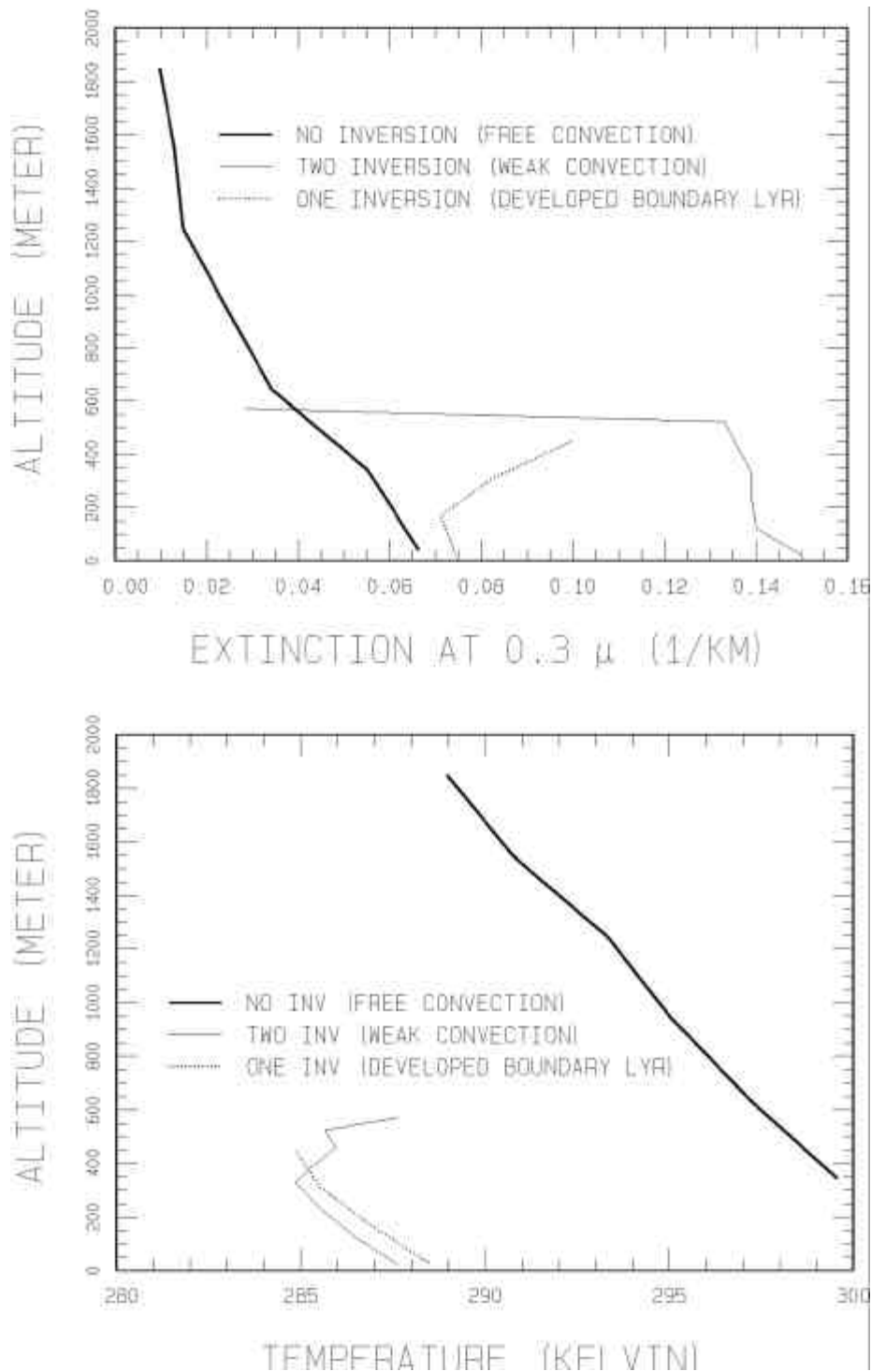
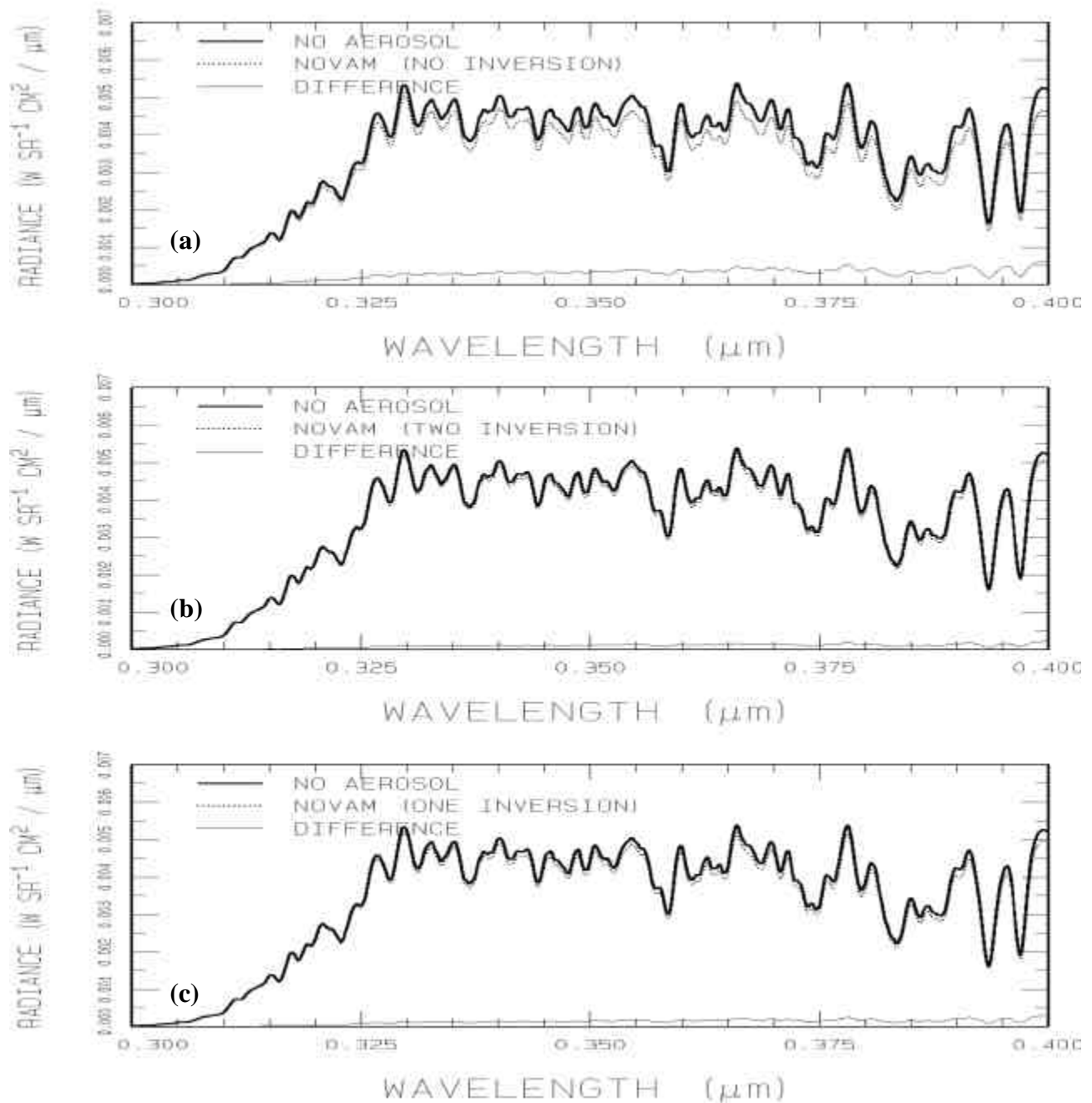


Figure 1a and b. The 3 aerosol and coincident temperature profiles (in extinction at $0.3\mu\text{m}$ and K, respectively) as a function of altitude. These profiles were chosen to capture the number of temperature inversions used as a parameter in NOVAM, 1 or no inversion, 2 or two inversions, and 3 for 1 inversion. There was not attempt to find the most perturbing case, so these can be considered typical. Note the MODTRAN merges these profiles into those describing the rest of the atmospheric profile from whatever source has been specified, ‘default’ or ‘user-defined’. This can lead to very coarse discontinuities whose impact might need to be further explored.



B.4 NOVAM input and MODTRAN input Files

The NOVAM files were described earlier. So they are not reproduced here. In the delivered code, there are several **novam.in**, **Surface Observation** and **Radiosonde Profile** files.

The **tape5** used to run MODTRAN with NOVAM aerosols for the calculations in this report is shown below. The 'N' in the third line invokes the NOVAM aerosol option in MODTRAN.

```
T 6 2 2 1 0 0 0 0 0 0 1 0 1 .0500
F 0F 0
  1N 0 0 0 0 0 0.000 .000 .000 .000
0050.0000 .10 180.00000
  2 2 0 0
  45. 60.
  .3 .4 .0001 .0010 $ M1
0
```

First NOVAM is executed to produce the **novam.out** file. This file then should be copied to the directory containing the MODTRAN executable as **NOVAM.OUT**; MODTRAN requires this file with the uppercase name.

B.5 Future Upgrades to NOVAM Implementation

There are at least six general areas in which the aerosol product in MODTRAN can be improved.

1. The first is to enable NOVAM to run from MODTRAN's input file, **tape5**. This task will enable MODTRAN to use radiosonde data consisting of several hundred altitude layers several of which can even be redundant. This will alleviate the need for NOVAM to have its own input file as is required in the current input scheme. Note that there still may be a need for the NOVAM input file, for example, to input surface observations.
2. MODTRAN does not now have phase functions for several aerosols (e.g., the desert aerosols) and for none of the cloud models. In the future this can be rectified by generation of the phase functions using the Mie code and incorporating them in MODTRAN.
3. The phase functions for NOVAM are also not available. In consultation with S. Gathman, they can be generated for the NOVAM aerosols and incorporated in MODTRAN.
4. The output of the Mie code can be put in a format so that user can include them in the MODTRAN input file without extensive editing.
5. Based on the El Chichon and Mt. Pinatubo eruptions, the content, size, type, and H₂SO₄ component of fresh and aging volcanic aerosols need to be altered from the default profiles now available within MODTRAN (E.P. Shettle, private communication).

6. MODTRAN currently merges NOVAM-generated profiles (e.g., extinction and temperature) into those describing the rest of the atmospheric profile from whatever source has been specified, 'default' or 'user-defined'. This could lead to very coarse discontinuities whose impact might need to be explored. General validation against real sonde data will provide additional confidence in the procedure.

B.6 Modifications to NOVAM to Code

As mentioned NOVAM modifications were kept to a bare minimum. Here is a list of types of coding changes to NOVAM.

1. All structure variables were replaced using this scheme:

structure.member was replaced by **structure_member**

This of course meant that numerous corresponding changes to subroutine arguments had to be made.

2. The **driver3.f** routine was substantially changed to output the **novam.out** file described earlier.
3. The **assym1** routine in the file **optics2.f** was substantially rewritten to fix an interpolation problem with the asymmetry parameters.
4. The calls to **gettlim** were eliminated as it is not available on all machines.
5. **potential_temperature** was replaced by **potential_temp** as this variable and routine name is too long.
6. The file **drivesub2.f** was renamed **drivesb2.f** so that the new prefix has no more than eight characters which is the maximum for the PC environment.
7. As before the **sigfile** is created by calling it with **repeatflag** equal to **.false.**. In the same call, a new file called **invfile** is created with inversion and other extra layers to be used as MODTRAN layers. This file also contains pressure, air temperature (not potential temperature) and RH. It is created by modifying the routine **make_rdataary**. Later the driver (with **repeatflag = .true.**) reads the **invfile** and creates the **novam.out** file at these altitudes.
8. The driver checks to see that all altitudes in the **invfile** that are greater than 2 km are discarded. Also discarded is the set of all top altitudes if the first altitude in the set has a relative humidity, which is below 50%. That is because the NOVAM aerosols appear to be restricted to be in an environment of 50% humidity or higher.

B.7 References

Gathman, S.G. and Davidson, K.L., The Navy Oceanic Vertical Aerosol Model, TR-1634, Naval Command Control and Ocean Surveillance Center, RDT&E Division, San Diego CA (1993).

Houghton, J.T., The Physics of Atmospheres, Cambridge University Press (1986).

APPENDIX C: MODTRAN INSTALLATION AND I/O FILES

This file outlines the steps required to obtain, install and execute MODTRAN on a UNIX system. It also mentions a new input/output (I/O) file structure for MODTRAN. Therefore, this file should be read even if one has already installed the code, or is familiar with the installation process. This file is duplicated as the 'README' file in the MODTRAN distribution tar file.

The top-level directory for MODTRAN is now called something like mod4r01, mod37r00, etc. The '4r01' refers to MODTRAN4, revision 01, whereas '37r00' refers to version 3.7, revision 00.

For questions regarding installation, please contact either Jim Chetwynd (chetwynd@plh.af.mil) or Gail Anderson (ganderson@plh.af.mil and /or ganderson@cmdl.noaa.gov). Technical questions may be address to either Gail Anderson (ganderson@plh.af.mil and / or ganderson@cmdl.noaa.gov) or Alexander (Lex) Berk (lex@spectral.com).

C.1 New Features

MODTRAN4 adds the following features (references are in the user manual): Two Correlated-k (CK) options: the standard option which uses 17 k values (absorption coefficients) per spectral bin and a slower, 33 k value option primarily for upper-altitude (>40 km) cooling rate and weighting function calculations (CARD 1); An option to include azimuth dependencies in the calculation of DISORT solar scattering contributions (CARD 1A); Upgraded ground surface modeling including parameterized forms for spectral BRDFs (Bidirectional Reflectance Distribution Functions) and an option to define a ground image pixel (H2) different from its surrounding surface. A high-speed option, only appropriate in short-wave and UV spectral regions, that uses 15 cm⁻¹ band model parameters (CARD 1A); Scaling options for water vapor and ozone column amounts (CARD 1A); Improved, higher spectral resolution, cloud parameter database; and More accurate Rayleigh scattering and indices of refraction. Both Correlated-k options permit more accurate calculation of molecular absorption in the presence of multiple scattering. Without the azimuth dependent DISORT option, the multiple (not single) scatter solar contributions included in MODTRAN line-of-sight calculations are averaged over azimuth. The BRDFs are fully coupled into the Isaacs multiple scattering model; upon release of the recently developed BRDF-dependent DISORT,MODTRAN4 BRDFs will be coupled to that code. The dual surface option enables modeling of adjacency effects. The updated Rayleigh scattering algorithm models the spectral dependence of the depolarization

Appendix C: MODTRAN Installation

factor, and the refractivity (equal to one minus the real part of the index of refraction) now varies not only with water density but also with CO₂ partial pressure (Bodhaine *et al.*, 1999). All MODTRAN3.5 input files are fully compatible with MODTRAN4. Minimally, six input cards (1, 1A, 2, 3, 4, and 5) are required to run MODTRAN for a given problem. For specific problems, combinations of several additional optional control cards are possible.

C.2 Installation Steps

- 1) Contact Gail P. Anderson (email: ganderson@plh.af.mil and / or ganderson@cmdl.noaa.gov) or Jim Chetwynd (chetwynd@plh.af.mil) and obtain the code (bundled into a single UNIX tar file and compressed to save space).
- 2) Unzip the file: 'gunzip mod4r01.tar.gz' will produce the tar file mod4r01.tar. The 'uncompress' command will also work. Then untar the file: 'tar xvf mod4r01.tar'; this will build a MODTRAN directory structure, mod4r01, beneath the directory in which mod4r01.tar is located. The top-level directory, mod4r01/, will contain these subdirectories: DATA/, DOCS/, src/, obj/, TEST/, mie/, novam/, novam/src/ and novam/test/.
- 3) Create correlated-*k* binary data files in the DATA/ subdirectory. In that directory, compile CKBIN.f (f77 CKBIN.f -o CKBIN.exe). Run CKBIN.exe; you will be prompted for a correlated-*k* ASCII file name. Reply with 'CORK15.ASC', which should have been placed in this directory during the untar process. You will then be prompted for a binary name; reply with 'CORK15.BIN'. The program should announce a successful write and place the file in the DATA/ directory. Repeat for CORK01.ASC.
- 4) Create band model parameter files. Compile and run MOLBMP.f. Select a binary-to-ASCII conversion. Although entering names of ASCII files is possible, the files of interest should appear in the menu; select 5 for BMP98_15.ASC (MODTRAN4 only), or 4 for BMP98_01.ASC. Another menu permits choosing output filenames; select the corresponding BIN names. The outputs of the conversions specify the value, for your computer, of the RECL parameter. Note this number for the following step.
- 5) Edit the file openbm.f in the scr/ sub-directory. Find the 'RECL=' specification in the OPEN statement, and change its value to that specified by MOLBMP.exe for your platform and compiler. For a HP 9000/735, for example, the value will be 60; for an SGI, 15; for GNU and PC (Lahey and WATCOM) compilers, it is also 60.
- 6) The command 'make -f Makefile' will run the FORTRAN compiler (using 'Makefile') to create the executable file mod4r01.exe. Object files will be placed in the obj/ directory. You may need to edit the makefile to set compiler parameters as needed by your compiler. Most likely, editing will not be needed.
- 7) This version of MODTRAN (version 3.7 and higher) has the ability to use the Navy Oceanic Vertical Aerosol Computer Model (NOVAM). If you need to use this code, NOVAM must be compiled and run before MODTRAN, producing output files for use when needed. The NOVAM files are located in the novam/ subdirectory tree under the top MODTRAN directory. Depending on need, not all users will require NOVAM. MODTRAN is independent of NOVAM. To prepare using NOVAM, go to the novam/ subdirectory. Execute the UNIX script

Appendix C: MODTRAN Installation

file `createnovamexecutable`, which will create the NOVAM executable, `novam.exe`. NOVAM (`novam.exe`) reads input from `novam.in`, and writes output to `novam.out`. Three test case inputs are located in the `novam/test/` subdirectory. Copy one into the `novam.in` file name, or create one, and use '`novam.exe`' to create `novam.out`. Copy that to NOVAM.OUT (upper case) in the topmost MODTRAN directory, which contains `mod4r01.exe`, for use in runs requiring NOVAM data.

- 8) The TEST/ subdirectory holds a number of input files designed to exercise various parts of MODTRAN. The input files are named in the pattern `*.tp5`; output files have `.tp6`, `.tp7`, `.tp8`, `.7sc`, `.7sr`, `.plt`, `.psc`, `.clr`, `flx`, and `.chn` extensions. Copy a `*.tp5` file into `tape5` in the top-level directory, and then '`mod4r01.exe`' will run that case. The other way of running MODTRAN and naming I/O files makes use of the file '`modroot.in`' or '`MODROOT.IN`' as described below. For MODTRAN4, the `*.tp6` output files shipped were created on a PC.
- 9) The subdirectory `pcfiles/` contains an executable, and binary files, for a PC. If you are using MODTRAN4 on a PC, copy the executable to the `mod4r01` directory, and move the `*.BIN` files to the `DATA/` directory. You need not compile these files yourself.

C.3 I/O Files

An attempt has been made in MODTRAN 3.7/4 to make it easier for the users to keep track of input and output (I/O) files. The need for easier file handling is evident to anyone who runs MODTRAN using different `tape5`'s and wants to save the corresponding output files (the `tape6`'s, `pltout`'s, `tape7`'s and so on). The problem is that every MODTRAN input file must be called '`tape5`' and that earlier I/O files must be renamed to avoid overwriting them with newer files. The need for renaming is now avoided by creating a new MODTRAN input file (referred to as the root name file) called `modroot.in` or `MODROOT.IN`. If '`modroot.in`' does not exist, '`MODROOT.IN`' is looked for. If neither exists, MODTRAN I/O files are the usual ones: '`tape5`', '`tape6`', '`tape7`', '`tape8`', etc. If the root name file exists and contains a non-null string (maximum length is 80 characters), this string is treated as a prefix. It is suggested that this string contain no blanks other than leading and trailing ones. If the string consists of all blanks or is a null string, the I/O files are the usual ones. Otherwise, this string, stripped of all leading and trailing blanks, is used as a prefix for the I/O files whose names have mnemonic suffixes listed below.

Appendix C: MODTRAN Installation

As an example, if the string is 'case1', the MODTRAN I/O files will have these names:

case1.tp5	(corresponding to tape5)
case1.tp6	(corresponding to tape6)
case1.tp7	(corresponding to tape7)
case1.tp8	(corresponding to tape8)
case1.7sc	(corresponding to tape7.scn)
case1.7sr	(corresponding to tape7.scr)
case1.plt	(corresponding to pltout)
case1.psc	(corresponding to pltout.scn)
case1.clr	(corresponding to clrates in MODTRAN4)
case1.chn	(corresponding to channels.out in MODTRAN4)
case1.flx	(corresponding to specflux in MODTRAN4)