

# MODTRAN<sup>®</sup> 6.0 User's Manual

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## 1. INTRODUCTION

This manual is designed to help the MODTRAN6 user set up and run the MODTRAN atmospheric radiative transfer model. Chapter 1 provides a short introduction to MODTRAN. The MODTRAN6 Algorithm Theoretical Basis Document (ATBD) [A], included in the MODTRAN6 distribution, describes MODTRAN radiative transfer theory. Validation of the MODTRAN line-by-line (LBL) algorithm and its statistical band model and correlated- $k$  methods is detailed in a 2017 Journal of Quantitative Spectroscopy and Radiative Transfer (JQSRT) article [B]. Chapter 2 provides instructions for running the MODTRAN6 GUI. MODTRAN6 can also be run from an API (Application Programming Interface); an Interface Control Document (ICD) [C] provides the details for setting up an API. When running MODTRAN6 as a standalone module, the preferred MODTRAN6 input is a JSON (JavaScript Object Notation) formatted file, <ROOTNAME>.json. MODTRAN6 continues to support the legacy “tape5” input files, <ROOTNAME>.tp5, but some newer options are unavailable; users wishing to use this older format need to refer back to the MODTRAN5.4 manual [D] for instructions, included here as an appendix. Chapter 3 describes each of the JSON inputs, including those required to run the newly introduced MODTRAN6 line-by-line option [A, B]. Output files are described in Chapter 4, while Chapter 5 answers selected frequently asked questions (FAQs). MODTRAN6 includes instructions for the option to model local chemical (gas) clouds using line-of-sight based gas concentration profiles; these profiles are defined in auxiliary <ROOTNAME>.rng input files, and their format options are delineated in Chapter 6. MODTRAN6 can be run in parallel as an MPI (Message Passing Interface) application, although the model has yet to be made thread-safe; the MPI readme file is included as Chapter 7. MODTRAN6 includes tools for generating climatology based atmospheres and particulate (aerosol, cloud and rain) optical data. The atmospheric generator toolkit (AGT) and the aerosol toolkit (ATK) are described in Chapters 8 and 9, respectively. Finally, Chapter 10 acknowledges the many contributors to MODTRAN over its first three decade tenure; in particular, *we dedicate this manual to Ms. Gail Anderson, who spent over 25 years working to insure that the integrity of the MODTRAN model never waned.*

Table 1.1 provides a list of all MODTRAN6 input and output files. All of the MODTRAN legacy files remain accessible. However, much of the spectral data is now available in (1) an ASCII comma separated value (.csv) format, importable into Microsoft Excel®; (2) an ASCII tab delimiter file (.txt) format, and (3) a binary ENVI® spectral library (.sli) format with accompanying header file (.hdr). Table 1.1 lists the full set of file names and/or extensions, the chapters and sections in which the files are described, and a very brief description of their content.

The information in this manual will occasionally fall short of providing users with all the help they need to download, install, run, and post-process MODTRAN. Users with current maintenance agreements are encouraged to email Alexander Berk, Tim Perkins and Paula Wing at <[modtran@spectral.com](mailto:modtran@spectral.com)> with their questions. Those requiring U.S. Government support can also contact Jeannette van den Bosch at <[ARFL.RVBYI.MODTRANOrgMailbox@us.af.mil](mailto:ARFL.RVBYI.MODTRANOrgMailbox@us.af.mil)>.

### 1.1 Review of Modtran 5.4

MODTRAN has been and continues to be developed by Spectral Sciences, Inc. (SSI) under the expert guidance and oversight of the Air Force Research Laboratories (AFRL). MODTRAN is the U.S. Air Force (USAF) standard moderate spectral resolution radiative transfer model for wavelengths extending from the Thermal InfraRed (TIR) through the visible and into the ultraviolet (0.2 to 10,000.0  $\mu\text{m}$ ; 0.0 to 50,000.0  $\text{cm}^{-1}$ ). The molecular spectroscopy of MODTRAN is based on HITRAN line compilation data [E, F]. The MODTRAN statistical band model was originally developed to provide a fast alternative to the first principles, high fidelity line-by-line (LBL) radiative transfer approach.

**Table 1.1.** Legacy and MODTRAN6 input and output files.

Legacy File Names (* = <ROOTNAME>)	I=Input <i>B=Binary</i>	File Name of Mod6 Option	Chapter .Section	Short Description
*.tp5 or tape5	<b>I</b>	*.json	3	Primary Input
*.rng or Yrange.asc	<b>I</b>		6	Local Gas Plume Path Definition
*.sap or SpecAerProf.dat	<b>I</b>		3.5.4	Spectral Aerosol Profile Data
*.pth or rfracpth.dat	<b>I</b>		3.7.2	Refractive Path Definition
*._pth or rfracpth.dat			3.7.2	Refractive Path Definition
*.wrn or warnings.txt			4.1	List of Comments/Warnings/Errors
*.tp6 or tape6		GUI Log	4.2	General Output Data
*.tp7 or tape7		*.(csv,txt)	4.3	LOS Spectral Data
*_b.tp7 or tape7b	<b>B</b>	*.(sli,hdr)	4.3	LOS Spectral Data
*.7sc or tape7.scn		*_scan.(csv,txt)	4.3	Scanned LOS Spectral Data
	<b>B</b>	*_scan.(sli,hdr)	4.3	Scanned LOS Spectral Data
*.plt or pltout		*.(csv,txt)	4.3	LOS Spectral (x,y) Data
*_b.plt or pltoutb	<b>B</b>	*.(sli,hdr)	4.3	LOS Spectral (x,y) Data
*.psc or pltout scn		*_scan.(csv,txt)	4.3	Scanned LOS Spectral (x,y) Data
	<b>B</b>	*_scan.(sli,hdr)	4.3	Scanned LOS Spectral (x,y) Data
*.chn or channels.out		*_chan.(csv,txt)	4.4	Sensor Spectral Channel Data
	<b>B</b>	*_chan.(sli,hdr)	4.4	Sensor Spectral Channel Data
*.flx or specflux.asc		*_flux.(csv,txt)	4.5	Profiles of Spectral Flux Data
*_b.flx or specflux.bin	<b>B</b>	*_flux.(sli,hdr)	4.5	Profiles of Spectral Flux Data
*.acd or atmcor.asc			4.6	Atmospheric Correction Data
*_b.acd or atmcor.bin	<b>B</b>		4.6	Atmospheric Correction Data
*.t_k or t_kdis.dat		*_highres.(csv,txt)	4.7	LBL or Ck Transmittance Data
*_b.t_k or t_kdis.bin	<b>B</b>	*_highres.(sli,hdr)	4.7	LBL or Ck Transmittance Data
*.r_k or r_kdis.dat		*_highres.(csv,txt)	4.7	LBL or Ck Radiance Data
*_b.r_k or r_kdis.bin	<b>B</b>	*_highres.(sli,hdr)	4.7	LBL or Ck Transmittance Data
*.tp8 or tape8			4.8	Segment Spectral Data
*_b.tp8 or tape8b	<b>B</b>		4.8	Segment Spectral Data
*.clr or clrates			4.9	Spectral Cooling Rates
*.ms or msdata.asc			4.10	Saved Multiple Scatter Data
*.msB or msdata.bin	<b>B</b>		4.10	Saved Multiple Scatter Data

MODTRAN5 upgrades and improvements raised the utility and physics of the model to a new level. New features introduced with MODTRAN5 included:

- Reformulated the band model parameters and radiative transfer algorithms, increasing the resolution of MODTRAN spectral calculations to  $0.1 \text{ cm}^{-1}$  [H, I, J].
- Developed a multiple line-of-sight ([MLOS](#)) option to enable the DISORT general solution to the radiative transfer equation to be used for an arbitrary number of paths through a fixed environment (i.e. a given solar zenith, atmosphere and ground surface).
- Provided option to save and re-use DISORT scattering data.
- Upgraded MODTRAN to facilitate inclusion of auxiliary (non-standard) molecules and provided spectral band model data for all HITRAN molecular line-by-line species.

MODTRAN compatible data files have also been generated for the full suite of molecules in the Pacific Northwest National Laboratory (PNNL) Infra-Red Spectral Library (IRSL). These files are not included in the standard MODTRAN distribution, but are available for purchase.

- Added option to generate spectral atmospheric spherical albedo and diffuse transmittance data in an atmospheric correction data file, <ROOTNAME>.acd.
- Added option to model aerosol spectral extinction coefficients either in the boundary layer or in the boundary layer plus troposphere using an Angstrom law dependence or perturbation.
- Increased accuracy of line center band model by introducing the use of two pairs of absorption coefficient and line spacing band model parameters.
- Developed a much improved algorithm for computing the finite bin Voigt transmittance [J].
- Added option to write spectral output files in binary; a binary to ASCII utility is provided.
- Added flux and atmospheric correction binary output files, <ROOTNAME>\_b.flx and <ROOTNAME>\_b.acd. Facilitated running the DISORT multiple scattering algorithm with an arbitrarily large number of streams.
- Replaced the spherical refractive geometry package with an iterative circular arc algorithm for improved accuracy, appendix E of [A].
- Introduced Fontenla top-of-atmosphere (TOA) solar irradiance data [K, L], adopting the Fontenla “medium 2” solar activity data file as the new MODTRAN default and increasing the finest available spectral resolution to  $0.1\text{ cm}^{-1}$ .
- Eliminated DISORT singular matrix issues by introducing dithering of the solar zenith angle.
- Introduced a <ROOTNAME>.wrn output files containing comments, warnings and errors in a common format.
- Added option to use distinct temperature grid data for each auxiliary (Y) species.
- Added atmospheric correction data to the channel spectra output.
- Introduced a thin surface water layer model.
- Added <ROOTNAME>.\_pth path geometry output files to facilitate running of the user-defined refractive path option.
- Added the path thermal scatter radiance component as a DISORT spectral output.
- Added H<sub>2</sub>-H<sub>2</sub>, H<sub>2</sub>-He, H<sub>2</sub>-CH<sub>4</sub> and CH<sub>4</sub>-CH<sub>4</sub> collision induced absorption (CIA) features for modeling extra-terrestrial planetary atmospheres.

## **1.2 Introduction to Using MODTRAN 6**

A C/C++ library interface has been developed to provide new methods to use MODTRAN. The functions of this library read input data, launch the MODTRAN executable, and store and/or generate output files in new formats. The preferred JSON, or JavaScript Object Notation, input format is described in detail in Chapter 3. The MODTRAN6 console executable can read either JSON input <ROOTNAME>.json or legacy “tape5” <ROOTNAME>.tp5 input files supplied on a command line.

It is anticipated that most new users will choose, at least initially, to use the MODTRAN6 GUI to perform calculations and view spectral outputs in the plot window. Experienced MODTRAN users will also find the GUI option advantageous for running quick calculations. Some may opt to run the GUI to only to create MODTRAN input files. The GUI operation is described in Chapter 2. This section describes methods for running MODTRAN outside of the GUI.

The MODTRAN6 distributions include a set of ~100 test cases. For the Linux and Mac operating systems, the JSON input files are stored in the <*modtran6\_directory*>/TEST\_c/ directory and the “tape5” input files are stored in the <*modtran6\_directory*>/TEST/ directory. Here <*modtran\_directory*> is the full or relative path to the MODTRAN6 directory. On Windows, test

case JSON input files are stored in the Documents\MODTRAN6\TestCases\JSON\ folder and “tape5” input files are stored in the Documents\MODTRAN6\TestCases\Tape5\ folder. Each of these directories and folders contain a Compare\ sub-directory (folder), which includes test case output that can be compared to test runs of MODTRAN. Any of these input files can be used to test the methods for running MODTRAN discussed in the remaining of this section. However, the user must navigate to the appropriate test case directory.

Under Linux, the MODTRAN console executable (mod6c\_cons) can be launched from the command line as follows:

```
<modtran6_directory>/bin/linux/mod6c_cons <ROOTNAME>.json  
<modtran6_directory>/bin/linux/mod6c_cons <ROOTNAME>.tp5
```

(*You may receive the error message “STAT\_CRITICAL MODTRAN license is not valid. Please activate or visit http://modtran.com to purchase a license.” In that case type*

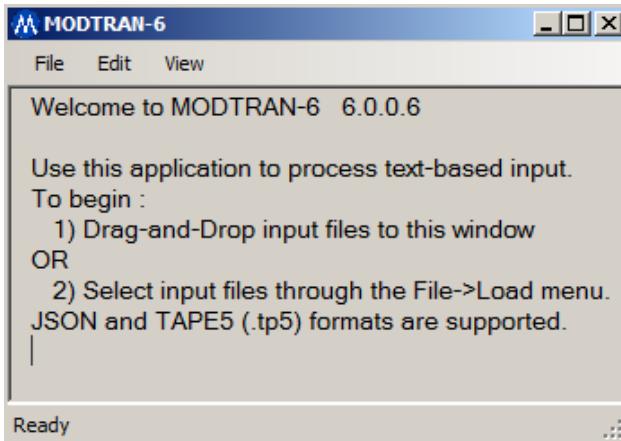
```
<modtran6_directory>/bin/linux/mod6c_cons -activate_license [KEY string]
```

*The activation [KEY string] should have been received along with you MODTRAN6 download instructions.)*

The processing is identical for Mac operating systems, except that the MODTRAN console executable is located in the macos/ instead of the linux/ directory:

```
<modtran6_directory>/bin/macos/mod6c_cons <ROOTNAME>.json  
<modtran6_directory>/bin/macos/mod6c_cons <ROOTNAME>.tp5
```

Although MODTRAN can be run from a command line in Windows using the mod6con.exe application (found in “Documents\MODTRAN6\Utilities\console\x86\_64\” or “Documents\MODTRAN6\Utilities\console\x86\_32\”), the preferred Windows approach for running MODTRAN is initiated by selecting either “MODTRAN6 (64-bit)” or “MODTRAN6 (32-bit)” from the Start menu. This will open the window of Figure 1.1.



**Figure 1.1.** The MODTRAN-6 Window that is used to run MODTRAN6.

As the text indicates, MODTRAN is run either by either a Drag-and-Drop of a <ROOTNAME>.json or legacy <ROOTNAME>.tp5 input file, or by navigating to a input file via the File→Load menu.

Former MODTRAN5 users who wish to run MODTRAN with their old inputs have a choice. They can either use the MODTRAN6 executable directly, as shown above, or run the tape5 to json converter. For Linux and Mac operating systems, tp5tojson is run as follows:

```
<modtran6_directory>/bin/linux/tp5tojson <ROOTNAME>.tp5 [<ROOTNAME'>.json]
```

or

```
<modtran6_directory>/bin/macos/tp5tojson <ROOTNAME>.tp5 [<ROOTNAME'>.json]
```

The default output file name is <ROOTNAME>.json, but that name can be modified with the optional argument. In Windows, one can select Edit→Convert Tape5 from the MODTRAN-6 window to create the JSON formatted input file.

A few options that are new to MODTRAN6 have been made available through the tape5 input file [e.g., set [MODTRN](#) to “H” and BMNAME to “LBL2013” to run the line-by-line option], but other options [e.g., ENVI® spectral library (<ROOTNAME>.sli), comma separated values (<ROOTNAME>.csv), and tab delimited (<ROOTNAME>.txt) output formats] are only accessible through JSON input files. Future options will also only be accessible through the JSON format.

There are a number of options for serially running multiple MODTRAN6 cases. Within Linux and Mac operating systems, one can create a batch file with multiple command lines. In Windows, multiple input files can be Dragged-and-Dropped into the MODTRAN-6 Window. Alternatively, a set of JSON files can essentially be concatenated (some reformatted is necessary) into a single JSON file containing multiple MODTRAN6 runs. Former MODTRAN5 users may wish to process multiple <ROOTNAME>.tp5 files using the legacy mod5root.in file. This is accomplished using a “-modroot” option. For Linux and Mac operating systems, the command line entries are

```
<modtran6_directory>/bin/linux/mod6c_cons -modroot
```

and

```
<modtran6_directory>/bin/macos/mod6c_cons -modroot
```

respectively. In Windows, one must use the mod6con.exe from a command line:

```
Documents\MODTRAN6\Utilities\console\x86_64\mod6con.exe -modroot
```

or

```
Documents\MODTRAN6\Utilities\console\x86_32\mod6con.exe -modroot
```

The first line runs the 64-bit executable and the second line runs the 32-bit executable.

## 2. THE MODTRAN6 GRAPHICAL USER INTERFACE (GUI)

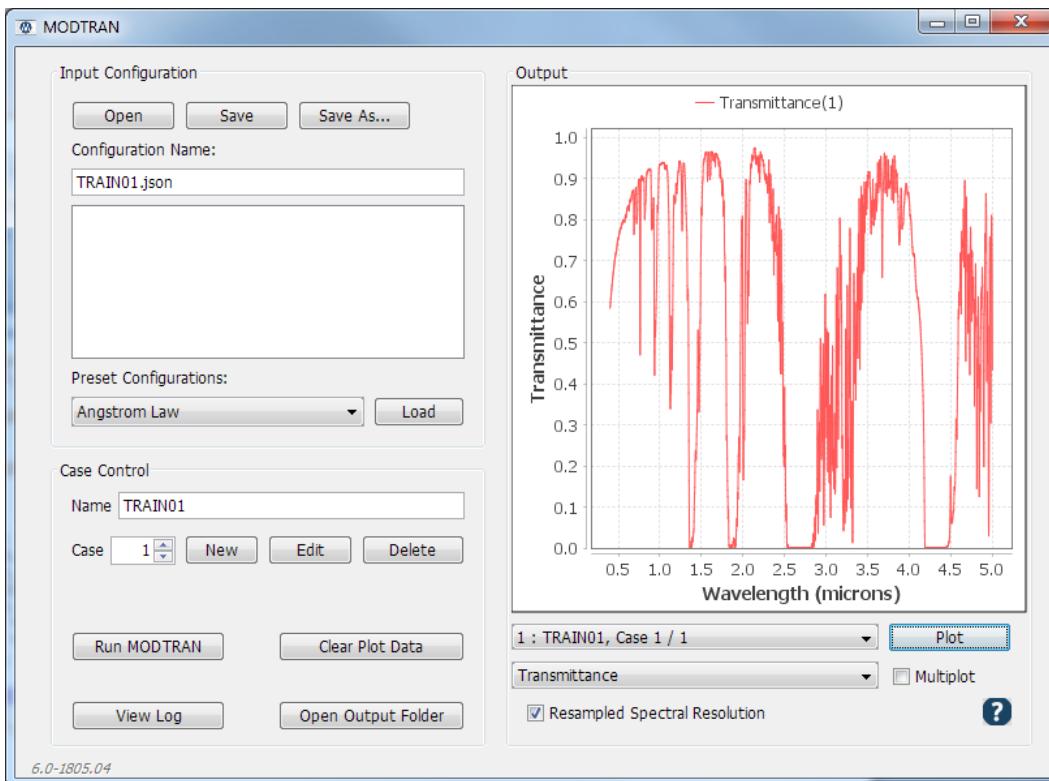
MODTRAN6 includes a GUI for defining cases, running MODTRAN and displaying output results. The MODTRAN6 GUI requires installation of Java Version 8 or higher. To run the GUI from Windows, users simply need to click on the “MODTRAN6 GUI” shortcut within the “MODTRAN 6” program group that was created upon installation of MODTRAN6. If the shortcut fails to open, the installation of Java may be invalid or older than version 8.

For Linux and Mac users, the GUI is initialized by running a script found within the /bin/linux/ or /bin/macos/ directories:

```
<modtran_directory>/bin/linux/mod6gui
```

Here *<modtran\_directory>* is the full or relative path to the MODTRAN6 directory.

Figure 2.1 contains the main window of the MODTRAN6 GUI (*All the figures of GUI windows in this chapter are displayed with the entries of the Section 2.3 TRAIN01 demonstration*). By clicking on the question mark in the lower right corner, a GUI help window will appear. In this chapter information is provided to help users get started.



**Figure 2.1.** The main window of the MODTRAN6 GUI.

There are three primary methods for defining MODTRAN inputs using the GUI:

1. Run one of the “Preset Configurations:”,
2. “Open” an pre-existing <ROOTNAME>.json file, or
3. Create a “New” input file from scratch.

Each of these options is described in the following sub-sections.

## **2.1 Run one of the “Preset Configurations:”**

The easiest way to get started and confirm that the MODTRAN6 GUI is set up properly on your system is to run one of the 23 Preset Configurations listed in Table 2.1. Use the drop down menu to select a test case. Once selected, the box just above Preset Configurations will contain a brief description of the test case.

**Table 2.1.** The MODTRAN6 GUI preset configurations.

Preset Configuration Names		
Angstrom Law	Anti-solar Sky Radiance	BRDF
Brightness Temperature	Cloud Profile	Cloudtop Radiance
Cumulus	Disort Scatter	Dust Storm
Extreme Volcanic	Isaacs Scatter	Lambertian
Microwave LBL	MODIS	Ocean View
Radiosonde Profiles	Shadowband Radiometer	Solar Irradiance
Surface Emission	SWIR/MWIR Transmittance	SWIR/MWIR Radiance
User-Defined Aerosol	Surface Water Layer	

To proceed, click on Load to read the MODTRAN inputs into the GUI. A message box stating Loaded <n> case(s) will appear and the Case number will increase from 0 to 1. Hit OK to continue. One could continue by editing the preset configuration, but discussion of editing is postponed to Section 2.3.

Before running MODTRAN, click on Save or Save As.... This will save the input selections to a JSON file. By default, the input is saved in a MODTRAN6 directory (folder). Hit Save to save the file and close the Window. If one wishes to generate MODTRAN I/O in an alternative folder/directory, one can always click Save As... and navigate to the desired directory (folder).

You should now be ready to run MODTRAN. Hit Run MODTRAN. When the run is complete, a message box stating MODTRAN run finished will appear. Click OK. A spectral plot should appear in the Output box. Most likely, it is a spectral (total) Transmittance plot, but it depends on which Preset Configuration was selected. Most of the Preset Configurations define a spectral slit function. In those cases, MODTRAN generates spectral data at the raw band model resolution, and spectral data convolved with the chosen slit function. To view the convolved data, click the box labeled Resampled Spectral Resolution, and click on Plot. Generally, this will create a smoother (less structured) plot. If you hit the arrow in the drop down box just above Resampled Spectral Resolution, you will see a list of the other spectral outputs available for plotting; the list depends on the input selections for the Preset Configuration. Choose one and click on Plot. Note that you can stretch the entire MODTRAN Window to increase the size of the plot. You can also use your mouse to select a sub-region use wish to plot; you must select from upper left to lower right. Click on Plot once again to return to the original plot. Note, there is no option at this point to save the spectral images themselves.

If you next click on View Log, a MODTRAN Log Window will open. This contains the MODTRAN standard output, a copy of the <ROOTNAME>.tp6 file. Users are always encouraged to peruse the standard output to verify that the calculation they requested is actually the calculation that was run.

For example, they might have defined a sensor to space path, but, if the line-of-sight intersected the Earth, a sensor to ground calculation was run instead.

Finally, one can click on **Open Output Folder**. This will open the output folder containing the generated I/O. These files contain the information described in Chapter 4. If, for example, you click on the <ROOTNAME>.csv file, it will open Microsoft Excel if the \*.csv files are appropriately associated. You can now close the I/O folder.

Congratulations, you have now completed your first MODTRAN run.

## **2.2 “Open” an pre-existing <ROOTNAME>.json file**

The MODTRAN6 GUI can load almost any pre-existing <ROOTNAME>.json input file, and then run MODTRAN with either the baseline or edited input values. This option can be used to run MODTRAN6 test case <ROOTNAME>.json input files. As noted earlier, these JSON input files are stored in the <modtran6\_directory>/TEST/TESTjson/ directory on Linux and Mac systems; in Windows, these files are stored in the Documents\MODTRAN6\TestCases\JSON\ folder.

To run a test case from the MODTRAN6 GUI, click on **Open**. Navigate to the JSON test case directory (folder). Select a JSON input file. Many of the files contain more than one case. When the JSON file is loaded, a Message box will appear with the message **Loaded <n> cases** where <n> is the actual number of cases. Click **OK** to close the Message box. The Case number will be set to 1, but if more than one case was loaded, one can use the up and down arrows to select any of the <n> cases. When **Editing** a JSON input file, as discussed in Section 2.3, only one case can be edited at a time and you must use the up and down arrows to select which case to edit. Also, if did not want to include all the loaded cases in your run, you can use the arrows to select a case you wish to remove; then, click on the **Delete** button. If you have an existing plot in the GUI Window, you can choose to keep access to the output from an earlier run or clear it by clicking the **Clear Plot Data** button.

Click on **Run MODTRAN** to start processing, and on **OK** in the Message box stating that MODTRAN run finished when processing is complete. Just below the plot window, there is a drop down box. It contains lines of the form: <i> : <ROOTNAME>, Case <j> / <k>. Here, <i> is the MODTRAN run number; <ROOTNAME> is the name of that MODTRAN run; <j> is the Case number for that MODTRAN run; and <k> is the number of Cases that the run contained. One can plot data from any of the listed cases. Most often, users choose to plot the Resampled Spectral Resolution output, so that box should be checked. Use the 2<sup>nd</sup> drop down box to select a spectral curve, and click on **Plot** to generate the plot. As before, one can click on **View Log** to view standard output, or click on **Open Output Folder** to view the generated output files.

## **2.3 Create a “New” input file from scratch**

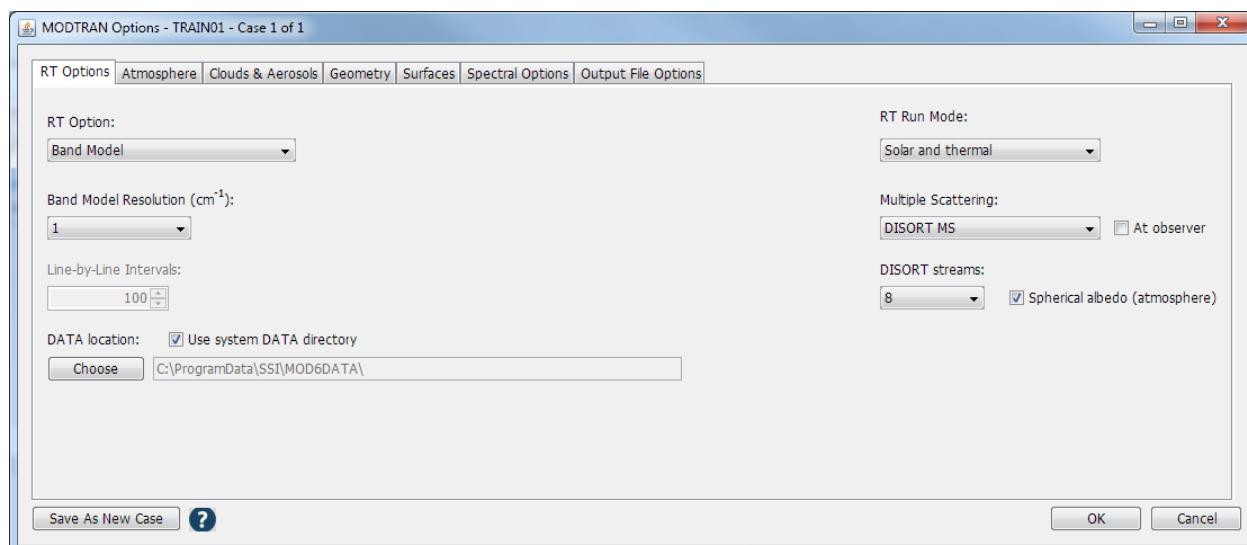
This section is designed to provide the MODTRAN6 GUI user with an introduction into how to define a MODTRAN JSON input stream. It is not meant to be comprehensive, defining all the available entries or describing all the GUI input windows. The hope is that this introduction will be comprehensive enough that users needing to invoke options not covered will have received experience sufficient to enable them to make any additional changes. If this is not the case, the developers of the GUI ask that you provide feedback using the email addresses listed at the end of the Introduction to this manual.

It is assumed that readers of this section have already read Sections 2.1 and 2.2, which described how to run MODTRAN from the GUI. It is suggested that if you already have the GUI open, that you close it so an input stream can be defined from scratch. Open the GUI as described at the beginning of this section.

To begin, a Configuration Name needs to be defined. This is the name of your JSON file. Enter a name such as `Training.json`. Next, click on `New` [All instructions, without the detailed explanations, are highlighted in dark red text]. A Message box stating Click "Edit" to define a configuration for the new case will appear. Click "OK". "mod6" should appear under Name in the Case Control box and the Case number should increase to 1. The entry following Name is the root name that will be used in all I/O files. If you do not change it from mod6, your I/O file names will be `mod6.tp6`, `mod6.csv`, etc. Change the Name from `mod6` to `TRAIN01` for this demonstration. You could also have had the I/O placed in an arbitrary, but pre-existing directory of your choosing; an error will be logged by the GUI if a directory is chosen that cannot be found.

### 2.3.1 RT Options Tab

You are now ready to edit Case 1 of your input file. Click on `Edit`. The MODTRAN Options window will appear, as shown in Figure 2.2. This window contains the 6 primary input tabs: RT Options, Atmosphere, Clouds & Aerosols, Geometry, Surfaces and Spectral Options. These will be covered in order.



**Figure 2.2.** The RT Options Window.

It is important to describe the function of the `Save As New Case` button in the lower left corner before discussing the individual tabs. This is NOT analogous to a `Save to File` operation in other applications. `Save As New Case` replicates all current input settings and increases the Case number on the MODTRAN6 GUI main menu, Figure 2.1. It is designed to allow the user to define a case with all entries initialized to the value from an earlier case. If, for example, you just want to validate an earlier case by switching from the band model (BM) to the line-by-line (LBL) radiative transfer method, you can load the BM case, hit `Edit` from the main menu, hit `Save As New Case`, set RT Option to Line-by-line, hit `OK`, and then Run MODTRAN from the main menu. Do not hit `Save As New Case` each time you modify a MODTRAN entry; it is saved automatically!

The RT Options page, and all the other Edit pages, contain default entries. In principle, these correspond to the values in the `keywords.json` file located in the MODTRAN6 Data directory; the `keywords.json` file is described in Chapter 3. The location of the MODTRAN6 Data directory appears on the RT Options page, greyed out following the `Choose` box under DATA location. This location was defined by an environment variable defined during MODTRAN installation. If you moved the MODTRAN6 data, you must hit the `Choose` box and locate the data.

The RT Option drop-down box lists four options. For the TRAIN01 case, a solar scattering calculation with DISORT multiple scattering [M, N, O] will be set up. Multiple scattering is most accurate when run with a radiative transfer algorithm that satisfies Beer's Law, either Correlated-k or Line-by-line. This suggests that Correlated-k (fast) is a preferred choice over Band Model [the Correlated-k (slow) option is seldom required]. However, for computational expediency, select the MODTRAN Band Model as the RT Option for TRAIN01; the results of the Band Model calculation can be validated against the Correlated-k (fast) or Line-by-Line algorithms after the demonstration is complete. MODTRAN includes four band model resolutions, 0.1, 1.0, 5.0 and 15.0 cm<sup>-1</sup>. TRAIN01 will use the 1.0 cm<sup>-1</sup> band model, the default value. Notice that if you choose Line-by-line as the RT Option, the band model resolution defaults to 0.1 cm<sup>-1</sup>, the only compatible value. Also, the Line-by-Line Intervals spinner box comes active. This box defines the number of sub-intervals into which the 0.1 cm<sup>-1</sup> bins are to be partitioned for the LBL calculations. The default value is 100, corresponding to a spectral resolutions of 0.001 cm<sup>-1</sup>. Any positive integer can be selected.

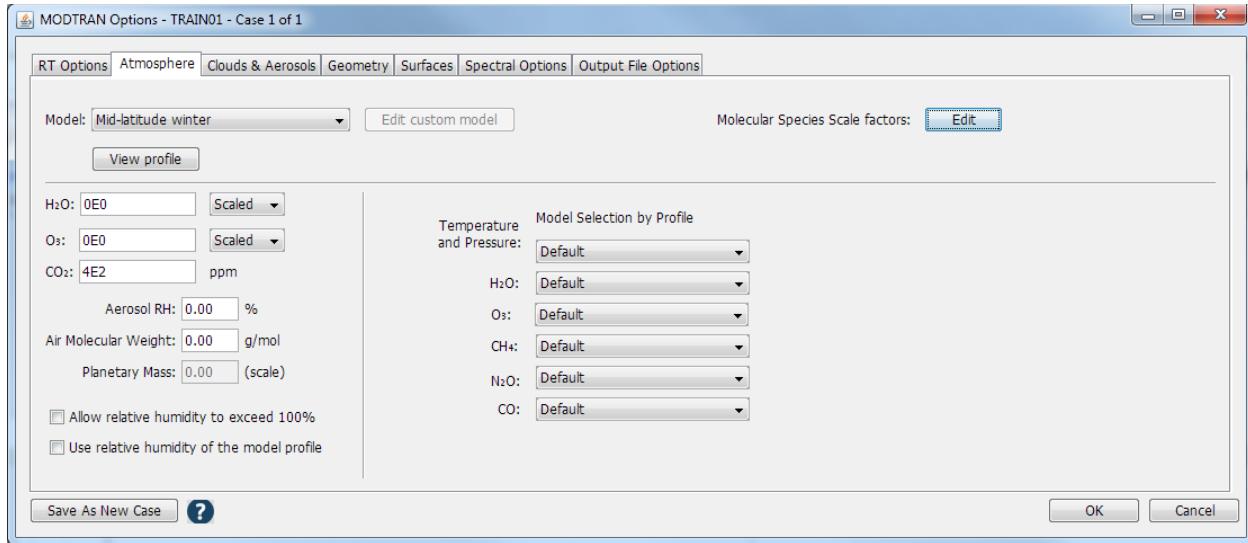
Six RT Run Mode options are available. All six generate a value for the line-of-sight (LOS) direct spectral transmittance. The transmittance option is designed to additionally generate distinct direct transmittances for every MODTRAN extinction source. This is only available with the BM RT Option. The band model assumes that the transmittance from each extinction source is randomly correlated, so the combined species BM transmittance at the spectral resolution of the BM equals to product of the individual components. Therefore the individual components are calculated. This random correlation assumption is not invoked for the Correlated-k and LBL models; if either of these RT Options is selected with the Transmittance RT Run Model, MODTRAN will revert to the Band Model RT Option. The BM is also used if the Solar irradiance or Lunar irradiance mode is selected. These modes simply compute the spectrally convolved product of solar/lunar TOA irradiances and LOS direct transmittances. Solar and thermal radiances will be computed in TRAIN01; make that selection.

The highest fidelity multiple scattering model is DISORT. If one can afford the computation costs, it is highly recommended; select DISORT MS from the Multiple Scattering drop-down menu. The plane-parallel atmosphere DISORT model solves the radiative transfer equation (RTE) at a single location, i.e. latitude and longitude. Since multiple scattering is most important at lower altitudes, it is generally best to solve the RTE at the observer for up-looking sensor geometries and at the final or tangent altitude for down-looking sensor geometries. Since the Train01 LOS's will defined an Earth viewing sensor, leave the At observer box unchecked. The number of DISORT streams equates to the number of polar and azimuth terms in the expansion of the path radiance. For thermal only calculations, a value of 2 is often sufficient; a value of at least 8 is recommended for solar radiance calculations. Select 8 from the DISORT Streams drop-down menu. Finally, MODTRAN provides the option to compute spectral atmospheric spherical albedos from the ground and spectral diffuse LOS and solar path transmittances; these are output in an atmospheric correction data file, <ROOTNAME>.acd. Click the Spherical albedo (atmosphere) box to generate the TRAIN01.acd data file.

### **2.3.2 Atmosphere Tab**

Click on the Atmosphere tab to specify the altitude PROFILES of pressure, temperature and molecular species. The Atmosphere window is illustrated in Figure 2.3. The MODTRAN provides 8 Model options. There are 6 built-in model atmospheres: Tropical, Mid-latitude summer, Mid-latitude winter, Sub-arctic summer, Sub-arctic winter and US Standard 1976. One can also enter user-supplied profiles by selecting either User-defined (altitude profile) or User-defined (pressure-dependent). If the pressure-dependent option is selected, only the ground altitude is input; all other altitude levels are computed by solving the hydrostatic

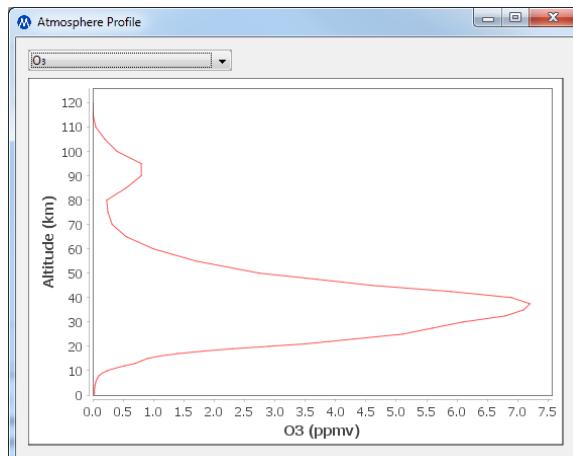
equation. For Train01, select the relatively dry Mid-latitude winter model atmosphere from the drop-down menu.



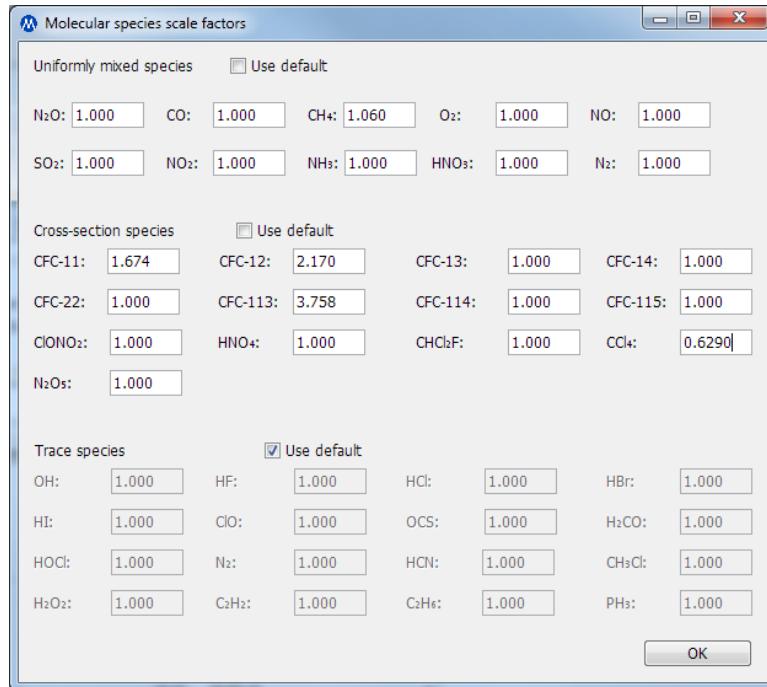
**Figure 2.3.** The Atmosphere Window.

One can view altitude profiles for pressure, temperature, H<sub>2</sub>O, CO<sub>2</sub>, O<sub>3</sub>, N<sub>2</sub>O, CO, CH<sub>4</sub> and O<sub>2</sub> by clicking View profile, and selecting the desired plot from the drop-down menu. The Mid-Latitude Winter profile for O<sub>3</sub> is shown in Figure 2.4. Close the window when done viewing.

Any of the molecular profiles can be scaled. Figure 2.3 lists scale factors of 0.0000 for H<sub>2</sub>O and O<sub>3</sub>. This is somewhat deceiving. A scale factor of 0.0000 is interpreted as no scaling, equivalent to 1.0000. If you actually want to zero out the H<sub>2</sub>O and/or O<sub>3</sub> profile, you must use the drop-down boxes to replace Scaled with column density units of either g/cm<sup>2</sup> or atm-cm. A problem can arise when scaling up the H<sub>2</sub>O profile. The relative humidity (RH) can be made to exceed 100%. By default, MODTRAN does not allow this to happen; the maximum H<sub>2</sub>O concentration at any level cannot exceed 100% and cannot exceed 5 times the default value. However, MODTRAN does try to match the input total column density. Therefore, MODTRAN will try to place the missing H<sub>2</sub>O amount in adjacent levels if they can accommodate the increase. You can choose not to be restricted by the 100% RH limit. Click on the Allow relative humidity to exceed 100% box if you wish to avoid the restriction.



**Figure 2.4.** The Mid-Latitude Winter O<sub>3</sub> Profile.



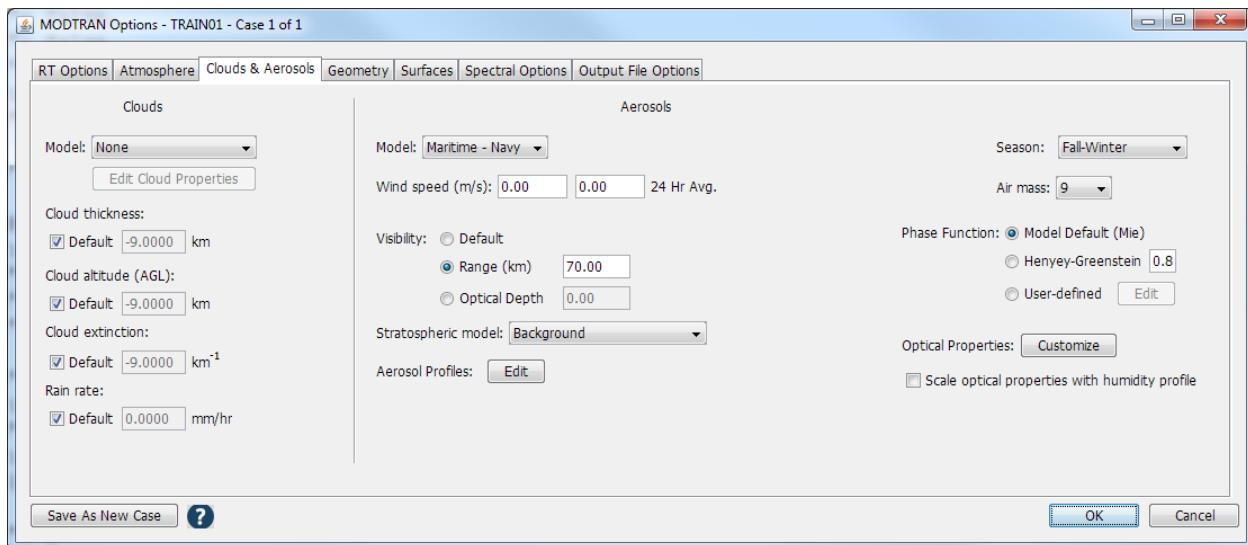
**Figure 2.5.** The Mid-Latitude Winter O<sub>3</sub> Profile.

Even if you do not choose to define a user-defined [Model](#) atmosphere, you can scale any of the defined molecular profiles. Click on [Edit](#) next to [Molecular Species Scale Factors](#); the window illustrated in Figure 2.5 will appear. Many of the default profiles in MODTRAN are out-of-date. The CH<sub>4</sub> profile is too low by ~6%. The 2015 northern hemisphere values from [http://cdiac.ornl.gov/oceans/CFC\\_ATM\\_Hist2015.html](http://cdiac.ornl.gov/oceans/CFC_ATM_Hist2015.html) indicate that the CFC-11, CFC-12, CFC-113 and CCl<sub>4</sub> profiles should be scaled by 1.674, 2.170, 3.758 and 0.629, respectively. Un-check the Use default boxes for the Uniformly mixed species and Cross-section species to enter these values. When done, click OK.

A number of the MODTRAN aerosol models are RH dependent. By default, MODTRAN calculates aerosol averaged RH values for each aerosol vertical region. Occasionally, one may wish to override that value. Insert a positive value for Aerosol RH to override the default. Also, MODTRAN assumes a default air molecular weight of 28.9644 g/mol. Insert a positive value for Air Mass (Air Molecular Weight would be a better label) if you wish to override the default.

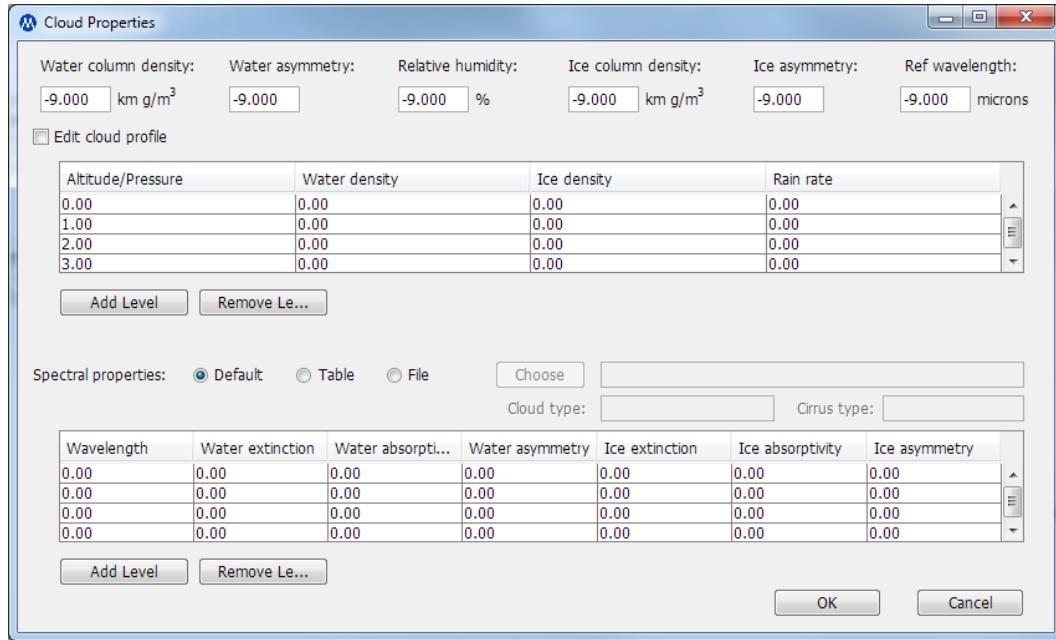
### 2.3.3 Clouds & [Aerosols](#) Tab

Click on the [Clouds & \[Aerosols\]\(#\)](#) (& Rain) tab to open the particulates window illustrated in Figure 2.6. On the left in the window, MODTRAN includes a number of cloud models, which can be selected from the Model drop-down menu. Once a model is selected, one can change the Cloud thickness [km], the Cloud Altitude (AGL) [km] i.e., the Above Ground Level base height, the Cloud extinction (coefficient) [1/km] and the Rain rate [mm/hr]. The product of the Cloud thickness and the Cloud extinction equals the cloud 550 nm vertical optical depth. A value of -9.0000 for any cloud input is a flag indicating that the MODTRAN default will be used. After selecting a cloud Model, the user can click on [Edit Cloud Properties](#) to specify user-defined cloud optical and profile data with the window illustrated in Figure 2.7. The TRAIN01 case will not include any clouds. Choose None from the Clouds Model drop-down menu.



**Figure 2.6.** The Clouds & [Aerosols](#) Window.

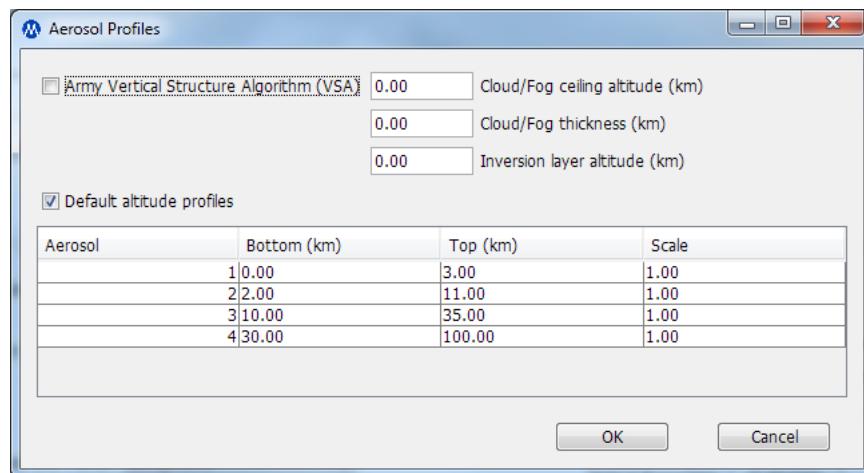
The TRAIN01 case will model an ocean viewing sensor. MODTRAN includes 9 built-in aerosol models, available from the Model drop-down menu in the [Aerosols](#) section: 23 km visibility Rural, 5 km visibility Rural – Dense, Maritime – Navy (formally known as the Navy Aerosol Model, NAM), Maritime, Urban, Tropospheric, Fog – Advective, Fog – Radiative, and Desert. Over ocean, the Maritime – Navy is generally preferred over Maritime; both models depend on RH, but the Maritime – Navy also varies wind current and 24-hr wind speeds. Select **Maritime – Navy** from the drop-down menu. To be consistent with the Mid-latitude winter model atmosphere, select **Fall-Winter** from the **Season** drop-down menu. Distinct instantaneous and 24 Hr Avg. Wind speeds (m/s) could be entered, but default values will be used by leaving these entries as 0.00. The Air mass character is a qualitatively measure of ocean fetch, the distance traveled by the local wind since it passed over land. A value of 1 is used for open ocean and 10 if there is a strong continental influence. For TRAIN01, set it to 9 for a near coastal scenario with trade winds from land. The surface meteorological range, referred to as the visibility in MODTRAN, could be set by the NAM model based on the wind speeds, but a clear sky scenario is defined by selecting the Range (km) radio button, and setting the visibility to 70 km. The Phase Function defines the angular distribution of single scattered radiation as a function of wavelength. The MODTRAN aerosol models have been generated assuming spherical (Mie) particles. The radio button labeled **Model Default (Mie)** selects the default data. Various **Stratospheric** models are available; the default **Background** model is used in TRAIN01.



**Figure 2.7.** The Cloud Properties Window.

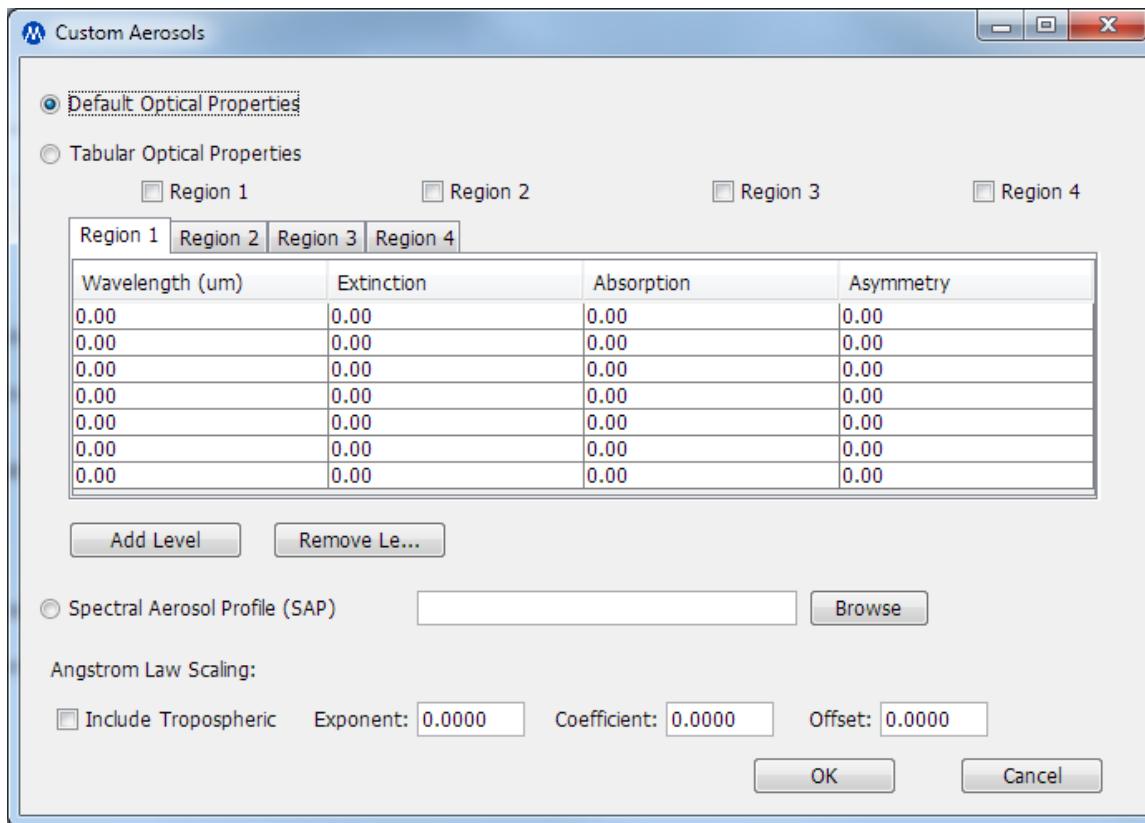
MODTRAN defines 4 aerosol regions. Nominally, Region 1 is the Boundary Layer Aerosol extending from 0 to 3 km; Region 2 is the Tropospheric Aerosol extending from 2 to 11 km; Region 3 is the Stratospheric Aerosol extending from 10 to 35 km; and Region 4 is the Volcanic Aerosol extending from 30 to 100 km. These aerosol regions can be moved and their densities scaled up or down by unclicking the Default profiles box, and clicking on Edit Profiles to bring up the window illustrated in Figure 2.8. TRAIN01 will used the default aerosol profiles, so click the Default profiles box.

If the default H<sub>2</sub>O profile was either scaled or defined by a user specified column density (in g/cm<sup>2</sup> or atm-cm) under the [Atmosphere](#) tab, the user may or may wish to not ve the aerosol optical properties simultaneously perturbed. Click on Scale Optical properties with humidity profile (humidity scaling) only if you wish to have the aerosol properties adjusted in response to altered H<sub>2</sub>O column. **Do not select the Scale Optical properties with humidity profile box for TRAIN01.**



**Figure 2.8.** The Aerosol Profiles Window.

The Custom [Aerosols](#) button brings up the window illustrated in Figure 2.9. This can be used (1) to define aerosol spectral Extinction coefficient, Absorption coefficient and Asymmetry factor data for each aerosol region, (2) to indicate that a Spectral Aerosol Profile (SAP) <ROOTNAME>.sap input file is to be read in, or (3) to define the aerosol extinction coefficient based on Angstrom Law Scaling data. None of these options will be used in the TRAIN01 case, so **the Custom [Aerosols](#) window can be closed without making any changes to it.**



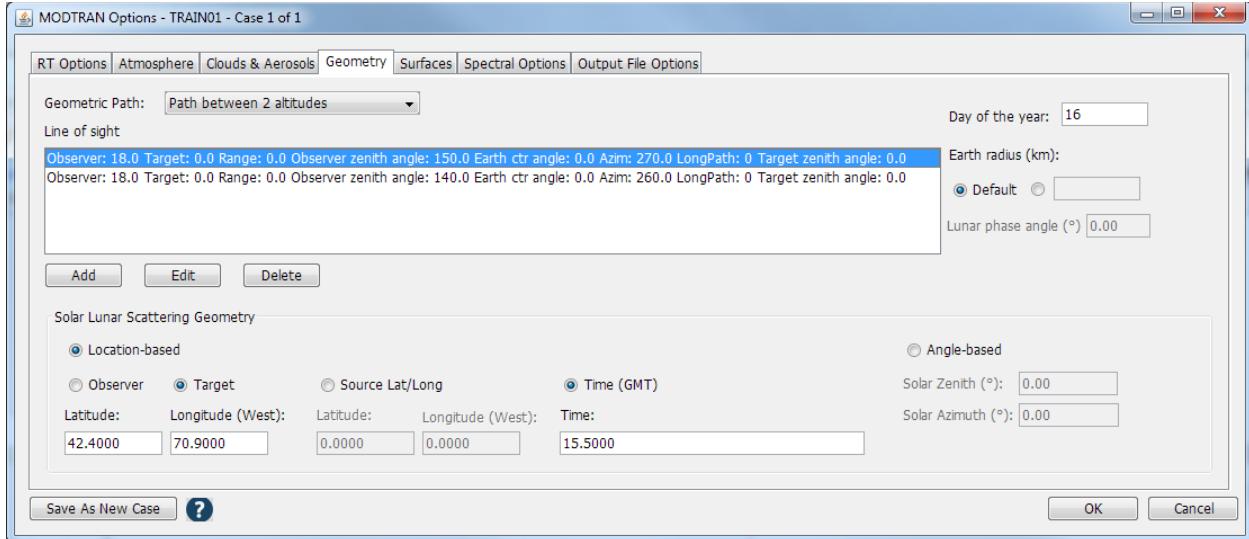
**Figure 2.9.** The Custom [Aerosols](#) Window.

### 2.3.4 Geometry Tab

Click on the **Geometry tab** to open the window illustrated in Figure 2.10, which is used to define the sensor line(s)-of-sight and the solar position. One begins by selecting the Geometric Path type from the drop-down menu. Almost all MODTRAN calculations are performed using either the Path between 2 altitudes or the Path to/from Space or Ground selections. The Horizontal path option is designed to allow a user to model transmittance and/or path thermal emission (no solar contributions) for a constant pressure path, as one might encounter when performing laboratory measurements. The other seldom used option is User defined path; this is designed to allow users to define their own refractive LOS path. Most users choose to have MODTRAN compute the spherical refractive path.

The Path between 2 altitudes is typically defined by three inputs, such as sensor/observer altitude, sensor/observer zenith angle, and path range. The Path to/from Space or Ground is always defined by two inputs, such as sensor/observer altitude and sensor/observer zenith angle. Given these two inputs, the forward or reverse path terminates when either the top-of-atmosphere (TOA) or the ground is encountered. Since TRAIN01 will define Earth viewing paths, either the Path to/from Space or Ground option or the Path between 2 altitudes option can be selected. Both options

will be demonstrated. Select Path to/from Space from the Geometric Path drop-down menu first.

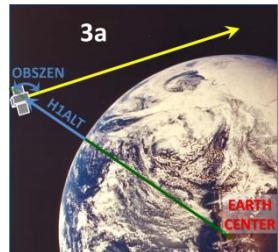


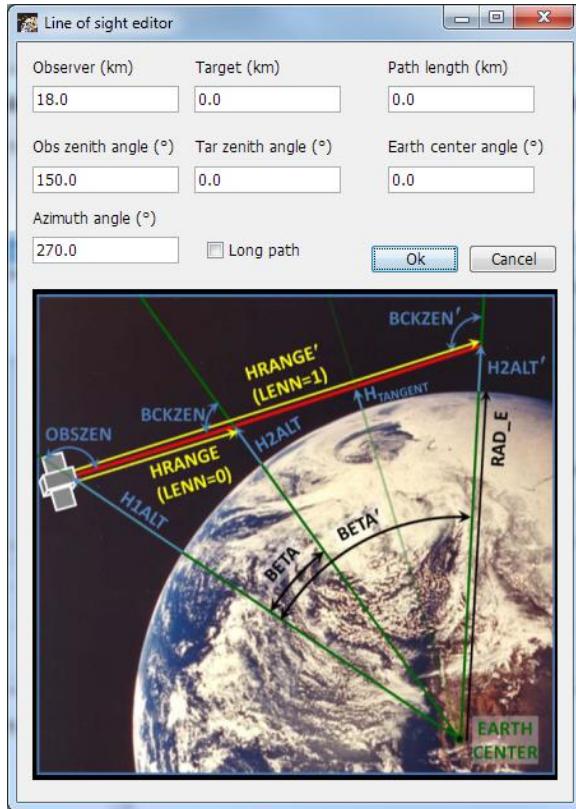
**Figure 2.10.** The Geometry Window.

#### **2.3.4.1 Path to/from Space**

Next, click on the Edit button to open the Line of sight editor, Figure 2.11. Two values from four inputs [Observer altitude (km), Target altitude (km), Observer zenith angle ( $^{\circ}$ ) and Target zenith angle ( $^{\circ}$ )] define the Path to/from Space or Ground. The following hierarchy determines which inputs are used:

- **Case 3c:** If the Target zenith angle ( $^{\circ}$ ) exceeds zero, the LOS is defined by the Target altitude (km) and the Target zenith angle ( $^{\circ}$ ). These inputs are H2ALT and BCKZEN, respectively, in the image on the right. This defines a LOS from either the TOA or the ground that terminates at the target altitude; the Target zenith angle ( $^{\circ}$ ) defines the zenith angle for the reverse path from the target back to the observer/sensor.
- **Case 3a:** Else if the Target altitude (km) is zero, the LOS is defined by the Observer altitude (km) and the Observer zenith angle ( $^{\circ}$ ). These inputs are H1ALT and OBSZEN, respectively, in the image on the right. This defines a LOS from the observer (sensor) altitude in the direction defined by the observer (sensor) zenith angle that terminates at the TOA unless the path intersect the Earth; in that case, it terminates at the ground.
- **Case 3b:** Else, the LOS is defined by the Observer altitude (km) and the Target altitude (km). These inputs are H1ALT and H<sub>TANGENT</sub>, respectively, in the image on the right. This defines a limb LOS from the observer altitude with the target altitude tangent height that terminates at the TOA. If the Observer altitude (km) does not exceed the Target altitude (km), an error is logged and the calculation is skipped.





**Figure 2.11.** The Line of sight editor Window.

For TRAIN01, a  $30^\circ$  off-nadir Path to/from Space or Ground from 18 km is defined by setting Observer altitude (km) to 18.0, Target altitude (km) to 0.0 (so it will not be used), Observer zenith angle ( $^\circ$ ) to 150.0 and Target zenith angle ( $^\circ$ ) to 0.0 (so it also will not be used). Click Ok to close the Line of sight Window.

#### 2.3.4.2 Path between 2 altitudes

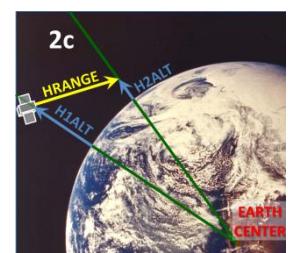
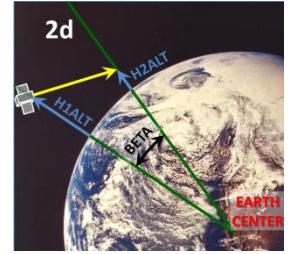
To demonstrate the Path between 2 altitudes option, select that entry from Geometry Path drop-down menu. The Path between 2 altitudes also requires a hierarchy to determine which three inputs are to be used to define the LOS:

- **Case 2f:** If both the Target zenith angle ( $^\circ$ ) and the Path length (km) exceed 0.0, the LOS is defined by the Target altitude (km), the Target zenith angle ( $^\circ$ ) and the Path length (km). These inputs are H2ALT, BCKZEN and HRANGE, respectively, in the image on the right. This defines a LOS of fix path length that terminates at the target altitude; the Target zenith angle ( $^\circ$ ) defines the zenith angle for the reverse path from the target back to the observer/sensor.
- **Case 2e:** Else if the Target zenith angle ( $^\circ$ ) exceeds 0.0, the LOS is defined by the Target altitude (km), the Observer altitude (km) and the Target zenith angle ( $^\circ$ ). The Long path length switch (see the click box in Figure 2.11) must also be defined if the Observer altitude (km) is less than the Target



altitude (km) and the extended path does not intersect the Earth. The inputs in the image on the right are H2ALT, H1ALT and BCKZEN (notice that the observer/sensor has been moved from the left to the right). This defines a LOS from the observer (sensor) altitude that terminates at the target altitude; the Target zenith angle ( $^{\circ}$ ) defines the zenith angle for the reverse path from the target back to the observer/sensor. As illustrated on the right, two distinct paths can initiate at H1ALT. Click on the Long path box to select the longer of these.

- **Case 2d:** Else if Earth center angle ( $^{\circ}$ ) exceeds 0.0, the LOS is defined by the Observer altitude (km), the Target altitude (km) and Earth center angle ( $^{\circ}$ ). These inputs are H1ALT, H2ALT and BETA, respectively, in the image on the right. This defines a LOS in which the Earth center angle between observer (sensor) and the target is equal to the input value. If the Earth center angle is too large, the path will intersect the Earth, an error will be logged and the calculation will be skipped.
- **Case 2b:** Else if both the Path length (km) and the Observer zenith angle ( $^{\circ}$ ) exceed 0.0, the LOS is defined by the Observer altitude (km), the Observer zenith angle ( $^{\circ}$ ) and the Path length (km). These inputs are H1ALT, OBSZEN and HRANGE, respectively, in the image on the right. This LOS begins at the observer (sensor) altitude in the observer (sensor) zenith angle direction; it terminates when the path length equals the input value.
- **Case 2c:** Else if the Path length (km) exceeds 0.0, the LOS is defined by the Observer altitude (km), the Target altitude (km) and the Path length (km). These inputs are H1ALT, H2ALT and HRANGE, respectively, in the image on the right. This defines a LOS in which the path length between the observer (sensor) altitude and the target altitude is specified. An error is logged and the calculation skipped if the path length is less than the altitude difference.
- **Case 2a:** Else, the LOS is defined by the Observer altitude (km), the Target altitude (km), and the Observer zenith angle ( $^{\circ}$ ). The Long path length switch (see the click box in Figure 2.11) must also be defined if the Observer altitude (km) is greater than the Target altitude (km) and the extended path does not intersect the Earth. The inputs in the image on the right are H1ALT, H2ALT and OBSZEN. This defines a LOS from the observer (sensor) altitude in the observer (sensor) zenith angle direction that terminates at the target altitude. As illustrated on the right, two distinct paths terminate at H2ALT. Click on the Long path box to select the longer of these.



For TRAIN01, the 30° off-nadir sensor at 18 km altitude is to view the ocean, so the ground altitude will be 0.0 km. **The Path between 2 altitudes line-of-sight geometry is defined by setting the Observer altitude (km) to 18.0, the Target altitude (km) to 0.0 km and the Observer zenith angle ( $^{\circ}$ ) to 150.0. The other three inputs, Path length (km), Target zenith angle ( $^{\circ}$ ) and Earth center angle ( $^{\circ}$ ) should all be set to 0.0 to avoid their use in defining the LOS.**

Examining the heirarchy with these inputs one finds that: the Target zenith angle ( $^{\circ}$ ) is 0.0, so Cases 2f and 2e are bypassed; the Earth center angle ( $^{\circ}$ ) is 0.0, so Case 2d is bypassed; and the Path length (km) is 0.0, so Cases 2b and 2c are bypassed. Case 2a: Observer altitude (km), the Target altitude (km) and the Observer zenith angle ( $^{\circ}$ ) define the LOS even though the target altitude is 0.0.

#### **2.3.4.3 Path Azimuth Angle ( $^{\circ}$ ), Earth radius (km) and Lunar phase angle ( $^{\circ}$ )**

The Line of sight editor Window, Figure 2.11, includes one additional input, the true path Azimuth Angle ( $^{\circ}$ ). Because the MODTRAN atmosphere is horizontally homogeneous (constant within spherical shells above the Earth), thermal radiances do not depend on the path azimuth angle. If the solar position is defined relative to the LOS, with solar zenith and relative solar azimuth angle inputs, solar radiances will also not depend on the specific true path azimuth angle. However, if ephemeris data is to be used to define the solar position, the true path Azimuth Angle ( $^{\circ}$ ) in degrees East of North must be specified. There is an added complication. When the Solar Lunar Scattering Geometry is defined as Location-based under the Geometry tab, one must select whether the Observer/sensor or the Target will be the reference location. If the Observer is chosen as the reference location, the true path Azimuth Angle ( $^{\circ}$ ) is defined for the path from the Observer/Sensor to the Target; on the other hand, if the Target is chosen as the reference location, the true path Azimuth Angle ( $^{\circ}$ ) is defined for the path from the Target to the Observer/Sensor.

TRAIN01 will define the Target, a point on the ocean surface, as the reference location. To define an Easterly pointing sensor, the Target to Observer/Sensor Azimuth Angle ( $^{\circ}$ ) must point to the West and should be set to 270.0 in the Line of sight editor Window. Note the Sensor azimuth direction will not be due East because of the Earth's curvature. After entering 270.0, click on Ok to close the window.

Under the Geometry tab, there is an option to input Earth radius (km). The default value for the tropical model atmosphere is 6378.39 km; the default value for the sub-arctic summer and winter is 6356.91 km; otherwise, the default value is 6371.23 km. A user-defined value can be entered by selecting the radio button to the right of Default. This input is of particular importance when modeling planetary atmospheres. For TRAIN01, the Default Earth radius (km) radio button should be selected.

The Lunar phase angle ( $^{\circ}$ ) entry is only active if Lunar and Thermal or Lunar Irradiance was selected from the RT Run Mode drop-down menu under the RT Options tab. The lunar angle is defined as a Moon centered angle, so 0.00 $^{\circ}$  is a full moon, 90.00 $^{\circ}$  is a half moon, etc.

#### **2.3.4.4 Multiple Lines-of-Sight (MLOS)**

There is a significant computation cost associated with running DISORT solar multiple scatter, which TRAIN01 opted for under the RT Options tab. However, a nice feature of DISORT is that it solves the radiative transfer equation for arbitrary lines of sight through a fixed atmosphere with a given solar zenith angle and ground surface. This option is only available if the Geometric path is set to Path between 2 altitudes. To invoke this option, Click on Add under the Geometry tab. For TRAIN01, the second LOS will be defined with the same observer and target altitudes, 18.0 and 0.0 km, respectively, but with the off-nadir angles to 40 $^{\circ}$  and the Target to Observer/Sensor azimuth defined to be 10 $^{\circ}$  South of West. Decrease Observer zenith angle ( $^{\circ}$ ) to 140.0 and decrease true path Azimuth Angle ( $^{\circ}$ ) to 260.0. Click Ok to close the Line of sight editor after making the changes. The Line of sight box under the Geometry tab should now have two lines-of-sight defined with the chosen values.

#### **2.3.4.5 Solar Lunar Scattering Geometry**

The position of the sun can be entered either relative to the LOS using Angle-based inputs (this is not an option when [MLOS](#) are defined) or as ephemeris data using Location-based inputs. In either case, the Day of the year needs to be specified. This input is used to scale solar irradiance data based on Earth-Sun distance. The default value, Day 93, corresponds to the mean Earth-Sun distance. **For TRAIN01, the Day of the year is set to 16**, a mid-January winter day in the Northern Hemisphere.

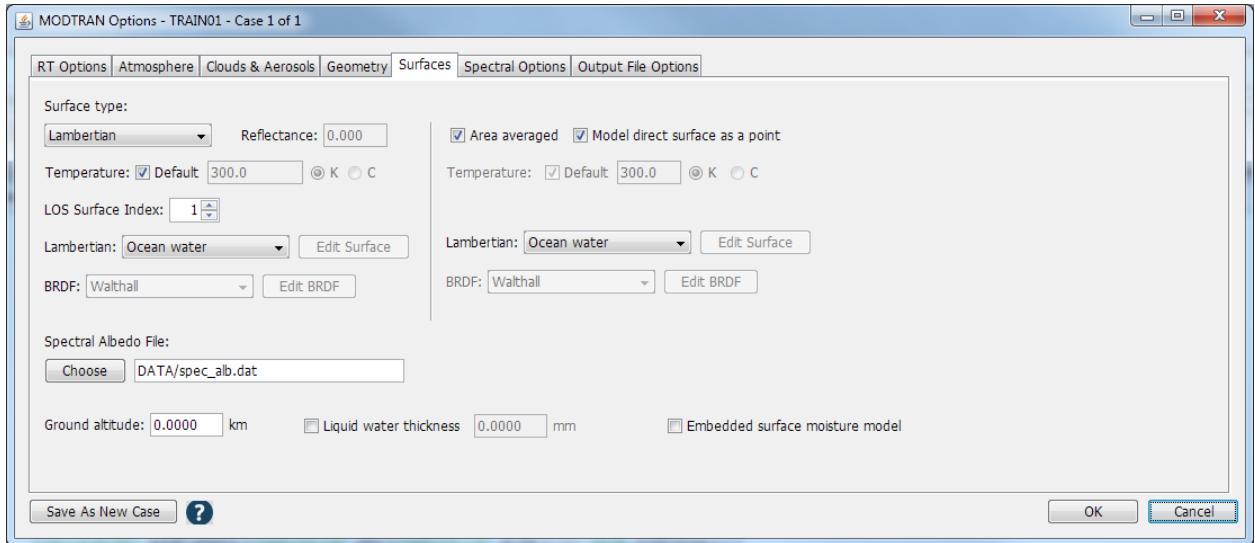
The simplest method for specifying solar position is to specify Angle-based inputs: Solar Zenith ( $^{\circ}$ ) and Solar Azimuth ( $^{\circ}$ ). Using the radio buttons in the lower left under the Geometry tab, one can choose whether the solar zenith and azimuth angles are to be defined at the Observer or at the Target. Note that if the LOS is defined via Case 3b (see Section 2.3.4.1), the target location at which the solar angles are defined is the tangent point for the limb path.

Alternatively, Location-based ephemeris data can define the solar position relative to the LOS. The Latitude and Longitude (West) (degrees **West** of Greenwich) must be defined at either the Observer or the Target. Radio buttons allow the user to choose between the two allowed reference locations, and, again, the target location for Case 3b is the limb path tangent point. Either the sub-solar Latitude and Longitude (West) or the Day of the year and decimal Time (GMT) can be used to specify the sun location. Select the Source Lat/Long radio button for the first of these options, and the Time (GMT) radio button for the second option.

Since the TRAIN01 test case defines two lines-of-sight (the [MLOS](#) option), the Solar Lunar Scatter Geometry must be Location-based. For the TRAIN01 test case, entry of an Observer reference location would fix the position of the observer/sensor and view two distinct locations on the ocean. **TRAIN01 will instead use a Target reference location**. This produces a scenario where the same point on the ocean surface is viewed from two distinct sensor locations. **Set the target Latitude to 42.4° North and 70.9° West**, in the harbor of Boston, MA, just South of Nahant Island. To model a morning sun with local time of 11:30 am, **select the Time (GMT) radio button and set the Greenwich Mean Time to 15.5**. This completes the definition of the LOS and solar geometries for TRAIN01.

#### **2.3.5 Surfaces Tab**

Click on the [Surfaces](#) tab to define the ground surface temperature, altitude, moisture content and its spectral and angular reflectance and emission. The Surfaces Window is illustrated in Figure 2.12. MODTRAN allows the user to define distinct surfaces for each LOS pixel and for the spatially averaged ground. The LOS pixel surface is used to calculate the directly transmitted ground emission and reflectance; the area averaged surface serves as the lower boundary condition for multiple scattering and is used to calculate the diffusely scattering surface radiance components.



**Figure 2.12.** The Surfaces Window.

### 2.3.5.1 LOS Surface Pixel

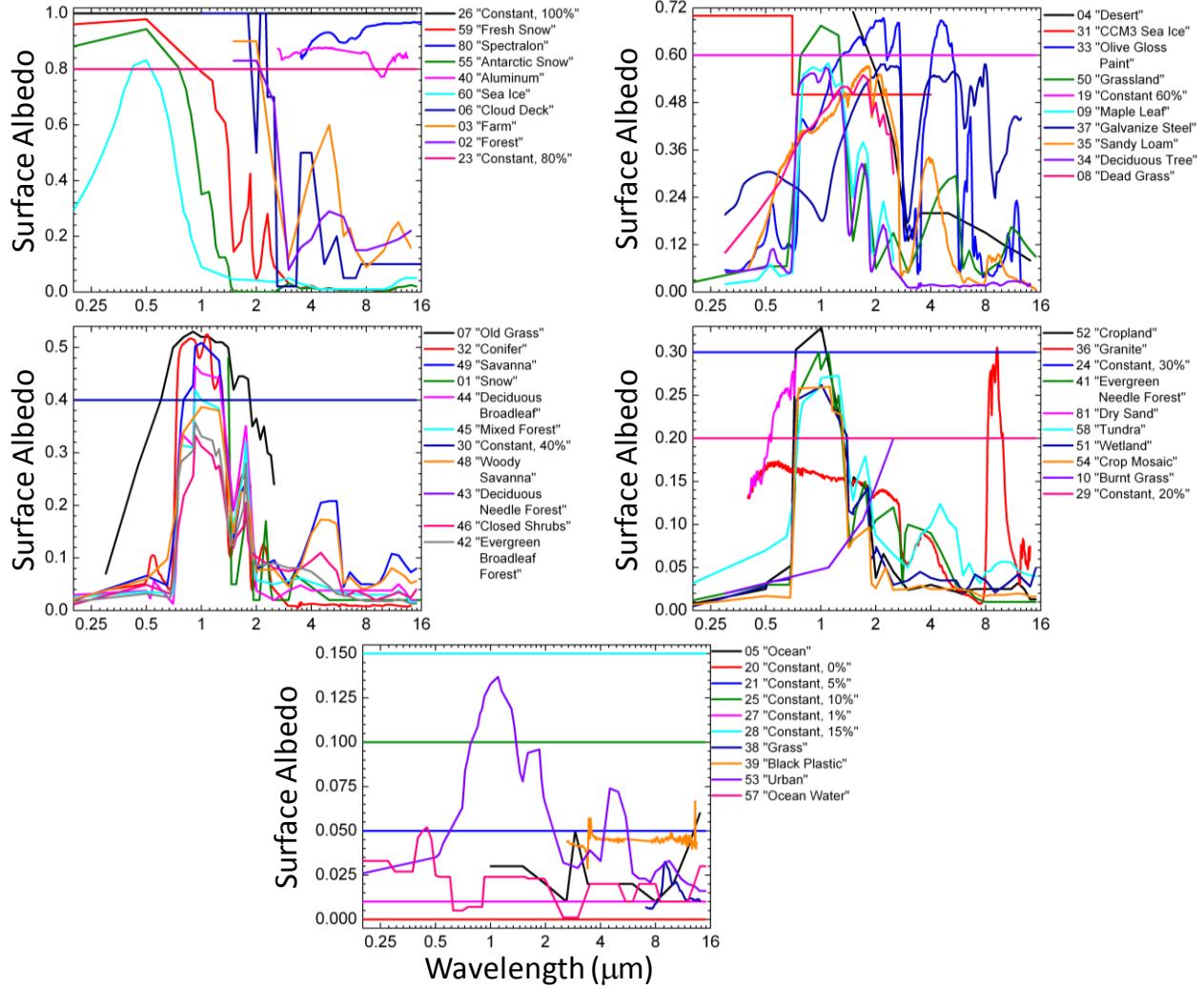
Three Surface types are supported: Constant, spectral Lambertian and spectral Bi-direction Reflectance Distribution Function (BRDF). If a spectrally and angularly constant reflectance value is selected, its value is entered in the Reflectance box.

If the Lambertian option is selected, one can choose from a large number of MODTRAN spectral reflectance curves, all of which are plotted in Figure 2.13. These curves are defined in the spec\_alb.dat file, stored in the MODTRAN6 DATA directory. It is best to restrict ones selection to a curve whose spectral coverage spans the spectral range of the calculation (defined under the Spectral Options tab). The Lambertian drop-down menu is used to select among the surfaces. *Currently, the MODTRAN6 GUI does not support user-defined Lambertian surface reflectances; if one Chooses an alternate spectral reflectance file, it is ignored.* For TRAIN01, set the Surface type to spectral Lambertian. For the marine scenario, select Ocean water from the Lambertian drop-down menu (near the bottom of the list). TRAIN01 includes two lines-of-sight. A path endpoint reflectance for each LOS must be defined. The LOS Index spinner box, which counts starting at 0, should be incremented to 1 to define the Lambertian reflectance curve for the second LOS. Ocean water is also used for the second LOS, so select that value.

One can also choose from 10 parameterized spectral BRDF surface models: Walhall, Walthall analytic, Walthall sine, Walthall sine analytic, Hapke, Rahman, Roujean, Pinty Verstraete, Ross Li and Ross-Sea. Each of these is briefly described in Section 3.8.1, and original references are provided for further details.

The ground surface temperature defaults to the surface air temperature, defined by the atmospheric temperature profile. One can override this default value by removing the check on the Default box following Temperature. Then enter the desired ground temperature, using radio buttons to choose between Kelvin and Celsius units. If a temperature is specified, then grey-body surface emission will be included in the LOS radiance calculation even if the LOS does not terminate at the ground; the emissivity is defined as one minus surface reflectance. *For TRAIN01, the Default Temperature box should be checked.*

MODTRAN ground altitudes must be less than 6.0 km, and negative, below sea-level values can be allowed. *For TRAIN01, 0.0000 km is entered for sea-level.*



**Figure 2.13.** Curves of surface spectral reflectance data from the MODTRAN file 'DATA/spec\_alb.dat'.

MODTRAN includes the option to model surface liquid water; however, problems with these models were recently discovered, and users are advised not to use them until corrections have been implemented.

### 2.3.5.2 Area Averaged Surface

One can choose to define a spatially or Area averaged ground surface distinct from the surface defined for LOS pixels. This option is only available with Lambertian and BRDF Surface types. *If you choose one of these Surface types and you use the [MLOS](#) option, you must define an Area averaged ground surface even if it identical to the surfaces used for the LOS pixels.* Click on the Area averaged box to activate the option and define the temperature and reflectance. A Model direct surface as a point box will also become active. If checked, forward scattered photons entering the sensor are modeled as originating from the Area averaged surface; otherwise, they are modeled as originating from the LOS pixel surface.

For TRAIN01, click on the Area averaged box and select the Ocean water Lambertian surface.

### 2.3.6 Spectral Options Tab

Click on the Spectral Options tab to open the spectral output window, illustrated in Figure 2.14. For this window, it is appropriate to begin in the upper right, defining the desired spectral Units and the type of Slit function. For TRAIN01, visible through mid-wave infrared (MWIR) calculations will be performed. Choose microns from the Units drop-down menu, and Gaussian from the Slit function drop-down menu. Set the Initial and Final spectral bandpass values to 0.4 and 5.0 (microns). Generally, it is recommended that the spectral resolution, entered as a full-width at half-maximum (FWHM), be at least twice the output step size or Increment. For TRAIN01, set the Increment to 0.002 (microns, i.e. 2 nm) and the FWHM to 0.005 (microns, i.e. 5 nm). The 5 nm value is an Absolute resolution. By clicking the Relative (%) radio button, one can enter the FWHM as a percent. For example, if the FWHM were set to 1.0 with the Relative (%) radio button selected, a 0.004 micron (4 nm) spectral resolution calculation would be performed at 0.4 microns and a 0.05 micron (50 nm) spectral resolution calculation, at 5.0 microns.

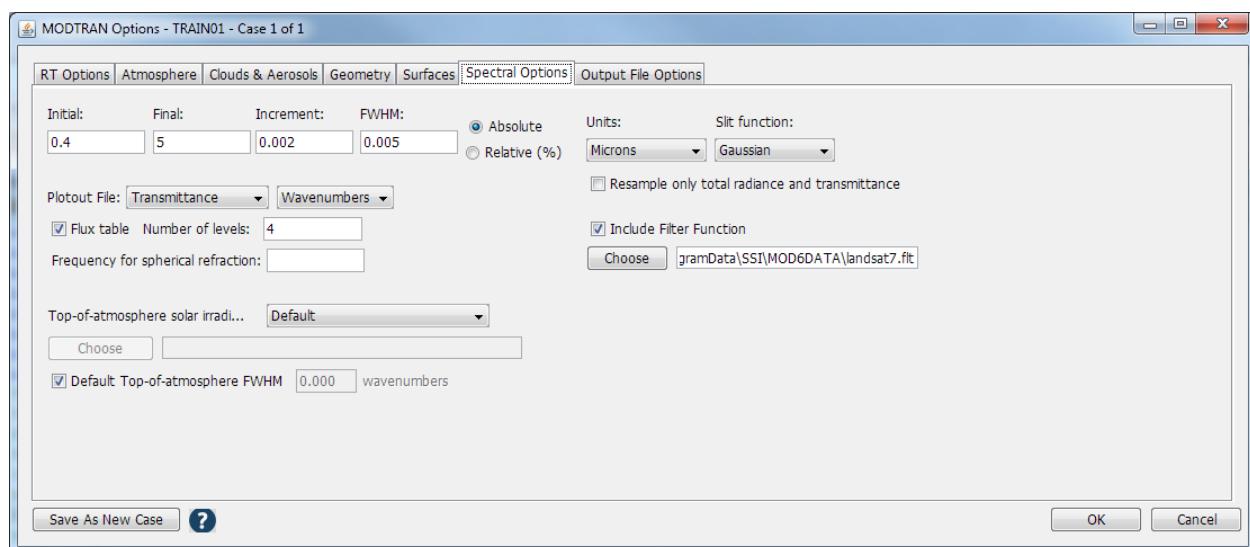


Figure 2.14. The Spectral Options Window

When Multiple Scattering calculations are performed, as defined under the RT Options tab, spectral horizontal flux data is generated at each altitude level. The upward and downward horizontal fluxes are hemispherical integrals over radiance weighted by projected area. Click on Flux table to generate a <ROOTNAME>.flx output file. By default the output file contains spectral flux data at every altitude level. This can be a sizable amount of output. If a positive Number of levels <N> is entered, the output file will only contain data for the first <N> altitude levels and for the TOA level. If, for example, the Number of levels is set to 1, the flux table will only contain ground and TOA spectral flux values. For TRAIN01, click the Flux table box and set the Number of levels to 4. With 1 km vertical spacing up to 25 km and a 100 km TOA, this Number of levels will produce a table of spectral fluxes at 0, 1, 2, 3 and 100 km.

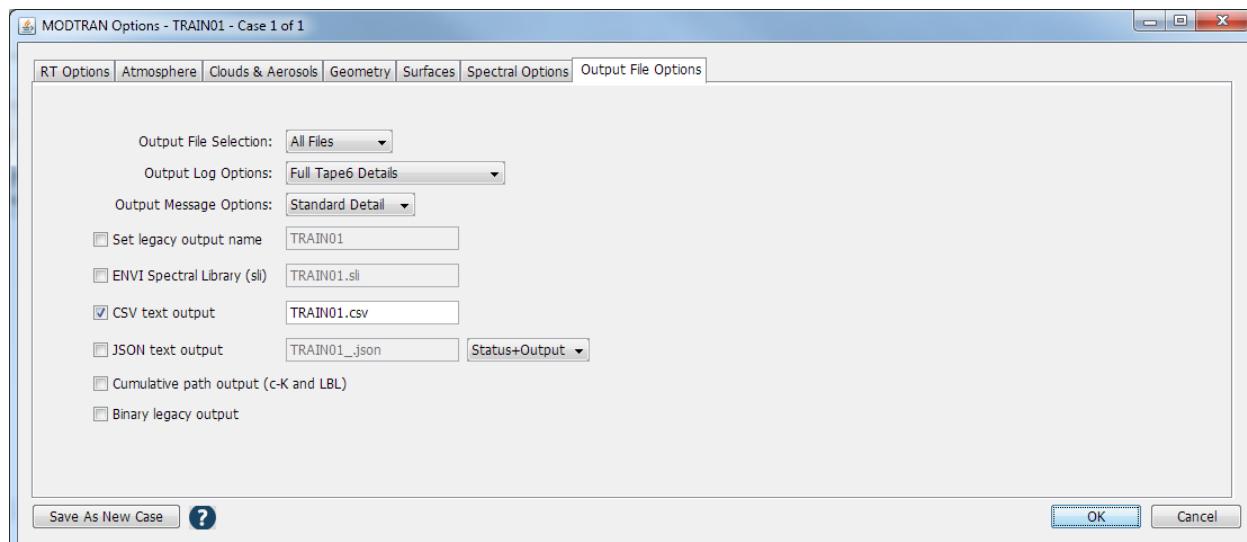
MODTRAN provides an option to convolve the band model spectral resolution data over user-defined sensor spectral response functions. Click the Include Filter Function box to initiate this option. MODTRAN is delivered with nominal spectral response functions defined for a number of sensors. For TRAIN01, click on Choose, select the “landsat7.fl” Landsat7 spectral response function file, and click on Open (Note that data will not be generated for Band 6 which lies long of 10 microns). Users can define their own filter function, and click on Choose to navigate to their file.

MODTRAN performs the spherical refraction calculation at a single frequency. By default, the frequency is chosen to be the central value of the spectral range. Users can overwrite the reference frequency used by inserting a wavenumber ( $\text{cm}^{-1}$ ) value in the Frequency for spherical refraction box. **TRAIN01 uses the default value so the Frequency for spherical refraction box** should be left empty.

The MODTRAN default TOA solar irradiance data is the Fontenla “medium2” solar activity file [K, L]. MODTRAN provides a number of alternatives listed in the Top-of-atmosphere solar irradiance drop-down menu. Users can also define their own solar irradiance file. **The Default Top-of-atmosphere solar irradiance is used with TRAIN01.** By default, the chosen spectral resolution of the MODTRAN band model (0.1, 1.0, 5.0 and 15.0  $\text{cm}^{-1}$ ) is also the spectral resolution of the solar irradiance data. There is an option to further degrade the solar irradiance data. Remove the check from the Default TOA FWHM box to enter a coarser resolution. **TRAIN01 uses the Default TOA FWHM.**

### 2.3.7 Output File Selection

Before running MODTRAN, output options need to be selected. **Click on the Output File Options tab** to open the selection options for output files, illustrated in Figure 2.15. Information on the contents of the output files is described in Chapter 4 of this manual. For the initial run, it is recommended that one selects All Files from the Output File Selection drop down box. Other new output file formats available from the GUI are: a comma separated values (<ROOTNAME>.csv) ASCII file that can be opened as a spread sheet by Microsoft Excel, a JSON output text file, and an ENVI® spectral library (<ROOTNAME>.sli) binary file (ENVI® is Harris Corporation image processing software). Check the CSV box to create this type of file. If you are an ENVI® user, you may wish to also check the ENVI sli box. **Click on the OK button to save the settings and exit the MODTRAN Options – TRAIN01 window.**



**Figure 2.15.** The Output File Options Window

### 2.3.7 Running TRAIN01

Save Train01.json by clicking on either Save or Save As.... Figure 2.16 contains a copy of the TRAIN01.json file. The format of the JSON file is not described until Chapter 3. However, a number of entries can immediately be related back to selections made from the GUI. Solar and thermal radiative transfer (RT) equations were solved using 8-stream DISORT. The Mid-Latitude Winter model

atmosphere was selected along with the Navy Aerosol Model. Two lines-of-sight were defined with an 18 km altitude sensor and zenith angles of 150° and 140°. The ground was model using the Ocean Water spectral Lambertian reflectance curve. The spectral range extends from 0.4 to 5.0  $\mu\text{m}$ , with a 2 nm (0.002  $\mu\text{m}$ ) step size and a 5 nm (0.005  $\mu\text{m}$ ) FWHM. Figure 2.17 contains screen shots of the total spectral radiance curve; the plot window was stretched and the mouse was used to select one plot extending from 0.4 to 1.0  $\mu\text{m}$ , and another extending from 1.0 to 5.0  $\mu\text{m}$ .

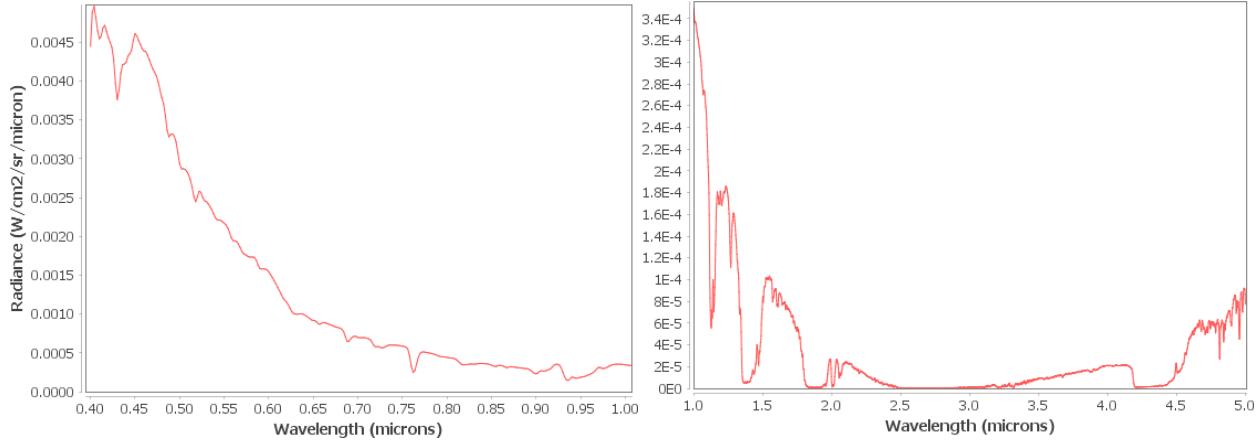
```
{
  "MODTRAN": [
    {
      "MODTRANINPUT": {
        "NAME": "TRAIN01",
        "DESCRIPTION": "",
        "CASE": 0,
        "RTOPTIONS": {
          "MODTRN": "RT_MODTRAN",
          "LYMOLC": false,
          "T_BEST": false,
          "IEMSCT": "RT_SOLAR_AND_THERMAL",
          "IMULT": "RT_DISORT",
          "DISALB": true,
          "NSTR": 8,
          "SOLCON": 0.0
        },
        "ATMOSPHERE": {
          "MODEL": "ATM_MIDLAT_WINTER",
          "M1": "ATM_MIDLAT_WINTER",
          "M2": "ATM_MIDLAT_WINTER",
          "M3": "ATM_MIDLAT_WINTER",
          "M4": "ATM_MIDLAT_WINTER",
          "M5": "ATM_MIDLAT_WINTER",
          "M6": "ATM_MIDLAT_WINTER",
          "C_PROF": 3,
          "S_UMIX": [ 1.0, 1.0, 1.06, 1.0, 1.0, 1.0, 1.0, 1.0, 1.0, 1.0 ],
          "S_XSEC": [ 1.674, 2.17, 1.0, 1.0, 1.0, 3.758, 1.0, 1.0, 1.0, 1.0, 0.629, 1.0 ]
        },
        "AEROSOLS": {
          "CDASTM": "b",
          "IHAZE": "AER_MARITIME_NAVY",
          "ISEASN": "SEASN_FALL_WINTER",
          "ICSTL": 9,
          "VIS": 70.0
        },
        "GEOMETRY": {
          "ITYPE": -2,
          "IDAY": 16,
          "IPARM": 11,
          "PARM1": 42.400001525878906,
          "PARM2": 70.9000015258789,
          "GMTIME": 15.5,
          "NLDS": 2,
          "MLDS": [
            {
              "H1ALT": 18.0,
              "OBSZEN": 150.0,
              "AZ_INP": 270.0
            },
            {
              "H1ALT": 18.0,
              "OBSZEN": 140.0,
              "AZ_INP": 260.0
            }
          ]
        },
        "SURFACE": {
          "SURFTYPE": "REFL_LAMBER_MODEL",
          "NSURF": 2
        }
      }
    }
  ]
}
```

```

    "SALBFL": "spec_alb.dat",
    "SURFA": {
        "CSALB": "LAMB_OCEAN_WATER"
    },
    "SURFNLOS": 2,
    "SURFLOS": [
        {
            "CSALB": "LAMB_OCEAN_WATER"
        },
        {
            "CSALB": "LAMB_OCEAN_WATER"
        }
    ],
    "SPECTRAL": {
        "V1": 0.4,
        "V2": 5.0,
        "DV": 0.002,
        "FWHM": 0.005,
        "XFLAG": "M",
        "FLAGS": "MG A T",
        "FILTNM": "C:\\\\ProgramData\\\\SSI\\\\MOD6DATA\\\\landsat7.flt"
    },
    "FILEOPTIONS": {
        "NOPRNT": -2,
        "CSVRNT": "TRAIN01.csv"
    }
}
]
}
}

```

**Figure 2.16.** The Training.json Input file (Cont'd).



**Figure 2.17.** TRAIN01 Total (Resampled) Spectral Radiance

### 3. MODTRAN6 JSON-STYLE INPUT DATA FORMAT

#### 3.1 Overview of JSON-style Input Data Format

For the MODTRAN 6.0.0 release, a JSON format can be used for the input. The JSON standard is given by ECMA-404, October 2013 (<https://www.ecma-international.org/publications/files/ECMA-ST/ECMA-404.pdf>). Much like XML, JSON is a structured text format that allows data interchange between programming languages. The JSON syntax is composed of braces, brackets, colons, and commas and provides support for ordered lists of keyword/value pairs. As such it was chosen to provide the structured input necessary for MODTRAN6. An example of a MODTRAN JSON input file is shown in Figure 3.1.

The main items to note about the use of JSON are as follows:

- Basic to JSON is the concept of a "JSONObject". This is an unordered collection of keyword/value pairs. Its external form is a string wrapped in curly braces [i.e. an opening brace {}, the string, and a closing brace {}] with colons between the keywords and values, and commas between the keyword/value pairs. The values can be any of these types: JSONArray, JSONObject, Number, or String.
- A JSONArray is an ordered sequence of values.
- Keywords must be enclosed in quotes ("") and followed by a colon (:).
- Each keyword/value pair in a JSONObject must be followed by a comma if it is followed by another pair, e.g. the keyword/value pair "[H1ALT](#)":20.0, in Figure 3.1. The last item in a JSONObject, before the closing brace, cannot be followed by a comma.
- All keyword/value pairs are optional. Default values are used for any that are omitted.
- The types of values in use for MODTRAN6 are given the following names in the tables which follow:
  - "Boolean", with 2 values, true or false, which should **not** be enclosed in quotes (e.g., "BINARY": true).
  - "Integer", which represents a whole number (e.g., "CASE":0).
  - "Float", which represents a floating point number (e.g., "CO2MX": 400.0).
  - "String", which represents a character string, whose length may or may not be fixed (e.g. "BMNAME":"15\_2013"). Any character string entered as input must be enclosed in quotes (""). For a quote within a character string, use \". For backslashes within character strings, use \\.

An array of values is indicated by adding "[]" after the type, so an integer array is indicated using "Integer[]".

- When the value is a JSONArray, the keyword is followed by an opening square bracket ([]), the array values, and a closing square bracket ([]). An example is "S\_UMIX":[1.0,1.0,1.05,1.0,1.0,1.0,1.0,1.0,1.0,1.0], in the 1500mGround.json test case input file.
- while all of the keywords in the examples in this text and from the tape5 to JSON converter code are in uppercase (capital letters), the console executable is agnostic to case. Uppercase is used for ease of comparison to the legacy variables.

```

{
  "MODTRAN": [
    {
      "MODTRANINPUT": {
        "NAME": "05vs15nadirRAD",
        "DESCRIPTION": "Comparison of results generated with the 5 and 15 cm-1 band models",
        "CASE": 0
      },
      "RTOPTIONS": {
        "IMULT": "RT_ISAACS_2STREAM_AT_OBS"
      },
      "ATMOSPHERE": {
        "MODEL": "ATM_US_STANDARD_1976",
        "CO2MX": 400.0
      },
      "AEROSOLS": {
        "IHAZE": "AER_RURAL_DENSE"
      },
      "GEOMETRY": {
        "H1ALT": 20.0,
        "IDAY": 1,
        "PARM2": 60.0
      },
      "SURFACE": {
        "SURREF": 0.4
      },
      "SPECTRAL": {
        "LEMNAM": "T",
        "BMNAME": "15_2013",
        "V1": 13995.0,
        "V2": 34005.0,
        "DV": 90.0,
        "FWHM": 90.0,
        "YFLAG": "R",
        "XFLAG": "N",
        "FLAGS": "WTAA"
      },
      "FILEOPTIONS": {
        "BINARY": true
      }
    },
    {
      "MODTRANINPUT": {
        "CASE": 1,
        "CASE TEMPLATE": 0,
        "SPECTRAL": {
          "BMNAME": "05_2013"
        }
      }
    }
  ]
}

```

**Figure 3.1.** MODTRAN structured JSON file for the 05vs15nadirrad test case. Only values that are not defaults are delineated.

- **Deviation from the JSON Standard:** While Standard JSON does not allow for comments in a JSON file or string, the MODTRAN JSON implementation does allow for comments which must be placed after a # symbol. Any information which follows the # on a given line of the file will be ignored.

Referring to the example shown in Figure 3.1, it is seen that the structure of the input file is in the form of nested JSONObjects as follows:

- Opening {} and{} closing braces encompass a single "MODTRAN" JSONArray, with the array running over the cases.
- Each case is represented by a "MODTRANINPUT" JSONObject. Multiple input cases can be included in one JSON file, as shown. Each entire "MODTRANINPUT" JSONObject except the final one must be followed by a comma. Therefore, the JSON file of Figure 3.1 has the following structure:

```
{
  "MODTRAN": [
    {
      "MODTRANINPUT": { ... }
    },
    {
      "MODTRANINPUT": { ... }
    }
  ]
}
```

- The "MODTRANINPUT" keyword is followed by combinations of keyword/value pairs enclosed within its braces. The available keywords, described in Section 3.2 below, are
  1. the "NAME", used to identify the output file root names,
  2. the "DESCRIPTION", used to describe the input file,
  3. the "CASE" number, used to delineate each MODTRAN run,
  4. the "CASE TEMPLATE", used to label an earlier case which is to serve as a template, and
  5. the JSONObjects to input the parameters associated with the following: RT Algorithm, Atmosphere, Aerosols, Geometry, Surface, Spectral, and File options. The respective keywords for these are "RTOPTIONS", "ATMOSPHERE", "AEROSOLS", "GEOMETRY", "SURFACE", "SPECTRAL", and "FILEOPTIONS".
- For multiple cases, the "CASE TEMPLATE" keyword can be used to simplify the input. This allows just those inputs which differ from the case associated with "CASE TEMPLATE" to be provided. In Figure 3.1, case number 1 uses the same input as case number 0 (note that case numbers begin at 0 not 1) but with the band model file name, BMNAME, changed from 15\_2013 (the 15 cm<sup>-1</sup> band model) to 05\_2013 (the 5 cm<sup>-1</sup> band model).

The structure of JSON files may be verified using validation tools, including ones that may be found online such as JSONLint (<http://jsonlint.com>). Note that such tools do not accept comments that are valid in MODTRAN JSON files.

Specific keywords are described in the sections that follow. For the remainder of Section 3, keywords are shown in typewriter (COURIER NEW) font, typically without the enclosing quotes e.g. ITEMSCT.

Specific values are shown in Arial font, e.g. RT\_TRANSMITTANCE. Generic values are also shown in Arial font using the name of the corresponding keyword, e.g. [IEMSCT](#). Default values are shown in *italics*.

The full set of default JSON keywords for MODTRAN are listed in the “keywords.json” file residing in the MODTRAN DATA directory (the location of this directory is defined by the environment variable MODTRAN\_DATA). Figure 3.2 contains a copy of this file.

### 3.1.1 Units

All inputs involving dimension of length are in kilometers (km) by default. All angle inputs are in degrees ( $^{\circ}$ ) by default. All temperature inputs are in Kelvin (K) by default. Frequency inputs are in wavenumber, i.e.  $\text{cm}^{-1}$ . Unless otherwise stated, these units are used for all MODTRAN inputs. Units are stated within square brackets ([]).

### 3.1.2 Abbreviations

<b>AGT</b>	Atmospheric Generator Toolkit
<b>API</b>	Application Programming Interface
<b>ATBD</b>	Algorithm Theoretical Basis Document
<b>ATK</b>	Aerosol ToolKit
<b>BRDF</b>	Bi-directional reflectance distribution function
<b>CIA</b>	Collision induced absorption
<b>C<sub>k</sub></b>	Correlated- $k$
<b>DISORT</b>	Discrete ordinate radiative transfer
<b>FAQ</b>	Frequently Asked Question
<b>GSF</b>	Generalized Spherical Function
<b>GUI</b>	Graphical User Interface
<b>ICD</b>	Interface Control Document
<b>LBL</b>	Line-by-line
<b>LOS</b>	Line-of-sight
<b>MLOS</b>	Multiple lines-of-sight
<b>MPI</b>	Message Passing Interface
<b>MS</b>	multiple scattering or multiply-scattered
<b>RH</b>	Percent relative humidity
<b>SRF</b>	Spectral Response Function
<b>TOA</b>	Top-of-atmosphere

```

# A list of keywords used in MODTRAN (20 Sep 2016). There are 2 elements here. The
# first is the original format MODTRAN keyword name with a descriptive comment as
# a value sorted by card. The second translated natural language variable names to
# the original MODTRAN keyword that acts as a lookup table. In processing, incoming
# keywords are validated against these lists. If a natural keyword is found,
# it gets replaced in the JSON structure with the original MODTRAN name, which is
# used internally in MODTRAN. All input keywords are case-insensitive. The
# valid_modtran text can also be used as a template for creating a new input file.
#
# Special case for default values: arrays. These are defined IN THIS FILE ONLY as
# a dictionary with three values to indicate that they are arrays with a specific
# type, expectation, and a default value:
#   "SOME ARRAY": {"ARRAY":true,"DEFAULT":[1.0,2.0],"TYPE":0.0}
# where "TYPE" is a single value of the type expected in the array. This allows
# for default empty arrays to still be typed.
{
"VALID_MODTRAN": {
    # Top level array. See note above.
    "MODTRAN": {"ARRAY":true, "DEFAULT":[], "TYPE":{} },
    # The entries in ModtranInput are the elements in the MODTRAN Array. They are
    # defined here outside of the array, for programmer convenience and simpler
    # syntax in this file.
    "MODTRANINPUT": {
        "NAME": "MOD6",
        "DESCRIPTION": "MOD6 Input",
        "CASE": 0,
        "CASE TEMPLATE": -1,
        "RTOPTIONS": {
            "IEMSCT": {"ENUM": "RT_TRANSMITTANCE"},  

            "MODTRN": {"ENUM": "RT_MODTRAN"},  

            "LYMOLC": false,  

            "T_BEST": false,  

            "IMULT": {"ENUM": "RT_NO_MULTIPLE_SCATTER"},  

            "DISALB": false,  

            "NSTR": 8,  

            "NLBL": 100,  

            "SOLCON": 0.0
        }, # end RTOptions
        "ATMOSPHERE": {
            "MODEL": {"ENUM": "ATM_MIDLAT_SUMMER"},  

            "M1": {"ENUM": "ATM_MIDLAT_SUMMER"},  

            "M2": {"ENUM": "ATM_MIDLAT_SUMMER"},  

            "M3": {"ENUM": "ATM_MIDLAT_SUMMER"},  

            "M4": {"ENUM": "ATM_MIDLAT_SUMMER"},  

            "M5": {"ENUM": "ATM_MIDLAT_SUMMER"},  

            "M6": {"ENUM": "ATM_MIDLAT_SUMMER"},  

            "M2_RHC": false,  

            "MDEF": 0,  

            "HMODEL": "",  

            "NLAYERS": 0, #ML  

            "NPROF": 0, #NMOLYC + standard  

            "CO2MX": 400.0,
        }
    }
}

```

**Figure 3.2.** The keywords.json file.

```

    "H2OSTR":0.0,
    "H2OUNIT":" ",
    "O3STR":0.0,
    "O3UNIT":" ",
    "C_PROF":0,
    "S_UMIX": {"ARRAY":true,"DEFAULT":[],"TYPE":0.0},
    "S_XSEC": {"ARRAY":true,"DEFAULT":[],"TYPE":0.0},
    "S_TRAC": {"ARRAY":true,"DEFAULT":[],"TYPE":0.0},
    "AERRH": 0.0,
    "AYRANG":false,
    "E_MASS":1.0,
    "AIRMWT":0.0,
    "ATMPROFILE": {
        "TYPE": {"ENUM": "PROF_UNKNOWN"},
        "UNITS": {"ENUM": "UNT_UNKNOWN"}, #JCHAR
        "UNAME": "", #YNAME
        "PROFILE": {"ARRAY":true,"DEFAULT":[],"TYPE":0.0}, #ZM,P,T,WMOL,WMOLX,WMOLY
        "PRO_MASK": {"ARRAY":true,"DEFAULT":[],"TYPE":0} #JCHAR use default
    }, #end AtmProfile
    "PROFILES": {"ARRAY":true,"DEFAULT":[],"TYPE":{}}
}, # end Atmosphere
"AEROSOLS": {
    "IHAZE": {"ENUM": "AER_RURAL"},
    "VIS":0.0,
    "WSS":0.0,
    "WHH":0.0,
    "ICSTL":3,
    "ISEASN": {"ENUM": "SEASN_AUTO"},
    "IVULCN": {"ENUM": "STRATO_BACKGROUND"},
    "ICLD": {"ENUM": "CLOUD_NONE"},
    "RAINRT":0.0,
    "IPH":2,
    "HGPF":0.8,
    "H2OAER":false,
    "CNOVAM": false,
    "ARUSS": " " ,
    "SAPFILE": "",
    "IVSA": false,
    "ZCVSA":0.0,
    "ZTVSA":0.0,
    "ZINVSA":0.0,
    "ASTMX":0.0,
    "CDASTM": " " ,
    "ASTMC":0.0,
    "ASTMO":0.0,
    "SSALB": {
        "NSSALB":0,
        "AWAVLN": {"ARRAY":true,"DEFAULT":[],"TYPE":0.0},
        "ASSALB": {"ARRAY":true,"DEFAULT":[],"TYPE":0.0},
        "ACOALB":0.0,
        "RHASYM":0.0
    }, #end SSALB
}

```

**Figure 3.2** (cont'd). The keywords.json file.

```
"APLUS":"",
"REGALT": {
    "ZAER1": {"ARRAY":true, "DEFAULT": [0.0,3.0], "TYPE":0.0},
    "SCALE1":1.0,
    "ZAER2": {"ARRAY":true, "DEFAULT": [2.0,11.0], "TYPE":0.0},
    "SCALE2":1.0,
    "ZAER3": {"ARRAY":true, "DEFAULT": [10.0,35.0], "TYPE":0.0},
    "SCALE3":1.0,
    "ZAER4": {"ARRAY":true, "DEFAULT": [30.0,100.0], "TYPE":0.0},
    "SCALE4":1.0
},
"PHASEFN": {
    "NANGLS":0,
    "NWLF":0,
    "ANGE": {"ARRAY":true, "DEFAULT": [], "TYPE":0.0},
    "WLF": {"ARRAY":true, "DEFAULT": [], "TYPE":0.0},
    "AERPF": {"ARRAY":true, "DEFAULT": [], "TYPE":0.0}
},
"IREGSPC": {"ARRAY":true, "DEFAULT": [], "TYPE":{}},
"REGSPC": {
    "IREG":0,
    "AWCCON":0.0,
    "AERNAM":"",
    "NARSPC":47,
    "VARSPC": {"ARRAY":true, "DEFAULT": [], "TYPE":0.0},
    "EXTC": {"ARRAY":true, "DEFAULT": [], "TYPE":0.0},
    "ABSC": {"ARRAY":true, "DEFAULT": [], "TYPE":0.0},
    "ASYM": {"ARRAY":true, "DEFAULT": [], "TYPE":0.0}
},
#end REGSPC
"CTHIK": -9.0,
"CALT": -9.0,
"CWAVLN": -9.0,
"CEXT": -9.0,
"CCOLWD": -9.0,
"CCOLIP": -9.0,
"CHUMID": -9.0,
"ASYMWWD": -9.0,
"ASYMIP": -9.0,
"CLDALT": {
    "NCRALT":0,
    "ZPCLD": {"ARRAY":true, "DEFAULT": [], "TYPE":0.0},
    "CLD": {"ARRAY":true, "DEFAULT": [], "TYPE":0.0},
    "CLDICE": {"ARRAY":true, "DEFAULT": [], "TYPE":0.0},
    "RR": {"ARRAY":true, "DEFAULT": [], "TYPE":0.0}
},
}
```

**Figure 3.2** (cont'd). The keywords.json file.

```

"CLDSPC": {
    "NCRSPC":0,
    "WAVLEN": {"ARRAY":true,"DEFAULT":[],"TYPE":0.0},
    "EXTC6": {"ARRAY":true,"DEFAULT":[],"TYPE":0.0},
    "ABSC6": {"ARRAY":true,"DEFAULT":[],"TYPE":0.0},
    "ASYM6": {"ARRAY":true,"DEFAULT":[],"TYPE":0.0},
    "EXTC7": {"ARRAY":true,"DEFAULT":[],"TYPE":0.0},
    "ABSC7": {"ARRAY":true,"DEFAULT":[],"TYPE":0.0},
    "ASYM7": {"ARRAY":true,"DEFAULT":[],"TYPE":0.0},
    "CFILE":"",
    "CLDTYP":"",
    "CIRTYP":""
},
    # end Aerosol
"GEOMETRY": {
    "ITYPE":2,
    "H1ALT":20.0,
    "H2ALT":0.0,
    "OBSZEN":180.0,
    "HRANGE":0.0,
    "BETA":0.0,
    "LENN":0,
    "BCKZEN":0.0,
    "RAD_E":0.0,
    "CKRANG":0.0,
    "IDAY":93,
    "IPARM":2,
    "PARM1":0.0,
    "PARM2":0.0,
    "PARM3":0.0,
    "PARM4":0.0,
    "GMTIME":0.0,
    "TRUEAZ":0.0,
    "ANGLEM":0.0,
    "LOSEOMETRY": {
        "H1ALT":0.0,
        "H2ALT":0.0,
        "OBSZEN":0.0,
        "HRANGE":0.0,
        "BETA":0.0,
        "AZ_INP":0.0,
        "LENN":0,
        "BCKZEN":0.0,
        "CKRANG":0.0
    },
    "NLOS":0,
    "MLOS": {"ARRAY":true,"DEFAULT":[],"TYPE":[]}
},
    # end Geometry

```

**Figure 3.2** (cont'd). The keywords.json file.

```

"SURFACE" : {
    "SURFTYPE" : { "ENUM" : "REFL_CONSTANT" },
    "SURREF" : 0.0,
    "NSURF" : 1,
    "TPTEMP" : 0.0,
    "AATEMP" : 0.0,
    "WIDERP" : false,
    "GNDALT" : 0.0,
    "DH2O" : 0.0,
    "MLTRFL" : false,
    "SALBFL" : "spec_alb.dat",
    "SURFP" : { }, #type SurfaceParam
    "SURFA" : { }, #type SurfaceParam
    "SURFNLOS" : 0,
    "SURFLOS" : { "ARRAY" : true, "DEFAULT" : [], "TYPE" : {} }, # type SurfaceParam array
    "SURFACEPARAM" : {
        "CBRDF" : { "ENUM" : "BRDF_WALTHALL" },
        "NWVSRF" : 0,
        "SURFZN" : 0.0,
        "SURFAZ" : 0.0,
        "WVSURF" : { "ARRAY" : true, "DEFAULT" : [], "TYPE" : 0.0 },
        "PBRDF1" : { "ARRAY" : true, "DEFAULT" : [], "TYPE" : 0.0 },
        "PBRDF2" : { "ARRAY" : true, "DEFAULT" : [], "TYPE" : 0.0 },
        "PBRDF3" : { "ARRAY" : true, "DEFAULT" : [], "TYPE" : 0.0 },
        "PBRDF4" : { "ARRAY" : true, "DEFAULT" : [], "TYPE" : 0.0 },
        "PBRDF5" : { "ARRAY" : true, "DEFAULT" : [], "TYPE" : 0.0 },
        "PBRDF6" : { "ARRAY" : true, "DEFAULT" : [], "TYPE" : 0.0 },
        "PBRDF7" : { "ARRAY" : true, "DEFAULT" : [], "TYPE" : 0.0 },
        "CSALB" : { "ENUM" : "LAMB_MODEL_USER_DEF" },
        "UDSALB" : { "ARRAY" : true, "DEFAULT" : [], "TYPE" : 0.0 }
    }
},
    # end Surface
"SPECTRAL" : {
    "V1" : 800.0,
    "V2" : 1250.0,
    "DV" : 1.0,
    "FWHM" : 2.0,
    "YFLAG" : "T",
    "XFLAG" : "W",
    "DLIMIT" : " $      ",
    "FLAGS" : "",
    "MLFLX" : 0,
    "VRFRAC" : 0.0,
    "SFWHM" : 0.0,
    "LSUNFL" : "  ",
    "CH2OCM" : "  ",
    "LBMNAM" : "  ",
    "USRSUN" : "  ",
    "BNNAME" : "  ",
    "FILTNM" : ""
},
    # end Spectral

```

**Figure 3.2** (cont'd). The keywords.json file.

```

"FILEOPTIONS": {
    "NOFILE": {"ENUM": "FC_ALLOWALL"}, 
    "MSGPRNT": {"ENUM": "MSG_INFO"}, 
    "JSONOPT": {"ENUM": "WRT_STAT_OUTPUT"}, 
    "BINARY": false, 
    "CKPRNT": false, 
    "NOPRNT": 0, 
    "DATDIR": "", 
    "FLROOT": "", 
    "CSVPRNT": "", 
    "JSONPRNT": "", 
    "SLIPRNT": "" 
}      # end FileOptions
} # ModtranInput
}, # VALID_MODTRAN
}

```

**Figure 3.2** (cont'd). The keywords.json file.

### 3.2 MODTRANINPUT Content

The input options JSONObject associated with the keyword [MODTRANINPUT](#) organizes the options which drive the MODTRAN code. The available JSON keywords for [MODTRANINPUT](#) are listed in Table 3.1 with a brief description of each. All keywords are used for the example in Figure 3.1. The JSONObjects associated with the keywords [RTOPTIONS](#), [ATMOSPHERE](#), [AEROSOLS](#), [GEOMETRY](#), [SURFACE](#), [SPECTRAL](#), and [FILEOPTIONS](#) are described in the sections listed.

**Table 3.1.** MODTRANINPUT keywords with descriptions.

Keyword	Type/Section	Description
NAME	Omit	<i>Uses MOD6 for root name</i>
	String	Name of case (equivalent to root name of MODTRAN5 discussed in 4.1)
DESCRIPTION	String	Description of case
CASE	Integer	Case number, should start at <i>default value of 0</i> and be incremented by 1
CASE TEMPLATE	Integer	If present, input only the changes from case number CASE TEMPLATE
<a href="#">RTOPTIONS</a>	3.3	JSONObject for radiative transfer options
<a href="#">ATMOSPHERE</a>	3.4	JSONObject for atmosphere options
<a href="#">AEROSOLS</a>	3.5 and 3.6	JSONObject for aerosol and cloud options
<a href="#">GEOMETRY</a>	3.7	JSONObject for geometry options
<a href="#">SURFACE</a>	3.8	JSONObject for surface description
<a href="#">SPECTRAL</a>	3.9	JSONObject for spectral bandpass and related inputs
<a href="#">FILEOPTIONS</a>	3.10	JSONObject for file options

### 3.3. Radiative Transfer Options

The [RTOPTIONS](#) JSONObject provides the main radiative transfer (RT) options which drive the MODTRAN code. The JSON keywords in this JSONObject are listed in Table 3.2 along with their type, values and description. The description of the reserved names used for [ITEMSCT](#), [MODTRN](#), and [IMULT](#) are provided in Tables 3.3, 3.4 and 3.5, respectively.

**Table 3.2.** Listing of the RTOPTIONS keywords, the associated types, values, and description.

Keyword	Type/Values	Description
<a href="#">IEMSCT</a>	See Table 3.3	Radiative transfer mode of execution (type of calculation).
<a href="#">MODTRN</a>	See Table 3.4	Radiative transfer algorithm.
LYMOLC	FALSE TRUE	<i>Do not include "Y" species with built-in model profiles.</i> Include the 16 auxiliary trace ("Y") species OH, HF, HCl, HBr, HI, ClO, OCS, H <sub>2</sub> CO, HOCl, N <sub>2</sub> , HCN, CH <sub>3</sub> Cl, H <sub>2</sub> O <sub>2</sub> , C <sub>2</sub> H <sub>2</sub> , C <sub>2</sub> H <sub>6</sub> , PH <sub>3</sub> .
T_BEST	FALSE TRUE	<i>Do not use benchmark numeric Voigt line transmittance integration.</i> Use slow and precise Voigt line transmittance integration. This painstakingly slow option should only be selected if the user suspects that there is a problem with MODTRAN's standard Voigt line transmittance calculation. Transmittance differences of significance (> 0.0001) should be reported to modtran@spectral.com
<a href="#">IMULT</a>	See Table 3.5	Multiple scattering (MS) algorithm. MS contributions are calculated using plane parallel geometry but with each path segment defined from MODTRAN's spherical refractive geometry calculation.
DISALB	FALSE TRUE	<i>mittances.</i> Generate spectral atmospheric spherical albedos from the ground and diffuse spectral transmittances for ground-viewing lines-of-sight and sun-to-ground paths. This data is useful in atmospheric correction data analysis [41, 28]. This option is only accessible with DISORT solar scattering and for lines-of-sight terminating at the ground.
NSTR	Integer	Number of <i>streams</i> (expansion terms) used in DISORT. MODTRAN only permits powers of 2 (2, 4, 8, ...). Higher values improve accuracy but slow computation. The <i>default value</i> of 8 is recommended for solar/lunar applications. Up to 32 streams may be run with the compiled MODTRAN code; email <a href="mailto:modtran@spectral.com">modtran@spectral.com</a> if a higher number of streams is required.
NLBL	Integer	Number of spectral points in each 0.1 cm <sup>-1</sup> bin at which LBL calculations are performed; <i>default is 100 corresponding to 0.001 cm<sup>-1</sup> spacing.</i>
SOLCON	Omitted or 0. > 0. Float < 0. Float	No scaling of TOA (Top-Of-Atmosphere) solar irradiance. Spectrally integrated TOA solar irradiance in W/m <sup>2</sup> . The absolute value of SOLCON, likely close to +1, is used as a scale factor to adjust the TOA solar irradiance for the selected data file (located in the path defined by the environment variable MODTRAN_DATA). The integrated solar irradiances for the provided data files are
	1362.1 W/m <sup>2</sup> 1359.7 W/m <sup>2</sup> 1361.0 W/m <sup>2</sup> 1361.6 W/m <sup>2</sup> 1360.9 W/m <sup>2</sup> 1368.6 W/m <sup>2</sup> 1368.0 W/m <sup>2</sup> 1400.5 W/m <sup>2</sup> 1361.0 W/m <sup>2</sup> 1358.8 W/m <sup>2</sup> 1361.0 W/m <sup>2</sup> 1361.0 W/m <sup>2</sup> 1376.2 W/m <sup>2</sup>	SUNxxcebkur SUNxxchkur SUNxxfontenla SUNxxhigh1irradwnNormt SUNxxhigh2irradwnNormt SUNxxkurucz1995 SUNxxkurucz1997 SUNxxkurucz2005 SUNxxlowirradwnNormt SUNxxmed1irradwnNormt SUNxxmed2irradwnNormt SUNxxpeakirradwnNormt SUNxxthkur
	Here, xx is the spectral resolution of the solar irradiance data file, equal to 'p1' for 0.1 cm <sup>-1</sup> , '01' for 1.0 cm <sup>-1</sup> , '05' for 5.0 cm <sup>-1</sup> and '15' for 15.0 cm <sup>-1</sup> . An additional scaling of the solar irradiance value to account for Earth-to-Sun distance (based on day of year) is applied within the code. This Earth-to-Sun correction factor is written to <ROOTNAME>.tp6.	

**Table 3.3.** Names, values and descriptions for RT Mode of execution keyword, [IEMSCT](#)

IEMSCT Name	#	Description
<i>RT_TRANSMITTANCE</i>	0	Spectral transmittance only mode (for <a href="#">MODTRN</a> keyword equal to <i>RT_MODTRAN</i> only).
<i>RT_THERMAL_ONLY</i>	1	Spectral thermal radiance (no Sun/Moon) mode.
<i>RT_SOLAR_AND_THERMAL</i>	2	<i>Thermal plus solar radiance mode.</i>
<i>RT_SOLAR_IRRADIANCE</i>	3	Directly transmitted spectral solar irradiance mode (for <a href="#">MODTRN</a> keyword equal to <i>RT_MODTRAN</i> only).
<i>RT_LUNAR_AND_THERMAL</i>	4	Thermal plus lunar radiance mode.
<i>RT_LUNAR_IRRADIANCE</i>	5	Directly transmitted spectral lunar irradiance mode (for <a href="#">MODTRN</a> keyword equal to <i>RT_MODTRAN</i> only).

**Table 3.4.** Names, values and descriptions for RT algorithm keyword, MODTRN

MODTRN Name	#	Description
<i>RT_MODTRAN</i>	0	<i>MODTRAN statistical band model algorithm.</i>
<i>RT_CORRK_SLOW</i>	1	MODTRAN statistical Correlated- <i>k</i> ( <i>Ck</i> ) algorithm, in which segment transmittances are tied to MODTRAN band model values. The SLOW treatment uses 33 absorption coefficients ( <i>k</i> values) per spectral bin (0.1, 1, 5, or 15 cm <sup>-1</sup> ). The FAST option is essentially always preferred. ( <a href="#">IEMSCT</a> radiance modes only; most accurate but slower runtime).
<i>RT_CORRK_FAST</i>	2	<i>Ck</i> option with 17 <i>k</i> values ( <a href="#">IEMSCT</a> radiance modes only).
<i>RT_MODTRAN_POLAR</i>	3	Polarimetric MODTRAN (unavailable)
<i>RT_LINE_BY_LINE</i>	4	Line-by-line (LBL) capability. The standard output files contain data generated from the LBL results degraded to a spectral resolution of 0.1 cm <sup>-1</sup> . High resolution transmittance and radiance data are also generated (see <a href="#">CKPRNT</a> ).

MODTRAN provides three scattering model options. Running the DISORT scattering model is preferable if one can afford the computational costs. Quick approximate solar results are available from the Isaacs 2-stream model (DISORT and Isaacs 2-stream thermal calculations are equally fast). However, instances arise in which the accuracy of the 2-stream approach is insufficient but the computation time of DISORT processing is too long. MODTRAN provides an alternative for the solar dominated spectral regime (<4 μm) – the Isaacs 2-stream scaled to DISORT option. DISORT scattering calculations are performed for a small fixed set of spectral points in atmospheric window regions. The ratio of DISORT to Isaacs multiple scatter solar path radiances is calculated at each spectral grid point, creating a spectral correction curve. This curve is used to adjust the Isaacs multiple scatter solar path radiances at each spectral point. An analogous correction is made to the ground reflected downward diffuse flux for lines-of-sight that intersect the ground. The Isaacs scaled to DISORT option should really only be used for the shortwave (<4 μm). Moreover, one should compare the scaled results to a full DISORT calculation for a subset of runs, to verify that the accuracy of the approximation is sufficient for the application.

**Table 3.5.** Names, values and descriptions for multiple scattering option keyword, `IMULT`. The location at which the plane-parallel atmosphere is defined is specified. Input `IEMSCT` must be set to `RT_THERMAL_ONLY` or `RT_SOLAR/LUNAR_AND_THERMAL` to execute with multiple scattering.

<code>IMULT</code>	Name	#	Description	Location
	<code>RT_NO_MULTIPLE_SCATTER</code>	0	<i>Program runs without multiple scattering.</i>	
			If <code>IEMSCT</code> is <code>RT_SOLAR _AND_THERMAL</code> or <code>RT_LUNAR _AND_THERMAL</code> , then single scatter solar/lunar radiance is included.	
<code>RT_DISORT</code>		1	Includes multiple scattering using the plane parallel atmosphere DISORT discrete ordinate multiple scattering algorithm. Scattering calculation centered at path final or tangent latitude and longitude.	$H_2$ (end of LOS; tangent point for limb paths)
<code>RT_DISORT_AT_OBS</code>		2	Same as <code>RT_DISORT</code> but with scattering calculation centered at sensor latitude and longitude.	$H_1$ (sensor)
<code>RT_ISAACS_2STREAM</code>		3	Includes multiple scattering using fast but lower fidelity Isaacs's two-stream algorithm. Scattering calculation centered at path final or tangent latitude and longitude.	$H_2$ (end of LOS; tangent point for limb paths)
<code>RT_ISAACS_2STREAM_AT_OBS</code>		4	Same as <code>RT_ISAACS_2STREAM</code> but with scattering calculation centered at sensor latitude and longitude.	$H_1$ (sensor)
<code>RT_ISAACS_SCALED</code>		5	Multiple scattering is calculated using DISORT algorithm at selected spectral points in atmospheric window regions. These DISORT radiances are used to scale Isaac's 2-stream multiple scattering values for the entire wavelength window. Scattering calculation centered at path final or tangent latitude and longitude.	$H_2$ (end of LOS; tangent point for limb paths)
<code>RT_ISAACS_SCALED_AT_OBS</code>		6	Same as <code>RT_ISAACS_SCALED</code> but with scattering calculation centered at sensor latitude and longitude.	$H_1$ (sensor)

### 3.4 [Atmosphere](#) Specification Options

The `ATMOSPHERE` options JSONObject provides the [atmosphere](#) specification options which drive the MODTRAN code. An example of a fairly basic use of the `ATMOSPHERE` JSONObject is provided in Figure 3.1.

One purpose of the `ATMOSPHERE` JSONObject is to define the atmosphere [PROFILES](#), i.e. how the constituents of the atmosphere vary with altitude. The keywords used to set up the atmospheric [PROFILES](#) are listed in Table 3.6 and the tables referenced by it. The use of the keyword [PROFILES](#) is an advanced option described in Section 3.4.3 below. Table 3.9 contains types, valid values and descriptions of keywords in `ATMOSPHERE` used for scaling atmospheric constituents. Finally, Table 3.10 contains the remaining keywords in `ATMOSPHERE`, with associated types, valid values, and description.

#### 3.4.1 The atm-cm and atm-cm/km Units used in MODTRAN

Band model absorption coefficient data were traditionally measured in units of  $\text{cm}^{-1}/\text{atm}$ . A gas would be placed in a 1 cm long cell at standard pressure and temperature, and the spectral bin extinction measured. With this setup, column densities had units of atm-cm at standard temperature and pressure (STP) and absorption coefficients were defined in  $\text{cm}^{-1}/\text{atm}$  at STP. Since column density is a path integral over molecular concentration,  $\text{mol}/\text{cm}^2$  is a more natural unit from a molecular perspective. To convert  $\text{mol}/\text{cm}^2$  to atm-cm, multiply by the ideal gas standard volume ( $22,413.83 \text{ cm}^3/\text{atm}/\text{mole}$ ) and divide by Avogadro's constant ( $6.022045E+23 \text{ mol}/\text{mole}$ ). Alternatively, divide by Loschmidt number at

STP ( $2.686754 \times 10^{19}$  mol  $\text{cm}^{-3}/\text{atm}$ ), equal to Avogadro's number over the ideal gas standard volume.

MODTRAN molecular constituent profiles define molecular densities as a function of altitude. MODTRAN provides five density unit choices for all molecular species: (A) volume mixing ratio in ppmv, (B) number density in molecules/ $\text{cm}^3$ , (C) mass mixing ratio in g/kg-air, (D) mass density in g/ $\text{m}^3$ , and (E) partial pressure in mb. Three additional input options are provided by H<sub>2</sub>O only: (F) dew point temperature in Kelvin, (G) dew point temperature in Celsius, and (H) relative humidity in percent. Internally, MODTRAN converts each of these to atm-cm/km. With this unit, densities can be integrated over a path length in km to obtain a column density in atm-cm. In turn, the column density can be multiplied by a temperature dependent absorption coefficient in  $\text{cm}^{-1}/\text{atm}$  to compute a dimensionless weak-line optical depth. The various molecular density inputs are converted to atm-cm/km as follows:

A. Given volume mixing ratio in ppmv:

1. Divide by  $10^6$  ppmv ( $\Rightarrow$  unitless mole fraction),
2. Multiply by pressure in atm ( $\Rightarrow$  atm),
3. Multiply by  $10^5$  cm / km ( $\Rightarrow$  atm cm / km)

B. Given number density in molecules/ $\text{cm}^3$ :

1. Divide by Avogadro's Number [ $6.022045 \times 10^{23}$  molecules per mole] ( $\Rightarrow$  mole/ $\text{cm}^3$ )
2. Multiply by standard volume of ideal gas [ $22,413.83 \text{ cm}^3 \text{ atm} / \text{mole}$ ] ( $\Rightarrow$  atm),
3. Multiply by ambient temperature [in K] over standard temperature [273.15 K] ( $\Rightarrow$  atm),
4. Multiply by  $10^5$  cm / km ( $\Rightarrow$  atm cm / km)

C. Given mass mixing ratio in g/kg-air:

1. Divide by  $10^3$  g/kg ( $\Rightarrow$  g/g-air),
2. Multiply by molecular weight of air [28.9644 g-air/mole] ( $\Rightarrow$  g/mole),
3. Divide by molecular weight in g/mole ( $\Rightarrow$  unitless mole fraction),
4. Multiply by pressure in atm ( $\Rightarrow$  atm),
5. Multiply by  $10^5$  cm / km ( $\Rightarrow$  atm cm / km)

D. Given mass density in g/ $\text{m}^3$ :

1. Divide by molecular weight in g/mole ( $\Rightarrow$  mole/ $\text{m}^3$ ),
2. Divide by  $10^6 \text{ cm}^3/\text{m}^3$  ( $\Rightarrow$  mole/ $\text{cm}^3$ ),
3. Multiply by standard volume of ideal gas [ $22,413.83 \text{ cm}^3 \text{ atm} / \text{mole}$ ] ( $\Rightarrow$  atm),
4. Multiply by ambient temperature [in K] over standard temperature [273.15 K] ( $\Rightarrow$  atm),
5. Multiply by  $10^5$  cm / km ( $\Rightarrow$  atm cm / km)

E. Given partial pressure in mb:

1. Divide by 1,013.25 mb/atm ( $\Rightarrow$  atm),
2. Multiply by  $10^5$  cm / km ( $\Rightarrow$  atm cm / km)

F. Given dew point temperature in Kelvin:

1. Determine H<sub>2</sub>O saturation density from the standard to dew point temperature ratio ( $\Rightarrow$  g/ $\text{m}^3$ ),

$$\text{H}_2\text{O saturation density} = T_r \exp[18.9766 - (14.9595 + 2.43882 T_r) T_r] ; \quad T_r = 273.15 \text{ K} / T_{dp}$$

2. Multiply by dew point temperature over standard temperature [273.15 K] ( $\Rightarrow$  g/ $\text{m}^3$ ),
3. Divide by molecular weight in g/mole ( $\Rightarrow$  mole/ $\text{m}^3$ ),
4. Divide by  $10^6 \text{ cm}^3/\text{m}^3$  ( $\Rightarrow$  mole/ $\text{cm}^3$ ),
5. Multiply by standard volume of ideal gas [ $22,413.83 \text{ cm}^3 \text{ atm} / \text{mole}$ ] ( $\Rightarrow$  atm),
6. Multiply by  $10^5$  cm / km ( $\Rightarrow$  atm cm / km)

G. Given dew point temperature in Celsius:

1. Add standard temperature [273.15 K] to convert from Celsius to Kelvin ( $\Rightarrow$  K),
2. Follow instructions from F ( $\Rightarrow$  atm cm / km)

H. Given relative humidity in percent:

- Determine H<sub>2</sub>O saturation density from the standard to ambient temperature ratio ( $\Rightarrow \text{g/m}^3$ ),

$$\text{H}_2\text{O saturation density} = T' \exp [18.9766 - (14.9595 + 2.43882 T') T'] ; \quad T' = 273.15 \text{ K/T}$$

- Multiply by relative humidity over 100 ( $\Rightarrow \text{g/m}^3$ ),
- Follow instructions from D ( $\Rightarrow \text{atm cm / km}$ )

**Table 3.6.** Names, values and descriptions for keywords for defining [ATMOSPHERE](#) profile in ATMOSPHERE JSONObject.

Keyword	Type/ Values	Description
<a href="#">MODEL</a>	Table 3.7	Model for atmospheric profiles. Selects one of 6 geographical-seasonal model atmospheres which have built-in profiles or specifies either use of user-defined meteorological (e.g. radiosonde) data or, for # 0, the value of each constituent at a single altitude.
M1, M2, ..., M6	Omit or 0	Used to modify or supplement user-specified profiles with model atmosphere values for temperature and pressure and for 5 molecular gases. <i>Assigned the <a href="#">MODEL</a> value if it is between 1 and 6.</i>
	Table 3.7	If M1 is set to any of the built-in atmospheric profiles in Table 3.7, temperature and pressure from that model is used. If M2 is set to an atmospheric profile in Table 3.7, H <sub>2</sub> O from that model is used. If M3 is set to an atmospheric profile in Table 3.7, O <sub>3</sub> from that model is used. If M4 is set to an atmospheric profile in Table 3.7, CH <sub>4</sub> from that model is used. If M5 is set to an atmospheric profile in Table 3.7, N <sub>2</sub> O from that model is used. If M6 is set to an atmospheric profile in Table 3.7, CO from that model is used.
M2_RHC	Omit or FALSE	<i>No effect on code.</i>
	TRUE	Uses the H <sub>2</sub> O relative humidity profile of M2-selected model (instead of its mixing ratio). This RH profile values will be used regardless of the chosen temperature profile. Depending on the temperature profile, the water concentration will generally differ from the model selected by M2.
MDEF	0	<i>Include the default CO<sub>2</sub>, O<sub>2</sub>, NO, SO<sub>2</sub>, NO<sub>2</sub>, NH<sub>3</sub> and HNO<sub>3</sub> profiles.</i>
	1	Also include the heavy molecules with their default profiles, namely the 9 chlorofluorocarbons (CFCs) and ClONO <sub>2</sub> , HNO <sub>4</sub> , CCl <sub>4</sub> and N <sub>2</sub> O <sub>5</sub> , as listed in Table 3.8, in addition to the MDEF = 0 profiles.
	2	Profiles for the heavy molecules will be defined via input arrays.
HMODEL	String	Character string of length 20 that can be used to label the atmosphere or calculation.
NLAYERS	Integer	Number of layers (actually, layer boundaries or levels) in the custom atmosphere.
NPROF	Integer	Number of PROFILE entries in <a href="#">PROFILES</a> .
<a href="#">PROFILES</a>	JSONArray	See Table 3.12.

**Table 3.7.** Names, values and descriptions for the [ATMOSPHERE](#) keyword [MODEL](#). Atmospheres 1 through 6 have built-in atmospheric profiles.

MODEL Name	#	Description
ATM_CONSTANT	0	User to define pressure, temperature and constituent densities at a single-altitude for a constant pressure, horizontal path (ATM_CONSTANT can also be used to define any of inputs M1, M2, ..., M6 to indicate that it is to be assigned of the <a href="#">MODEL</a> value, a number between 1 and 6, inclusive).
ATM_TROPICAL	1	Tropical Atmosphere ( $15^{\circ}$ North Latitude).
ATM_MIDLAT_SUMMER	2	<i>Mid-Latitude Summer (<math>45^{\circ}</math> North Latitude), default when used with <a href="#">MODEL</a></i>
ATM_MIDLAT_WINTER	3	Mid-Latitude Winter ( $45^{\circ}$ Latitude).
ATM_SUBARC_SUMMER	4	Sub-Arctic Summer ( $60^{\circ}$ North Latitude).
ATM_SUBARC_WINTER	5	Sub-Arctic Winter ( $60^{\circ}$ North Latitude).
ATM_US_STANDARD_1976	6	1976 US Standard Atmosphere.
ATM_USER_ALT_PROFILE	7	User-specified atmosphere for which data for its constituents (e.g. radiosonde data) is input in the <a href="#">PROFILES</a> JSONArray. User must provide a set of monotonically-increasing altitudes in PROF_ALTITUDE.
ATM_USER_PRESS_PROFILE	8	Pressure-dependent atmospheric profiles. Similar to user-specified atmosphere but profile levels are specified as PROF_PRESSURE pressure values. Altitudes are determined from the pressure profile and a ground altitude by solving the hydrostatic equation. The user must provide atmospheric constituents for the set of monotonically decreasing pressures.

**Table 3.8.** The cross-section (X) molecular gases (alternative chlorofluorocarbons names are listed).

1	2	3	4	5	6	7	8
CCl <sub>3</sub> F	CCl <sub>2</sub> F <sub>2</sub>	CCl <sub>3</sub> F	CF <sub>4</sub>	CHClF <sub>2</sub>	C <sub>2</sub> Cl <sub>3</sub> F <sub>3</sub>	C <sub>2</sub> Cl <sub>2</sub> F <sub>4</sub>	C <sub>2</sub> ClF <sub>5</sub>
F11	F12	F13	F14	F22	F113	F114	F115
CFC-11	CFC-12	CFC-13	CFC-14	CFC-22	CFC-113	CFC-114	CFC-115
9	10	11	12	13	14	15	
ClONO <sub>2</sub>	HNO <sub>4</sub>	CHCl <sub>2</sub> F	CCl <sub>4</sub>	N <sub>2</sub> O <sub>5</sub>	H <sub>2</sub>	He	

**Table 3.9.** Types, valid values and descriptions of keywords in [ATMOSPHERE](#) used for scaling atmospheric constituents.

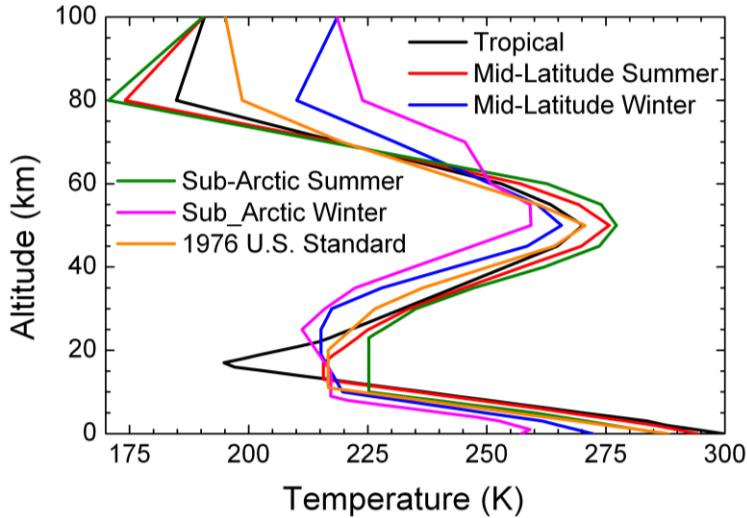
Keyword	Type/Value	Description
CO2MX	Omit or 0. >0., Float	400 ppmv CO <sub>2</sub> concentration (circa 2017 nominal value). CO <sub>2</sub> concentration in ppmv.
H2OSTR	Omit >0., Float	No scaling of H <sub>2</sub> O. Scale factor or absolute vertical column density of H <sub>2</sub> O (see H2OUNIT).
H2OUNIT	= 0.	Either no scaling or absolute vertical column density of H <sub>2</sub> O (see H2OUNIT).
		The water column modified by scaling densities. The water number density at each profile altitude is generally not 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 achieve the desired water column. Levels containing clouds are modeled differently, as dictated by input CHUMID (see Table 3.33).
	" "	H2OSTR is a scale factor <b>unless</b> H2OSTR is 0.; in that case, there is no scaling.
	"+"	H2OSTR is a scale factor <b>unless</b> H2OSTR is 0.; in that case, there is no scaling. This option, however, allows the 100% RH limit to be ignored. The restriction that the H <sub>2</sub> O density not exceed 5 times the nominal value is still invoked.
	"g"	H2OSTR input is absolute vertical water vapor column in g/cm <sup>2</sup> . The H <sub>2</sub> O column is scaled to achieve this value to the extent possible given the above restrictions.
	"a"	H2OSTR input is absolute vertical water vapor column in ATM-cm. The H <sub>2</sub> O column is scaled to achieve this value to the extent possible given the above restrictions.
O3STR	Omit >0., Float	No scaling of O <sub>3</sub> . Scale factor or absolute vertical column density of O <sub>3</sub> .
O3UNIT	= 0. " "	Either no scaling or absolute vertical column density of O <sub>3</sub> (see O3UNIT).
	"g"	O3STR is a scale factor <b>unless</b> O3STR is 0.; in that case, there is no scaling.
	"a"	O3STR input is absolute vertical column density of O <sub>3</sub> in g/cm <sup>2</sup> .
C_PROF	0 1 2 3 4 5 6 7	O3STR input is absolute vertical column density of O <sub>3</sub> in atm-cm (one Dobson unit equals 10 <sup>3</sup> atm-cm at 273.15 K). Do not scale uniformly mixed (UMIX), cross-section (X) or trace (Y) species profiles. Scale uniformly mixed (UMIX) species using the S_UMIX input array (see below). Scale cross-section (X) species using the S_XSEC input array (see below). Scale UMIX and X species using the S_UMIX and S_XSEC arrays. Scale trace (Y) species using the S_TRAC array (see below). Scale UMIX and Y species using the S_UMIX and S_TRAC arrays. Scale X and Y species using the S_XSEC and S_TRAC arrays. Scale UMIX, X and Y species using the S_UMIX, S_XSEC and S_TRAC arrays.
S_XSEC [10]	Omit > 0. Float[]	No scaling of the UMIX species. Scale factors for profiles of 10 ordered uniformly mixed (UMIX) molecular species [Sea level mixing ratios (ppmv) listed in brackets]: N <sub>2</sub> O[0.32], CO[0.15], CH <sub>4</sub> [1.7], O <sub>2</sub> [2.09×10 <sup>5</sup> ], NO[0.0003], SO <sub>2</sub> [0.003], NO <sub>2</sub> [0.00023], NH <sub>3</sub> [0.0005], HNO <sub>3</sub> [0.0005] and N <sub>2</sub> [7.81×10 <sup>5</sup> ].
S_XSEC [15]	Omit > 0. Float[]	No scaling of the XSEC species. Scale factors for profiles of the 15 ordered cross-section (X) species [Sea level mixing ratios (ppmv) listed in brackets]: F11[0.00014], F12[0.00024], F13[1×10 <sup>-2</sup> ], F14[1×10 <sup>-2</sup> ], F22[0.0006], F113[0.000019], F114[0.000012], F115[1×10 <sup>-2</sup> ], CIONO <sub>2</sub> [5.75×10 <sup>-6</sup> ], HNO <sub>4</sub> [4.34×10 <sup>-7</sup> ], CHCl <sub>2</sub> F[1×10 <sup>-2</sup> ], CCl <sub>4</sub> [0.00013], N <sub>2</sub> O <sub>5</sub> [2.42×10 <sup>-9</sup> ], H <sub>2</sub> [0.58] and He[5.2].
S_TRAC [16]	Omit > 0. Float[]	No scaling of the trace species. Scale factors for profiles of the 16 ordered trace (Y) molecules [Sea level mixing ratios (ppmv) listed in brackets]: OH[4.4×10 <sup>-8</sup> ], HF[1×10 <sup>-8</sup> ], HCl[0.001], HBr[1.7×10 <sup>-6</sup> ], HI[3×10 <sup>-6</sup> ], ClO[1×10 <sup>-8</sup> ], OCS[0.006], H <sub>2</sub> CO[0.0024], HOCl[7.7×10 <sup>-9</sup> ], N <sub>2</sub> [7.81×10 <sup>-5</sup> ], HCN[0.00017], CH <sub>3</sub> Cl[0.0007], H <sub>2</sub> O <sub>2</sub> [0.0002], C <sub>2</sub> H <sub>2</sub> [0.0003], C <sub>2</sub> H <sub>6</sub> [0.002], and PH <sub>3</sub> [1×10 <sup>-14</sup> ].

**Table 3.10.** Remaining keywords in [ATMOSPHERE](#), with associated types, valid values, and description.

Keyword	Type/Value	Description
AERRH	Omit or $\leq 0$ .	<i>RH for boundary layer aerosols determine from aerosol density weighted average.</i>
	> 0. Float	Relative humidity [%] that defines RH-dependent boundary layer aerosol optical properties.
AYRANG	Omit or FALSE	<i>No local chemical (gas) plume range profile data.</i>
	TRUE	Range profile data read from AYRANGFL, <ROOTNAME>.rng, or yrangle.asc. This file specifies the temperature and the density of all local species as a function of slant range from the sensor. The format of range profile file is described in Chapter 6. Input array <a href="#">UNAME</a> (Table 3.12) defines the set of local chemical (gas) species.
AYRANGFL	Omit or blank	<i>If AYRANG=TRUE, input chemical (gas) plume range profile data from a local file named &lt;ROOTNAME&gt;.rng or yrangle.asc.</i>
	String	If AYRANG=TRUE, full path file name to local chemical gas range profile data.
E_MASS	Omit or 0.	<i>Set to unity.</i>
	> 0. Float	Planetary mass in Earth units (0.5 means half as massive as the Earth). Used to solve the hydrostatic equation when modeling extra-terrestrial planets [only invoked when <a href="#">MODEL</a> (Table 3.7) is ATM_USER_PRESS_PROFILE].
AIRMWT	Omit or 0.	<i>Uses default molecular weight of air at Earth's surface, 28.9644 g/mol.</i>
	> 0. Float	Molecular weight of air at the surface in g/mol.

### 3.4.2 How do the Model Atmospheres Differ?

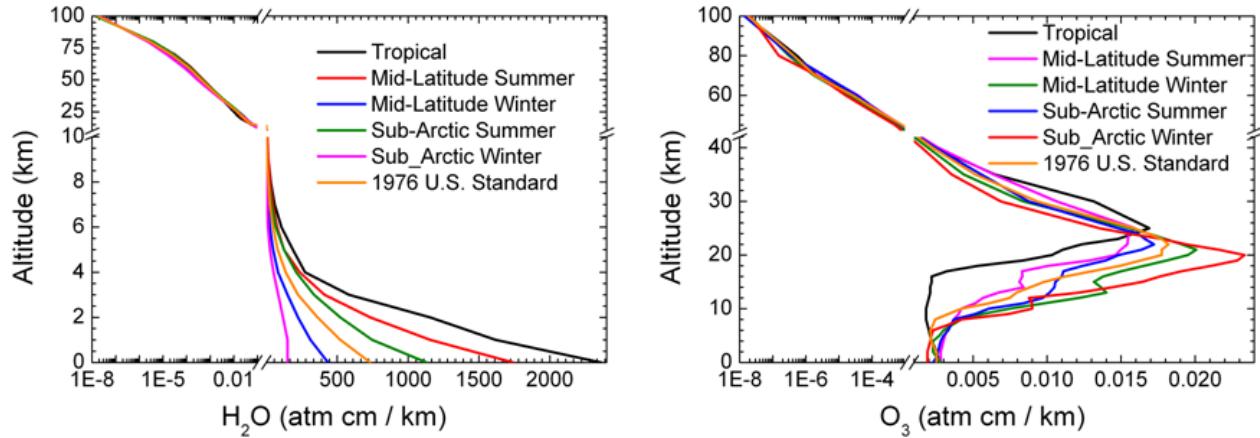
The six model atmospheres in MODTRAN differ most significantly in their temperature, H<sub>2</sub>O and O<sub>3</sub> profiles. The temperature profiles are illustrated in Figure 3.3.



**Figure 3.3.** Temperature profiles of the MODTRAN model atmospheres.

The Sub-Arctic Winter Atmosphere has the coolest surface temperature; the Mid-Latitude Winter Atmosphere has the next coolest surface temperature. The Tropical and Mid-Latitude Summer Atmospheres have the warmest surface temperatures. At the tropopause (the altitude where the temperature stops decreasing), the temperature of the Tropical Atmosphere is the coolest and the temperature of the Sub-Arctic Summer Atmosphere is the warmest. For all six model atmospheres, a secondary temperature peak occurs near 50 km; here the Sub-Arctic Summer temperature is the warmest, essentially equal to that of the Mid-Latitude Summer. The Sub-Arctic Winter temperature is the coolest at this altitude. The 1976 U.S. Standard Atmosphere temperature profile provides an effective median for the set of profiles.

The density profiles for  $\text{H}_2\text{O}$  and  $\text{O}_3$  are shown on Figure 3.4. Total vertical column amounts for the 12 ambient band model species are listed in Table 3.11; the  $\text{CO}_2$  mixing ratio used in creating this table was 380 ppmV. Note that the six model atmospheres provide a nice spread of boundary layer and lower tropospheric water densities.



**Figure 3.4.** MODTRAN model atmosphere profiles for  $\text{H}_2\text{O}$  and  $\text{O}_3$ . Note there is a break in the altitude vertical scales, at 10 km for  $\text{H}_2\text{O}$  and 42 km for  $\text{O}_3$ .

**Table 3.11.** MODTRAN model atmosphere vertical molecular column amounts in atm-cm. The  $\text{CO}_2$  mixing ratio was set to 400 ppmV.

Molecule	Tropical	Mid Latitude Summer	Mid Latitude Winter	Sub-Arctic Summer	Sub-Arctic Winter	US Standard
$\text{H}_2\text{O}$	5119.4	3635.9	1059.7	2589.4	517.73	1762.3
$\text{O}_3$	0.27727	0.33176	0.37681	0.34492	0.37550	0.34356
$\text{CO}_2$	321.97	321.19	322.09	319.44	320.22	320.51
CO	0.087663	0.087740	0.090032	0.088048	0.090924	0.088742
$\text{CH}_4$	1.3243	1.2684	1.2806	1.2556	1.2719	1.3203
$\text{N}_2\text{O}$	0.24649	0.23743	0.24037	0.21920	0.23993	0.24593
$\text{O}_2$	168230	167820	168290	166910	167320	167460
$\text{NH}_3$	0.00016986	0.00017121	0.00018032	0.00017393	0.00018409	0.00017517
NO	0.00031691	0.00032271	0.00030953	0.00032243	0.00030233	0.00031390
$\text{NO}_2$	0.00021091	0.00021814	0.00019842	0.00021543	0.00018654	0.00020418
$\text{SO}_2$	0.00010799	0.00010838	0.00011245	0.00010928	0.00011391	0.00010997
$\text{HNO}_3$	0.00037983	0.00038298	0.00035617	0.00037403	0.00033808	0.00036287

### 3.4.3 User-provided Atmospheric [PROFILES](#)

The [PROFILES](#) JSONArray provides an advanced option used to customize the altitude variation of the atmospheric constituents as an alternative to using the built-in atmospheres. It also allows the user to enter profiles of one or more auxiliary species not included in traditional MODTRAN. Its members are defined in Table 3.12 and the tables referenced by it. Note that the number of [PROFILES](#) and number of layers in each PROFILE must match the `NPROF` and `NLAYERS` variables, respectively.

**Table 3.12.** Names, values and descriptions for keywords in PROFILES.

Keyword	Type/Value	Description
<a href="#">TYPE</a>	Table 3.14	Type of the atmospheric constituent.
<a href="#">UNITS</a>	Table 3.13	Unit used for PROFILE.
UNAME	String	Molecular species name used when <a href="#">TYPE</a> is PROF_USER_DEF.
PROFILE	Float[]	Array over atmospheric layers containing the constituent values.
PRO_MASK	Integer[]	Array over atmospheric layers indicating which profile to use:
0		<i>Use profile data for the atmospheric model specified by <a href="#">MODEL</a> (Table 3.7).</i>
-1		Use whichever M1 to M6 (Table 3.6) profile corresponds to the constituent.
1 → 6		Use model atmosphere profile with this #.

**Table 3.13.** Names, values and descriptions for units provided in UNITS

UNITS Value	Value	Description
UNT_UNKNOWN	-1	(temporary value used prior to making selection)
UNT_KILOMETERS	0	Altitude in kilometers (km)
UNT_TKELVIN	1	Ambient temperature in Kelvin (K)
UNT_TCelsius	2	Ambient temperature in Celsius (°C)
UNT_TDELTAKELVIN	3	Temperature difference from M1 profile, see below
UNT_TDEWPOINT_KELVIN	4	Dew point in Kelvin (K)
UNT_TDEWPOINT_Celsius	5	Dew point in Celsius (°C)
UNT_PMillibar	6	Total or partial pressure in millibars (mb)
UNT_Patm	7	Total or partial pressure in atmospheres (atm)
UNT_DPPMV	8	Volume mixing ratio in ppmv
UNT_DMOL_PER_CM3	9	Density in molecules/cm <sup>3</sup>
UNT_DGRAM_PER_KG	10	Mass mixing ratio in gram/kg
UNT_DGRAM_PER_M3	11	Mass density in gram/m <sup>3</sup>
UNT_REL_HUMIDITY	12	Relative humidity in %

As an example for UNT\_TDELTAKELVIN, the mid-latitude summer surface temperature is 294.2 K; if M1 is ATM\_MIDLAT\_SUMMER and the PROFILE value is -10.0 at 0 km altitude, then the profile temperature will be set to 294.2 K - 10.0 K = 284.2 K at that altitude.

**Table 3.14.** Alternative values and descriptions for type of atmospheric profile, TYPE

#	Values	Description	
-1	PROF_USER_DEF		
0	PROF_ALTITUDE	Altitude	
1	PROF_PRESSURE	Pressure	
2	PROF_TEMPERATURE	Temperature	
3	PROF_H2O	PROF_WATER_VAPOR	water vapor
4	PROF_CO2	PROF_CARBON_DIOXIDE	carbon dioxide
5	PROF_O3	PROF_OZONE	ozone
6	PROF_N2O	PROF_NITROUS_OXIDE	nitrous oxide
7	PROF_CO	PROF_CARBON_MONOXIDE	carbon monoxide
8	PROF_CH4	PROF_METHANE	methane
9	PROF_O2	PROF_OXYGEN	oxygen
10	PROF_NO	PROF_NITRIC_OXIDE	nitric oxide
11	PROF_SO2	PROF_SULFUR_DIOXIDE	PROF_SULPHUR_DIOXIDE
			sulfur dioxide
12	PROF_NO2	PROF_NITROGEN_DIOXIDE	nitrogen dioxide
13	PROF_NH3	PROF_AMMONIA	ammonia
14	PROF_HNO3	PROF_NITRIC_ACID	nitric acid
15	PROF_CCl3F	PROF_F11	PROF_CFC11
16	PROF_CCl2F2	PROF_F12	PROF_CFC12
17	PROF_CClF3	PROF_F13	PROF_CFC13
18	PROF_CF4	PROF_F14	PROF_CFC14
19	PROF_CHClF2	PROF_F22	PROF_CFC22
20	PROF_C2Cl3F3	PROF_F113	PROF_CFC113
21	PROF_C2Cl2F4	PROF_F114	PROF_CFC114
22	PROF_C2ClF5	PROF_F115	PROF_CFC115
23	PROF_CIONO2		chlorine nitrate
24	PROF_HNO4		hydroxyl nitrate
25	PROF_CHCl2F		dichlorofluoromethane
26	PROF_CCl4		carbon tetrachloride
27	PROF_N2O5		dinitrogen pentoxide
28	PROF_AHAZE		
29	PROF_AHAZE2		
30	PROF_AHAZE3		
31	PROF_AHAZE4		
32	PROF_EQLWCZ		
33	PROF_RRATZ		
34	PROF_IHA		
35	PROF_ICLD		
36	PROF_IVUL		
37	PROF_ISEA		
38	PROF_ICHR		

```

"Atmosphere": {
    "MODEL": "ATM_USER_ALT_PROFILE",
    "M1": "ATM_MIDLAT_SUMMER",
    "M2": "ATM_MIDLAT_SUMMER",
    "M3": "ATM_MIDLAT_SUMMER",
    "M4": "ATM_MIDLAT_SUMMER",
    "M5": "ATM_MIDLAT_SUMMER",
    "M6": "ATM_MIDLAT_SUMMER",
    "MDEF": 1,
    "CO2MX": 380.0,
    "H2OSTR": 0.0,
    "O3STR": 0.0,
    "NLAYERS": 60,
    "NPROF": 1,
    "PROFILES": [
        {
            "TYPE": "PROF_ALTITUDE",
            "UNITS": "UNT_KILOMETERS",
            "PROFILE": [
                0.0, 0.04, 0.08, 0.12, 0.16, 0.2, 0.24, 0.28, 0.32, 0.36, 0.4, 0.44, 0.48, 0.52, 0.56, 0.6, 0.64, 0.68, 0.72,
                0.76, 0.8, 0.84, 0.88, 0.92, 0.96, 1.0, 2.0, 3.0, 4.0, 5.0, 6.0, 7.0, 8.0, 9.0, 10.0, 11.0, 12.0, 13.0, 14.0,
                15.0, 16.0, 17.0, 18.0, 19.0, 20.0, 21.0, 22.0, 23.0, 24.0, 25.0, 30.0, 35.0, 40.0, 45.0, 50.0, 55.0, 60.0,
                70.0, 80.0, 100.0]
        }
    ]
}

```

**Figure 3.5.** [ATMOSPHERE](#) JSONObject from test case CKoutputBIN.json used for modifying the ATM\_MIDLAT\_SUMMER atmosphere altitudes. Note the plural and singular use of PROFILE.

```

"ATMOSPHERE": {
    "MODEL": "ATM_MIDLAT_SUMMER",
    "M1": "ATM_MIDLAT_SUMMER",
    "M2": "ATM_MIDLAT_SUMMER",
    "M3": "ATM_MIDLAT_SUMMER",
    "M4": "ATM_MIDLAT_SUMMER",
    "M5": "ATM_MIDLAT_SUMMER",
    "M6": "ATM_MIDLAT_SUMMER",
    "NLAYERS": 74,
    "NPROF": 2,
    "PROFILES": [
        {
            "TYPE": "PROF_ALTITUDE",
            "UNITS": "UNIT_KILOMETERS",
            "PROFILE": [
                0.00000E+00, 0.10000E+01, 0.20000E+01, 0.30000E+01, 0.40000E+01,
                ...
                0.11400E+03, 0.11600E+03, 0.11800E+03, 0.12000E+03 ]
        },
        {
            "TYPE": "PROF METHANE",
            "UNITS": "UNIT_DPPMV",
            "PROFILE": [
                0.10000E-07, 0.10000E-07, 0.10000E-07, 0.10000E-07, 0.10000E-07,
                ...
                0.36900E-04, 0.36700E-04, 0.36400E-04, 0.36100E-04 ]
        }
    ]
}

```

**Figure 3.6.** Example of a user-defined atmospheric profile with the methane profile provided by the user.

### 3.5 Aerosol Specification Options

The aerosol options JSONObject, [AEROSOLS](#), provides the aerosol specification options which drive the MODTRAN code. An example of a fairly basic use of [AEROSOLS](#) is provided on Figure 3.1. The basic keywords in [AEROSOLS](#) are listed in Table 3.15 along with their type, values and descriptions. Examples of the use of more advanced features are presented together with the descriptions later.

**Table 3.15.** Basic AEROSOLS keywords with associated types, valid values, and descriptions.

Keyword	Type/Values	Description
<a href="#">IHAZE</a>	Table 3.16	Selects the type of extinction and a default meteorological range (visibility) for the boundary-layer (nominally, 0 to 3 km altitude) aerosol model.
VIS*		Surface meteorological range (km; see footnote).
	Omit or 0.	<i>Use default value set by IHAZE, see Table 3.16</i>
	> 0. Float	Use specified value as surface meteorological range (km).
	< 0. Float	Use absolute value as 550 nm vertical aerosol optical depth. This is combined with ground altitude, season, and volcanic aerosol inputs to determine the surface meteorological range.
WSS	> 0. Float	Current wind speed (m/s), only for <a href="#">IHAZE</a> = AER_MARITIME_NAVY model or <a href="#">IHAZE</a> = AER_DESERT model.
WHH	> 0. Float	24-hour average wind speed (m/s), only for <a href="#">IHAZE</a> = AER_MARITIME_NAVY model.
ICSTL	1, 2, 3, ..., 10	Measure of the continental influence, only used with <a href="#">IHAZE</a> = AER_MARITIME_NAVY: 1 = Open Ocean, ..., 10 = Strong continental influence. <i>Default value is 3.</i>
ISEASN	Table 3.18	Selects the seasonal profile for the tropospheric (2 to 10 km) and stratospheric (10 to 30 km) aerosols. Also selects the tropospheric aerosol extinction coefficients (nominally, 2 to 10 km). <i>Default values defined by the ATMOSPHERE JSONObject input MODEL.</i>
IVULCN	Table 3.19	Selects both the profile and 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.
ICLD	Table 3.31	Cloud and precipitation model. Also see Section 3.6
RAINRT	Omit or 0.	<i>No rain.</i>
	> 0. Float	Rain rate (mm/hr). Constant rate from ground to top of cloud when cloud is present and from ground to 6km when no cloud is defined.
IPH	0	Spectrally-independent Henyey-Greenstein aerosol phase function.
	1	User-supplied aerosol phase function (see Table 3.27).
	2	<i>Uses Mie-generated internal database of aerosol phase functions.</i>
HGPF	-1. → +1., Float	Asymmetry factor for use with Henyey-Greenstein phase function when IPH (Table 3.15) equals 0: +1 for complete forward scattering, 0 for isotropic or symmetric scattering, and -1 for complete back scattering.

\*[VIS](#) is defined as a function of the surface aerosol extinction coefficient at 550 nm in  $\text{km}^{-1}$ , EXT550, by the formula  $\text{VIS}[\text{km}] = \ln(50) / (\text{EXT550} + 0.01159)$ , where 0.01159 is the surface Rayleigh scattering coefficient at 550 nm in  $\text{km}^{-1}$ . This is not actually the Visibility. Visibility is a subjective quantity depending on the ability of an observer to see and identify a prominent bright object against the horizon sky or, at night, a light source. Point Visibility Meters, or other instruments that measure "visibility", are generally calibrated to match the sensitivity of a typical observer, and replace the threshold contrast " $\mathcal{E} = 0.02$ " in the visual range formula by " $\mathcal{E} = 0.05$ ". More generally, [VIS](#) can be estimated from reported values of visibility by  $\text{VIS} = (1.3 \pm 0.3) \times \text{Visibility}$ .

**Table 3.16.** Boundary layer aerosols – names, values and descriptions for **IHAZE**.

<b>IHAZE Value</b>	<b>#</b>	<b>Aerosol Extinction Model</b>	<b>Default <u>VIS</u> (km)</b>
<b>AER_NONE</b>	<b>0</b>	<i>No aerosol attenuation</i>	
<b>AER_RURAL</b>	<b>1</b>	RURAL	23
<b>AER_RURAL_DENSE</b>	<b>2</b>	RURAL	5
<b>AER_MARITIME_NAVY</b>	<b>3</b>	Navy Aerosol Maritime (NAM)	Based on current (WSS) and 24-hr (WHH) wind speeds and relative humidity; if WSS and WHH are omitted or set to 0., their values are set base on the <u>MODEL</u> atmosphere, see Table 3.17.
<b>AER_MARITIME</b>	<b>4</b>	MARITIME (from LOWTRAN)	23
<b>AER_URBAN</b>	<b>5</b>	URBAN	5
<b>AER_TROPOSPHERIC</b>	<b>6</b>	TROPOSPHERIC	50
<b>AER_USER_DEFINED</b>	<b>7</b>	User-defined coefficients	
<b>AER_FOG_ADVECTIVE</b>	<b>8</b>	FOG1 (Radiative Fog)	0.2
<b>AER_FOG_RADIATIVE</b>	<b>9</b>	FOG2 (Radiative Fog)	0.5
<b>AER_Desert</b>	<b>10</b>	DESERT	Based on wind speed, WSS; 10 m/s if omitted.

Note that the extinction and absorption coefficients vary with relative humidity for the RURAL, Navy Aerosol Maritime (NAM), MARITIME, URBAN, and TROPOSPHERIC models.

**Table 3.17.** Default wind speeds for AER\_MARITIME\_NAVY aerosols.

<b>MODEL #</b>	<b>MODEL Name</b>	<b>Default Wind Speeds (m/s)</b>
		<b>Current (WSS) and 24-hr (WHH)</b>
1	Tropical, 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
0, 7, 8	User-defined	6.9

**Table 3.18.** Tropospheric aerosols – names, values and descriptions for **ISEASN**.

<b>ISEASN Value</b>	<b>#</b>	<b>Description</b>
<b>SEASN_AUTO</b>	<b>0</b>	<i>FALL-WINTER if <u>MODEL</u> atmosphere is ATM_MIDLAT_WINTER or ATM_SUBARC_WINTER; otherwise SPRING-SUMMER.</i>
<b>SEASN_SPRING_SUMMER</b>	<b>1</b>	SPRING-SUMMER tropospheric/stratospheric aerosols.
<b>SEASN_FALL_WINTER</b>	<b>2</b>	FALL-WINTER tropospheric/stratospheric aerosols.

**Table 3.19.** Stratospheric aerosols – names, values and descriptions for **IVULCN**.

<b>IVULCN Name</b>	<b>#</b>	<b>Profile</b>	<b>Extinction</b>
<b>STRATO_BACKGROUND</b>	<b>0</b>	<i>Background Stratospheric</i>	<i>Background Stratospheric</i>
<b>STRATO_MODERATE_VOLCANICAGED</b>	<b>2</b>	Moderate Volcanic	Aged Volcanic
<b>STRATO_HIGH_VOLCANICFRESH</b>	<b>3</b>	High Volcanic	Fresh Volcanic
<b>STRATO_HIGH_VOLCANICAGED</b>	<b>4</b>	High Volcanic	Aged Volcanic
<b>STRATO_MODERATE_VOLCANICFRESH</b>	<b>5</b>	Moderate Volcanic	Fresh Volcanic
<b>STRATO_MODERATE_VOLCANICBACKGROUND</b>	<b>6</b>	Moderate Volcanic	Background Stratospheric
<b>STRATO_HIGH_VOLCANICBACKGROUND</b>	<b>7</b>	High Volcanic	Background Stratospheric
<b>STRATO_EXTREME_VOLCANICFRESH</b>	<b>8</b>	Extreme Volcanic	Fresh Volcanic

### 3.5.1 Advanced Aerosol Options

**Table 3.20.** Advanced [AEROSOLS](#) keywords, with associated types, valid values, and descriptions.

Keyword	Type/Values	Description
H2OAER	TRUE	Modify aerosol optical properties to reflect changes from the original relative humidity profile due to scaling of the water column (see also H2OSTR, Table 3.9).
	FALSE	<i>Do not modify aerosol optical properties to reflect changes from the original relative humidity profile due to scaling of the water column</i>
CNOVAM	TRUE	Use Navy Oceanic Vertical Aerosol Model (NOVAM). See Chapter 10 for instructions.
	FALSE	<i>Do not use Navy Oceanic Vertical Aerosol Model (NOVAM).</i>
ARUSS	"USS"	User-defined aerosol optical properties (see Tables 3.23 and 3.28).
	"SAP"	Spectral Aerosol Profiles: allows vertical profiles of aerosol spectral extinction, spectral absorption and spectral phase functions to be read in (see Section 3.5.4).
<b>"DEFAULT"</b>		<i>No user-defined aerosol optical properties.</i>
SAPFILE	String	If ARUSS = "SAP", full path file name to the spectral aerosol profile data.
	Blank or Omit	If ARUSS = "SAP", load spectral aerosol profile data using a default file name (see Section 3.5.4).
IVSA	TRUE	Use the Army Vertical Structure Algorithm (VSA) for aerosols in the boundary layer. This option cannot be used in conjunction with auxiliary species. The set of VSA cases are described in Table 3.21. Input are defined in this table.
	FALSE	<i>Do no use the Army Vertical Structure Algorithm for aerosols in the boundary layer.</i>
ZCVSA	> 0. Float	Cloud ceiling height for VSA (km).
	Omit or 0.	Ceiling height calculated by code for case 2; 1.8 km for case 2' (see Table 3.21).
ZTVSA	< 0.	No cloud ceiling (cases 3 and 4, see Table 3.21).
	> 0. Float	Cloud thickness for VSA (km).
ZINVSA	Omit or 0.	Uses default thickness of 0.2 km.
	> 0. Float	Height of inversion layer (km).
ZINVSA	Omit or 0.	Uses default inversion height of 2 km or 0.2 km for fog.
	< 0.	No inversion layer (case 4, if ZCVSA < 0.).

**Table 3.21.** Descriptions of VSA cases.

Case	Description	Selected by
1	Cloud/fog at the surface; increasing extinction with height from cloud/fog base to top. Use case 2 or 2' below the cloud and case 1 inside it.	<a href="#">VIS</a> ≤ 0.5 km and ZCVSA ≤ 0.
2	Hazy/light fog; increasing extinction with height up to the cloud base.	0.5 < <a href="#">VIS</a> ≤ 10 km, ZCVSA ≥ 0.
2'	Clear/hazy; increasing extinction with height, but less so than case 2, up to the cloud base.	<a href="#">VIS</a> > 10 km and ZCVSA ≥ 0.
3	No cloud ceiling but a radiation fog or an inversion or boundary layer present; decreasing extinction with height up to height of fog or layer.	ZCVSA < 0 and ZINVSA ≥ 0.
4	No cloud ceiling or inversion layer; constant extinction with height.	ZCVSA < 0 and ZINVSA < 0.

### 3.5.2 MODTRAN Aerosol Angstrom Exponent Input Option

MODTRAN includes the capability to model the boundary layer (nominally, 0-3 km) and troposphere (nominally, 2-11 km) aerosol extinction coefficients,  $Ext(\lambda)$ , using either of two Angstrom Law options. In Option 1, a generalized Angstrom law parameterization is used. Option 2 modifies a reference spectral extinction from a MODTRAN built-in model aerosol with an Angstrom law perturbation. This latter option can be applied either solely to the boundary layer aerosol or to both the boundary layer and tropospheric aerosols. The use of Angstrom Law parameters is invoked by setting input [ASTMX](#) to a non-

zero value. The value of case-insensitive 1-element character string input CDASTM, listed in Table 3.22, defines how the Angstrom law parameterization is to be used. In general, MODTRAN normalizes all its aerosol spectral extinction coefficients to 1 at 550 nm; the extinction coefficient at 550 nm is entered as a separate parameter. For the boundary layer aerosol, the visibility (input [VIS](#)) sets the 550 nm extinction at the ground.

For the generalized Angstrom law parameterization, Option 1, the spectral extinction coefficients,  $Ext(\lambda)$ , have the following form:

$$Ext(\lambda) = Ext(550nm) \left( \frac{ASTMO + ASTMC (550nm/\lambda)^{ASTMX}}{ASTMO + ASTMC} \right) \quad (3.1)$$

The Angstrom law coefficient,  $ASTMC$ , must be positive and the Angstrom law offset,  $ASTMO$ , should be chosen to insure that the numerator of Eq. (3.1) is non-negative over the entire MODTRAN spectral range,  $\lambda \geq 200$  nm.

**Table 3.22.** [AEROSOLS](#) keywords for using Angstrom Law for aerosol spectral extinction, with associated types, valid values, and descriptions.

Keyword	Type/Values	Description
ASTMX	Omit or 0. $\neq 0$ .	<i>Angstrom Law parameters not used.</i> Angstrom Law exponent for the boundary layer and the tropospheric aerosol. Use Angstrom Law parameters provided for the layers determined by CDASTM.
CDASTM	"t", "T", "d" or "D" "b" "B"	Perturb both the boundary layer and tropospheric aerosol reference spectral extinction data. Only perturb the boundary layer aerosol reference spectral extinction.
	Omit or otherwise	<i>Use Angstrom Law description for boundary layer and tropospheric aerosol extinction spectral extinction coefficients.</i>
ASTMC	0.0 $> 0$ .	<i>Perturb the reference spectral extinction using Eq. (3.2).</i> Angstrom Law coefficient, used for both boundary layer and tropospheric aerosols using Eq. (3.1).
ASTMO	float	Angstrom Law offset, used for both boundary layer and tropospheric aerosols using Eq. (3.1).

With Option 2, the reference spectral extinction coefficients,  $Ext_{ref}(\lambda)$ , are perturbed via the equation:

$$Ext(\lambda) = Ext_{ref}(\lambda) \left( \frac{550 nm}{\lambda} \right)^{ASTMX} \quad (3.2)$$

Spectral single scattering albedo curves,  $\omega(\lambda)$ , from the built-in model aerosols retain their original values unless input NSSALB is non-zero. The retained spectral single scattering albedo values are defined by

$$\omega(\lambda) = \frac{Ext_{ref}(\lambda) - Abs_{ref}(\lambda)}{Ext_{ref}(\lambda)}, \quad (3.3)$$

The scattering,  $Sct(\lambda)$ , and absorption,  $Abs(\lambda)$ , coefficient curves are then defined by

$$Sct(\lambda) = \omega(\lambda)Ext(\lambda) \quad and \quad Abs(\lambda) = Ext(\lambda) - Sct(\lambda). \quad (3.4)$$

Test case AngstromLaw.json illustrates the use of the Angstrom exponent. The [AEROSOLS](#) input array for this case has the following form:

```
"AEROSOLS": {
    "H2OAER": false,
    "CDASTM": "D",
    "ASTMC": 0.0,
    "ASTMX": -0.6,
    "ASTMO": 0.0,
    "APLUS": "    ",
    "IHAZE": "AER_RURAL",
    "CNOVAM": false,
    "ISEASN": "SEASN_AUTO",
    "ARUSS": "    ",
    "IVULCN": "STRATO_BACKGROUND",
    "ICSTL": 0,
    "ICLD": "CLOUD_NONE",
    "IVSA": false,
    "VIS": 26.1,
    "WSS": 0.00,
    "WHH": 0.00,
    "RAINRT": 0.00
},
```

### 3.5.3 Flexible aerosol options in [AEROSOLS](#)

MODTRAN includes the ability to define aerosols in several ways. These are accessed using the options given in Table 3.23.

**Table 3.23.** Available flexible Aerosol options in MODTRAN.

Keyword	Type/Values	Description
SSALB	Table 3.24	User-defined aerosol spectral single scattering albedo. This is applied to the boundary layer region unless CDASTM (Table 3.22) equals "t", "T", "d" or "D". In that case, it also applies to the tropospheric aerosol region.
APLUS	blank	<i>Do not use REGALT structure.</i>
	"A+"	Translate, stretch and scale aerosol regions using REGALT (see next entry).
REGALT	Table 3.25	Must be present to translate, stretch and scale aerosols using APLUS Option.
PHASEFN	Table 3.27	User-defined scattering phase functions for solar/lunar single scattering radiance when <a href="#">IPH</a> (Table 3.15) equals 1.
<a href="#">IREGSPC</a> [4]	Table 3.28	Required input for user-defined aerosols and clouds, i.e. if <a href="#">IHAZE</a> (Table 3.16) equals AER_USER_DEFINED; if <a href="#">ARUSS</a> (Table 3.20) equals "USS"; or if ICLD (Table 3.31) equals CLOUD_USER_DEFINED. The 4 members are defined for the 4 aerosol altitude regions.
<a href="#">CLDALT</a>	Table 3.35	For user-defined cloud and rain profiles for ICLD (Table 3.31) equals 1 – 10.
CLDSPC	Table 3.36	For user-defined cloud optical properties for ICLD (Table 3.31) equals 1 – 10.

**Table 3.24.** Content of SSALB for aerosol spectral single scattering albedo, with associated types, valid values, and descriptions.

Keyword	Type/Values	Description
NSSALB	0	<i>Use reference aerosol spectral single scattering albedo and relative humidity values</i>
	> 0	Number of spectral single scattering albedo, ASSALB, grid points
	< 0	Enter aerosol single scattering coalbedo (one minus single scatter albedo), ACOALB, and relative humidity, RHASYM
AWAVLN	> 0. Float[]	Wavelengths for boundary layer (and tropospheric) aerosol single scattering albedo in monotonically increasing order [ $\mu\text{m}$ ].
ASSALB	0. → 1., Float[]	Boundary layer (and tropospheric) aerosol spectral single scattering albedo values.
ACOALB	≥ 0.	Aerosol single scattering co-albedo (1 – albedo) scaling factor. ACOALB may exceed 1, but the spectral co-albedo at each grid point is restricted to not exceed 1.
RHASYM	≥ 0., Float	Relative humidity used to define the aerosol asymmetry factor [%].

**Table 3.25.** Content of REGALT for the flexible aerosol option with associated types, valid values, and description.

Keyword	Type/Values	Description
ZAER1 (1)	> 0., Float	Base/bottom altitude of Region 1 (boundary layer) aerosol [km].
	Omit or 0.	<b><i>Retain default Region 1 (boundary layer) aerosol base altitude, 0.0 km.</i></b>
	> ZAER1 (1)	Top of stretched/compressed Region 1 (boundary layer) aerosol [km].
ZAER1 (2)	= ZAER1 (1)	<b><i>Default ZAER1 (1) and ZAER1 (2) values, 0.0 and 3.0 km, respectively, used.</i></b>
	< ZAER1 (1)	Default aerosol layer thickness retained, ZAER1 (2) = ZAER1 (1) + 3.0 km.
SCALE1	Omit or 0.	<b><i>No scaling of Region 1 atmospheric level aerosol densities. Vertical Aerosol Optical Depth (AOD) is not conserved if aerosol layer was stretched or compressed.</i></b>
ZAER1 (1)	> 0., Float	<b><i>Scale Region 1 atmospheric level aerosol densities by SCALE1.</i></b>
	> 0., Float	Base/bottom altitude of Region 2 (tropospheric layer) aerosol [km].
	Omit or 0.	<b><i>Retain default Region 2 (tropospheric layer) aerosol base altitude, 2.0 km.</i></b>
ZAER2 (2)	> ZAER2 (1)	Top of stretched/compressed Region 2 (tropospheric layer) aerosol [km].
	= ZAER2 (1)	<b><i>Default ZAER2 (1) and ZAER2 (2) values, 2.0 and 11.0 km, respectively, used.</i></b>
	< ZAER2 (1)	Default aerosol layer thickness retained, ZAER2 (2) = ZAER2 (1) + 9.0 km.
SCALE2	Omit or 0.	<b><i>No scaling of Region 2 atmospheric level aerosol densities. Vertical AOD is not conserved if aerosol layer was stretched or compressed.</i></b>
ZAER2 (1)	> 0., Float	Base/bottom altitude of Region 3 (stratospheric layer) aerosol [km].
	Omit or 0.	<b><i>Retain default Region 3 (stratospheric layer) aerosol base altitude, 10.0 km.</i></b>
	> ZAER3 (1)	Top of stretched/compressed Region 3 (stratospheric layer) aerosol [km].
ZAER3 (2)	= ZAER3 (1)	<b><i>Default ZAER3 (1) and ZAER3 (2) values, 10.0 and 35.0 km, respectively, used.</i></b>
	< ZAER3 (1)	Default aerosol layer thickness retained, ZAER3 (2) = ZAER3 (1) + 25.0 km.
SCALE3	Omit or 0.	<b><i>No scaling of Region 3 atmospheric level aerosol densities. Vertical AOD is not conserved if aerosol layer was stretched or compressed.</i></b>
ZAER3 (1)	> 0., Float	Base/bottom altitude of Region 4 (volcanic layer) aerosol [km].
	Omit or 0.	<b><i>Retain default Region 4 (volcanic layer) aerosol base altitude, 30.0 km.</i></b>
	> ZAER4 (1)	Top of stretched/compressed Region 4 (volcanic layer) aerosol [km].
ZAER4 (2)	= ZAER4 (1)	<b><i>Default ZAER4 (1) and ZAER4 (2) values, 30.0 and 100.0 km, respectively, used.</i></b>
	< ZAER4 (1)	Default aerosol layer thickness retained, ZAER4 (2) = ZAER4 (1) + 70.0 km.
SCALE4	Omit or 0.	<b><i>No scaling of Region 4 atmospheric level aerosol densities. Vertical AOD is not conserved if aerosol layer was stretched or compressed.</i></b>
> 0., Float		Scale Region 4 atmospheric level aerosol densities by SCALE4.

### Examples of the two forms taken by SSALB:

```
"SSALB": {
    "NSSALB":2
    "AWAVLN": [5.0, 7.0], # Wavelengths in microns
    "ASSALB": [0.1, 0.6] # Boundary layer/tropospheric spectral albedo
}

"SSALB": {
    "NSSALB": -1
    "ACOALB": 3.0, # Single scattering co-albedo scale factor
    "RHASYM": 50. # Relative humidity used to define aerosol asymmetry factor
}
```

By using REGALT, the user can move MODTRAN's built-in aerosols from their original positions to arbitrary altitude regions (which may overlap) and also compress and stretch them. If [GNDALT](#) in GEOMETRY (see Table 3.43) is non-zero, the aerosol densities below 6 km will undergo an additional compression or stretching. An important benefit is the ability to move the tropospheric height. This cannot be used in conjunction with NOVAM (Chapter 10). Furthermore, if this is used with [MODEL](#) = ATM\_USER\_ALT\_PROFILE, the atmospheric profile must contain atmospheric levels precisely at GNDALT, GNDALT + (6 – GNDALT)/3, GNDALT + (6 – GNDALT)/2, 10.0, 11.0, 30.0, 35.0 and 100.0 km.

The MODTRAN definition of an aerosol region can lead to some confusion. Possibly a preferred definition of the aerosol region would be the contiguous altitudes over which the aerosol 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. Each altitude pair we describe here refers to the bounding altitudes, which sandwich the entire region where the aerosol concentration is positive. The default values of these bounding altitudes along with the commonly referred to region boundaries for each aerosol are listed in Table 3.26.

### Example of REGALT usage:

```
"REGALT": { # From 1500mGround test case
    "ZAER1": [1.0, 0.0], # Boundary layer aerosol shifted to new base
    "SCALE1": 0.5          # Scaling factor
}
```

**Table 3.26.** Default altitude boundaries for the 4 aerosol regions.

Aerosol, i	Default altitude levels with positive aerosol density (km)	Default ZAERi – Positive aerosol density altitude range (km)	
1	0, 1, 2	0	3
2	3, 4, ..., 10	2	11
3	11, 12, ..., 24, 25, 30	10	35
4	35, 40, 45, 50, 55, 60, 70, 80, 100	30	100

There is another caveat that pertains to the Tropospheric aerosol model, AER TROPOSPHERIC. For this aerosol model selection, MODTRAN combines the boundary layer (Aerosol 1) and tropospheric (Aerosol 2) regions; therefore, these regions may not be scaled independently. Thus, the parameters used to scale the tropospheric aerosol model are min (ZAER1(1), ZAER2(1)), max (ZAER2(1), ZAER2(2)) and max (SCALE1, SCALE2).

**Table 3.27.** Content of PHASEFN for aerosol phase function with associated types, valid values, and descriptions. This is used for solar scattering calculations when [IPH](#) (Table 3.15) equals 1.

Keyword	Type/Values	Description
NANGLS	> 0 Integer	Number of scattering phase function angular grid points
NWLF	> 0 Integer	Number of scattering phase function spectral wavelength grid points
ANGF	0. → 180.0 Float[]	Monotonically increasing scattering angle array (decimal degrees) with NANGLS elements.
WLF	> 0. Float[]	Monotonically increasing wavelength array ( $\mu\text{m}$ ) with NWLF elements.
AERPF	> 0. Float[][][]	Unit-normalized scattering phase function values [1/sr]. The 1-D array is ordered with [ (PF for 4 regions) over the angles ] over the spectral grid.

#### Example of PHASEFN:

```
"PHASEFN": {
    "NANGLS": 3, # of scattering angles
    "NWLF": 2, # spectral grid point
    "ANGF": [0.0, 90.0, 180.0], # Scattering angles in decimal degrees
    "WLF": [1.0, 2.0], # Monotonic phase function spectral grid in  $\mu\text{m}$ 
    "AERPF": [0.111, 0.211, 0.311, 0.411, 0.121, 0.221, 0.321, 0.421, 0.131, 0.231, 0.331,
               0.431, 0.112, 0.212, 0.312, 0.412, 0.122, 0.222, 0.322, 0.422, 0.132, 0.232,
               0.332, 0.432] # ((PF for 4 regions) over the angles) over the spectral grid
}
```

**Table 3.28.** Content of IREGSPC[n] for  $n$  equals 1 to 4, an option for defining user-defined aerosols or clouds, with associated types, valid values, and descriptions.

Keyword	Type/Values	Description
IREG	1, 2, 3 or 4	The number of the aerosol region for which data is being defined
	0	No user defined data in <a href="#">IREGSPC [n]</a>
AWCCON	> 0. Float	Conversion factor ( $\text{km g} / \text{m}^3$ ) from extinction coefficient ( $\text{km}^{-1}$ ) to equivalent liquid water content ( $\text{g/m}^3$ ), only for fog extinction at microwave wavelengths ( $> 287.9 \mu\text{m}$ , wavenumber $< 37.4 \text{ cm}^{-1}$ ). It is numerically equal to the equivalent liquid water content corresponding to extinction coefficient of $1.0 \text{ km}^{-1}$ , at wavelength of $0.55 \mu\text{m}$ .
AERNAM	String	Name for IREG aerosol region.
NARSPC	> 0	<b>Number of aerosol spectral grid points.</b>
	= 0	Use the 47 default spectral grid points, Table 3.29.
VARSPC	Omit	Uses 47 built-in values (see Table 3.29); cannot be omitted if NARSPC exceeds zero.
	> 0. Float[]	NARSPC user-supplied wavelengths ( $\mu\text{m}$ ).
EXTC	> 0. Float[]	NARSPC extinction coefficients [ $\text{km}^{-1}$ ], normalized so that value at $\lambda = 0.55 \mu\text{m}$ is $1/\text{km}$ .
ABSC	> 0. Float[]	NARSPC absorption coefficients [ $\text{km}^{-1}$ ], normalized so that value at $\lambda = 0.55 \mu\text{m}$ over the extinction coefficient for $\lambda = 0.55 \mu\text{m}$ ( $1/\text{km}$ ) equals the co-albedo, one minus the single scattering albedo.
ASYM	-1. → 1. Float[]	NARSPC asymmetry parameters. <a href="#">IPH</a> (Table 3.15) must be set to 2 to insure that the asymmetry factor will not be overwritten.

Arrays EXTC, ABSC, and ASYM of Table 3.28 are defined for the spectral grid in VARSPC.

**Table 3.29.** VARSPC array of fixed wavelengths.

Index	Wavelength(μm)	Index	Wavelength(μm)	Index	Wavelength(μm)
1	0.2000	17	5.5000	33	15.0000
2	0.3000	18	6.0000	34	16.4000
3	0.3371	19	6.2000	35	17.2000
4	0.5500	20	6.5000	36	18.5000
5	0.6943	21	7.2000	37	21.3000
6	1.0600	22	7.9000	38	25.0000
7	1.5360	23	8.2000	39	30.0000
8	2.0000	24	8.7000	40	40.0000
9	2.2500	25	9.0000	41	50.0000
10	2.5000	26	9.2000	42	60.0000
11	2.7000	27	10.0000	43	80.0000
12	3.0000	28	10.5910	44	100.0000
13	3.3923	29	11.0000	45	150.0000
14	3.7500	30	11.5000	46	200.0000
15	4.5000	31	12.5000	47	300.0000
16	5.0000	32	14.8000		

The default VARSPC array contains the 47 wavelengths at which the spectral data are read in when NARSPC is zero. 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 MODTRAN inputs.

**Example of IREGSPC Usage from test case CD2c3\_USS.json:**

```

"IREGSPC": [
    {
        "IREG":1,
        "NARSPC":40,
        "AWCCON":0.000000000000000e+00,
        "AERNAM":"region #1 desert summer aerosol",
        "VARSPC": [
            2.00e-01, 3.00e-01, 3.400e-01, 5.50e-01, 6.80e-01,
            1.06e+00, 1.54e+00, 2.000e+00, 2.25e+00, 2.50e+00,
            ...
            1.85e+01, 2.13e+01, 2.500e+01, 3.00e+01, 4.00e+01 ],
        "EXTC": [
            1.0167e+00, 1.0167e+00, 1.0194e+00, 1.0000e+00, 1.0370e+00,
            1.1149e+00, 1.2084e+00, 1.0471e+00, 9.0502e-01, 7.7022e-01,
            ...
            4.4203e-01, 4.8520e-01, 4.5705e-01, 4.0179e-01, 3.6801e-01 ],
        "ABSC": [
            4.3495e-01, 4.3495e-01, 4.4735e-01, 2.1935e-01, 1.6743e-01,
            3.7210e-02, 4.3480e-02, 4.2120e-02, 3.5770e-02, 5.0250e-02,
            ...
            1.8161e-01, 2.6897e-01, 2.2352e-01, 2.5847e-01, 2.3947e-01 ],
        "ASYM": [
            8.797e-01, 8.797e-01, 8.857e-01, 7.980e-01, 7.666e-01,
            7.143e-01, 7.689e-01, 8.557e-01, 8.936e-01, 9.116e-01,
            ...
            6.366e-01, 5.959e-01, 5.460e-01, 5.494e-01, 4.688e-01 ]
    },
    {
        "IREG":2,
        "NARSPC":40,
        "AWCCON":0.000000000000000e+00,
        "AERNAM":"region #2 desert summer darkened",
        "VARSPC": [
            2.00e-01, 3.00e-01, 3.400e-01, 5.50e-01, 6.80e-01,
            1.06e+00, 1.54e+00, 2.000e+00, 2.25e+00, 2.50e+00,
            ...
            1.85e+01, 2.13e+01, 2.500e+01, 3.00e+01, 4.00e+01 ],
        "EXTC": [
            1.0167e+00, 1.0167e+00, 1.0194e+00, 1.0000e+00, 1.0370e+00,
            1.1149e+00, 1.2084e+00, 1.0471e+00, 9.0502e-01, 7.7022e-01,
            ...
            4.4203e-01, 4.8520e-01, 4.5705e-01, 4.0179e-01, 3.6801e-01 ],
        "ABSC": [
            8.3495e-01, 8.3495e-01, 8.4735e-01, 4.1935e-01, 3.6743e-01,
            1.3721e-01, 1.4348e-01, 1.4212e-01, 1.3577e-01, 1.5025e-01,
            ...
            3.8161e-01, 4.6897e-01, 4.2352e-01, 3.5847e-01, 3.3947e-01 ],
        "ASYM": [
            8.797e-01, 8.797e-01, 8.857e-01, 7.980e-01, 7.666e-01,
            7.143e-01, 7.689e-01, 8.557e-01, 8.936e-01, 9.116e-01,
            ...
            6.366e-01, 5.959e-01, 5.460e-01, 5.494e-01, 4.688e-01 ]
    }
]

```

### 3.5.4 Spectral Aerosol Profiles (SAP) Option

Spectral aerosol profiles (SAP) are read in when [ARUSS](#) is set to “SAP” and the selected [MODEL](#) is ATM\_USER\_ALT\_PROFILE or ATM\_USER\_PRESS\_PROFILE. SAP allows vertical profiles of aerosol spectral extinction, spectral absorption and spectral phase functions to be read. The SAP data is stored in a ASCII <ROOTNAME>.sap file. A sample SAP input file is shown in Table 3.30. The column headers have been inserted for clarity.

**Table 3.30.** Sample Spectral Aerosol Profiles (SAP) input data file.

Alt(m)	Wave	Bext ( $km^{-1}$ )	Bsca ( $km^{-1}$ )	Pmom <sup>0</sup>	Pmom <sup>1</sup>	...	Pmom <sup>64</sup>	Phase Function vs Angle (°)		
<b>40</b>	<b>64</b>	<b>181</b>						0.0000	1.0000	...
										<b>180.000</b>
<b>.0003653</b>	.2000	.9173681	.9158943	1.0000	.7966921	...	.1319957	208.9782	193.6871	...
<b>.0003653</b>	.3000	.8726480	.8726359	1.0000	.8118536	...	.1070675	208.8804	194.0608	...
<b>.0003653</b>	.3371	.8525812	.8525700	1.0000	.8112088	...	.1012243	207.9938	193.4231	...
...	...									
<b>.0003653</b>	25.00	.2620940	.0969520	1.0000	.7294320	...	.0000000	38.06391	37.61441	...
<b>.0003653</b>	30.00	.2369326	.0895308	1.0000	.7221835	...	.0000000	29.82364	29.57460	...
<b>.0003653</b>	40.00	.2156776	.0699561	1.0000	.6948593	...	.0000000	21.41463	21.30646	...
<b>.1260741</b>	.2000	.3358318	.3343440	1.0000	.7796006	...	.0807715	172.1363	160.5204	...
<b>.1260741</b>	.3000	.3008995	.3008881	1.0000	.7767678	...	.0675285	161.2990	150.9579	...
<b>.1260741</b>	.3371	.2897007	.2896896	1.0000	.7733779	...	.0646587	157.8538	147.8797	...
...	...									
<b>.1260741</b>	25.00	.0616450	.0247540	1.0000	.6856267	...	.0000000	17.56935	17.49937	...
<b>.1260741</b>	30.00	.0562292	.0217360	1.0000	.6611843	...	.0000000	14.18904	14.14785	...
<b>.1260741</b>	40.00	.0584414	.0161276	1.0000	.5706048	...	.0000000	10.02048	10.00178	...
...	...									
<b>1993.880</b>	.2000	.2613175	.2602409	1.0000	.7697431	...	.0518847	152.5157	142.7655	...
<b>1993.880</b>	.3000	.2297381	.2297099	1.0000	.7593464	...	.0413473	136.5168	128.3560	...
<b>1993.880</b>	.3371	.2196234	.2196121	1.0000	.7543240	...	.0390868	131.9052	124.1712	...
...	...									
<b>1993.880</b>	25.00	.0295673	.0118886	1.0000	.6489874	...	.0000000	13.93146	13.88930	...
<b>1993.880</b>	30.00	.0271156	.0099214	1.0000	.6250932	...	.0000000	11.57627	11.55026	...
<b>1993.880</b>	40.00	.0317162	.0074431	1.0000	.5096798	...	.0000000	8.037910	8.026117	...
<b>2237.286</b>	.2000	.0000000	.0000000	0.0000	.0000000	...	.0000000	0.000000	0.000000	...
<b>2237.286</b>	.3000	.0000000	.0000000	0.0000	.0000000	...	.0000000	0.000000	0.000000	...
<b>2237.286</b>	.3371	.0000000	.0000000	0.0000	.0000000	...	.0000000	0.000000	0.000000	...
...	...									
<b>2237.286</b>	25.00	.0000000	.0000000	0.0000	.0000000	...	.0000000	0.000000	0.000000	...
<b>2237.286</b>	30.00	.0000000	.0000000	0.0000	.0000000	...	.0000000	0.000000	0.000000	...
<b>2237.286</b>	40.00	.0000000	.0000000	0.0000	.0000000	...	.0000000	0.000000	0.000000	...
							0.0000	1.0000	...	<b>180.000</b>
<b>.0003653</b>	.2000	.9173681	.9158943	1.0000	.7966921	...	.1319957	208.9782	193.6871	...
<b>.0003653</b>	.3000	.8726480	.8726359	1.0000	.8118536	...	.1070675	208.8804	194.0608	...
<b>.0003653</b>	.3371	.8525812	.8525700	1.0000	.8112088	...	.1012243	207.9938	193.4231	...
...	...									

Each line of the <ROOTNAME>.sap file is read in using a free format; values must be separated by spaces and/or a comma, but no tabs. The first line contains 3 integers, NWVSAP (the number of spectral grid points), NLGSAP (the number of scattering phase function Legendre moments) and NANSAP (the number of scattering phase function angular points). Header information can follow these numbers on this line; it is not read in. The second line contains the scattering phase function angular grid. Angles are in degrees. The angular grid must begin with 0., be monotonically increasing, and end with 180. The next NWVSAP lines contain the aerosol data for the first (i.e. ground) MODTRAN altitude. The altitude,

which is entered in meters, is the first entry in each line and it must correspond to the first altitude in PROF\_ALTITUDE, which is entered in km. The second entry on each line is the wavelength in microns. Wavelengths must be monotonically increasing. The 3rd and 4th entry on each line are the extinction and scattering coefficients in units of  $\text{km}^{-1}$ . The remainder of each line contains phase function data. The NLGSAP Legendre moments are listed first (with the  $N^{\text{th}}$  term divided by  $2N+1$  so that  $\sum(2N+1)P_{mom}(N)$  equals the forward peak of the phase function). The Legendre moments should be normalized so that  $P_{mom}(1)$  always equals 1. Phase function values at each of the angular grid points are listed after the Legendre moments, on the same line. Within MODTRAN, the tabulated phase function is renormalized to 1 (not  $4\pi \text{ sr}$ ) assuming exponential variation between the cosine of scattering angle values. Data for the second altitude in PROF\_ALTITUDE, again with NWVSAP lines, follows the data from the first altitude. The spectral grid is re-entered as the second entry on each line, but it must fully correspond to the spectral grid from the first altitude. The SAP input altitude grid is terminated by entering NWVSAP lines containing the terminating altitude (2,237.286 m in the table). These lines must also contain the spectral wavelengths and **zeros for all other entries**. [MODTRAN keys in on the zero value for  $P_{mom}(1)$  ]. For the terminating altitude and all altitudes above it, aerosol properties are determined by the keywords [IHaze](#), [ISEASN](#), [IVULCN](#), [ICSTL](#), [ICLD](#), [VIS](#), [WSS](#), [WHH](#), and [GNDALT](#). However, these “background” aerosols are set to zero at all altitude levels below the SAP termination altitude. See the MODTRAN test cases UserPath, UserPathBinary and UserPathDisort for examples.

### **3.6 Clouds and Precipitation**

**Table 3.31.** Clouds and precipitation - names, values and descriptions for [ICLD](#).

<b>ICLD Name</b>	<b>#</b>	<b>Description</b>
CLOUD_NONE	0	<i>No cloud or precipitation.</i>
CLOUD_CUMULUS	1	<b>Cumulus</b> cloud layer.
CLOUD_ALTOSTRATUS	2	<b>Altostratus</b> cloud layer.
CLOUD_STRATUS	3	<b>Stratus</b> cloud layer.
CLOUD_STRATOCUMULUS	4	<b>Stratus/stratocumulus</b> layer.
CLOUD_NIMBOSTRATUS	5	<b>Nimbostratus</b> cloud layer.
CLOUD_RAIN_DRIZZLE	6	<b>2.0 mm/hr ground Drizzle</b> (Stratus cloud and 0.86 mm/hr at 1.0 km).
CLOUD_RAIN_LIGHT	7	<b>5.0 mm/hr ground Light rain</b> (Nimbostratus cloud and 2.6 mm/hr at 0.66 km).
CLOUD_RAIN_MODERATE	8	<b>12.5 mm hr ground Moderate rain</b> (Nimbostratus cloud and 6.0 mm/hr at 0.66 km).
CLOUD_RAIN_HEAVY	9	<b>25.0 mm hr ground Heavy rain</b> (Cumulus cloud and 0.2 mm/hr at 3.0 km).
CLOUD_RAIN_EXTREME	10	<b>75.0 mm hr ground Extreme rain</b> (Cumulus cloud and 1.0 mm/hr at 3.0 km).
CLOUD_USER_DEFINED	11	Read in user-defined cloud extinction coefficient, absorption coefficient, and asymmetry factor data. Triggers reading data for up to 4 altitude regions (Option retained for backward compatibility; other input options afford greater flexibility in specifying user-defined clouds).
CLOUD_CIRRUS	18	<b>Standard Cirrus model</b> (64 $\mu\text{m}$ mode radius for ice particles).
CLOUD_CIRRUS_THIN	19	<b>Sub-visual Cirrus model</b> (4 $\mu\text{m}$ mode radius for ice particles).

The five MODTRAN liquid water droplet model clouds are defined by the parameters listed in Table 3.32. The keywords for cumulus and stratus clouds (1 – 10) are documented in Table 3.33 and those for cirrus clouds (18, 19), are detailed in Table 3.34.

The rain profiles decrease linearly from the ground to the top of the associated cloud model. There is no rain above the cloud top.

**Table 3.32.** Properties of the MODTRAN cumulus and stratus type model clouds.

Cloud Type	I <sub>CLD</sub>	Thickness (km)	Base (km)	Top (km)	0.55 μm Ext. (km <sup>-1</sup> )	Column Amt. (km g / m <sup>3</sup> )
Cumulus	1, 9, 10	2.34	0.66	3.0	92.6	1.6640
Altostratus	2	0.60	2.40	3.0	128.1	0.3450
Stratus	3, 6	0.67	0.33	1.0	56.9	0.2010
Stratus/Stratocumulus	4	1.34	0.66	2.0	38.7	0.2165
Nimbostratus	5, 7, 8	0.50	0.16	0.66	92.0	0.3460

**Table 3.33.** Names, Values and descriptions for water/ice clouds (I<sub>CLD</sub> = 1–10) in [AEROSOLS](#). All values are floats.

Keyword	#	Description
CTHIK	≤ 0.	<i>Use default thickness (see Table 3.32).</i>
	> 0.	User-defined thickness.
CALT	< 0.	<i>Use default cloud base altitude (see Table 3.32).</i>
	≥ 0.	Cloud base altitude relative to <b>ground level</b> .
CWAVLN	0.2 → 200.	Reference wavelength for defining cloud vertical extinction (μm).
	Otherwise	<i>Uses default wavelength, 0.55 μm.</i>
CEXT	≤ 0.	<i>Do not scale extinction coefficients. See Table 3.32 for default cloud extinctions at 0.55 μm for each of the five MODTRAN liquid water droplet model clouds.</i>
	> 0.	Cloud water particle extinction coefficient [km <sup>-1</sup> ] at CWAVLN. CEXT scales the extinction (and absorption) coefficient curves. The ratio of the input optical depth (CEXT*CTHIK) to the optical depth calculated from 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.
CCOLWD	< 0.	<i>Use default water droplet column densities (no scaling of densities).</i>
	≥ 0.	Cloud liquid water droplet vertical column density [km g/m <sup>3</sup> ].
CCOLIP	≤ 0.	<i>Use default ice particle column densities (no scaling of densities).</i>
	> 0.	Cloud ice particle vertical column density [km g/m <sup>3</sup> ]. If both CCOLIP and CCOLWD are zero, there is no scaling for either water or ice amount.
CHUMID	> 0. and < 105.	Cloud/rain relative humidity(RH) [%] at all layer boundaries with positive rain rate or positive cloud density; 5 % supersaturation is permitted.
	Omitted or < 0.	Assume 100% relative humidity at cloud/rain layer boundaries.
	> 105.	The relative humidity profile defined in the absence of the cloud is not modified due to the presence of cloud.
ASYMWD	-1. → 1.	Water droplet Henyey-Greenstein wavelength-independent scattering phase function asymmetry factor. Use this value and ignore any spectral asymmetry inputs.
	Otherwise	<i>Use user-defined or model spectral asymmetry factors for scattering by cloud liquid water droplets.</i>
ASYMIP	-1. → 1.	Ice particle Henyey-Greenstein wavelength-independent scattering phase function asymmetry factor.
	Otherwise	<i>Use user-defined or model (standard cirrus) spectral asymmetry factors for scattering by cloud ice particles.</i>

**Table 3.34.** Names, values and descriptions for cirrus clouds ( $\text{ICLD} = 18\text{--}19$ ) in [AEROSOLS](#). All values are floats.

Keywords	Value	Description
CTHICK	Omit or $\leq 0$ .	<i>Use default thickness statistics.</i>
	$> 0$ .	User-defined thickness (km).
CALT	Omit or $\leq 0$ .	<i>Use default value for cirrus cloud base altitude</i>
	$> 0$ .	User-defined cirrus cloud base altitude relative to sea level (km).
CEXT	Omit or $\leq 0$ .	<i>Use <math>0.14 \text{ km}^{-2} * \text{CTHICK}</math> for cirrus cloud extinction coefficient (<math>\text{km}^{-1}</math>) at <math>0.55 \mu\text{m}</math></i>
	$> 0$ .	User-defined cirrus cloud extinction coefficient ( $\text{km}^{-1}$ ) at $0.55 \mu\text{m}$ .

**Table 3.35.** Keywords in CLDALT, for user-defined cloud and rain profiles, with associated types, valid values, and descriptions. An illustration of its use is provided below the table.

Keyword	Type/Values	Description
NCRALT	0	<i>No user-defined cloud or rain profiles</i>
	$> 0$	Number of user-defined cloud and rain profile altitudes.
ZPCLD	$\geq 0$ . <b>Float</b> []	<p><b>If MODEL does not equal ATM USER PRESS PROFILE:</b> ZPCLD array contains monotonically increasing above ground level (AGL) altitudes [km]. The first altitude level can be 0., i.e., the ground; this is necessary if rain is to be modeled at the ground or if the cloud is to sit on the ground. The highest altitude cannot exceed the top of atmosphere (TOA).</p> <p><b>If MODEL equals ATM USER PRESS PROFILE:</b> ZPCLD contains a monotonically decreasing array of AGL pressure levels [mbar].</p>
CLD	$\geq 0$ . <b>Float</b> []	Liquid water droplet density profile [ $\text{g/m}^3$ ]. The densities are modeled to vary linearly between altitudes. The entire CLD array is scaled if CCOLWD is non-negative.
CLDICE	$\geq 0$ . <b>Float</b> []	Ice particle density profile [ $\text{g/m}^3$ ]. The densities are modeled to vary linearly between altitudes. The entire CLDICE array is scaled if CCOLIP is non-negative.
RR	<b>≥ 0. Float</b> []	Rain rate array [mm/hr] profile. If a rain rate is entered through RAINRT, that constant rain rate supersedes this array of values. Thus, if a user-defined rain rate profile is desired, RAINRT must be omitted.

Example of [CLDALT](#) usage from test case UserDefinedCld.json:

```
"CLDALT": {
    "NCRALT": 5,
    "ZPCLD": [0.00, 0.09, 0.11, 2.49, 2.50],
    "CLD": [0.00, 0.00, 0.68, 0.68, 0.00],
    "CLDICE": [0.00, 0.00, 0.00, 0.00, 0.00],
    "RR": [0.00, 0.00, 0.00, 0.00, 0.00]
},
```

**Table 3.36.** Keywords in CLDSPC for wavelength-dependent cloud extinction coefficients, absorption coefficients and asymmetry factors with associated types, valid values, and descriptions. All arrays use the spectral grid in WAVLEN (defined in this table).

Keyword	Type/Values	Description
NCRSPC	0	No cloud user-defined spectral data
	1	Cloud data entered from external file with the CFILE name.
	> 1	Number of spectral grid points in user-defined cloud optical data.
WAVLEN	$\geq 0.0$ Float[ ]	Monotonically increasing spectral grid of wavelengths in $\mu\text{m}$ . If a positive vertical cloud extinction, CEXT (Table 3.34) is input, the reference wavelength, CWAVLN (Table 3.34) or $0.55 \mu\text{m}$ , must be within the range of wavelength.
EXTC6	$\geq 0.$ , Float[ ]	Liquid water droplet extinction coefficients [ $\text{km}^{-1} \text{m}^3 / \text{g}$ ].
	Omitted	Wavelength-interpolated extinction coefficients from cloud model ICLD.
ABSC6	$> 0.$ , Float[ ]	Liquid water droplet absorption coefficients [ $\text{km}^{-1} \text{m}^3 / \text{g}$ ].
	$-1. \rightarrow < 0$	Liquid water droplet scattering albedos, minus 1.
	$<-1$ or ABSC6(I) > EXTC6(I)	ABSC6(I) is calculated by first determining the default absorption to extinction ratio for cloud model ICLD, and then multiplying EXTC6(I) by this ratio, i.e., the liquid water model cloud single scatter albedo is used to determine the absorption coefficient.
ASYM6	$-1. \rightarrow 1.$ , Float[ ]	Henyey-Greenstein scattering phase function asymmetry factors for liquid water droplets.
	Otherwise	Assigned the wavelength-interpolated value from cloud model ICLD.
EXTC7	$\geq 0.$ , Float[ ]	Ice cloud particle extinction coefficients [ $\text{km}^{-1} \text{m}^3 / \text{g}$ ].
ABSC7	$> 0.$ , Float[ ]	Ice cloud particle absorption coefficients [ $\text{km}^{-1} \text{m}^3 / \text{g}$ ].
	$-1. \rightarrow < 0$	Ice cloud particle scattering albedos, minus 1.
	$<-1$ or ABSC7(I) > EXTC6(I)	ABSC7(I) is calculated by first determining the default absorption to extinction ratio for cloud model ICLD, and then multiplying EXTC7(I) by this ratio, i.e., the ice particle model cloud single scatter albedo is used to determine the absorption coefficient.
ASYM7	$-1. \rightarrow 1.$ , Float[ ]	Henyey-Greenstein scattering phase function asymmetry factors for ice cloud particles.
CFILE	String	If NCRSPC = 1, cloud spectral data full path file name.
CLDTYP	String	If NCRSPC = 1, name of first cloud from CFILE (usually a water cloud).
CIRTYP	String	If NCRSPC = 1, name of second cloud from CFILE (usually an ice cloud).

**Format of cloud spectral data file:** The format of the cloud spectral data file read in using the CFILE keyword is exemplified by the file “DATA/Macke.dat”, included in MODTRAN DATA directory. This data set, although based on [40], is strictly a sample file; its spectral resolution is coarser than MODTRAN internal cloud data. The cloud spectral data files can contain data for any number of cloud types. The format for each cloud type is as follows:

Input 1: CLDNAM Water or cirrus cloud type name; 256 characters or less.  
 Input 2: NCLDAN, NCLDLG, NCLDWV Number of angular grid points, number of Legendre expansion coefficients minus one, and number of spectral points.

Input 3: INPSTR Angular grid header; not used; 256 character string.

Input 4: CLDANG(1:NCLDAN) Scattering angles, from 0 to 180 degrees.

*Loop over NCLDWV increasing spectral wavelengths:*

Input 5: CLDWAV, CLDEXT, CLDABS Wavelength [ $\mu\text{m}$ ], extinction cross-section over average particle mass at CLDWAV [ $\text{km}^{-1} \text{m}^3 / \text{g}$ ], and absorption cross-section over average particle mass at CLDWAV [ $\text{km}^{-1} \text{m}^1 / \text{g}$ ].

Input 6: INPSTR Phase function header; not used. 80 character string.

Input 7: CLDPF(1:NCLDAN) Scattering phase function as a function of angle at CLDWAV [ $\text{sr}^{-1}$ ]

Input 8: INPSTR Legendre expansion coefficients; not used. 80 character string.

Input 9: CLDLEG(0:NCLDLG) Legendre expansion coefficients over (2 ICLDLG + 1); ICLDLG is index.

*End loop over NCLDWV spectral wavelengths*

**Note:** CLDTYP and CIRTYP must each match a cloud type name, CLDNAM, from the CFILE data file. The comparison is case-sensitive, but leading blanks are ignored. Extensive checking is performed on the input data. The spectral scattering phase functions are assumed to be normalized to unity, and they are re-normalized (and a warning is generated) if the normalization condition is not satisfied. The Legendre expansion coefficients (over  $2N+1$ ) are normalized such that the leading order coefficient is 1.

## Examples of CLDSPC usage from test case UserDefinedCld.json:

```

"CLDSPC": {
    "NCRSPC": 6,
    "WAVLEN": [ 0.89, 1.48, 1.78, 2.00, 2.36, 2.72 ],
    "EXTC6": [ 130.9577, 133.3623, 134.4573, 135.2213, 136.4137, 137.5468 ],
    "ABSC6": [ 0.0131, 3.7075, 1.4118, 9.2221, 5.1974, 55.0462 ],
    "ASYM6": [ 0.80877, 0.85828, 0.85074, 0.86247, 0.85577, 0.95672 ],
    "EXTC7": [ 0.0, 0.0, 0.0, 0.0, 0.0, 0.0 ],
    "ABSC7": [ 0.0, 0.0, 0.0, 0.0, 0.0, 0.0 ],
    "ASYM7": [ 0.0, 0.0, 0.0, 0.0, 0.0, 0.0 ]
}
"CLDSPC": {
    "NCRSPC": 1,
    "CFILE": "DATA/Macke.dat",
    "CLDTYP": "12.0 Micron mean \"spheres\" size (A. Macke, 2001)",
    "CIRTYP": "100.0 Micron mean \"ice-fractals\" size (A. Macke, 2001)"
}

```

### 3.7 Geometry Specification Options

The geometry options JSONObject, [GEOMETRY](#), provides the geometry specification inputs defining the MODTRAN line(s)-of-sight (LOS) and the solar/lunar position. An example of a fairly basic use of this JSONObject, defining a nadir path from 2 km altitude, is provided in Figure 3.1, with defaults defined in Figure 3.2. Images of the LOS options are provided in Sections 2.3.4.1 and 2.3.4.2. One of the key components of [GEOMETRY](#) is to set up the LOS path, and the keywords for this purpose are listed in Table 3.37 along with their type, values and descriptions. Note that in the path radiance mode of program execution, [H1ALT](#) always defines the altitude of the observer (or sensor) and [H2ALT](#) is usually the path final altitude. The one exception occurs for a limb path to space, in which [H2ALT](#) is the path tangent point altitude.

**Table 3.37.** GEOMETRY keywords describing a single LOS with associated types, valid values, and descriptions.

Variable	Type/Values	Description
<a href="#">ITYPE</a>		Geometric type for the atmospheric line-of-sight (LOS) path, as follows:
	1	Horizontal (constant-pressure) path, i.e., flat Earth constant altitude path.
	2	<i>Vertical or slant path between two altitudes.</i>
	3	Vertical or slant path to space or ground.
	4	User-defined Line-Of-Sight (LOS), see Section 3.7.2.
<a href="#">H1ALT</a>	$\geq$ Ground altitude, Float	Sensor/observer altitude [km].
<a href="#">H2ALT</a>	$\geq$ Ground altitude, Float	Tangent height for <a href="#">ITYPE</a> = 3 limb paths; otherwise, path final altitude [km].
<a href="#">OBSZEN</a>	0. $\rightarrow$ 180. Float	Sensor/observer zenith angle, measured at <a href="#">H1ALT</a> [ $^{\circ}$ ].
<a href="#">HRANGE</a>	$\geq$ 0. Float	LOS path length [km].
<a href="#">BETA</a>	0. $\rightarrow$ 180. Float	Earth center angle subtended by LOS [ $^{\circ}$ ].
<a href="#">LENN</a>	0 1	“Short” path, used when there is an ambiguity. “Long” path passing through a tangent height.
<a href="#">BCKZEN</a>	0. $\rightarrow$ 180. Float	Zenith angle at final altitude ( <a href="#">H2ALT</a> ) for reverse path towards <a href="#">H1ALT</a> [ $^{\circ}$ ].
<a href="#">MLOS</a> []	Table 3.39	JSONArray for multiple LOS.

### 3.7.1 Geometry Figures

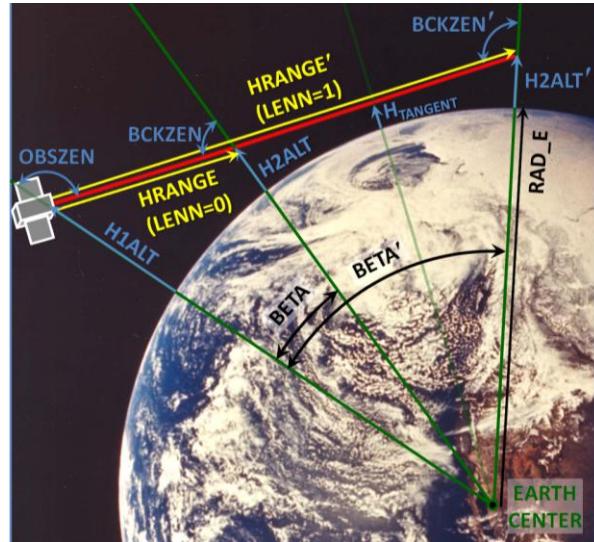
The MODTRAN line-of-sight (LOS) inputs are shown in Figure 3.7 (also in Sections 2.3.4.1 and 2.3.4.2). The full set contains keywords H1ALT, H2ALT, OBSZEN, HRANGE, BETA, LENN, RAD\_E and BCKZEN of Table 3.37. These inputs all lie within a plane defined by 3 points: the center of the Earth, the sensor (observer), and the final altitude. Two LOS's, with a common observer location and view angle, and with the same final altitude H2ALT' = H2ALT are illustrated via yellow lines; primes ('') are appended to the longer path variable names. Generally, 4 geometry inputs (one being RAD\_E, the Earth radius) define a slant path (ITYPE = 2), although only the cases specified in Table 3.38 are allowed. The following hierarchy defines which set of inputs is used if too many geometry inputs are specified:

```

IF (ITYPE = 2: slant path between two altitudes), THEN
    IF (BCKZEN: zenith angle from final altitude back to sensor > 0°), THEN
        IF(HRANGE: slant range > 0 km), THEN
            CASE 2f (H2ALT: final altitude, HRANGE: slant range and
                        BCKZEN: zenith angle from final altitude back to sensor)
        ELSE IF (H2ALT: final altitude > H1ALT: sensor altitude and
                    BCKZEN: zenith angle from final altitude back to sensor > 0°), THEN
            CASE 2e (H1ALT: sensor altitude, H2ALT: final altitude, LENN: short vs long flag
                        and BCKZEN: zenith angle from final altitude back to sensor)
        ELSE
            CASE 2e (H1ALT: sensor altitude], H2ALT: final altitude and
                        BCKZEN: zenith angle from final altitude back to sensor)
        END IF
    ELSE IF (BETA: Earth center angle > 0°), THEN
        CASE 2d (H1ALT: sensor altitude, H2ALT: final altitude and BETA: Earth center angle)
    ELSE IF (HRANGE: slant range > 0 km), THEN
        IF(OBSZEN: zenith angle at sensor > 0°), THEN
            CASE 2b (H1ALT: sensor altitude, OBSZEN: zenith angle at sensor
                        and HRANGE: slant range)
        ELSE
            CASE 2c (H1ALT: sensor altitude, H2ALT: final altitude and HRANGE: slant range)
        END IF
    ELSE IF (H1ALT: sensor altitude > H2ALT: final altitude and
                OBSZEN: zenith angle at sensor > 90°), THEN
        CASE 2a (H1ALT: sensor altitude, H2ALT: final altitude, LENN: short vs long flag
                    and OBSZEN: zenith angle at sensor)
    ELSE
        CASE 2a (H1ALT: sensor altitude, H2ALT: final altitude, and OBSZEN: zenith angle at sensor)
    END IF
ELSE IF (ITYPE = 3: slant path to space or ground), THEN
    IF (BCKZEN: zenith angle from final altitude back to sensor > 0), THEN
        CASE 3c (H2ALT: final altitude and BCKZEN: zenith angle from final altitude back to sensor)
    ELSE IF (H2ALT: final altitude = 0), THEN
        CASE 3a (H1ALT: sensor altitude and OBSZEN: zenith angle at sensor)
    ELSE
        CASE 3b (H1ALT: sensor altitude and H2ALT: tangent altitude)
    END IF
END IF
```

As illustrated in Figure 3.7, an ambiguity arises with Case 2a when the observer zenith angle, OBSZEN, exceeds 90°, the observer altitude, H1ALT, exceeds the final altitude, H2ALT, and the LOS does not intersect the Earth; these inputs are consistent with both a short and long path, with the long path passing

through a tangent height,  $H_{TANGENT}$ . The keyword `LENN` selects which of these two paths to use, 0 for short and 1 for long. Note that the same ambiguity arises for the slant path which is defined by the input set (`BCKZEN`, `H2ALT`, `H1ALT`), Case 2e, when  $BCKZEN > 90^\circ$  and `H2ALT > H1ALT`; this case also requires use of the keyword `LENN`. MODTRAN also includes an option to have the line-of-sight specified as a path to space or ground (`ITYPE = 3`). For these paths, there are only 3 input options: (`H1ALT`, `OBSZEN`), (`H1ALT`, `H2ALT`), and (`H2ALT`, `BCKZEN`). It is important to remember that when the (`H1ALT`, `H2ALT`) option is used, the input `H2ALT` defines tangent height,  $H_{TANGENT}$ , not a final path altitude, and that `H1ALT` must exceed `H2ALT`. Also, note that input `RAD_E` is used if provided; otherwise, a default value is selected based on the chosen model atmosphere, `MODEL`.



**Figure 3.7.** MODTRAN (CARD 3) line-of-sight geometry inputs. When the observer (sensor) zenith angle exceeds  $90^\circ$ , the observer altitude, `H1ALT`, exceeds the final altitude, `H2ALT'` = `H2ALT`, and the path does not intersect the Earth, both a shorter (`LENN` = 0) and a longer (`LENN` = 1) path are possible, distinguished using the keyword `LENN`.

**Table 3.38.** Allowed combinations of slant path parameters.

Case	<code>H1ALT</code>	<code>H2ALT</code>	<code>OBSZEN</code>	<code>HRANGE</code>	<code>BETA</code>	<code>LENN</code>	<code>BCKZEN</code>
2a	✓	✓	✓			if <code>H1ALT &gt; H2ALT</code>	
2b	✓		✓		✓		
2c	✓	✓			✓		
2d	✓	✓			✓		
2e	✓	✓				if <code>H2ALT &gt; H1ALT</code>	✓
2f		✓			✓		✓
3a	✓		✓				
3b	✓	✓					
3c		✓					✓

**Table 3.39.** The MLOS JSONArray defines a LOSGEOMETRY structure for each LOS after the first, with associated types, defaults, descriptions and units.

Keyword	Type	Default	Description	Unit
<a href="#">H1ALT</a> , <a href="#">H2ALT</a> , HRANGE, <a href="#">CKRANG</a>	Float	0.0	See Tables 3.37, 3.38 and 3.40	km
<a href="#">OBSZEN</a> , BCKZEN, BETA	Float	0.0	See Tables 3.37 and 3.38	deg
AZ_INP	Float	0.0	True path azimuth angle, for location based solar/lunar calculations	deg East of North
LENN	Integer	0	See Table 3.37 and 3.38	

**Table 3.40.** Additional GEOMETRY keywords with associated types, valid values, and descriptions.

Variable	Type/Values	Description
RAD_E	Omit or 0.	Radius of the Earth set by <a href="#">MODEL</a> selection: ATM_TROPICAL: 6378.39 km ATM_SUBARC_SUMMER or ATM_SUBARC_WINTER: 6356.91 km Others: 6371.23 km
CKRANG	Float	Slant range for $k$ -distribution output (when CKPRNT is TRUE), interpreted as follows: 0. <i>Output k-dependent data only at full slant range (minimum output).</i> > 0. Output $k$ -dependent data at all path boundary intersections up to the first one exceeding <a href="#">CKRANG</a> and at the total path slant range. < 0. Output $k$ -dependent data at all path boundary intersections (maximum output).
IDAY	Omit or 0 1 to 365 Integer	<i>Chooses IDAY = 93 as the day of year, the average Earth-to-Sun distance.</i> Day of the year, used to correct for variation in the Earth-to-Sun distance and to define solar position when ephemeris data is to be used..

A second set of MODTRAN geometry inputs defines the solar (or lunar) geometry as illustrated in Figure 3.8. The direction of incident radiation is specified from the perspective of either the sensor ([IPARM](#) equal 0, 1, or 2) or the path end point ([IPARM](#) equal 10, 11 or 12). Whichever frame of reference is used, the solar direction is ultimately defined in terms of solar zenith and relative solar azimuth angles. The solar zenith angle is the angle between the vertical at the reference point and the refracted path to the Sun (yellow ray) at that point. The relative azimuth is the angle between two vertical planes at the reference point, one containing the line-of-sight (green ray in left image; red ray in right image) and the second containing the solar illumination path. If the solar zenith and relative azimuth angles are not entered directly via [IPARM](#) equal 2 or 12, the required inputs are the latitude and longitude of the reference point along with [TRUEAZ](#), the true path azimuth (degrees East of North) at the reference point. In addition, the absolute angular location of the Sun from the Earth's perspective must be determined either by directly entering the solar latitude and longitude ([IPARM](#) equal 0 or 10) or from temporal data by specifying the day of year using [IDAY](#) and Coordinated Universal Time using [GMTIME](#). For all cases, the Earth-to-Sun distance is determined from the day of year, [IDAY](#).

**Table 3.41.** GEOMETRY keywords for source geometry with associated types, valid values, and descriptions. Many of the required inputs depend on the value of IPARM, see Table 3.42.

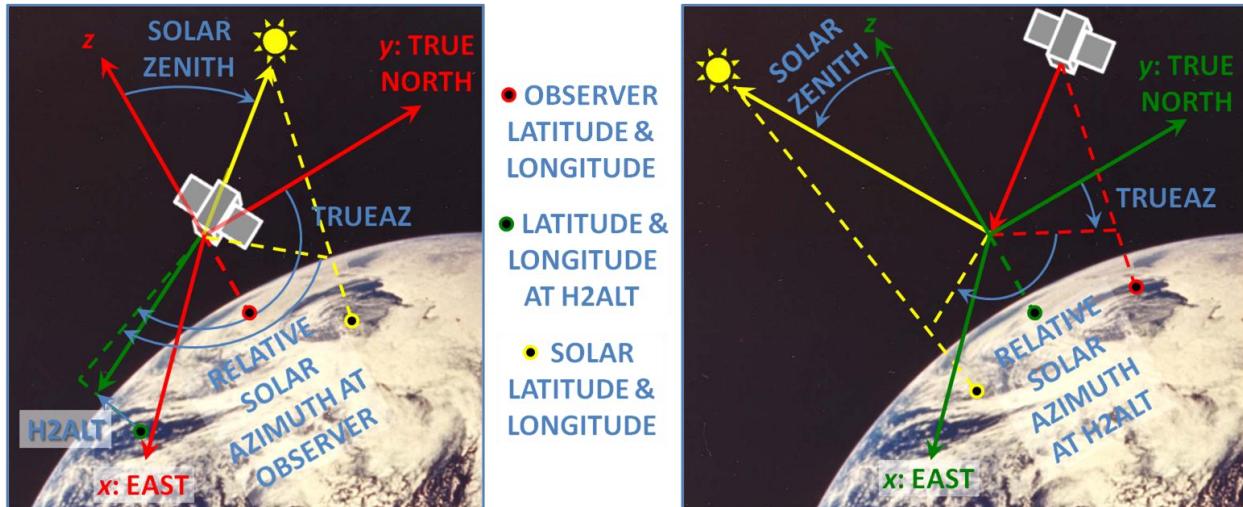
Variable	Type/Values	Description
IPARM	0, 1, 2, 10, 11, 12	Solar/lunar geometry specification parameters for solar/lunar scattering.
PARM1	Float	Depends on IPARM, see Table 3.42.
PARM2	Float	Depends on IPARM, see Table 3.42.
PARM3	Float	Extraterrestrial source (sun or moon) latitude [deg North].
PARM4	Float	Extraterrestrial source (sun or moon) longitude [deg West of Greenwich].
GMTIME	0. to 24., Float	Universal Time in decimal hours, i.e., 8:45 a.m. is 8.75, 5:20 p.m. is 17.33, etc.
TRUEAZ	0. to 360., Float	True path azimuth [degrees East of North].
ANGLEM	0. → 180., Float	Phase angle of the moon [°], required for <a href="#">IEMSCT = RT_LUNAR_...</a> : 0 for full moon and 90 for half moon.

**Notes:** TRUEAZ is the true path azimuth input if there is a single LOS. If there are multiple lines-of-sight (MLOS), then AZ\_INP(1) is the true path azimuth input for the first LOS.

**Table 3.42.** Required inputs for different choices of IPARM.

IPARM	0	1	2	10	11	12
PARM1	Sensor/observer latitude (-90°→90°North of Equator)	Sensor/observer relative solar azimuth (0°→360°)	Final altitude latitude (-90°→90° North of Equator)	Final altitude relative solar azimuth (0→360°)		
PARM2	Sensor/observer longitude (0°→360°West of Greenwich)	Sensor/observer solar zenith angle* (0→180°)	Final altitude longitude (0°→360°West of Greenwich)	Final altitude solar zenith angle* (0°→180°)		
PARM3	✓	---	---	✓	---	---
PARM4	✓	---	---	✓	---	---
GMTIME	---	✓	---	---	✓	---
TRUEAZ	True path azimuth from sensor to final altitude (degrees East of North)	---	---	True path azimuth from final altitude to sensor (degrees East of North)	---	---
ANGLEM	If <a href="#">IEMSCT = RT_LUNAR_...</a>	Not available	If <a href="#">IEMSCT = RT_LUNAR_...</a>	If <a href="#">IEMSCT = RT_LUNAR_...</a>	Not available	If <a href="#">IEMSCT = RT_LUNAR_...</a>

Notes: (1) The IPARM = 10, 11 and 12 are analogous to IPARM = 0, 1 and 2 with the roles of the sensor/observer and path final point reversed. (2) The calculated apparent solar zenith angles are for the refracted path to the Sun.



**Figure 3.8.** Illustration of observer (left) and final altitude (right) based MODTRAN solar geometry inputs.

### 3.7.2 User-defined Path Option

Setting I<sub>TYPE</sub> to 4 allows definition of a user-defined refracted path LOS. When this option is invoked, the only GEOMETRY keywords used are the Earth radius, RAD\_E, and the *k*-distribution output path range parameter, CKRANG. Path parameters are read from a <ROOTNAME>.pth auxiliary ASCII input file. A sample file is provided in Figure 3.9.

!	Cumulative Earth surface distance (m)	Altitude (m)	Zenith Angle (deg)	Segment Lengths (m)
!	0.000000000000000D+00	2.990000000000000D+01	9.011065008827840D+01	0.000000000000000D+00
!	1.865039351814560D+03	2.653824400000000D+01	9.009590149948814D+01	1.865050635869602D+03
!	2.301316972427381D+03	2.582124400000000D+01	9.009242293777251D+01	4.362800018605984D+02
!	3.869259428800919D+03	2.346306600000000D+01	9.007992145403672D+01	1.567950289744289D+03
!	6.071982104641306D+03	2.073129500000000D+01	9.006219209538108D+01	2.202731999117346D+03
!	8.791421497516112D+03	1.830458400000000D+01	9.004006418816192D+01	2.719448786449194D+03
!	1.365194407755667D+04	1.660521603179851D+01	9.000000000000000D+01	4.860536077356031D+03
!	1.851246665759723D+04	1.830458400000000D+01	8.995993581183808D+01	4.860536077356031D+03
!	2.123190605047204D+04	2.073129500000000D+01	8.993780790461892D+01	2.719448786449194D+03
!	2.343462872631243D+04	2.346306600000000D+01	8.992007854596328D+01	2.202731999117346D+03
!	2.500257118268597D+04	2.582124400000000D+01	8.990757706222749D+01	1.567950289744289D+03
NEXT				
!	0.000000000000000D+00	2.990000000000000D+01	9.013870000000000D+01	0.000000000000000D+00
!	1.431453597829651D+03	2.653823500000000D+01	9.013041676609856D+01	1.431463882762580D+03
!	2.824155686581604D+03	2.346304800000000D+01	9.012260876001717D+01	1.392710946005405D+03
!	4.138897385155579D+03	2.073127100000000D+01	9.011548944110680D+01	1.314749094663646D+03
!	5.377427942586154D+03	1.830455300000000D+01	9.010903526183911D+01	1.238536727581931D+03
!	6.541191705959513D+03	1.614882900000000D+01	9.010323056367585D+01	1.163768904599269D+03
!	7.631454936554313D+03	1.423383700000000D+01	9.009804336515123D+01	1.090267511802032D+03
!	8.649403539304471D+03	1.253269400000000D+01	9.009345587120367D+01	1.017952160846840D+03
!	9.596236761685530D+03	1.102151900000000D+01	9.008943560583094D+01	9.468361779642800D+02
!	1.047328474990027D+04	9.679099000000001D+00	9.008595945174619D+01	8.770504406506010D+02
!	1.128209888461397D+04	8.486587000000000D+00	9.008299373890210D+01	8.088161668477835D+02
!	1.202455811387757D+04	7.427245000000000D+00	9.008050555624035D+01	7.424609117347162D+02
!	1.270287177845017D+04	6.486200000000000D+00	9.007847067005035D+01	6.783150574446910D+02
!	1.331963774322460D+04	5.650243000000000D+00	9.007684523682573D+01	6.167671178067677D+02
!	1.387786664546848D+04	4.907637000000000D+00	9.007559463024036D+01	5.582298599407261D+02
!	1.438084639932773D+04	4.247960000000000D+00	9.007469647893517D+01	5.029805470216679D+02
!	1.483211778919159D+04	3.661949000000000D+00	9.007410951787159D+01	4.512720506454899D+02
!	1.523540258106806D+04	3.141378000000000D+00	9.007380833816427D+01	4.032853432866309D+02
!	1.559447608623816D+04	2.678940000000000D+00	9.007377000791443D+01	3.590739675856685D+02
!	1.591309879815236D+04	2.268143000000000D+00	9.007397167000887D+01	3.186231001854769D+02
!	1.619494436432820D+04	1.903220000000000D+00	9.007439711114530D+01	2.818458940579427D+02
!	1.644352554889067D+04	1.579048000000000D+00	9.007504044320049D+01	2.485814641770773D+02
!	1.666214775936566D+04	1.291077000000000D+00	9.007590047371244D+01	2.186224500816290D+02
!	1.685386888268373D+04	1.035264000000000D+00	9.007699871129610D+01	1.917213283557683D+02
!	1.702148995811861D+04	8.080170000000000D-01	9.007835515778822D+01	1.676212537914045D+02
!	1.716752509378976D+04	6.061480000000000D-01	9.008004836730548D+01	1.460352905915871D+02
!	1.729416234343392D+04	4.268210000000000D-01	9.008222110905973D+01	1.266373870235673D+02
!	1.740320128685697D+04	2.675200000000000D-01	9.008519205886779D+01	1.090390664410280D+02
!	1.749572534828186D+04	1.260090000000000D-01	9.009007033362739D+01	9.252417257420100D+01
!	1.751158964578694D+04	1.000000000000000D-01	9.009779940987171D+01	1.586431906022910D+01

**Figure 3.9.** User-defined path parameter file from test case UserPath.json.

Stringent rules apply to the definition of a user-defined refracted path. Four columns of data, separated by spaces or commas (not tabs) are required. These columns contain the cumulative (spherical) Earth surface distance in meters, the above sea-level (ASL) altitude in meters, the path zenith angle in degrees, and the incremental path segment length in meters. All lines beginning with an exclamation and all line entries following an exclamation (in-line comments) are ignored. Leading or trailing blanks are also ignored. The first non-blank character in each data line must be a plus sign, a minus sign, a decimal or a digit, 0 through 9. Any line not beginning with one of these characters or with an exclamation is interpreted as a delimiter between defined paths; in Figure 3.9, the word `NEXT` separates the two lines-of-sight. Every atmospheric profile level between the sensor/observer altitude, `H1ALT`, and the final altitude, `H2ALT`, must be explicitly included in the user-defined path file. In addition, if the line-of-sight passes through a tangent point, the altitude of the tangent point and the altitude of the minimum of `H1ALT` and `H2ALT` must be included in the path definition. In the example shown, the minimum altitude of LOS #1 is at 1.660521603179851D+01 meters, and the final altitude (2.582124400000000D+01 m) is listed as the second entry in the last line of LOS #1. If a non-zero ground altitude or a cloud were to be added to the MODTRAN atmosphere, it would be necessary to run MODTRAN first without a user-defined path to determine the model relayering. Note that it is not necessary that “mirrored” path segments within a single atmospheric layer (on both sides of the tangent point) have identical path lengths or angles; thus, one could use the user-defined path option to model bent paths such as a sensor to ground to Sun path. All these requirements do make the use of the user-defined path rather difficult, but it does provide an option for modeling strong index of refraction gradients such as those observed in the marine boundary layer.

### **3.8 Surface Specification Options**

The `JSONObject` used for describing the surface is `SURFACE`; an example of its usage is provided on Figure 3.1. Examples of using the more advanced features are presented together with the descriptions in this section. The keywords in this `JSONObject` are listed in Table 3.43 along with their type, values and descriptions.

**Table 3.43.** The SURFACE keywords, with associated types, valid values, and descriptions.

Keyword	Type/Values	Description
<a href="#">SURFTYPE</a>	Table 3.44	Method used to describe ground surface.
SURREF	0. to 1., Float	Constant surface reflectance if <a href="#">SURFTYPE</a> equals REFL_CONSTANT.
NSURF	1 2	Imaged-pixel and area-averaged surfaces modeled as the same, a single surface type. Imaged-pixel and area-averaged surfaces modeled as distinct, two surface types
TPTEMP	Omit or $\leq 0$ .	<i>No surface emission unless H2ALT is the ground altitude. If the path intersects the Earth, code uses the temperature of the first atmospheric level (the surface air temperature) as the boundary temperature. If AATEMP (the next entry) is omitted and the path intersects the Earth, the temperature of the first atmospheric level is also used as the lower boundary temperature for the multiple scattering models.</i>
	$> 0$ . Float	Boundary temperature of “image pixel” (i.e., at final altitude), used in radiance mode for slant paths that intersect the Earth OR terminate at a gray boundary such as a cloud or a target. If AATEMP is omitted and the LOS intersects the Earth, <a href="#">TPTEMP</a> is also used as the lower boundary temperature for the multiple scattering models.
AATEMP	Omit or $\geq 0$ .	<i>The area-averaged ground surface temperature, used to define the lower boundary condition in the multiple scattering algorithms, is set to the value of <a href="#">TPTEMP</a>.</i>
	$> 0$ . Float	Area-averaged ground surface temperature (K) used to define the lower boundary condition in the thermal multiple scattering calculations.
WIDERP	Omit or FALSE	<i>The ground from which forward scattered photons are emitted or reflected is modeled with the area-averaged surface.</i>
	TRUE	The ground from which forward scattered photons are emitted or reflected is modeled with the imaged-pixel surface.
GNDALT	Omit or 0.	<i>Surface at sea level, but set to the first profile altitude when user-defined profile (radiosonde) data is used, i.e. if <a href="#">MODEL</a> is ATM_USER_ALT_PROFILE.</i>
	$\leq 6$ ., Float	Altitude of surface relative to sea level (km), which may be negative. The baseline 0 to 6 km aerosol profiles are compressed (or stretched) based on input GNDALT.
DH2O	Omit or 0.	<i>No water layer on surface.</i>
	$> 0$ . Float	Liquid water layer thickness [mm] used to model a shallow “pool” of water on surface ( <i>not functioning properly at this time</i> ).
MLTRFL	Omit or FALSE	<i>Uses embedded surface moisture attenuation model.</i>
	TRUE	Invoke surface water layer model.
SALBFL	Omit	<i>Uses the default spectral albedo file, DATA/spec_alb.dat.</i>
	String	Name of the user-supplied spectral albedo data file, which must conform to the format described in the default file (currently, not a MODTRAN6 GUI option).
SURFP	Table 3.45	Imaged-pixel Lambertian or BRDF surface.
SURFA	Table 3.45	Area-averaged Lambertian or BRDF surface.
SURFNLOS	0 $> 0$	Multiple Line-of-Sight ( <a href="#">MLOS</a> ) option not being used. Surfaces for multiple lines-of-sight will be defined using SURFLOS structure.
SURFLOS []	Table 3.45	JSONArray with Lambertian or BRDF surfaces for multiple LOS geometry.

**Table 3.44.** Ground surface - names, values and descriptions for SURFTYPE .

ICLD Name	#	Description
REFL_CONSTANT	0	<i>Spectrally constant Lambertian reflectance.</i>
REFL_LAMBER_MODEL	1	Lambertian spectral reflectance from external file or UDSALB.
REFL_BRDF	3	Spectral Bi-directional Reflectance Distribution Function (BRDF).

**Table 3.45** SURFPARAM keywords used for the SURFP, SURFA, and SURFLOS,with associated types, default values, and descriptions.

Keyword	Type/Values	Description
CSALB	Table 3.46, Figure 3.10	Name (ENUM) or number of a Lambertian model to read from the SALBFL file.
SALBSTR	String	Name of a Lambertian model to read from the SALBFL file.
SURFZN	Omit or 0.	The zenith angle of the surface normal, currently the only allowed value is 0.
SURFAZ	Omit or Float	The true azimuth angle of the image pixel surface normal in ° [0 for N, 90 for E, 180 for S, and 270 for W], currently not used.
CBRDF	Table 3.47	BRDF models.
NWVSRF	> 0	Number of surface spectral grid points.
WVSURF	Float[ ]	Monotonically increasing spectral wavelength grid in $\mu\text{m}$ for BRDF.
PBRDF1-7	Float[ ]	PBRDF1, PBRDF2, PBRDF3, PBRDF4, PBRDF5, PBRDF6 and PBRDF7 are BRDF parameters at WVSURF wavelengths. Each requires input of the number of spectrally-dependent parameters listed in the third column of Table 3.47.
UDSALB	Float[ ]	If CSALB=LAMB_USER_DEFINED, reflectivity of spectral Lambertian surface. Use in conjunction with NWVSRF and WVSURF to define the wavelength response..

#### Example of SURFP for Lambertian surface from test case BRDF.json:

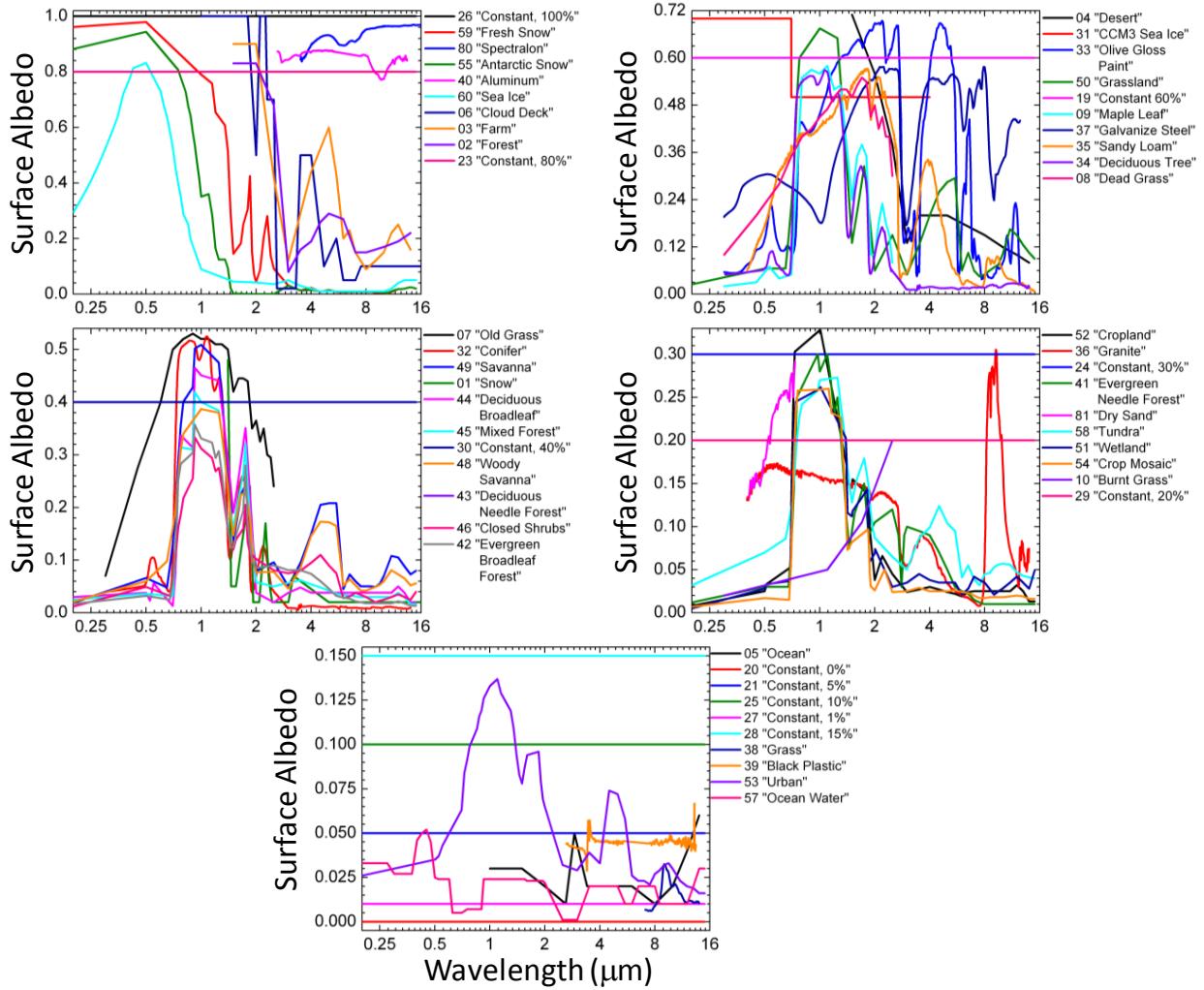
```
"SURFP": {
  "CSALB": "LAMB_DESERT"
}
```

#### Example of SURFP for BRDF surface:

```
"SURFP": {
  "CBRDF": "BRDF_WALTHALL",           # BRDF Model
  "NWVSRF": 2,                         # Number of spectral grid points
  "WVSURF": [4.0, 10.0],               # Array of wavelengths in um
  "PBRDF1": [0.2302, 0.2503],          # 1st BRDF parameter
  "PBRDF2": [0.0652, 0.0725],          # 2nd BRDF parameter
  "PBRDF3": [0.0878, 0.0564],          # 3rd BRDF parameter
  "PBRDF4": [-0.0315, -0.0289]         # 4th BRDF parameter
}
```

#### Example for 3 LOS with Lambertian surface:

```
"Surface": {
  "SURFA": {
    "CSALB": "LAMB_DECAYED_GRASS"
  },
  "SURFNLOS": 3,
  "SURFLOS": [
    {
      "CSALB": "LAMB_BURNED_GRASS"
    },
    {
      "CSALB": "LAMB_CONST_50_PCT"
    },
    {
      "CSALB": "LAMB_CROPLAND"
    }
  ]
}
```



**Figure 3.10.** Curves of surface spectral reflectance data from the MODTRAN file 'DATA/spec\_alb.dat'. The maximum value of the surface albedo scale differs on each graph. Within each graph, spectral curves have varying spectral coverage.

**Table 3.46.** Lambertian spectral albedo models in the `spec_alb.dat` file.

CSALB Name	#	Description
LAMB_MODEL_USER_DEF	0	User defined spectral albedo (see UDSALB)
LAMB_SNOW_COVER	1	Snow cover
LAMB_FOREST	2	Forest
LAMB_FARM	3	Farm
LAMB_DESERT	4	Desert
LAMB_OCEAN	5	Ocean
LAMB_CLOUD_DECK	6	Cloud deck
LAMB_OLD_GRASS	7	Old grass
LAMB_DECAYED_GRASS	8	Decayed grass
LAMB_MAPLE_LEAF	9	Maple leaf
LAMB_BURNT_GRASS	10	Burnt grass
LAMB_CONST_0_PCT	20	Constant, 0%
LAMB_CONST_5_PCT	21	Constant, 5%
LAMB_CONST_50_PCT	22	Constant, 50%
LAMB_CONST_80_PCT	23	Constant, 80%
LAMB_CONST_30_PCT	24	Constant, 30%
LAMB_CONST_10_PCT	25	Constant, 10%
LAMB_CONST_100_PCT	26	Constant, 100%
LAMB_SEA_ICE_CCM3	31	CCM3 sea ice
LAMB_CONIFER	32	Conifer
LAMB OLIVE_GLOSS_PAINT	33	Olive gloss paint
LAMB_DECIDUOUS_TREE	34	Deciduous tree
LAMB_SANDY_LOAM	35	Sandy loam
LAMB_GRANITE	36	Granite
LAMB_GALVANIZED_STEEL	37	Galvanized steel
LAMB_GRASS	38	Grass
LAMB_BLACK_PLASTIC	39	Black plastic
LAMB_ALUMINUM or LAMB_ALUMINIUM	40	Aluminum
LAMB_EVERGREEN_NEEDLE_FOREST	41	Evergreen needle forest
LAMB_EVERGREEN_BROADLEAF_FOREST	42	Evergreen broadleaf forest
LAMB_DECIDUOUS_NEEDLE_FOREST	43	Deciduous needle forest
LAMB_DECIDUOUS_BROADLEAF_FOREST	44	Deciduous broadleaf forest
LAMB_FOREST_MIXED	45	Mixed forest
LAMB_SHRUBS_CLOSED	46	Closed shrubs
LAMB_SHRUBS_OPEN	47	Open shrubs
LAMB_SAVANNA_WOODY	48	Woody savanna
LAMB_SAVANNA	49	Savanna
LAMB_GRASSLAND	50	Grassland
LAMB_WETLAND	51	Wetland
LAMB_CROPLAND	52	Cropland
LAMB_URBAN	53	Urban
LAMB_CROP_MOSAIC	54	Crop mosaic
LAMB_SNOW_ANTARCTIC	55	Antarctic snow
LAMB_DESERT_BARREN	56	Barren desert
LAMB_OCEAN_WATER	57	Ocean water
LAMB_TUNDRA	58	Tundra
LAMB_SNOW_FRESH	59	Fresh snow
LAMB_SEA_ICE	60	Sea ice
LAMB_SPECTRALON	80	Spectralon
LAMB_SAND_DRY	81	Dry sand

### 3.8.1 BRDF Models

When the CBRDF keyword is present in a SURFP or SURFA JSONObject or a member of the SURFLOS JSONArray, it indicates that a BRDF model is to be used. Its value must be one of the 10 BRDF model options listed in Table 3.47. The symmetric Walthall [59] and symmetric Sinusoidal-Walthall are empirical models; the Hapke [30, 31], Rahman [45], Roujean [52], and Ross-Li [61, 62, 39] are all semi-empirical models; and the Pinty-Verstraete [44] and Ross-Sea [46, 47] are physical models. Generally, the BRDFs are numerically integrated to define surface albedo, directional (hemispherical) reflectivities and emissivities, and azimuth moments (required for interfacing to DISORT multiple scattering); 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 define the BRDF parameters required by MODTRAN; the user is encouraged to consult the original references for further details.

**Table 3.47.** BRDF models.

CBRDF Value	#	Description	# of parameters
BRDF_WALTHALL	2	Walthall	4
BRDF_WALTHALL_ANALYTIC	51	Analytically evaluated Walthall	4
BRDF_WALTHALL_SINE	11	Sine-Walthall	4
BRDF_WALTHALL_SINE_ANALYTIC	52	Analytically evaluated Sine-Walthall	4
BRDF_HAPKE	4	Hapke	4
BRDF_RAHMAN	5	Rahman	3
BRDF_ROUJEAN	6	Roujean	3
BRDF_PINTY_VERSTRAETE	10	Pinty-Verstraete	4
BRDF_ROSS_LI	12	Ross-Li	3 plus $P_4 = 1$ and $P_5 = 2$
BRDF_ROSS_SEA	13	Ross-Sea	7

The following formulae define the parameterized BRDF,  $\rho(\theta_v, \theta_s, \Delta\phi)$ , where

$\theta_v$  is the view zenith angle from the surface to the sensor;

$\theta_s$  is the source zenith at the surface; and

$\Delta\phi$  is the view-to-source relative azimuth angle from the surface.

Walthall:

$$\rho(\theta_v, \theta_s, \Delta\phi) = P_1 + P_2 \theta_v \theta_s \cos \Delta\phi + P_3 \theta_v^2 \theta_s^2 + P_4 (\theta_v^2 + \theta_s^2) .$$

Sine-Walthall:

$$\rho(\theta_v, \theta_s, \Delta\phi) = P'_1 + P'_2 \sin \theta_v \sin \theta_s \cos \Delta\phi + P'_3 \sin^2 \theta_v \sin^2 \theta_s + P'_4 (\sin^2 \theta_v + \sin^2 \theta_s) .$$

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 leads to the following relationships:

$$P'_1 = P_1 ; \quad P'_2 = 9 \pi^2 P_2 / 64 ; \quad P'_3 = (\pi^2/4 - 1)^2 P_3 ; \quad \text{and} \quad P'_4 = (\pi^2/4 - 1)^2 P_4 .$$

Hapke:

$$4 (\cos \theta_v + \cos \theta_s) \rho(\theta_v, \theta_s, \Delta\phi) = \left( P_1 + \frac{P_4}{B(\cos \phi, P_2, P_3)} \right) P_{HG}(\cos \phi, P_2) + H(\cos \theta_v, P_1) H(\cos \theta_s, P_1) P_1 - P_1 ,$$

where

$$\cos \phi = \cos \theta_v \cos \theta_s + \sin \theta_v \sin \theta_s \cos \Delta\varphi ; \quad P_{HG}(\cos \phi, g) = \left(1 - g^2\right) / \left(1 + g^2 + 2g \cos \phi\right)^{3/2}$$

$$B(\cos \phi, g, h) = \frac{1-g}{(1+g)^2} \left(1 + \frac{1}{h} \sqrt{(1+\cos \phi)/(1-\cos \phi)}\right) \quad \text{and} \quad H(x, \omega) = \frac{1+2x}{1+2x\sqrt{1-\omega}} .$$

Parameter  $P_1$  is the average single scattering albedo,  $\omega$ , of the particles making up the surface; parameter  $P_2$  is the Henyey-Greenstein asymmetry factor,  $g$ , ranging from  $-1$  (backward scattering) to  $+1$  (forward scattering); parameter  $P_3$  controls the width of the opposition effect (hot spot),  $h$ ; and parameter  $P_4$  controls the magnitude of the opposition effect,  $S_H$  [note that the atmospheric radiative transfer convention for the Henyey-Greenstein variables has been adopted in these equations. The BRDF community generally represents the asymmetry factor with the symbol  $\Theta$  (instead of  $g$ ) and represents the scattering angle with the symbol  $g$  (instead of  $\phi$ ) – a confusing state of affairs to say the least.]

Rahman:  $\rho(\theta_v, \theta_s, \Delta\varphi) = P_1 [\cos \theta_v \cos \theta_s (\cos \theta_v + \cos \theta_s)]^{P_3-1} P_{HG}(\cos \phi, P_2) \left(1 + \frac{1-P_1}{1+G(\theta_v, \theta_s, \Delta\varphi)}\right) ,$

where

$$G(\theta_v, \theta_s, \Delta\varphi) = \sqrt{\tan^2 \theta_v + \tan^2 \theta_s - 2 \tan \theta_v \tan \theta_s \cos \Delta\varphi} .$$

Parameter  $P_1$  characterizes the reflectance of the surface cover,  $\rho_0 \geq 0$ ; parameter  $P_2$  is the Henyey-Greenstein asymmetry factor,  $g$ , ranging from  $-1$  (backward scattering) to  $+1$  (forward scattering); and parameter  $P_3$  indicates the level of anisotropy of the surface,  $k$ .

Roujeau:  $\rho(\theta_v, \theta_s, \Delta\varphi) = P_1 + P_2 K_{geo}(\theta_v, \theta_s, \Delta\varphi) + 4P_3 K_{RT}(\theta_v, \theta_s, \Delta\varphi)/3\pi ,$

where

$$K_{geo} = \frac{(\pi - \Delta\varphi) \cos \Delta\varphi + \sin \Delta\varphi}{2\pi} \tan \theta_v \tan \theta_s - \frac{\tan \theta_v + \tan \theta_s + G(\theta_v, \theta_s, \Delta\varphi)}{\pi} \quad \text{and} \quad K_{RT} = \frac{(\pi/2 - \phi) \cos \phi + \sin \phi}{\cos \theta_v + \cos \theta_s} - \frac{\pi}{4} .$$

Parameter  $P_1$  is the Lambertian scattering component,  $k_{Lamb}$ , equal to the bidirectional reflectance for  $\theta_v$  and  $\theta_s$  both equal to zero; parameter  $P_2$  is the coefficient,  $k_{geo}$ , of the geometric scattering kernel  $K_{geo}$ ; and parameter  $P_3$  is the coefficient,  $k_{vol}$ , for the RossThick volume scattering kernel  $K_{RT}$ , so called for its assumption of a dense leaf canopy.

Pinty-Verstraete:  $\rho(\theta_v, \theta_s, \Delta\varphi) = \frac{\left\{ T(\theta_v, \theta_x, \Delta\varphi, P_3, P_4) P_{HG}(\cos \phi, P_2) + H\left(\frac{\cos \theta_v}{\kappa_v(P_3)}, P_1\right) H\left(\frac{\cos \theta_s}{\kappa_s(P_3)}, P_1\right) - 1 \right\} P_1}{4 \left[ \cos \theta_v + \kappa_v(P_3) \left( \frac{\cos \theta_s}{\kappa_s(P_3)} \right) \right]} ,$

where

$$T(\theta_v, \theta_s, \Delta\varphi, \chi_l, r\Lambda) = 1 + \frac{r\Lambda \kappa_v(\chi_l)}{r\Lambda \kappa_v(\chi_l) + (4 - 16/3\pi) \cos \theta_v G(\theta_v, \theta_s, \Delta\varphi)} \quad \text{and}$$

$$\kappa_x(\chi_l) = 1 + (1.754 \cos \theta_x - 1)(1.2666 + 0.66 \chi_l) \chi_l \quad ; \quad x = v \text{ or } s$$

Parameter  $P_1 = \omega$  is the average single scattering albedo of the surface particles; parameter  $P_2 = g$  is the Henyey-Greenstein asymmetry factor ranging from  $-1$  (backward scattering) to  $+1$  (forward scattering); parameter  $P_3 = \chi_l$  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  $P_4 = r\Lambda$  is the product of  $r$ , the radius of the Sun flecks on the inclined scatterers, and  $\Lambda$ , 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,  $\kappa_v$  and  $\kappa_s$ , are defined here as twice their normal value to be consistent with the definition of multiple scattering functions,  $H(x, \omega)$ .

Ross-Li

$$\rho(\theta_v, \theta_s, \Delta\phi) = P_1 + P_2 K_{LSR}(\theta_v, \theta_s, \Delta\phi, P_4, P_5) + P_3 K_{RT}(\theta_v, \theta_s, \Delta\phi) ,$$

where  $2K_{LSR} = 1 + \sec \theta'_v \sec \theta'_s + \tan \theta'_v \tan \theta'_s \cos \Delta\phi + 2(\sec \theta'_v + \sec \theta'_s)(t - \sin t \cos t - \pi)/\pi$  ,  $\tan \theta'_x = P_5 \tan \theta_x$

$$and \quad \cos^2 t = \min \left\{ \left( \frac{P_4}{\sec \theta'_v + \sec \theta'_s} \right)^2 [G(\theta'_v, \theta'_s, \Delta\phi)^2 + (\tan \theta'_v \tan \theta'_s \sin \Delta\phi)^2], 1 \right\} ; \quad x = v \text{ or } s$$

Parameter  $P_1 = k_{\text{Lamb}}$  is the Lambertian scattering component and equal to the bidirectional reflectance for  $\theta_v = 0$  and  $\theta_s = 0$ . Parameter  $P_2 = k_{\text{geo}}$  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  $P_3 = k_{\text{vol}}$  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) [33].

Ross-Sea: The Ross Sea model [46, 47] requires 7 parameters at each spectral grid point:

1. Real part of the complex refractive index
2. Imaginary part of the complex refractive index,
3. Upwind slope root-mean-square ( $\sigma_u$ ), negative value for horizon correction,
4. Crosswind slope root-mean square ( $\sigma_c$ ), negative value for horizon correction,
5. Azimuth angle between surface-receiver vector and wind vector [radians],
6. Whitecap coverage fraction, and
7. Whitecap hemispherical albedo.

See references for further details.

### **3.9 Spectral Specification Options**

The spectral options JSONObject, [SPECTRAL](#), provides the spectral specification options which drive the MODTRAN code. The keywords available for the spectral input with their associated types, default values and brief descriptions are listed in the Table 3.48 below. Further details for some of the keywords are provided in the tables that follow.

**Table 3.48.** SPECTRAL keywords with associated type, default value, and descriptions.

Keyword	Type	Default	Description
V1	Float	800.	Spectral bandpass lower bound ( $\text{cm}^{-1}$ , $\mu\text{m}$ or $\text{nm}$ )
V2	Float	1250.	Spectral bandpass upper bound ( $\text{cm}^{-1}$ , $\mu\text{m}$ or $\text{nm}$ )
DV	Float	1.	Frequency ( $\text{cm}^{-1}$ ) or wavelength ( $\mu\text{m}$ or $\text{nm}$ ) increment used for spectral outputs. DV applies to all spectral output files when using the default slit function (i.e. when <a href="#">FLAGS</a> [0:3] is blank). Otherwise, DV is only applied to the <ROOTNAME>.7sc, <ROOTNAME>.psc, <ROOTNAME>.flx, <ROOTNAME>.scan.csv, <ROOTNAME>.scan.txt and <ROOTNAME>.scan.sli output files. The frequency increment of other files (such as <ROOTNAME>.tp6, <ROOTNAME>.tp7, <ROOTNAME>.tp8, <ROOTNAME>.plt, <ROOTNAME>.acd, <ROOTNAME>.csv, <ROOTNAME>.txt, <ROOTNAME>.flx, <ROOTNAME>.flux.csv, and <ROOTNAME>.flux.sli) is set to the band model spectral resolution, 0.1, 1.0, 5.0 or 15.0 $\text{cm}^{-1}$ . The API spectral output is a replica of the *.csv output. To avoid under-sampling of output spectra, DV should not exceed <a href="#">FWHM</a> . The recommended value for DV is <a href="#">FWHM</a> /2, i.e., Nyquist sampling.
FWHM	Float	2.	Slit function Full Width at Half Maximum (FWHM) frequency ( $\text{cm}^{-1}$ ) or wavelength ( $\mu\text{m}$ or $\text{nm}$ ). For band model calculations, FWHM must not exceed 50 times the calculation bin size (0.1, 1, 5 or 15 $\text{cm}^{-1}$ ). The type of slit function is defined by <a href="#">FLAGS</a> [1]. A minimum of twice the bin size will insure proper sampling (Nyquist sampling). No convolution is performed if FWHM equals the band model bin size and the default triangular slit function ( <a href="#">FLAGS</a> [1] set to blank), is selected.
YFLAG	1-element String	"T"	Transmittances ("T") or radiances ("R") in output files <ROOTNAME>.plt and <ROOTNAME>.psc
XFLAG	1-element String	"W"	Abscissa spectral unit in plot output file <ROOTNAME>.psc if its generated ("W" = wavenumber, "M" = microns or "N" = nanometers); otherwise, it is the abscissa spectral unit in plot output file <ROOTNAME>.plt. For "W", the radiance unit is $\text{W cm}^{-2} \text{sr}^{-1} / \text{cm}^{-1}$ and the irradiance unit is $\text{W cm}^{-2} / \text{cm}^{-1}$ ; for "M", the radiance unit is $\text{W cm}^{-2} \text{sr}^{-1} / \mu\text{m}$ and the irradiance unit is $\text{W/cm}^2/\mu\text{m}$ ; for "N", the radiance unit is $\mu\text{W cm}^{-2} \text{sr}^{-1} / \text{nm}$ and the irradiance unit is $\mu\text{W cm}^{-2} \text{sr}^{-1} / \text{nm}$
DLIMIT	String	" "	Delimiter used to separate <ROOTNAME>.plt and <ROOTNAME>.psc output from repeat (sequential) runs.
<a href="#">FLAGS</a> [0:6]	7-element String	" "	Table 3.49
MLFLX	Integer	0	If <a href="#">FLAGS</a> [6] is not blank, write spectral flux data to <ROOTNAME>.flx at every altitude level (If MLFLX exceeds 0, values are only written for the first MLFLX altitude levels and for the top-of-atmosphere)
VRFRAC	Float	0.	Reference spectral frequency for refraction calculation ( $\text{cm}^{-1}$ ) if VRFRAC exceeds zero; the bandpass central frequency is used if it equals zero.
SFWHM	Float	0.	If positive, the TOA solar irradiance is degraded to this full-width at half-maximum (FWHM) using a triangular slit function (Table 3.50).
LSUNFL	1-element String	" "	USRSPN defines the TOA solar irradiance data file if LSUNFL is "T" or "t" (Table 3.50).
LBMNAM	1-element String	" "	If blank, "f" or "F", the $1.0 \text{ cm}^{-1}$ band model data file is used unless the line-by-line option has been selected; in that case, a $0.1 \text{ cm}^{-1}$ band model line tail data is used. If LBMNAM equals "t", "T" or "4", BMNAME defines the band model data file root name.

**Table 3.48.** (Cont'd) [SPECTRAL](#) keywords with associated type, default value, and descriptions.

Keyword	Type	Default	Description
USRSPN	String	" "	Name of solar irradiance file input if LSUNFL is "T" or "t".
BMNAME	String	" "	Band model file root name input if LBMNAM is "T", "t", "4" or "2". The five available root names for files in the DATA/ directory are "01_2013", "05_2013", "15_2013", "p1_2013" and "LBL2013". The first four of these are the 1.0 (default), 5.0, 15.0 and 0.1 $\text{cm}^{-1}$ band models, respectively. "LBL2013t.asc" and "LBL2013t.bin" contain 0.1 $\text{cm}^{-1}$ line tail ASCII and binary data, respectively, for the MODTRAN line-by-line algorithm.
FILTNM	String	" "	User-supplied filter function name. Sample spectral response function data are provided in the DATA/ directory for the AIRS, ASTER, AVIRIS, GOES, HyspIPI, LANDSAT-5, LANDSAT-7, LANDSAT-8, MODIS, CERES-PFM, ITRES®-TASI and the Yankee MSR-7 spectrometers.
CH2OCM	1-element String	" " or 1	Mlawer, Tobin, Clough, Kneizys, Davies (MT-CKD) 2.5 water continuum [set to 0 for Clough, Kneizys, Davies (CKD) 2.4 water continuum]

[V1](#), [V2](#), [DV](#), [FWHM](#): The user always needs to set up the spectral bandpass values. These four inputs share the same type (frequency or wavelength) and units. Frequency in wavenumbers ( $\text{cm}^{-1}$ ) is the default. Wavelengths, if chosen, can have units of either microns ( $\mu\text{m}$ ) or nanometers (nm). The choice is determined from input [FLAGS](#)[0]. The full descriptions of the 4 keywords are provided in Table 3.49.

[FLAGS](#) and [MLFLX](#): The input spectral bandpass unit is defined by the first character of the 7-element [FLAGS](#) string. The rest of this string, together with the [MLFLX](#) parameters control output. If the first two characters of [FLAGS](#) are both blank, the default slit function is used and the next 2 characters are ignored. Otherwise, an alternative slit function is used and the results written to <ROOTNAME>.psc and <ROOTNAME>.7sc. The full descriptions of these variables are provided in Table 3.49.

[FILTNM](#): When a user-supplied filter response function file name is entered, it must have the following format:

UNITS\_HEADER

HEADER(1)

$w_{11}$	$r_{11}$
$w_{12}$	$r_{12}$
$w_{13}$	$r_{13}$
...	

HEADER(2)

$w_{21}$	$r_{21}$
$w_{22}$	$r_{22}$
$w_{23}$	$r_{23}$
...	

etc.

UNITS\_HEADER is a string whose first character must be '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, which denotes the start of the list of (*wavelength, response*) pairs for the *i*<sup>th</sup> spectral channel; and ( $w_{ij}$ ,  $r_{ij}$ ) are the *j*<sup>th</sup> wavelength and response values for the *i*<sup>th</sup> channel.

**YFLAG, XFLAG, DLIMIT:** These inputs control the outputs in the <ROOTNAME>.plt and <ROOTNAME>.psc files. The full descriptions of these variables are provided in Table 3.51 below with the default values listed first for YFLAG and XFLAG.

**Table 3.49.** FLAGS keyword in [SPECTRAL](#), with values and descriptions.

Keyword	Value	Description
<a href="#">FLAGS</a> [0]		Defines the spectral units for input parameters <a href="#">V1</a> , <a href="#">V2</a> , <a href="#">DV</a> and <a href="#">FWHM</a> and for output files <ROOTNAME>.7sc, <ROOTNAME>.psc, <ROOTNAME>_scan.csv, <ROOTNAME>_scan.txt, <ROOTNAME>.flx and <ROOTNAME>_scan.sli.
	W or blank	<i>Spectral frequency bandpass in wavenumbers. Radiances are in W cm<sup>-2</sup> sr<sup>-1</sup> / cm<sup>-1</sup>.</i>
	M	Spectral wavelength bandpass in microns. Radiances are in W cm <sup>-2</sup> sr <sup>-1</sup> / $\mu\text{m}$ .
	N	Spectral wavelength bandpass in nanometers. Radiances are in $\mu\text{W}$ cm <sup>-2</sup> sr <sup>-1</sup> / nm.
<a href="#">FLAGS</a> [1]		<i>Selects the slit function as described by the following functional forms:</i>
	1, T or blank	Triangular: $(1 -  \delta - \delta_0 /\Delta)/\Delta$ for $ \delta - \delta_0  < \Delta$ and 0 elsewhere
	2 or R	Rectangular: $1/\Delta$ for $ \delta - \delta_0  < \Delta/2$ and 0 elsewhere
	3 or G	Gaussian: $s \exp \left[ -s^2 (\delta - \delta_0)^2 \right] / \sqrt{\pi}$ where $s = 2\sqrt{\ln 2}/\Delta$
	4 or S	Sinc [ $\text{sinc}(x) = \sin(\pi x)/(\pi x)$ ]: $s \text{sinc}[s(\delta - \delta_0)]$ where $s = 1.2067/\Delta$
	5 or C	Sinc2: $s \text{sinc}^2[s(\delta - \delta_0)]$ where $s = 0.88589/\Delta$
	6 or H	Hamming: $0.230822s \left\{ \begin{array}{l} 2.33235 \text{sinc}[s(\delta - \delta_0)] \\ + \text{sinc}[s(\delta - \delta_0) - 1] + \text{sinc}[s(\delta - \delta_0) + 1] \end{array} \right\}$ where $s = \frac{1.8218}{\Delta}$
	7 or U	User-supplied slit function ( <i>this option is currently unavailable</i> ).
<a href="#">FLAGS</a> [2]	A or blank	<a href="#">FWHM</a> is absolute.
	R	<a href="#">FWHM</a> is relative, in which case $\text{FWHM} = 100 \text{ d}V/V = 100 \text{ d}\lambda/\lambda$ .
<a href="#">FLAGS</a> [3]	blank	Degrad only total radiance and transmittance.
	A	Degrad all output file components.
<a href="#">FLAGS</a> [4]	blank	Should always be blank; the original option is obsolete.
<a href="#">FLAGS</a> [5]	blank	Should always be blank; the original option is obsolete.
<a href="#">FLAGS</a> [6]	blank	Do not output the spectral flux table.
	t or T	Write a <ROOTNAME>.flx file using 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 unless input MLFLX (see below) is used to limit the number of atmospheric levels (altitudes). The output data is spectrally-gridded based on the input value of <a href="#">DV</a> .
	f or F	Write a <ROOTNAME>.flx file with all altitude dependent flux values for each spectral point on a single line (i.e., there are no line feeds). These files can be quite large unless input MLFLX (see below) is used to limit the number of atmospheric levels (altitudes). Some FORTRAN compilers limit the number of characters per line; this input can cause this limit to be exceeded.
MLFLX		Controls the number of spectral <a href="#">fluxes</a> output (applies when <a href="#">FLAGS</a> [6] is not blank):
	0	<i>Spectral fluxes output at all atmospheric levels.</i>
	> 0	Number of atmospheric levels, starting from the ground, for which spectral <a href="#">fluxes</a> are output. The TOA value is also output.

The keywords [SFWHM](#) and [LSUNFL](#), fully described in Table 3.50, are inputs that can be used to define top-of-atmosphere solar irradiances.

If the user-defined file, [USRSPN](#), is used, it must be in a particular form, *which differs from that used in the solar irradiance data files delivered with MODTRAN*. The first line must contain a pair of integers. The first integer designates the spectral unit: 1 for frequency in wavenumbers (cm<sup>-1</sup>); 2 for wavelength in nanometers (nm); and 3 for wavelength in microns ( $\mu\text{m}$ ). The second integer denotes the irradiance unit: 1

for  $\text{W cm}^{-2}/\text{cm}^{-1}$ ; 2 for photons  $\text{sec}^{-1} \text{cm}^{-2}/\text{nm}$ ; and 3 for  $\text{W m}^{-2}/\mu\text{m}$ , which is equivalent to  $\text{mW m}^{-2}/\text{nm}$ . The subsequent lines contain one pair of frequency/wavelength and irradiance values 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 irradiances from SUN01med2irradwnNormt.dat (SUNp1med2irradwnNormt.asc for the  $0.1 \text{ cm}^{-1}$  band model) so that the data encompasses the full range of 0 to 50,000 wavenumbers.

**Table 3.50.** Full descriptions of SFWHM and LSUNFL keywords.

Keyword	Value	Description	
SFWHM	0.0	<i>0.1 cm<sup>-1</sup> resolution band model uses the SUNp1med2irradwnNormt.asc data. Other resolution band models use SUN01med2irradwnNormt.dat degraded to 5 cm<sup>-1</sup> spectral resolution.</i>	
	> 0.0	The FWHM (Full Width at Half Maximum) in wavenumbers of the triangular scanning function used to smooth TOA solar irradiance data.	
	< 0.	Spectral resolution set to $ SFWHM $ with spectrally convolved data output to a local data file. The data file is given the name “s0_xxxx.dat” where xxxx is $\text{int}(SFWHM)$ unless a $0.1 \text{ cm}^{-1}$ band model calculation is performed, in which case, xxxx is $\text{int}(10 \times  SFWHM )$ . If repeat runs are performed with SFWHM unchanged, only the last output file is saved.	
LSUNFL	"f" "F" " "	<i>Top-of-atmosphere (TOA) solar irradiance file dependent on the band model resolution:</i>	
		SUN15med2irradwnNormt.dat for $15 \text{ cm}^{-1}$	
		SUN05med2irradwnNormt.dat for $5 \text{ cm}^{-1}$	
		SUN01med2irradwnNormt.dat for $1 \text{ cm}^{-1}$	
		SUNp1med2irradwnNormt.bin for $0.1 \text{ cm}^{-1}$	
	"t" "T"	User specifies top-of-atmosphere (TOA) solar irradiance file name in USRSUN.	
"1"–"D"	<b>1, 5, 15 cm<sup>-1</sup> band models</b>	<b>0.1 cm<sup>-1</sup> band model</b>	<b>References</b>
1	SUN01kurucz2005.dat	SUNp1kurucz2005.bin	[38]
2	SUN01chkur.dat	SUNp1kurucz1997.dat	[18, 37]
3	SUN01cebchkur.dat	SUNp1kurucz1997.dat	[17, 18, 37]
4	SUN01thkur.dat	SUNp1rawkur.dat	[57, 58, 37]
5	SUN01fontenla.asc	SUNp1fontenla.bin	[26]
6	SUN01kurucz1997.dat	SUNp1kurucz1995.bin	[37]
7	SUN01kurucz1995.dat	SUNp1kurucz1995.bin	[36]
8	SUN01lowirradwnNormt.dat	SUNp1lowirradwnNormt.bin	[26]
9	SUN01med1irradwnNormt.dat	SUNp1med1irradwnNormt.bin	[26]
A	SUN01med2irradwnNormt.dat	SUNp1med2irradwnNormt.bin	[26]
B	SUN01high1irradwnNormt.dat	SUNp1high1irradwnNormt.bin	[26]
C	SUN01high2irradwnNormt.dat	SUNp1high2irradwnNormt.bin	[26]
D	SUN01peakirradwnNormt.dat	SUNp1peakirradwnNormt.bin	[26]

### 3.10 File Specification Options

The [FILEOPTIONS](#) JSONObject provides the file specification options which drive the MODTRAN code. The keywords available for the [FILEOPTIONS](#) input with their associated types, values, and full descriptions are listed in Table 3.50.

**Table 3.50.** [FILEOPTIONS](#) keywords with associated types, values, and descriptions.

Keyword	Value	Description
NOFILE	0	or <a href="#">FC_ALLOWALL</a> generates all legacy output files ( <a href="#"><code>&lt;ROOTNAME&gt;.tp6</code></a> , <a href="#"><code>&lt;ROOTNAME&gt;.tp7</code></a> , <a href="#"><code>&lt;ROOTNAME&gt;.tp8</code></a> , <a href="#"><code>&lt;ROOTNAME&gt;.flx</code></a> , etc.).
	1	or <a href="#">FC_TAPE6ONLY</a> only generates the <a href="#"><code>&lt;ROOTNAME&gt;.tp6</code></a> legacy output file.
	2	or <a href="#">FC_NOFILES</a> generates no legacy output files.
BINARY	FALSE	<i>Output files</i> <a href="#"><code>&lt;ROOTNAME&gt;.tp7</code></a> , <a href="#"><code>&lt;ROOTNAME&gt;.tp8</code></a> and <a href="#"><code>&lt;ROOTNAME&gt;.plt</code></a> are generated in an ASCII format.
	TRUE	Output files <a href="#"><code>&lt;ROOTNAME&gt;.tp7</code></a> , <a href="#"><code>&lt;ROOTNAME&gt;.tp8</code></a> and <a href="#"><code>&lt;ROOTNAME&gt;.plt</code></a> are generated in a binary format. ASCII equivalent files are generated from the binary files by running the auxiliary program <code>bin2as_mod6</code> , located in the <code>bin</code> directory.
CKPRNT	FALSE	<i>No output of cumulative path transmittances and radiances for Ck or LBL.</i>
	TRUE	If the Correlated- <i>k</i> option is on, <i>k</i> -distribution dependent cumulative path transmittances and radiances are written to <a href="#"><code>&lt;ROOTNAME&gt;.t_k</code></a> and <a href="#"><code>&lt;ROOTNAME&gt;.r_k</code></a> output files, respectively. The data is also written to output files <a href="#"><code>&lt;ROOTNAME&gt;.highres.csv</code></a> , <a href="#"><code>&lt;ROOTNAME&gt;.highres.csv</code></a> and <a href="#"><code>&lt;ROOTNAME&gt;.highres.sli</code></a> if <a href="#">CSVPRNT</a> and <a href="#">SLIPRNT</a> are set appropriately. If the LBL option is on, the same files are created and contain the high spectral resolution line-by-line data instead of the <i>k</i> -dependent data. For either Ck or LBL, if <a href="#">CKRANG</a> is used, the <i>k</i> -dependent data is output as a function of slant range (see input instructions for <a href="#">CKRANG</a> in Table 3.40 of the Geometry section for further details). If the BINARY output option is selected, the data is written to files <a href="#"><code>&lt;ROOTNAME&gt;.b.t_k</code></a> and <a href="#"><code>&lt;ROOTNAME&gt;.b.r_k</code></a> instead of <a href="#"><code>&lt;ROOTNAME&gt;.t_k</code></a> and <a href="#"><code>&lt;ROOTNAME&gt;.r_k</code></a> , respectively. Binary files can be translated to ASCII files by running the utility <code>bin2as_mod5_k</code> located in the <code>bin</code> directory.
NOPRNT	Integer	Controls <a href="#"><code>&lt;ROOTNAME&gt;.tp6</code></a> and <a href="#"><code>&lt;ROOTNAME&gt;.tp8</code></a> output; higher values = less output.
	0	<i>Normal content for</i> <a href="#"><code>&lt;ROOTNAME&gt;.tp6</code></a> .
	1	Create <a href="#"><code>&lt;ROOTNAME&gt;.tp6</code></a> but omit model atmosphere profiles (unless special options such as user-defined profiles is selected).
	2	Create <a href="#"><code>&lt;ROOTNAME&gt;.tp6</code></a> but omit spectral data and model atmosphere profiles.
	3	Delete <a href="#"><code>&lt;ROOTNAME&gt;.tp6</code></a> at end of processing if run is successful.
	-1	Create additional <a href="#"><code>&lt;ROOTNAME&gt;.tp8</code></a> output, including line-of-sight spectral fluxes in radiation mode when multiple scattering on. These values are generated at the band model spectral bin resolution, 0.1, 1.0, 5.0 or 15.0 cm <sup>-1</sup> . Spectral flux values convolved with the instrument slit function are output to <a href="#"><code>&lt;ROOTNAME&gt;.flx</code></a> if <a href="#">FLAGS[6]</a> is not left blank. Be warned that setting <a href="#">NOPRNT</a> to -1 for long paths (e.g., ground to space) over a large spectral range (e.g., 0.4 to 0.7 μm) will generate large <a href="#"><code>&lt;ROOTNAME&gt;.tp8</code></a> files.
	-2	Generates spectral cooling rate data in a <a href="#"><code>&lt;ROOTNAME&gt;.clr</code></a> file. <a href="#"><code>&lt;ROOTNAME&gt;.tp8</code></a> output is also generated.
MSGPRNT	Enum	Controls the verbosity of output messages reported to STDOUT.
	0	or <a href="#">MSG_NONE</a> disables all runtime output messages.
	1	or <a href="#">MSG_ERROR</a> displays only runtime error messages.
	2	or <a href="#">MSG_WARN</a> displays runtime error and warning messages.
	3	or <a href="#">MSG_INFO</a> displays runtime information, warnings, and error messages.
	4	or <a href="#">MSG_DEBUG</a> displays additional status and <a href="#">MSG_INFO</a> messages.
DATDIR	Omit or " "	Use directory specified by environment variable MODTRAN_DATA.
	String	Path to directory containing the MODTRAN data files, e.g. for a band model file whose name has been explicitly input.

FLROOT	String	Root name of MODTRAN output files, e.g., the string that replaces <ROOTNAME> in <ROOTNAME>.tp6. In the MODTRAN6 GUI, this is the Case Control Name (TRAIN01 in Figure 2.1).
CSVPRNT	String	File root name and extension for CSV-type output, default is " ". If the extension is .txt, tab delimited files are produced; if the extension is .csv, output files are produced in a comma separated values format.
SLIPRNT	String	File root name for ENVI spectral library output, default is " ".
JSONPRNT	String	File root name for JSON formatted output.
JSONOPT	enum	Selects the type of output written to JSONPRNT. 0 or WRT_NONE disables writing to JSONPRNT 1 or WRT_STATUS writes only status information to JSONPRNT 2 or WRT_INPUT writes only input settings to JSONPRNT 3 or WRT_STAT_INPUT writes status information and input settings to JSONPRNT 4 or WRT_OUTPUT writes only output data to JSONPRNT 5 or WRT_STAT_OUTPUT writes status information and output data to JSONPRNT 6 or WRT_INPUT_OUTPUT writes input settings and output data to JSONPRNT 7 or WRT_ALL writes status, input, and output data to JSONPRNT

#### 4. MODTRAN6 OUTPUT DATA FORMAT

Version 5 of MODTRAN uses a “**mod5root.in**” or “**MOD5ROOT.IN**” file to delineate the root names of MODTRAN5 calculations to be run. If “mod5root.in” does not exist, MODTRAN5 checks for the existence of a “**MOD5ROOT.IN**” file. If neither of these files are found, the original MODTRAN I/O file names (“tape5”, “tape6”, “tape7”, “tape8”, etc.), from the days of the LOWTRAN model, are used. If a root name file is found and its very first line contained a non-null string, this string serves as the I/O file root name. If a given root name includes a “.tp5” extension, this extension is ignored. As noted in Section 1.2, MODTRAN6 users can still define a set of input files using a “**mod5root.in**” or “**MOD5ROOT.IN**” file using the “**-modroot**” option with the `mod6c_cons` executable.

With the modern JSON input protocol, the root name string is the value associated with the `MODTRANINPUT` keyword `NAME`. If this input string is <ROOTNAME>, the MODTRAN output files would have the names listed in Table 4.1 (a duplication of Table 1.1). The set of legacy output files that are generated is determined by the `FILEOPTIONS` keyword `NOPRNT`. If the `FILEOPTIONS` keyword `CSVPRNT` is not blank and includes a .csv extension, then ASCII comma separated value files are generated; if `CSVPRNT` is not blank but does not include a .csv extension, then .txt tab delimited value ASCII output files are generated. ENVI® binary spectral library (.sli) and accompanying ASCII header (.hdr) files are generated if the `FILEOPTIONS` keyword `SLIPRNT` is not blank.

**Table 4.1.** Legacy and MODTRAN6 Input and Output Files.

Legacy File Names (* = <ROOTNAME>)	I=Input <i>B=Binary</i>	File Name of Mod6 Option	Chapter .Section	Short Description
*.tp5 or tape5	<b>I</b>	*.json	3	Primary Input
*.rng or Yrange.asc	<b>I</b>		6	Local Gas Plume Path Definition
*.sap or SpecAerProf.dat	<b>I</b>		3.5.4	Spectral Aerosol Profile Data
*.pth or rfracpth.dat	<b>I</b>		3.7.2	Refractive Path Definition
*._pth or rfracpth.dat			3.7.2	Refractive Path Definition
*.wrn or warnings.txt			4.1	List of Comments/Warnings/Errors
*.tp6 or tape6		GUI Log	4.2	General Output Data
*.tp7 or tape7		*.(csv,txt)	4.3	LOS Spectral Data
*_b.tp7 or tape7b	<b>B</b>	*.(sli,hdr)	4.3	LOS Spectral Data
*.7sc or tape7.scn		*_scan.(csv,txt)	4.3	Scanned LOS Spectral Data
	<b>B</b>	*_scan.(sli,hdr)	4.3	Scanned LOS Spectral Data
*.plt or pltout		*.(csv,txt)	4.3	LOS Spectral (x,y) Data
*_b.plt or pltoutb	<b>B</b>	*.(sli,hdr)	4.3	LOS Spectral (x,y) Data
*.psc or pltout scn		*_scan.(csv,txt)	4.3	Scanned LOS Spectral (x,y) Data
	<b>B</b>	*_scan.(sli,hdr)	4.3	Scanned LOS Spectral (x,y) Data
*.chn or channels.out		*_chan.(csv,txt)	4.4	Sensor Spectral Channel Data
	<b>B</b>	*_chan.(sli,hdr)	4.4	Sensor Spectral Channel Data
*.flx or specflux.asc		*_flux.(csv,txt)	4.5	Profiles of Spectral Flux Data
*_b.flx or specflux.bin	<b>B</b>	*_flux.(sli,hdr)	4.5	Profiles of Spectral Flux Data
*.acd or atmcor.asc			4.6	Atmospheric Correction Data
*_b.acd or atmcor.bin	<b>B</b>		4.6	Atmospheric Correction Data
*.t_k or t_kdis.dat		*_highres.(csv,txt)	4.7	LBL or Ck Transmittance Data
*_b.t_k or t_kdis.bin	<b>B</b>	*_highres.(sli,hdr)	4.7	LBL or Ck Transmittance Data
*.r_k or r_kdis.dat		*_highres.(csv,txt)	4.7	LBL or Ck Radiance Data
*_b.r_k or r_kdis.bin	<b>B</b>	*_highres.(sli,hdr)	4.7	LBL or Ck Transmittance Data
*.tp8 or tape8			4.8	Segment Spectral Data
*_b.tp8 or tape8b	<b>B</b>		4.8	Segment Spectral Data
*.clr or clrates			4.9	Spectral Cooling Rates
*.ms or msdata.asc			4.10	Saved Multiple Scatter Data
*.msB or msdata.bin	<b>B</b>		4.10	Saved Multiple Scatter Data

#### 4.1 The <ROOTNAME>.wrn Messages Output File

MODTRAN generates comments, warning and error messages when unexpected behavior is detected during a run. These messages are written to standard output, to the <ROOTNAME>.tp6 file, to the MODTRAN6 GUI log file, and to a <ROOTNAME>.wrn file. The <ROOTNAME>.wrn output file was introduced because messages embedded in the <ROOTNAME>.tp6 file were too easily hidden by the other data in the file. Messages labeled as comments are informational, and do not require any action. Most warnings can also be ignored, but they should be reviewed to insure that the executed calculation actually corresponds to the calculation the user intended. If, for example, a user-defined solar irradiance file is not found, MODTRAN will continue with its calculations but use default solar irradiance data. The <ROOTNAME>.wrn file will warn you that your data was not found and not used. Error messages are rare,

and cause the MODTRAN run to either discontinue or to skip to a next case if more than one case is included in the run.

Occasionally users are concerned that a warning indicates that their calculation is faulty. Generally that is not the case. In Table 4.2, a list of all the comments (**purple**) and warnings (**burnt orange**) that are generated from the ~100 MODTRAN6 test cases are listed. This is only a subset of possible comments and warnings. Almost all begin with the phrase “Comment from routine ...” or “Warning from routine ...” (specification of the FORTRAN routine was of greater utility to users when source code was provided). In Table 4.2, the messages are ordered alphabetically by routine. The expanded explanation in the table is designed to alleviate fears that a calculation did not process correctly. If you run into a comment or message not included in the table and/or you require further explanation, you are encouraged to send an inquiry to [modtran@spectral.com](mailto:modtran@spectral.com).

**Table 4.2.** Common MODTRAN6 Comments and Warnings.

Routine	Message / Explanation
<b>CD1</b> <b>Warning</b>	Invalid number of LBL subintervals. The default value, 100, will be used. For the line-by-line option, each $0.1\text{ cm}^{-1}$ spectral bin is partitioned into <a href="#">NLBL</a> equal width sub-intervals and calculation are performed at the center of these sub-intervals. <a href="#">RTOPTIONS</a> keyword <a href="#">NLBL</a> must be a positive integer.
<b>CD1</b> <b>Warning</b>	Multiple scattering has been turned off. If a line-of-sight radiance calculation is not being performed or a constant Pressure path has been selected, the multiple scattering models are not run.
<b>CD1</b> <b>Warning</b>	The user-specified atmosphere option has been selected and <a href="#">I_RD2C</a> on CARD 1 is not equal to 1. The atmosphere from the previous run will be reused. When multiple cases are run with user-defined atmospheres ( <a href="#">ATMOSPHERE</a> keyword <a href="#">MODEL</a> = <a href="#">ATM_USER_ALT_PROFILE</a> or <a href="#">ATM_USER_PRESS_PROFILE</a> ), one can choose to re-use the previous user-defined atmosphere. MODTRAN warns the user when this is occurring.
<b>CD2C</b> <b>Warning</b>	Molecule CCl4 is both an ambient X species with built-in spectral cross-section and concentration profile data, and an auxiliary (Y) molecule with an alternative external spectral data file and additional concentration data. This produces a spectrally uncorrelated treatment of the absorption for the X and Y versions of the molecule. The ambient X molecule can be excluded from the calculation by setting the profile scaling factor for CCl4 to zero on CARD 1A6. This is a warning that a built-in cross-section (i.e., X) molecule has also been entered as an auxiliary species, and they are being modeled separately. This is not the correct way to model the absorption from a single species. The recommendation is that the X molecule be removed by setting the appropriate <a href="#">ATMOSPHERE</a> keyword <a href="#">S_XSEC</a> scale factor to zero.
<b>CHKRES</b> <b>Warning</b>	DV is being increased from 3.000000 to 15.000000 CM-1. The output step size cannot be smaller than the band model resolution
<b>CHKRES</b> <b>Warning</b>	Output spectral step size (25.00000 CM-1) exceeds the spectral resolution (5.00000 CM-1). If the output spectral step size exceeds the spectral resolution, there are gaps in the spectral coverage.
<b>CHKRES</b> <b>Comment</b>	There is no band model (only continuum) molecular absorption for spectral frequencies above 25740.00 cm-1. Although a band model, correlated-k or line-by-line calculation was requested, MODTRAN databases includes no molecular line data above 25,740 $\text{cm}^{-1}$ . As a result, only continuum molecular absorption is modeled in this spectral region.

**Table 4.2.** Common MODTRAN6 Comments and Warnings (cont'd).

Routine	Message / Explanation
<b>CHKSPC</b> <b>Warning</b>	Although the reciprocal line spacing parameter (the number of lines per spectral bin) was increased by a factor of 8, the combined species segment absorbance is still 0.00037 less than the band model value. 0.98199 Transmittance from combined species band model parameters 0.98163 Product of single molecule band model transmittances
	For each path segment, the MODTRAN statistical correlated- $k$ algorithm interpolates among pre-computed $k$ -distributions to find one that whose transmittance matches the band model segment transmittance. Occasionally, this process does not converge, but typically the transmittance residual is small, as in this case.
<b>CKMSS</b> <b>Warning</b>	Weak-line optical depth to the sun is negative or decreasing with altitude. The depth to the sun from the bottom of layer 13 is 1.137E-02 The depth to the sun from the top of layer 13 is 1.205E-02
	This occurred for k-distribution interval number 5. One expects the attenuation of solar irradiance to increase with decreasing altitude from the top of the atmosphere to the ground. On rare occasions, MODTRAN does not exhibit this behavior for an individual layer at a specific spectral frequency, and this warning message is generated. The problem is that MODTRAN currently approximates the solar illumination path, which can pass through many layers, as a weighted averaged single segment. Although this problem has never been found to lead to radiance value outliers, a solution which eliminates the single segment approximation has been defined and implementation has been initiated.
<b>CRFILE</b> <b>Comment</b>	At 0.30800 Microns, the scattering phase function for cloud type 12.0 MICRON MEAN "SPHERES" SIZE (A. MACKE, 2001) was normalized to 1.39564 instead of 1. It is being renormalized. This comment will not be repeated if the problem occurs for other wavelengths. MODTRAN checks the normalization of every tabulated scattering phase function that is read in. If it is not normalized to one, then MODTRAN performs a renormalization and generates this comment. Sometimes input the phase function may have been normalized four pi. The input phase function actually may have been normalized to one, but a different assumption was made regarding the variation between grid points. MODTRAN assumes the phase functions varies exponentially with the cosine of the scattering angle.
<b>CRFILE</b> <b>Comment</b>	At 0.30800 Microns, the forward scatter value of the unit normalized phase function (= 1665.502 sr-1) does not equal the sum of the unit normalized Legendre expansion coefficients (= 1169.243 sr-1) for cloud type 12.0 MICRON MEAN "SPHERES" SIZE (A. MACKE, 2001). This comment will not be repeated if the problem occurs for other wavelengths. MODTRAN requires that scattering phase function input define both the tabulated phase function and the Legendre expansion. In principle, the sum of the coefficients in a Legendre expansion of a unit normalized scattering phase function should equal the forward scattering value. When there is a mismatch, this comment is generated.
<b>CRMERG</b> <b>Warning</b>	At altitude 4.5000 km, the liquid water droplet density is positive [0.1500 g/m3] even though the temperature is -14.2292 degrees celsius. MODTRAN checks whether a liquid water cloud is defined at an altitude whose temperature is well below 0 C, or whether an ice cloud is defined at an altitude whose temperature is well above 0 C. If so, MODTRAN warns the user of the potential problem but continues with the calculation as if the problem did not exist.

**Table 4.2.** Common MODTRAN6 Comments and Warnings (cont'd).

Routine	Message / Explanation
<b>D_LOOPR Warning</b>	At 2187.75 CM-1, the 3-parameter Curtis-Godson formulation is not producing a monotonic curve-of-growth. The O3 transmittance increased 0.0006109 from 0.9963859 to 0.9969968. Run the Correlated-k algorithm to avoid this problem. This warning will only be repeated if a larger increase in O3 transmittance occurs. See explanation for <b>D_LOOPE Warning</b> .
<b>DISORT Warning</b>	<b>UPBEAM--TEMPORARILY REDUCED COSINE SOLAR ZENITH BY 0.01% TO AVOID SINGULAR MATRIX</b>  The DISORT solar scattering model performs a matrix inversion to solve the radiative transfer equation. Occasionally this matrix will be singular. MODTRAN has discovered that the singularity can be avoided by repositioning the sun an inconsequential amount – far less than the diameter of the solar disk. When this repositioning is required, MODTRAN generates this warning. Recently, DISORT3 was released and it eliminates the singularity problem. This upgrade to DISORT has not yet been integrated into MODTRAN6, but it will be.
<b>disInit Warning</b>	The DISORT Spherical Albedo / Diffuse Transmittance Option was turned off because no solar scattering is being computed.  The DISORT atmospheric correction data file generates spectral ( $k$ -dependent with correlated- $k$ radiative transfer) values for the direct and diffuse transmittances and for the atmospheric spherical albedo from the ground. The transmittances are computed for a line-of-sight that terminates at the ground and for the sun-to-ground solar illumination path. If solar multiple scattering is not being calculated, then the diffuse transmittance and spherical albedo outputs are not be calculated and this warning message is generated.
<b>DPANDX Warning</b>	The product of the Earth center distance $R+H$ and the index of refraction $n(H)$ decreases with altitude $H$ at $H = 0.50000$ km, with $d[(R+H) * n(H)] / dH = -25.89820$ . Spherical refractive geometry routines may fail for path elevation angles near zero degrees.  Sharp vertical temperature and/or $H_2O$ gradients can lead to anomalous propagation. In particular, super refraction can cause a line-of-sight to bend towards the Earth. MODTRAN was not designed to handle this scenario, i.e., it is assumed that an upward propagating path in any atmospheric layer will cross the layer top if extended long enough. This warning indicates that super refractive conditions exist in the current layer that could cause the line-of-sight to turn downward. This will not happen for a vertical path. But it can happen for upward near horizontal paths. It is just a warning. If the refraction calculation determines that the specific path reaches a tangent maximum, then an separate error message is generated.

**Table 4.2.** Common MODTRAN6 Comments and Warnings (cont'd).

Routine	Message / Explanation
<b>FILTER Warning</b>	<p>Brightness temperature for channel 8 may be inaccurate!</p> <p>For monochromatic radiation, converting from spectral radiance to brightness temperature, the temperature a blackbody would need to produce that radiance, is straightforward. Converting a sensor channel radiance with an arbitrary spectral response function is more difficult. The analytic procedure developed for MODTRAN [Berk, A., "Analytically derived conversion of spectral band radiance to brightness temperature," J. Quant. Spectrosc. Radiat. Transfer, v109, 1266-1276 (2008).] requires that the width of the spectral band be small when compared to the band center location, a condition that is almost always satisfied. On the rare occasions that this condition is not satisfied, a warning message is generated. In this particular case, the band that is flagged is the Landsat7 panchromatic band whose FWHM (381.0 nm) is more than 50% of the band center (705.5 nm).</p>
<b>FILTER Comment</b>	<p>First filter weight for channel 1, GOES-12 Channel 01 Detector 1 (Peak = 683.7 cm<sup>-1</sup>, FWHM = 11.6 cm<sup>-1</sup>), is non-zero.</p> <p>MODTRAN needs to integrate over sensor spectral response functions. Optimally, these functions would drop to zero at the spectral endpoints. When they do not, MODTRAN models the responses as if they were exactly zero outside of the given spectral range. When this approximation is made, MODTRAN generates the above warning.</p>
<b>FILTER Comment</b>	<p>Last filter weight for channel 1, GOES-12 Channel 01 Detector 1 (Peak = 683.7 cm<sup>-1</sup>, FWHM = 11.6 cm<sup>-1</sup>), is non-zero.</p> <p>See previous explanation</p>
<b>FINDMN Comment</b>	<p>Tangent path with <u>H1ALT</u> = 4.9000 km and <u>OBSZEN</u> = 180.0000 deg intersects the Earth. <u>H2ALT</u> has been reset from 100.00000 km to 0.00000 km, and LENN reset from 1 to 0.</p> <p>When <u>GEOMETRY</u> keyword <u>ITYPE</u> is set to 3 (Vertical or slant path to space or ground), MODTRAN assumes a path to space. When the path intersects the Earth, as this nadir path clearly does, MODTRAN resets the final altitude to the ground altitude and warns the user that the path has been changed. Usually, this outcome is expected by the user. However, occasionally, the user expects to be running a tangent path but it actually intersects the Earth.</p>
<b>FLUXES Warning</b>	<p>A DISORT diffuse downward flux value was negative and reset to zero. This warning will not be repeated.</p> <p>For each spectral point and at each altitude level, the DISORT solar calculation computes the total (direct plus diffuse) downward flux. The direct downward flux is subtracted from the total value to determine the diffuse contribution. Occasionally, when the diffuse contribution to the total is small, this differencing produces a negative diffuse downward flux. MODTRAN resets this to 0.0 W cm<sup>-2</sup> / cm<sup>-1</sup>, and warns the user.</p>
<b>GEODRV Warning</b>	<p>The DISORT Spherical Albedo / Diffuse Transmittance Option was turned off because none of the lines-of-sight intersect the ground.</p> <p>The DISORT atmospheric correction data file generates spectral (<math>k</math>-dependent with correlated-<math>k</math> radiative transfer) values for direct and diffuse transmittances and for the atmospheric spherical albedo from the ground. The transmittances are computed for a line-of-sight that terminates at the ground and for the sun-to-ground solar illumination path. If the line-of-sight does not intersect the ground, then the diffuse transmittance and spherical albedo outputs are not be calculated and this warning message is generated.</p>
<b>GTaWQs Warning</b>	<p>Temperature for segment 2 of line-of-sight 1, 177.84 K, is below the minimum partition function temperature of 180 K.</p> <p>The MODTRAN6 line-by-line algorithm utilizes tabulated molecular partition functions to determine temperature-dependent line strength. The partition functions have been defined over a 180 to 330 K temperature range. When a temperature outside of this range is encountered, the user is warned and the partition function is defined based on the appropriate endpoint value. This is not a problem if the deviation from one of the endpoint temperatures is a few degrees, but the MODTRAN6 database must be expanded if temperatures well below 180 K or well above 330 K are to be modeled.</p>

**Table 4.2.** Common MODTRAN6 Comments and Warnings (cont'd).

Routine	Message / Explanation
<b>I_LOOPR_b</b> <b>Warning</b>	At 4002.00 CM-1, the 3-parameter Curtis-Godson formulation is not producing a monotonic curve-of-growth. The O3 transmittance increased 0.0007583 from 0.9811313 to 0.9818897. Run the Correlated-k algorithm to avoid this problem. This warning will only be repeated if a larger increase in O3 transmittance occurs. See explanation for <b>D_LOOPPE Warning</b> .
<b>KNTRP</b> <b>Comment</b>	Effective number of lines = 9.6907E-01 is less than 1.0000E+00. Band model tuning enables the value to be as small as a half. MODTRAN band model data has been generated at 4 spectral resolutions: 0.1, 1.0, 5.0 and 15.0 cm <sup>-1</sup> . One of the line-center band model parameters is the effective number of lines in the band model spectral bin. If no lines occur in a spectral bin, no line-center band model data is generated. One would expect that the minimum effective number of lines in an interval would be one. Indeed, this minimum is adhered to in the baseline calculation of line-center band model parameters. However, MODTRAN tunes its coarser resolution (1.0, 5.0 and 15.0 cm <sup>-1</sup> ) band model effective line numbers by comparing their predicted transmittance to spectral degraded 0.1 cm <sup>-1</sup> band model transmittances. The tuning can produce effective line numbers that are smaller than one, although MODTRAN does not allow the effective line number to drop below one-half. MODTRAN provides a comment whenever an effective line number less than one is encountered.
<b>KNTRP</b> <b>Comment</b>	The Doppler half-width = 0.02809384 cm-1 exceeds the K-table maximum = 0.02000000 cm-1. *** THIS WARNING WILL NOT BE REPEATED *** MODTRAN statistical k-distribution tables are generated for a range of Doppler half-widths. The range varies depending on the band model (BM) resolution: 1.E-5 to 0.1 cm <sup>-1</sup> for the 0.1 cm <sup>-1</sup> BM; 1E-5 to 0.02 cm <sup>-1</sup> for the 1.0 cm <sup>-1</sup> BM; 5.524E-5 to 0.02 cm <sup>-1</sup> for the 5.0 cm <sup>-1</sup> BM; and 8.8388E-4 to 0.02 cm <sup>-1</sup> for the 15.0 cm <sup>-1</sup> BM. Occasionally, MODTRAN will encounter a Doppler line width that extends outside of the current band model's range. When this occurs, a comment is generated and the appropriate endpoint distribution is used.
<b>KNTRP</b> <b>Comment</b>	The Lorentz half-width = 0.00000055 cm-1 is less than the table minimum value of 0.00000100 cm-1. The K-distribution interpolation will be based on the table minimum value. *** THIS WARNING WILL NOT BE REPEATED *** MODTRAN statistical k-distribution tables are generated for a range of Lorentz half-widths. The range varies depending on the band model (BM) resolution: 1.E-6 to 1.0 cm <sup>-1</sup> for the 0.1 cm <sup>-1</sup> BM; 1E-6 to 0.2 cm <sup>-1</sup> for the 1.0 cm <sup>-1</sup> BM; 8.632E-6 to 0.2 cm <sup>-1</sup> for the 5.0 cm <sup>-1</sup> BM; and 6.9053E-5 to 0.2 cm <sup>-1</sup> for the 15.0 cm <sup>-1</sup> BM. Occasionally, MODTRAN will encounter a Doppler line width that extends outside of the current band model's range. When this occurs, a comment is generated and the appropriate endpoint distribution is used.
<b>LRDSAP</b> <b>Comment</b>	At 0.000000 m altitude and 8.000000 microns, the aerosol phase function was normalized to 12.571743 instead of 1; it is being renormalized. This warning will not be repeated. MODTRAN checks the normalization of every tabulated scattering phase function that is read in. If it is not normalized to one, then MODTRAN performs a renormalization and generates this comment. Sometimes input the phase function may have been normalized four pi. The input phase function actually may have been normalized to one, but a different assumption was made regarding the variation between grid points. MODTRAN assumes the phase functions varies exponentially with the cosine of the scattering angle.
<b>LRDSAP</b> <b>Comment</b>	The aerosol phase function forward peak at 0.000000 m altitude and 8.000000 microns computed from the Legendre expansion is 4.856527 sr-1; however, the tabulated value is 4.854461 sr-1. Before normalization, the tabulated value was 61.029031. MODTRAN requires that scattering phase function input define both the tabulated phase function and the Legendre expansion. In principle, the sum of the coefficients in a Legendre expansion of a unit normalized scattering phase function should equal the forward scattering value. When there is a mismatch, this comment is generated.



**Table 4.2.** Common MODTRAN6 Comments and Warnings (cont'd).

Routine	Message / Explanation
<b>MSLOOP Warning</b>	At 625.25 CM-1, the 3-parameter Curtis-Godson formulation is not producing a monotonic curve-of-growth. The O3 transmittance increased 0.0005156 from 0.9989548 to 0.9994704. Run the Correlated-k algorithm to avoid this problem. This warning will only be repeated if a larger increase in O3 transmittance occurs. See explanation for <b>D_LOOPR Warning</b> .
<b>P_LOOPR_a Warning</b>	At 818.15 CM-1, the 3-parameter Curtis-Godson formulation is not producing a monotonic curve-of-growth. The O3 transmittance increased 0.0005015 from 0.9977155 to 0.9982169. Run the Correlated-k algorithm to avoid this problem. This warning will only be repeated if a larger increase in O3 transmittance occurs. See explanation for <b>D_LOOPR Warning</b> .
<b>RDUSRS Warning</b>	<b>Unable to open file DATA/SUN15quietSORCE.dat</b> The specified solar irradiance file was not found in the MODTRAN6 DATA/ directory (defined by the environment variable MODTRAN_DATA). MODTRAN will continue executing, using the default solar irradiance data file. In the initial distribution of MODTRAN6, the "SUN*SORCE.dat" files were not loaded into the DATA directory; they are now.
<b>REDUCE Warning</b>	<b>H1ALT</b> and/or <b>H2ALT</b> were above the Top-Of-Atmosphere altitude, ZMAX = 50.10000 km. ( <b>H1ALT</b> , <b>OBSZEN</b> ) and/or ( <b>H2ALT</b> , <b>BCKZEN</b> ) have been reset to (ZMAX, ANGMAX), where ANGMAX = 96.61229 deg. MODTRAN allows the user to place the sensor (or LOS final altitude) at any altitude, e.g. the altitude of a geostationary Earth orbit (35,786 km above the equator). The MODTRAN atmosphere is generally only defined up to ZMAX, an altitude of ~100 km above sea-level (ASL). The atmosphere above ZMAX is assumed to be transparent (non-attenuating). Therefore MODTRAN redefines the sensor (final) altitude to ZMAX, and computes the off-nadir (zenith) angle at which the LOS enters (exits). The value of ZMAX and the enter/exit angle is written into a warning statement.
<b>RM_EM Warning</b>	For Segment No. 18 and Correlated-k interval No. 1 of line-of-sight No. 1, the segment thermal emission (7.539695E-09 W CM-2 SR-1 / CM-1) exceeds the DISORT emitted plus scattered thermal radiance (7.532079E-09 W CM-2 SR-1 / CM-1)! This tends to occur at high altitudes, where scattering contributions are small. The thermal scattered radiance for this segment is being set to zero. This warning will only be repeated if the problem occurs for a larger segment emitted radiance. To avoid numerical inaccuracies that can arise with DISORT processing of optically thin layers, MODTRAN relayers the atmosphere at each spectral (or $k$ -dependent spectral) point. Layers are combined until a threshold optical depth of 0.0001 is reached. One issue with relayering is that the temperature of skipped altitude levels is not modeled. To minimize this potential problem, MODTRAN calculates the path thermal emission independent of DISORT using the original atmospheric layering. DISORT is only used to calculate the scattering component of thermal radiances. To extract the DISORT thermal scatter, the DISORT relayered atmosphere path thermal emission is subtracted from the DISORT relayered atmosphere path thermal radiance. When the path thermal scatter is small, the subtraction can incorrectly report a negative thermal scatter radiance. MODTRAN warns the user and sets the thermal scattering for the current segment to zero. The actual path thermal emission and radiance values are included in the warning so that the user can confirm that the negative value is small compared to the thermal emission.

**Table 4.2.** Common MODTRAN6 Comments and Warnings (cont'd).

Routine	Message / Explanation
<b>RM_SSS Warning</b>	<p>A negative scattering phase function resulted from the truncated delta-M Legendre expansion. It is recommended that the number of streams (input NSTR) be doubled.</p> <p>The Legendre expansion of aerosol and cloud phase functions are slowly converging [This fact is what led to the development and implementation of the delta-M approximation, W.J. Wiscombe, "The Delta-M Method: Rapid Yet Accurate Radiative Flux Calculations for Strongly Asymmetric Phase Functions," <i>J. Atmos. Sci.</i>, 34:1408-1422, 1977]. MODTRAN computes single scattering radiance using a tabulated scattering phase function. The DISORT single scattering radiance, computed from the Legendre expansion of the scattering phase function, must be subtracted from the total solar scattering path radiance to extract the multiplied scattered path radiance. Occasionally, the truncated scattering phase function is negative at the path solar scattering angle, producing a negative single scattering radiance. When this happens, MODTRAN generates this warning and suggests that the number of DISORT streams (terms in the Legendre expansion) be doubled.</p>
<b>RM_SSS Warning</b>	<p>For segment no. 4 of line-of-sight no. 1, the single scatter solar radiance (5.367208E-15 W CM-2 SR-1 / CM-1) was found to exceed the DISORT segment single plus multiple scatter solar radiance (5.297596E-15 W CM-2 SR-1 / CM-1)! This tends to occur at high altitudes, where scattering contributions are small. The solar multiple scatter radiance for this segment is being set to zero. This warning will only be repeated if the problem occurs for a larger segment single scatter solar radiance.</p> <p>DISORT computes solar scattering path radiances using a truncated Legendre expansion of the scattering phase function. For single scattering, it is more accurate to compute the single scattering component of the path radiance using a tabulated phase function. To extract the path solar radiance due to multiple scattering, the DISORT single scattering component must be subtracted from the DISORT total path solar radiance. Occasionally, the computed single scattering component exceed the DISORT total path solar radiance. When this happens, MODTRAN generates a warning and sets the multiplied scattered radiance for the current path segment to zero. Values for the single and total scattering solar radiance are included in the warning so that the user can verify that the two values have similar magnitude.</p>
<b>SSRAD Warning</b>	<p>Weak-line optical depth to the sun is increasing with altitude.      The depth to the sun from the bottom of layer 22 is 1.376E-03.      The depth to the sun from the top of layer 22 is 1.392E-03.</p> <p>This anomaly can occur because of curved-Earth effects or because of the Curtis-Godson approximation. The depth from layer top was decreased to match the depth from layer bottom. *** THIS WARNING WILL NOT BE REPEATED ***</p> <p>See explanation for <b>CKMSS Warning</b>.</p>
<b>TRLAY Warning</b>	<p>The estimated layer optical depth towards the sun is 1.0414E+00, but the vertical layer optical depth is 1.4313E+00. The solar path layer optical depth was reset to the vertical layer extinction optical depth over the cosine (= 0.7073) of the solar zenith.</p> <p>*** THIS WARNING WILL NOT BE REPEATED ***</p> <p>One expects the segment solar path optical depth through an atmospheric layer to exceed the layer vertical optical depth. On rare occasions, MODTRAN does not exhibit this behavior at a specific spectral frequency and atmospheric layer. When that happens, this warning message is generated. The problem is that MODTRAN currently approximates the solar illumination path, which can pass through many layers, as a weighted averaged single segment. This can lead to the anomaly in which the solar path optical depth is calculated to be too small. A modeling approach which eliminates the single segment approximation for the solar illumination path has been defined and implementation has been initiated.</p>

**Table 4.2.** Common MODTRAN6 Comments and Warnings (cont'd).

Routine	Message / Explanation
<b>YRANGE Warning</b>	Sensor to Auxiliary (Y) species final range, 11.600000 KM, exceeds either the Sensor to Earth or Sensor to Top-Of-Atmosphere distance. The final range has been reset to 11.600000 KM. The molecular densities for the local chemical plume model are defined as a function of distance along the LOS. If an input path range exceeds the range to the ground or to the top-of-atmosphere, the path range is truncated and this warning is generated. All these distances are defined internal to MODTRAN in double precision, but often entered in single precision. Numerical round-off errors can cause this warning to be generated even though the input distance does not exceed the maximum, as in the specific example above.

## 4.2 The <ROOTNAME>.tp6 General Output File

Information describing the specifics of a given MODTRAN calculation is written to a <ROOTNAME>.tp6 general output file. This section annotates the information included in a sample <ROOTNAME>.tp6 file. The goal is to familiarize the user with the type of information provided by these files. The sample output file was generated by loading the Cloud Profile Preset Configuration into the MODTRAN6 GUI. The Configuration Name was reset to CloudProfile30sun8disort.json and the Case Name was set to CloudProfile30sun8disort. After clicking on Edit, the multiple scattering model was changed from Isaacs 2-stream MS to DISORT MS using the default number of streams, 8. Under the Geometry tab, the Solar Zenith ( $^{\circ}$ ) was increased from 0.0 to 30.0 to make the CloudProfile30sun8disort.tp6 file more instructive.

### *The first page of the CloudProfile30sun8disort.tp6 output*

Highlighted in blue within the header of Figure 4.1 is the root name used for MODTRAN I/O.

The first few comments indicate that a radiance calculation is to include solar contributions and to solve for multiple scattering.

Although the new MODTRAN6 standard for defining input data is via a JSON file, the <ROOTNAME>.tp6 continues to echo input data using the CARD input nomenclature; the appendix includes the MODTRAN5 Users' Manual defining the CARD inputs.

The default profiles for CH<sub>4</sub>, for the chlorofluorocarbons F11, F12, F22 and F113, and for CHCl<sub>2</sub>F are all being scaled; absorption from the H<sub>2</sub>-H<sub>2</sub> and H<sub>2</sub>-He dimers is not to be modeled (the dimer profiles are being scaled by 0.0).

The “2013” 1.0 cm<sup>-1</sup> band model data files are being used to model line center (file 01\_2013c.bn4) and line tail (file 01\_2013t.bn) molecular absorption. CFC’s are to be modeled using the “2004” 1.0 cm<sup>-1</sup> cross-section data. The H<sub>2</sub>O continuum absorption is being calculated using Version 2.5 of the MT-CKD model.

Molecular profiles are defined from model atmosphere No. 2, the mid-latitude summer model. The calculation will include a cumulus cloud.

### *The second page of the CloudProfile30sun8disort.tp6 output*

Figure 4.2 begins with vertical profiles of altitude [km], pressure [mbar], temperature [K], relative humidity [%] and water density [g/m<sup>3</sup>]. It also lists the name of the aerosol type (optical property model) and aerosol profile used at each altitude level. Lines containing stars (“\*\*\*”) are inserted in place of skipped data. If a scale factor for H<sub>2</sub>O is entered (none was used in this input), this table would contain the H<sub>2</sub>O profiles prior to adjusting for that scale factor.

```

CloudProfile30sun8disort.tp6

*****
* MODTRAN(R) 6.0.0.6
*
* MODTRAN is an atmospheric radiative transfer model
* developed collaboratively by SPECTRAL SCIENCES, INC
* (SSI) [www.spectral.com] and the AIR FORCE RESEARCH
* LABORATORY (AFRL) [www.kirtland.af.mil/afrl_vs/]
*
* Please address questions and/or comments to
* SSI at modtran@spectral.com and/or to AFRL
* at jeannette.van_den_bosch@us.af.mil
*
* WARNING: Versions of MODTRAN acquired via a
* "GOVERNMENT PURPOSE USE" agreement can
* only be used for Government Purposes.
*
* I/O file root name: CloudProfile30sun8disort
*****
Calculations will be done using multiple scattering.

CARD 1 *****M F 2F 2 2 1 2 2 2 2 2 2 1 OF -2 0.000 0.3000
PROGRAM WILL COMPUTE RADIANCE + SOLAR SCATTER

ATMOSPHERIC MODEL
TEMPERATURE = 2 MID-LATITUDE SUMMER
WATER VAPOR = 2 MID-LATITUDE SUMMER
OZONE = 2 MID-LATITUDE SUMMER
M4 = 2 M5 = 2 M6 = 2 MDEF = 1

CARD 1A ****TTF 8 0.0 380.00000 0.000E+00 0.000E+00 3 F 0.000b 0.0000 0.0000 0.0000 0.0000 0
SCALE FACTORS FOR UNIFORMLY MIXED MOLECULAR SPECIES DEFAULT PROFILES
CH4 1.05000

SCALE FACTORS FOR CROSS-SECTION MOLECULAR SPECIES DEFAULT PROFILES
F11 1.85000
F12 2.25000
F22 2.75000
F113 4.00000
CHCL2F 0.73000
H2-H2 0.00000
H2-HE 0.00000

MOLECULAR BAND MODEL DATA FILES
C:\ProgramData\SSI\MOD6DATA\01_2013c.bn4
C:\ProgramData\SSI\MOD6DATA\01_2013t.bn4

CFC BAND MODEL DATA FILE: C:\ProgramData\SSI\MOD6DATA\CFC04_01.ASC
Version 2.5 of the Mlawer, Tobin-Clough, Kneizys, Davies Water Continuum Data from LBLRTM (19oct2012).

CARD 2 ***** 1 Odef 0 3 1 0 0.00000 0.00000 0.00000 0.00000 0.00000
CARD 2A ***** -9.000 -9.000 -9.000 5 0 -9.000 -9.000 -9.000 -9.000 -9.000
MODEL ATMOSPHERE NO. 2
CLOUD AND/OR RAIN TYPE CHOSEN IS CUMULUS

```

**Figure 4.1.** CloudProfile30sun8disort.tp6 output, first page.

Cloud vertical profile and spectral data are listed next. The cloud profile input is said to contain 5 levels, but only 4 are listed. The input includes cloud densities that are zero at 0.0 km above ground level (AGL); that value is excluded from the table. The cloud profile altitudes are all AGL values. The reported cloud water droplet vertical column density,  $1.632 \text{ km g / m}^3$  is calculated from the vertical density profile [ $= 0.02 \text{ km} \times 0.34 \text{ g / m}^3 + 2.38 \text{ km} \times 0.68 \text{ g / m}^3 + 0.02 \text{ km} \times 0.34 \text{ g / m}^3$ ]. The optical or spectral properties of the built-in clouds do not vary with altitude. They are tabulated at 787 spectral points, having been generated from relatively high resolution liquid water complex index of refraction data.

Information of the scaling of the  $\text{O}_3$  and  $\text{H}_2\text{O}$  profiles is listed next. In this case, unit scaling was defined.

Geometry input data is listed at the end of Figure 4.2. The default Earth radius for the mid-latitude summer atmosphere is 6,371.23 km. A slant path between 2 altitudes is defined. Based on the hierarchy defined in Sections 2.3.4.2 and 3.7.1, the path is defined by the sensor altitude (H1ALT = 3.0 km), the final altitude (H2ALT = 0.0 km) and the zenith angle at the sensor (OBSZEN = 104.0°).

```

CloudProfile30sun8disort.tp6

Z          P          T          REL H      H2O      AEROSOL      AEROSOL
(KM)        (MB)        (K)        (%)   (GM / M3)  TYPE    PROFILE
[Before scaling]
0.0000000 1012.999 294.20 76.18 1.400E-01 RURAL      RURAL
1.0000000 901.996 289.70 66.03 9.296E-00 RURAL      RURAL
2.0000000 802.001 285.20 55.20 5.898E-00 RURAL      RURAL
3.0000000 709.996 279.20 45.29 3.297E-00 TROPOSPHERIC TROPOSPHERIC SPRING-SUMMER
4.0000000 628.000 273.20 39.05 1.899E-00 TROPOSPHERIC TROPOSPHERIC SPRING-SUMMER
5.0000000 553.997 267.20 31.42 9.996E-01 TROPOSPHERIC TROPOSPHERIC SPRING-SUMMER
6.0000000 486.998 261.20 29.98 6.100E-01 TROPOSPHERIC TROPOSPHERIC SPRING-SUMMER
7.0000000 426.000 254.70 30.31 3.696E-01 TROPOSPHERIC TROPOSPHERIC SPRING-SUMMER
8.0000000 371.999 248.20 29.63 2.099E-01 TROPOSPHERIC TROPOSPHERIC SPRING-SUMMER
9.0000000 323.999 241.70 30.15 1.199E-01 TROPOSPHERIC TROPOSPHERIC SPRING-SUMMER
10.0000000 280.999 235.30 29.44 6.396E-02 TROPOSPHERIC TROPOSPHERIC SPRING-SUMMER
11.0000000 243.000 228.80 19.48 2.199E-02 BCKGD_STRATOSPHERIC BCKGD_STRATOSPHERIC SPRING-SUMMER
12.0000000 208.999 222.30 10.69 5.997E-03 BCKGD_STRATOSPHERIC BCKGD_STRATOSPHERIC SPRING-SUMMER
***      ***      ***      ***      ***      ***
80.0000000 0.012000 174.10 0.07 3.136E-08 BCKGD_STRATOSPHERIC BCKGD_STRATOSPHERIC SPRING-SUMMER
100.0000000 0.000258 190.50 0.00 1.174E-10 BCKGD_STRATOSPHERIC BCKGD_STRATOSPHERIC SPRING-SUMMER

User-defined cloud/rain model profiles with 5 level altitudes.

USER-DEFINED CLOUD/RAIN PROFILES
(CLOUD WATER DROPLET VERTICAL COLUMN DENSITY: 1.63200 KM GM/M3)
(CLOUD ICE PARTICLE VERTICAL COLUMN DENSITY: 0.00000 KM GM/M3)

BOUNDARY LAYER      WATER          ICE          RAIN
NUMBER ALTITUDE     DROPLET      PARTICLE      RATE
(KM)           (GM/M3)      (GM/M3)      (MM/Hr)
1       0.09000 0.00000 0.00000 0.00000
2       0.11000 0.68000 0.00000 0.00000
3       2.49000 0.68000 0.00000 0.00000
4       2.51000 0.00000 0.00000 0.00000

END OF CLOUD/RAIN PROFILES

CLOUD SPECTRAL DATA

WATER DROPLETS          ICE PARTICLES
IWAV  WAVLEN      FREQ  VERT EXT  EXT COEF ABS COEF SCT COEF ASYM  SCT ALB  EXT COEF ABS COEF SCT COEF ASYM  SCT ALB
(MICRON) (CM-1)      (KM-1) (KM-1) (KM-1 M3/GM) (KM-1 M3/GM) (KM-1 M3/GM) (KM-1 M3/GM)
1       0.2000 50000.000 87.49074 127.59064 0.00988 127.58076 0.83770 0.99992 17.12653 0.00134 17.12519 0.86260 0.99992
2       0.2051 48756.703 87.51126 127.62058 0.00576 127.61482 0.84050 0.99995 17.12825 0.00123 17.12702 0.86490 0.99993
***      ***      ***      ***      ***      ***      ***      ***      ***      ***      ***      ***      ***
786  279.9000 35.727 9.15196 13.34661 12.62083 0.72577 0.05600 0.05438 28.29668 1.87451 26.42217 0.57450 0.93376
787  289.7000 34.518 8.80227 12.83664 12.19716 0.63948 0.05240 0.04982 27.57214 1.73047 25.84167 0.57310 0.93724

END OF CLOUD PARTICLE SPECTRAL DATA

*** OZONE DENSITIES ARE BEING SCALED BY 1.00000
THE ORIGINAL VERTICAL COLUMN CONTAINED 7.10288 GM / M2 OF OZONE
THE CURRENT VERTICAL COLUMN CONTAINS 7.10288 GM / M2 OF OZONE

*** THE WATER PROFILE WAS DECREASED TO FIT THE INPUT WATER COLUMN VALUE
INITIAL: 4.14382 GM / CM2
INPUT: 4.14382 GM / CM2
FINAL: 4.14382 GM / CM2

CARD 3 ***** 3.00000 0.00000 104.00000 0.00000 0.00000 0.00000 0.00000 0.00000
6371.23 RADIUS OF THE EARTH [KM]. 

SLANT PATH No. 1. H1ALT TO H2ALT
H1ALT = 3.00000 KM
H2ALT = 0.00000 KM
OBSZEN = 104.00000 DEG
HRANGE = 0.00000 KM
BETA = 0.00000 DEG
BCKZEN = 0.00000 DEG
CKRANG = 0.00000 KM
LENN = 0

```

**Figure 4.2.** CloudProfile30sun8disort.tp6 output, second page.

#### *The third page of the CloudProfile30sun8disort.tp6 output*

Solar scattering input data is provided at the top of Figure 4.3. The extra-terrestrial source is the sun, not the moon. The solar position is defined by a 48° relative solar azimuth from the sensor and a 30° solar zenith. The Earth to Sun distance is defined by day of year 93. Aerosol scattering is modeled with the internal Mie (spherical particle) scattering phase function data.

The input spectral parameters requested a 1,500 to 2,500 nm (1.5 to 2.5  $\mu\text{m}$ ) bandpass, with 2 nm triangular slit data generated each nm. In order to spectrally convolve with the selected slit function, MODTRAN pads the spectral range in frequency ( $\text{cm}^{-1}$ ) and generates data at the resolution of the band model. In this case, the spectral calculation extends from 3,920 to 6,805  $\text{cm}^{-1}$  (the endpoint are always multiples of 5  $\text{cm}^{-1}$ ) and both the spectral step size (**DV**) and resolution (**FWHM**) are set to 1.0  $\text{cm}^{-1}$ .



$67.6 \text{ [N}_2\text{]} + 60.5 \text{ [Ar]} + 3.5 \text{ [Ne]} + 158.1 \text{ [CO}_2\text{]} + 151.2 \text{ [CH}_4\text{]} + 56.5 \text{ [O}_2\text{]} + 13.4 \text{ [H}_2\text{]} + \text{[He]}$ , where the bracketed terms are mole fractions of the individual molecules and atoms.

- Refractivity, the real part of the index of refraction minus one [derived from B.A. Bodhaine, N.B. Wood, E.G. Dutton and J.R. Slusser, "on Rayleigh Optical Depth Calculations," Journal of Atmospheric and Oceanic Technology, vol. 16, 1854-1861 (1999)]

$$\text{refractivity} = P \left( 0.022226 + \frac{7.147815 \times 10^8}{1.32274 \times 10^{10} - \nu^2} + \frac{5.029045 \times 10^6}{3.932957 \times 10^9 - \nu^2} \right) \frac{1 + 5.40335 \times 10^{-7} [\text{CO}_2]}{T} - \left( 1.9809 \times 10^{-10} - 3.1759 \times 10^{-21} \nu^2 \right) [\text{H}_2\text{O}] T ,$$

where  $P$  is the level pressure in atm,  $\nu$  is the spectral frequency in  $\text{cm}^{-1}$  at 550 nm,  $[\text{CO}_2]$  is the level carbon dioxide density in ppmV,  $[\text{H}_2\text{O}]$  is the level water vapor density  $\text{g/m}^3$ , and  $T$  is the level temperature.

- Partial pressure of  $\text{O}_3$  [atm] times  $10^5$  cm / km [atm cm/km]
- Partial pressure of  $\text{O}_2$  [atm cm/km] scaled by  $1.00 + 0.83 (273.15/T)$  ( $P/1013.25$  mb) for use in calculating UV Herzberg absorption
- Cloud water droplet density [ $\text{g/m}^3$ ]
- Cloud ice particle density [ $\text{g/m}^3$ ]
- Rain rate [mm/hr]
- 550 nm extinction coefficient for Aerosol 1, nominally the boundary layer aerosol defined at 0, 1 and 2 km altitude [1/km]
- 550 nm extinction coefficient for Aerosol 2, nominally the tropospheric aerosol defined at 3, 4, ..., 10 km altitude [1/km]
- 550 nm extinction coefficient for Aerosol 3, nominally the stratospheric aerosol defined at 11, 12, ..., 25 and 30 km altitude [1/km]
- 550 nm extinction coefficient for Aerosol 4, nominally the volcanic aerosol defined at 35, 40, ..., 60, 70, 80 and 100 km altitude [1/km]
- AER1\*RH, the product of the Aerosol 1 extinction coefficient [1/km] and a % relative humidity, RH, weighting factor equal to  $\ln[\max(100 - \text{RH}, 1)]$
- Relative humidity before and after scaling of the  $\text{H}_2\text{O}$  profile [%]
- Cirrus, cloud water droplet and cloud ice particle 550 nm extinction coefficients [1/km]

#### The fourth page of the CloudProfile30sun8disort.tp6 output

As illustrated in Figure 4.4, the fourth page of the `CloudProfile30sun8disort.tp6` output begins with molecular profiles in units of atm cm/km. These values will be integrated along lines-of-sight in km to compute column densities in atm-cm. The twelve molecules,  $\text{H}_2\text{O}$  to  $\text{HNO}_3$ , are the ambient (default) band model species. The 13 molecules F11 through  $\text{N}_2\text{O}_5$  and the four dimers are modeled with temperature dependent absorption coefficient data. The dimer absorption is insignificant in the terrestrial atmosphere, but included because of their importance in planetary atmospheres.

Figure 4.3 included specification of the solar position, defining a  $30^\circ$  solar zenith and a  $48^\circ$  relative solar azimuth. For all solar (lunar) cases, MODTRAN actually specifies a sensor latitude and longitude, and a solar (lunar) latitude and longitude. When solar (lunar) zenith and the relative solar (lunar) azimuth at the sensor are entered, the sensor is placed at  $0.0^\circ$  Latitude and  $0.0^\circ$  Longitude, as shown in Figure 4.5. The sun (or moon) is also placed on the equator, West of the sensor. The longitude is computed to give the correct solar zenith angle, taking spherical refraction into account. In this case, a solar longitude of  $30.00652^\circ$  West of Greenwich produces a  $30^\circ$  solar zenith at the sensor. The true path azimuth is defined from the input relative solar azimuth,  $48^\circ$ . In this case, the true path azimuth from the sensor ([H1ALT](#)) to the final altitude ([H2ALT](#)) is  $222.0^\circ$  East of North.









azimuth and the solar scattering angle, all in units of degrees. For the vertical path, the path zenith is a constant  $0.0^\circ$ . The relative solar azimuth and solar zenith inputs were  $48^\circ$  and  $30^\circ$  (in single precision), respectively, at the sensor (3.0 km altitude). These values are replicated in the table at 3.0 km. Of course, the relative solar azimuth is arbitrary for a zenith path. Spherical refraction affects the solar zenith angle, so that it is close to but not a constant value. The solar scattering angle equals the solar zenith angle for the vertical path.



computed upward from the path minimum altitude. If the LOS path had passed through a tangent point, this table would begin at the tangent height and contain two parts: one part for the lower segments which reside on both sides of the tangent point, and a second part containing the upper segments which reside on only one side of the tangent point. For the current LOS geometry, the refracted path is computed from the ground up to the 3.0 km sensor. For each path segment, the table includes

- the lower endpoint zenith angle, START TO END ZENITH [deg];
- the segment range, DELTA RANGE [km];
- the cumulative range TOTAL RANGE [km];
- the Earth center angle subtended by the segment, DELTA EARTH ANGLE [deg];
- the Earth center angle subtended by the cumulative path, EARTH CENTER ANGLE [deg];
- the zenith angle from the higher endpoint down to the lower endpoint, END TO START ZENITH [deg];
- the segment bending due to refraction, DELTA BENDING [deg];
- the cumulative path bending due to refraction, PATH BENDING [deg];
- the segment-averaged, density-weighted pressure, LAYER AVERAGE PRESSURE [mb];
- the segment-averaged, density-weighted temperature, LAYER AVG TEMP [K]; and
- segment-averaged density, LAYER AVERAGE DENSITY [g/cm<sup>3</sup>].

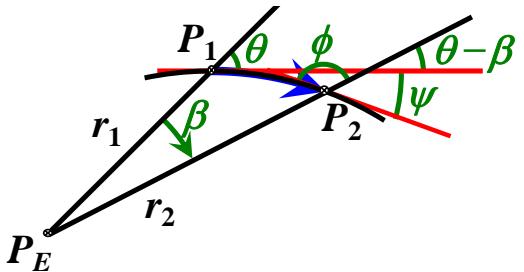
These latter three quantities are defined as described in the *fifth page* section. Note that the END TO START ZENITH of segment  $N$  must equal  $180^\circ$  minus the START TO END ZENITH of segment  $N+1$ ; considering the first two segments,  $103.91013^\circ$  plus  $76.08987^\circ$  equals  $180.00000^\circ$ .

The final table of Figure 4.8 contains the first LOS path-segment column-amount data. The definition of the column amount data is the same as that defined for Figure 4.5.

#### The ninth page of the CloudProfile30sun8disort.tp6 output

The remaining LOS path segment absorber and scatterer amounts are included in Figure 4.9. The first line in these tables contains the data for the segment from H1ALT (3.0 km) down to altitude level at 2.51 km, while the last line in these tables, Segment No. 7, contains the data for the segment from the altitude level at 0.09 km down to the ground at 0.0 km. The content of these output columns were described in the sections on the fifth and sixth page of `CloudProfile30sun8disort.tp6` output.

A summary of the LOS spherical refraction calculation is included at the end of Figure 4.9. Reiterating, the LOS was defined by the inputs were H1ALT = 3.0 km, H2ALT = 0.0 km and OBSZEN =  $104^\circ$ . With the defined refractivity profile (Figure 4.3), and the default Earth radius (Figure 4.2), the spherical refractive geometry path constant equation dictates that the zenith angle from H2ALT to H1ALT, i.e., BCKZEN, is  $76.09258^\circ$  [ $1.000197288$  (6374.23 km)  $\sin(104^\circ)$  =  $1.0002666564$  (6371.23 km)  $\sin(76.09258^\circ)$ ]. The spherical refractive geometry calculation computes a path range of HRANGE = 12.44140 km and a subtended Earth Center Angle of ECA =  $0.10856^\circ$ . The path does not pass through a tangent height (LENN equals 0), so the path minimum is the final altitude for the downward path, i.e. the 0.0 km ground altitude. As illustrated in the figure on the upper right in this paragraph, the path BENDING  $\psi$  is equal to the Earth Center Angle (ECA)  $\beta$  plus  $180^\circ$  minus the sum of the path zenith from H1ALT to H2ALT (OBSZEN)  $\theta$  and the path zenith from H2ALT to H1ALT (BCKZEN)  $\phi$ . In this case, BENDING =  $0.10856^\circ + 180^\circ - (104^\circ + 76.09258^\circ)$  =  $0.01598^\circ$  [Clearly, the difference between  $0.01598^\circ$  and the reported  $0.01597^\circ$  is just numerical roundoff]. The final value in the LOS summary is actually an input, CKRANG, which dictates the quantity of  $k$ -distribution dependent output (see Section 4.7).









surface leaving radiance can directly transmit to the sensor.



testcase, there is no sensor to ground transmittance, so the 3920 to 6805  $\text{cm}^{-1}$  band absorptivity (one minus transmittance) is  $(6805 \text{ cm}^{-1} - 3920 \text{ cm}^{-1}) \times (1.0000 - 0.0000) = 2885 \text{ cm}^{-1}$ .

Band model transmittances in MODTRAN are computed using a truncated infinite series. If this series does not converge for at least one frequency, for at least one band model molecule and for at least one path segment, then the largest magnitude of the last term in the transmittance sum is written out. In Figure 4.12, that term has a magnitude of 0.01504. Since the terms after the first few tend to have oscillating signs and decreasing magnitude, the transmittance residual is generally much smaller than the magnitude of the 8<sup>th</sup> term.

Values are provided for the band pass integrated total radiance, minimum spectral radiance and maximum spectral radiance. When updates are made to MODTRAN, these values sometimes change. However, the change in the integrated total radiance and the maximum spectral radiance values is seldom significant.

Area-averaged and imaged-pixel temperature and band pass emissivity (one minus Lambertian reflectivity) inputs are also written to the <ROOTNAME>.tp6 output file. If the adjacency option is used, these values can differ. That is not the case in Figure 4.12, where both temperatures are 294.2 K and both emissivities are 0.7.

Finally, unconvolved and convolved integrated radiances are generated for the input band pass. Unlike the integrated total radiance above, values are not summed for spectral padding frequencies. The unconvolved sum is the integral over the band model resolution data, while the convolved sum is the integral over the data convolved with the slit function.

### 4.3 Spectral Output

MODTRAN6's primary spectral output when the default slit function option is invoked, i.e. the input character string `FLAGS[0:3]` is blank, is written to <ROOTNAME>.csv, <ROOTNAME>.txt and/or <ROOTNAME>.sli files if the `CSVRNT` or `SLPRNT` are defined. These files contain transmittance, radiance and/or irradiance data. The same data can also be written to a legacy <ROOTNAME>.tp7 file; spectral path transmittance, total radiance or transmitted irradiance data can also be written to a legacy two column <ROOTNAME>.plt file. Many inputs affect the selection of `spectral` outputs, in particular `IEMSCT`, which defines the type of radiative transfer calculation. The keywords of the JSONObjects which correspond to the different selections for `IEMSCT` are listed in Table 4.3. For each case, the content is described in the table listed.

**Table 4.3.** `Spectral` keywords.

Keyword	Table	Mode	<code>IEMSCT</code>
TRANSMITTANCE	4.4	Transmittance only mode	RT_TRANSMITTANCE
RADIANCE	4.5	Thermal emission (with or without scattering)	RT_THERMAL_ONLY
		Thermal plus solar radiance calculations (with or without thermal scatter and solar multiple scatter)	RT_SOLAR_AND_THERMAL
		Thermal plus lunar radiance calculations (with or without thermal scatter and lunar multiple scatter)	RT_LUNAR_AND_THERMAL
IRRADIANCE	4.6	Transmitted solar irradiance	RT_SOLAR_IRRADIANCE
		Transmitted lunar irradiance	RT_LUNAR_IRRADIANCE

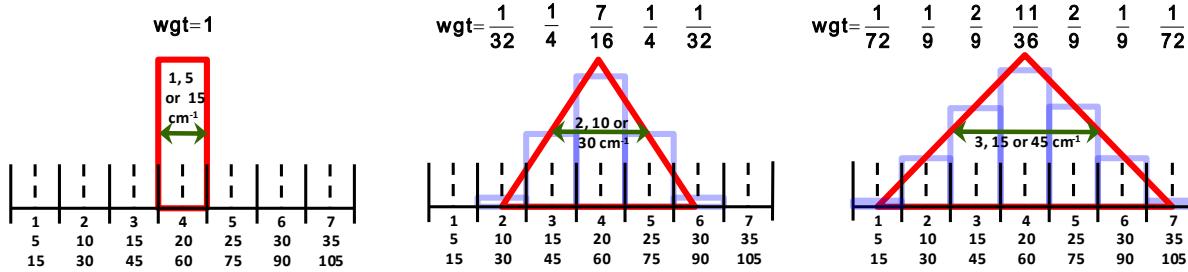
Whenever the input character string `FLAGS[0:3]` is blank, i.e., if the default triangular slit function option is invoked, the spectral bandpass lower bound, `V1`, the spectral upper bound, `V2`, the output step size or increment, `DV`, and the spectral resolution of the slit function, `FWHM`, are all frequency values in units of  $\text{cm}^{-1}$ . The `FWHM` can either be equal to or a multiple of the band model spectral bin resolution. When the `FWHM` and the MODTRAN band model spectral resolution are equal, a rectangular slit function

is used to generate output at the resolution of the band model with no spectral degradation. If, on the other hand, the input [FWHM](#) is a multiple of the band model resolution, then a discretized triangular slit function is defined. The procedure for weighting the spectral bin contributions is illustrated in Figure 4.13. Note that an odd number of spectral bins contribute to the triangular slit function for the 1, 5 and 15  $\text{cm}^{-1}$  band models, but an even number of bins contribute to the 0.1  $\text{cm}^{-1}$  band model. This difference arises because the 1, 5 and 15  $\text{cm}^{-1}$  spectral bins are centered on multiples of 1, 5, and 15  $\text{cm}^{-1}$ , while the edges of the 0.1  $\text{cm}^{-1}$  bins are multiples of 0.1  $\text{cm}^{-1}$ .

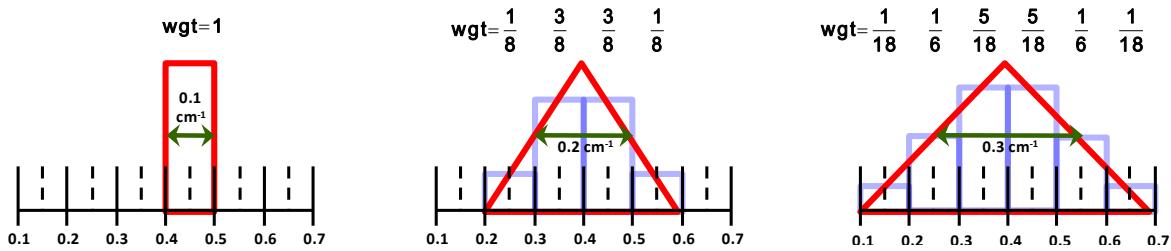
In Figure 4.13, the width of the green double-arrowed lines equals the [FWHM](#). The normalized spectral bin weights listed above the bins equal the fraction of total slit function area within each bin. MODTRAN models the (red) triangular slit functions with the discretized (purple) rectangular representation.

If the character string [FLAGS\[0:3\]](#) in [SPECTRAL](#) is not blank, a scanning (slit) function is defined. In this case, generated <ROOTNAME>.csv, <ROOTNAME>.txt, <ROOTNAME>.sli, <ROOTNAME>.tp7, and two column <ROOTNAME>.plt files will contain spectral data at the band model resolution, with no spectral degradation. The spectral region will be padded to provide the spectral coverage required to perform the scanning function convolution. The primary (scanned) spectral output is written to the <ROOTNAME>[\\_scan.csv](#), <ROOTNAME>[\\_scan.txt](#), <ROOTNAME>[\\_scan.sli](#), <ROOTNAME>[.7sc](#), and two column <ROOTNAME>[.psc](#) files.

## Coarser Spectral Resolution (1, 5 and 15 $\text{cm}^{-1}$ ) MODTRAN Band Models



## Finest Spectral Resolution (0.1 $\text{cm}^{-1}$ ) MODTRAN Band Model



**Figure 4.13.** Triangular slit function convolutions.

### 4.3.1 Transmittance Only Spectral Output

The unscanned [AngstromLaw.csv](#) and scanned [AngstromLaw\\_scan.csv](#) files, as displayed by Microsoft Excel, are illustrated for the [AngstromLaw](#) test case in Figures 4.14 and 4.15, respectively; two changes were made to the test case: the band model resolution was changed from 15 to 5  $\text{cm}^{-1}$  and the output step size, [DV](#), was decreased to 10  $\text{cm}^{-1}$ . The [FWHM](#) value of 15  $\text{cm}^{-1}$  was retained. The file output selections were modified to generate all legacy output, .csv output files and ENVI .sli output files. The [AngstromLaw.csv](#) file of Figure 4.14 provides the raw 5  $\text{cm}^{-1}$  band model data for the extended 3580 to 28625  $\text{cm}^{-1}$  spectral range. In Figure 4.15, the spectral data in the [AngstromLaw\\_scan.csv](#)

output file is written on the requested 10 cm<sup>-1</sup> grid with no spectral padding, covering the 3600 to 28600 cm<sup>-1</sup> spectral range.

It is edifying to verify the scanning function calculation. Consider the scanned H<sub>2</sub>O continuum transmittance value at 3600 cm<sup>-1</sup> from column H in Figure 4.15, namely 8.89E-07. According to upper right illustration in Figure 4.13, the 15 cm<sup>-1</sup> triangular slit value should equal the sum of 5 cm<sup>-1</sup> band model H<sub>2</sub>O continuum transmittances from column H of Figure 4.14, weighted by 1/72 at 3585 and 3615 cm<sup>-1</sup>, by 1/9 at 3590 and 3610 cm<sup>-1</sup>, by 2/9 at 3595 and 3605 cm<sup>-1</sup> and by 11/36 at 3600 cm<sup>-1</sup>. Indeed, one finds that  $(1.52\text{E}-05 + 4.04\text{E}-10) / 72 + (3.89\text{E}-06 + 3.72\text{E}-09) / 9 + 2 \times (8.33\text{E}-07 + 2.58\text{E}-08) / 9 + 11 \times (1.78\text{E}-07) / 36$  equals 8.889856E-07  $\cong$  8.89E-07.

The screenshot shows two tables in Microsoft Excel. The top table is titled 'AngstromLaw.csv - M' and has a header row with column labels A through T. It contains data for various atmospheric species like H<sub>2</sub>O, CO<sub>2</sub>, CH<sub>4</sub>, etc., with numerical values ranging from 0 to 1. The bottom table has a header row with column labels U through AM and contains similar data for other species like SO<sub>2</sub>, cloud, F11, etc.

**Figure 4.14.** Head and tail of AngstromLaw.csv 5 cm<sup>-1</sup> spectral resolution band model transmittance output with step size DV = 10 cm<sup>-1</sup> and FWHM = 15 cm<sup>-1</sup>: left side on top and right side on bottom.

Table 4.4 provides a description of the content in each column of the <ROOTNAME>.csv and <ROOTNAME>\_scan.csv files for a spectral transmittance only run. The header of the first column of the <ROOTNAME>\_scan.csv file can have one of three values: Freq [cm<sup>-1</sup>], Waveln [um] or Waveln [nm]. Columns B (combin trans) through AM (CH4-CH4 trans) all have fixed headers for transmittance only runs. If auxiliary species are included in the MODTRAN run by setting RTOPTIONS keyword LYMOLC to “TRUE” and/or by setting PROFILES keyword TYPE to “PROF\_USER\_DEF”, an additional column is added beyond Column AM for each new species.

Figures 4.16 and 4.17 contain the AngstromLaw.hdr and AngstromLaw\_scan.hdr ENVI header

files. The number of samples corresponds to the number of spectral points. The number of lines corresponds to the number of columns of data. The “wavelength” units can be “Wavenumbers”, “Microns” or “Nanometers” (Obviously, “Wavenumbers” is a frequency unit, not a wavelength unit).

The head and tail of the legacy AngstromLaw.tp7 and AngstromLaw.7sc files are illustrated in Figures 4.18 and 4.19, respectively. The column entries identical to those in the AngstromLaw.csv and AngstromLaw\_scan.csv files. However, the legacy files include additional header and tail data that was originally introduced to be used with a plotting package included with the LOWTRAN distribution, circa 1985.

The screenshot shows a Microsoft Excel spreadsheet titled "AngstromLaw\_scan.csv -". The top portion displays the first 13 rows of data, which include header information and several data columns. The columns are labeled with various chemical species and processes, such as H2O, umix, O3, trace, N2, H2Ocnt, molec, aercl, HNO3, aercl, CO2, CO, CH4, N2O, O2, NH3, NO, and NO2. The bottom portion of the screenshot shows the last few rows of data, continuing the pattern established in the header.

**Figure 4.15.** Head and tail of AngstromLaw\_scan.csv slit function transmittance output with the  $5\text{ cm}^{-1}$  band model, step size  $\text{DV} = 10\text{ cm}^{-1}$  and  $\text{FWHM} = 15\text{ cm}^{-1}$ : left-hand side on top and right-hand side on bottom.

**Table 4.4.** Spectral transmittance output descriptions. This output is only generated when the [MODTRN](#) keyword equals [RT\\_MODTRAN](#); individual species transmittances are not computed when the correlated- $k$  and the line-by-line radiative transfer options are invoked.

Header	Description
Freq [cm <sup>-1</sup> ]	<ROOTNAME>_scan.csv slit function central frequency in cm <sup>-1</sup> . Also the slit function central frequency in cm <sup>-1</sup> in the <ROOTNAME>.csv file if no <ROOTNAME>_scan.csv file is generated; when the scanned file is generated, this <ROOTNAME>.csv file column contains the band model spectral bin central frequency.
Waveln [um]	<ROOTNAME>_scan.csv slit function central wavelength in microns
Waveln [nm]	<ROOTNAME>_scan.csv slit function central wavelength in nanometers
combin trans	Slit function or band model direct transmittance for the line-of-sight (LOS) path, combining the extinction from all molecular and particulate sources.
H2O trans	Slit function or band model spectral bin water vapor (H <sub>2</sub> O) transmittance for LOS path EXCLUDING water continuum contributions

<b>Header</b>	<b>Description</b>
umix trans	Slit function or band model spectral bin uniformly mixed gases (CO <sub>2</sub> , CO, CH <sub>4</sub> , N <sub>2</sub> O and O <sub>2</sub> ) transmittance for LOS path
O3 trans	Slit function or band model spectral bin ozone (O <sub>3</sub> ) transmittance for LOS path
trace trans	Trace gas transmittance for LOS path. The trace gases are defined here to include NH <sub>3</sub> , NO, NO <sub>2</sub> , SO <sub>2</sub> and HNO <sub>3</sub> . Water vapor, the uniformly mixed gases, ozone and the trace gases together constitute the 12 MODTRAN default band model species
N2 trans	Slit function or band model spectral bin nitrogen gas (N <sub>2</sub> ) continuum transmittance for LOS path
H2Ocnt trans	Slit function or band model spectral bin water vapor (H <sub>2</sub> O) continuum transmittance for LOS path
molec scat	Slit function or band model spectral bin molecular (Rayleigh) scattering transmittance for LOS path
aercl trans	Slit function or band model spectral bin aerosols plus clouds transmittance for LOS path
HNO3 trans	Slit function or band model spectral bin nitric acid (HNO <sub>3</sub> ) transmittance for LOS path
aercl abtrns	Slit function or band model spectral bin transmittance for LOS path resulting from aerosol and cloud absorption. This term excludes the extinction from aerosol and cloud scattering.
CO2 trans	Slit function or band model spectral bin carbon dioxide (CO <sub>2</sub> ) transmittance for LOS path
CO trans	Slit function or band model spectral bin carbon monoxide (CO) transmittance for LOS path
CH4 trans	Slit function or band model spectral bin methane (CH <sub>4</sub> ) transmittance for LOS path
N2O trans	Slit function or band model spectral bin nitrous oxide (N <sub>2</sub> O) transmittance for LOS path
O2 trans	Slit function or band model spectral bin oxygen gas (O <sub>2</sub> ) transmittance for LOS path
NH3 trans	Slit function or band model spectral bin ammonia (NH <sub>3</sub> ) transmittance for LOS path
NO trans	Slit function or band model spectral bin nitric oxide (NO) transmittance for LOS path
NO2 trans	Slit function or band model spectral bin nitrogen dioxide (NO <sub>2</sub> ) transmittance for LOS path
SO2 trans	Slit function or band model spectral bin sulfur dioxide (SO <sub>2</sub> ) transmittance for LOS path
cloud trans	Slit function or band model spectral bin cirrus plus water cloud transmittance for LOS path
F11 trans	Slit function or band model spectral bin trichlorofluoromethane (CCl <sub>3</sub> F) transmittance for LOS path
F12 trans	Slit function or band model spectral bin dichlorodifluoromethane (CCl <sub>2</sub> F <sub>2</sub> ) transmittance for LOS path
CCl3F trans	Slit function or band model spectral bin chlorotrifluoromethane (CClF <sub>3</sub> ) transmittance for LOS path
CF4 trans	Slit function or band model spectral bin carbon tetrafluoride (CF <sub>4</sub> ) transmittance for LOS path
F22 trans	Slit function or band model spectral bin chlorodifluoromethane (CHClF <sub>2</sub> ) transmittance for LOS path
F113 trans	Slit function or band model spectral bin 1,1,2-trichlorotrifluoroethane (Cl <sub>2</sub> FC-CClF <sub>2</sub> ) transmittance for LOS path
F114 trans	Slit function or band model spectral bin 1,2-dichlorotetrafluoroethane (ClF <sub>2</sub> C-CClF <sub>2</sub> ) transmittance for LOS path
F115 trans	Slit function or band model spectral bin chloropentafluoroethane (ClF <sub>2</sub> C-CF <sub>3</sub> ) transmittance for LOS path
CIONO2 trans	Slit function or band model spectral bin chlorine nitrate (CIONO <sub>2</sub> ) transmittance for LOS path
HNO4 trans	Slit function or band model spectral bin hydroxyl nitrate (HNO <sub>4</sub> ) transmittance for LOS path
CHCl2F trans	Slit function or band model spectral bin dichlorofluoromethane (CHCl <sub>2</sub> F) transmittance for LOS path
CCl4 trans	Slit function or band model spectral bin carbon tetrachloride (CCl <sub>4</sub> ) transmittance for LOS path
N2O5 trans	Slit function or band model spectral bin dinitrogen pentoxide (N <sub>2</sub> O <sub>5</sub> ) transmittance for LOS path
H2-H2 trans	Slit function or band model spectral bin transmittance arising from H <sub>2</sub> -H <sub>2</sub> collision induced absorption (CIA) for LOS path

Header	Description
H2–He trans	Slit function or band model spectral bin transmittance arising from H <sub>2</sub> –He CIA for LOS path
H2–CH <sub>4</sub> trans	Slit function or band model spectral bin transmittance arising from H <sub>2</sub> –CH <sub>4</sub> CIA for LOS path
CH <sub>4</sub> –CH <sub>4</sub> trans	Slit function or band model spectral bin transmittance arising from CH <sub>4</sub> –CH <sub>4</sub> CIA for LOS path
Aux Species trans	Slit function or band model spectral bin transmittance arising from input set of auxiliary species for LOS path

<b>AngstromLaw.hdr</b>	
<pre> ENVI description = {     MODTRAN transmittance spectra. } samples = 5010 lines = 38 bands = 1 header offset = 0 file type = ENVI Spectral Library data type = 4 interleave = bsq byte order = 0 wavelength units = Wavenumbers spectra names = {     combin trans, H2O trans, umix trans, O3 trans, trace trans, N2 trans,     H2Ocnt trans, molec scat, aerclid trans, HNO3 trans, aerclid abtrns, CO2 trans,     CO trans, CH4 trans, N2O trans, O2 trans, NH3 trans, NO trans, M02 trans,     SO2 trans, cloud trans, F11 trans, F12 trans, CC13F trans, CF4 trans,     F22 trans, F113 trans, F114 trans, F115 trans, ClONO2 trans, HNO4 trans,     CHC12F trans, CC14 trans, N205 trans, H2-H2 trans, H2-He trans, H2-CH4 trans,     CH4-CH4 trans } wavelength = {     3580, 3585, 3590, 3595, 3600, ..., 28605, 28610, 28615, 28620, 28625 }</pre>	

**Figure 4.16.** The AngstromLaw.hdr ENVI header file for the AngstromLaw test case run with the 5 cm<sup>-1</sup> band model, a step size DV equal to 10 cm<sup>-1</sup> and the FWHM equal to 15 cm<sup>-1</sup>.

<b>AngstromLaw_scan.hdr</b>	
<pre> ENVI description = {     MODTRAN transmittance spectra. } samples = 2501 lines = 38 bands = 1 header offset = 0 file type = ENVI Spectral Library data type = 4 interleave = bsq byte order = 0 wavelength units = Wavenumbers spectra names = {     combin trans, H2O trans, umix trans, O3 trans, trace trans, N2 trans,     H2Ocnt trans, molec scat, aerclid trans, HNO3 trans, aerclid abtrns, CO2 trans,     CO trans, CH4 trans, N2O trans, O2 trans, NH3 trans, NO trans, M02 trans,     SO2 trans, cloud trans, F11 trans, F12 trans, CC13F trans, CF4 trans,     F22 trans, F113 trans, F114 trans, F115 trans, ClONO2 trans, HNO4 trans,     CHC12F trans, CC14 trans, N205 trans, H2-H2 trans, H2-He trans, H2-CH4 trans,     CH4-CH4 trans } wavelength = {     3600, 3610, 3620, 3630, 3640, ..., 28560, 28570, 28580, 28590, 28600 }</pre>	

**Figure 4.17.** The AngstromLaw\_scan.hdr ENVI header file for the AngstromLaw test case run with the 5 cm<sup>-1</sup> band model, a step size DV equal to 10 cm<sup>-1</sup> and the FWHM equal to 15 cm<sup>-1</sup>.





**Figure 4.22.** Head and tail of SolarRadiance\_Nanometers\_Ocean\_scan.csv radiance output file.

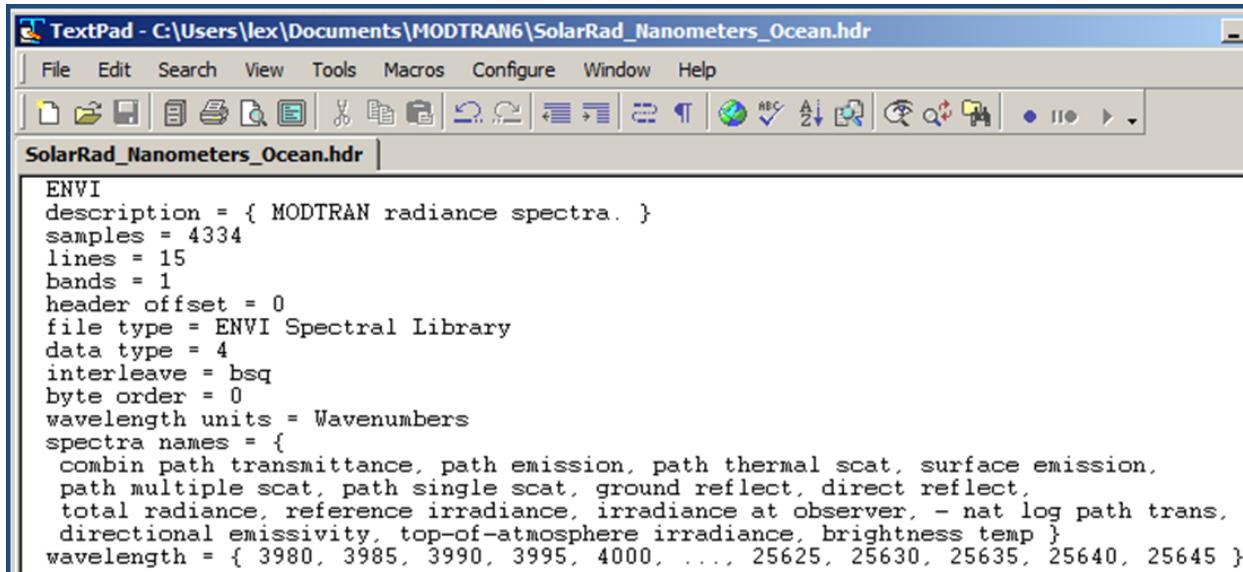
**Table 4.5.** Spectral radiance output descriptions. If the spectral grid is a frequency, specified in  $\text{cm}^{-1}$ , then the units for radiances is  $\text{W cm}^{-2} \text{ sr}^{-1}/\text{cm}^{-1}$  and the units for irradiances is  $\text{W cm}^{-2}/\text{cm}^{-1}$ . Alternatively, if a spectral wavelength grid is defined in units of  $\mu\text{m}$  (nm), then the units for radiances are  $\text{W cm}^{-2} \text{ sr}^{-1}/\mu\text{m}$  ( $\mu\text{W cm}^{-2} \text{ sr}^{-1}/\text{nm}$ ) and the units for irradiances are  $\text{W cm}^{-2}/\mu\text{m}$  ( $\mu\text{W cm}^{-2}/\text{nm}$ ).

Header	Description
Freq [cm <sup>-1</sup> ]	<ROOTNAME>_scan.csv slit function central frequency in $\text{cm}^{-1}$ . Also the slit function central frequency in $\text{cm}^{-1}$ in the <ROOTNAME>.csv file if no <ROOTNAME>_scan.csv file is generated; when the scanned file is generated, this <ROOTNAME>.csv file column contains the band model spectral bin central frequency.
Waveln [um]	<ROOTNAME>_scan.csv slit function central wavelength in microns
Waveln [nm]	<ROOTNAME>_scan.csv slit function central wavelength in nanometers
combin path trans	Slit function or band model direct transmittance for the line-of-sight (LOS) path, combining the extinction from all molecular and particulate sources.
path emission	Slit function or band model LOS path thermal emission, modeled with linear-in-tau variations of the Planck emission across path segments
path thermal scat	Slit function or band model atmospherically scattered path thermal radiance, i.e. the thermal radiation scattered by the atmosphere directly into the LOS and transmitted to the sensor. This includes photons that were emitted from and reflected off the ground before being atmospherically scattered into the LOS.
surface emission	Slit function or band model surface emission directly transmitted to the sensor. If the LOS terminates at the ground, this term is computed as the product of the Planck surface emission, the surface directional emissivity and the sensor-to-surface path transmittance. If the LOS does not terminate at the ground BUT a positive temperature is specified for the input <a href="#">SURFACE</a> keyword <a href="#">TPTEMP</a> , SURF_EMIS will contain the transmitted surface emission of a target object. If the LOS does not terminate at the ground AND the input <a href="#">SURFACE</a> keyword <a href="#">TPTEMP</a> is zero, then the surface emission is zero.
path multiple scatter	Slit function or band model solar/lunar radiation multiply scattered before being directly transmitted to the sensor. This excludes the single scatter component, sing scat (Previously, sol scat, the sum of sing scat and path multiple scatter, not path multiple scatter).
sing scat	Slit function or band model path single scatter solar/lunar radiance
grnd rflt	Slit function or band model ground reflected radiation directly transmitted to the sensor. It includes reflection of 3 downward flux components: direct solar, diffuse solar and diffuse thermal
drct rflt	Slit function or band model direct solar component of grnd rflt, i.e., the radiance arising from solar photons which travel along the Sun to ground to sensor path without being scattered or absorbed by the atmosphere
total rad	Slit function or band model total radiance observed by a sensor. This is the sum of path emission, path thermal scat, surface emission, path multiple scatter, sing scat and grnd rflt.
irrad ref	Slit function or band model product of the sensor-to-final_altitude-to-Sun transmittance (final_altitude is either the ground, the TOA or <a href="#">H2ALT</a> ) and the TOA solar/lunar irradiance. This irradiance does not include the surface Bidirectional Reflectance Distribution Function (BRDF) term. The output was introduced for use with target insertion applications.
irrad @obs	Slit function or band model solar/lunar irradiance transmitted to the observer, calculated as the product of the TOA spectral solar/lunar irradiance and the Sun to sensor or observer ( <a href="#">H1ALT</a> ) spectral transmittance.
- nat log path trans	The negative natural logarithm of the slit function or band model combin path trans. Since band model transmittances do not obey Beer's Law, this term should not be equated with an optical depth when the fine spectral structure within the spectral bin is significant.
direct emiss	Slit function or band model directional emissivity at ground towards sensor (between 0 and 1 inclusive).

Header	Description
ToA irrad	Slit function or band model top-of-atmosphere (TOA) solar irradiance.
bbody temp [K]	Slit function or band model brightness temperature in Kelvin, defined as the temperature a black-body needs to have to emit the total rad radiance. The calculation method, is described in [11].

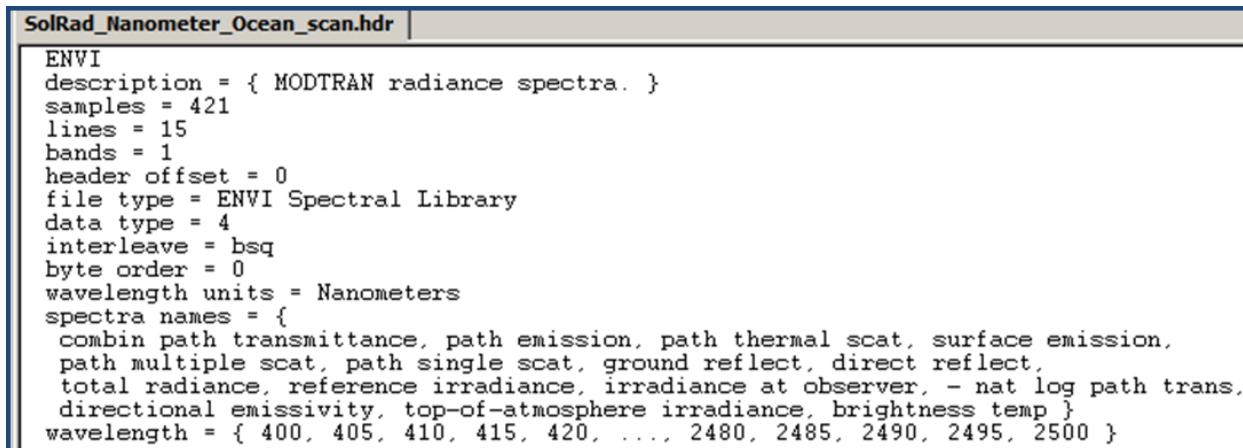
Table 4.5 provides a description of the content in each column of the <ROOTNAME>.csv and <ROOTNAME>\_scan.csv files for a spectral radiance run. The header of the first column of the <ROOTNAME>\_scan.csv file can have one three values: Freq [cm<sup>-1</sup>], Waveln [um] or Waveln [nm]. Columns B (combin path trans) through P (bbody temp [K]) all have fixed headers.

Figures 4.23 and 4.24 contain the ENVI header files SolarRadiance\_Nanometers\_Ocean.hdr and SolarRadiance\_Nanometers\_Ocean\_scan.hdr. The number of samples corresponds to the number of spectral points. The number of lines corresponds to the number of columns of data. The “wavelength” units can be “Wavenumbers”, “Microns” or “Nanometers” (Obviously, “Wavenumbers” is a frequency unit, not a wavelength unit). The spectra names are in one-to-one correspondence with those in Table 4.5, but a number of them have expanded descriptions.



```
TextPad - C:\Users\lex\Documents\MODTRAN6\SolarRad_Nanometers_Ocean.hdr
File Edit Search View Tools Macros Configure Window Help
SolarRad_Nanometers_Ocean.hdr |
ENVI
description = { MODTRAN radiance spectra. }
samples = 4334
lines = 15
bands = 1
header offset = 0
file type = ENVI Spectral Library
data type = 4
interleave = bsq
byte order = 0
wavelength units = Wavenumbers
spectra names =
  combin path transmittance, path emission, path thermal scat, surface emission,
  path multiple scat, path single scat, ground reflect, direct reflect,
  total radiance, reference irradiance, irradiance at observer, - nat log path trans,
  directional emissivity, top-of-atmosphere irradiance, brightness temp }
wavelength = { 3980, 3985, 3990, 3995, 4000, ..., 25625, 25630, 25635, 25640, 25645 }
```

**Figure 4.23.** The SolarRadiance\_Nanometers\_Ocean.hdr ENVI header file for the Ocean View Preset Configuration, generated by the MODTRAN6 GUI.



```
SolRad_Nanometer_Ocean_scan.hdr |
ENVI
description = { MODTRAN radiance spectra. }
samples = 421
lines = 15
bands = 1
header offset = 0
file type = ENVI Spectral Library
data type = 4
interleave = bsq
byte order = 0
wavelength units = Nanometers
spectra names =
  combin path transmittance, path emission, path thermal scat, surface emission,
  path multiple scat, path single scat, ground reflect, direct reflect,
  total radiance, reference irradiance, irradiance at observer, - nat log path trans,
  directional emissivity, top-of-atmosphere irradiance, brightness temp }
wavelength = { 400, 405, 410, 415, 420, ..., 2480, 2485, 2490, 2495, 2500 }
```



## Example of ENVI Spectral Library Header File, from SolarIrrad:

```
ENVI
description = {
    MODTRAN irradiance spectra. }
samples = 1531
lines = 4
bands = 1
header offset = 0
file type = ENVI Spectral
Library data type = 4
interlea e = bsq
byte order = 0
wavelength units = Wavenumbers
spectra names = {
    path transmittance, irradiance, top-of-atmosphere irradiance, optical depth }wavelength = {
5985, 5986, 5987, 5988, 5989, 5990, 5991, 5992, 5993, 5994, 5995, 5996, 5997,
5998, 5999, 6000, 6001, 6002, 6003, 6004, 6005, 6006, 6007, 6008, 6009, 6010,
6011, 6012, 6013, 6014, 6015, 6016, 6017, 6018, 6019, 6020, 6021, 6022, 6023,
6024, 6025, 6026, 6027, 6028, 6029, 6030, 6031, 6032, 6033, 6034, 6035, 6036,
6037, 6038, 6039, 6040, 6041, 6042, 6043, 6044, 6045, 6046, 6047, 6048, 6049,
...
}
```

Note that if the spectral library is \_scan output, the wavelength units can be either Wavenumbers, Micrometers, or Nanometers depending on the input.

## 4.4 Channel Output

The Channel Output are data that have been spectrally convolved with sensor response function (SRF) data. It is generated whenever the full path file name of a sensor filter file is provided using the [FILTNM](#) keyword. The MODTRAN distribution includes filter files for a number of sensors in its DATA directory:

- |                                   |   |
|-----------------------------------|---|
| • AIRS                            | airs.flt;   |
| • ASTER                           | ASTER_swir.flt, ASTER_tir.flt and ASTER_vnir.flt; |
| • AVIRIS                          | aviris.flt and aviris_05_bb1.flt;                 |
| • GOES                            | GOES12ir.flt;                                     |
| • HyspIRI                         | HyspIRI_TIR.flt;                                  |
| • LANDSAT-5                       | landsat5.flt;                                     |
| • LANDSAT-7                       | landsat7.flt;                                     |
| • LANDSAT-8                       | landsat8.flt;                                     |
| • MODIS                           | modis399_2176nm.flt and modis3p615_14p532.flt;    |
| • CERES-PFM                       | PFM1998011.flt;                                   |
| • ITRES®-TASI                     | TASI.flt; and                                     |
| • The Yankee MSR-7 spectrometers: | yankee.flt.                                       |

These 2-column files contain sensor channel or band spectral response function values. The format of these files is described in Section 3.9 for those who wish to create their own sensor filter file.

There are just 3 keywords in CHANNEL\_SPECTRA; these are the keywords of the JSONObjects which correspond to the different selections for [ITEMSCT](#), which defines the type of radiative transfer calculation, as listed in Table 4.7.

**Table 4.7** CHANNEL\_SPECTRA keywords.

Keyword	Table	Mode	<a href="#">ITEMSCT</a>
TRANSMITTANCE	4.8 & 4.9	Transmittance-only mode	RT_TRANSMITTANCE
RADIANCE	4.8 & 4.10	Thermal emission with or without scattering	RT_THERMAL_ONLY
		Thermal plus solar radiance calculations	RT_SOLAR_AND_THERMAL
		Thermal plus lunar radiance calculations	RT_LUNAR_AND_THERMAL
IRRADIANCE	4.8 & 4.11	Transmitted solar irradiance	RT_SOLAR_IRRADIANCE
		Transmitted lunar irradiance	RT_LUNAR_IRRADIANCE

A one-to-one correspondence exists between much of the CHANNEL\_SPECTRA and [SPECTRAL](#) content. Each keyword is described in the Tables 4.8 to 4.11, and the corresponding MODTRAN5 column header is noted. Table 4.8 contains CHANNELS structure, an array of channel outputs common to the three channel output files: TRANSMITTANCE, RADIANCE and IRRADIANCE. The general equations used to compute channel outputs given spectral response function  $f_x$  in either spectral frequency ( $x = \nu$ ) or wavelength ( $x = \lambda$ ) follow:

*Full Channel Equivalent Width* in frequency  $\nu$  [ $\text{cm}^{-1}$ ]:  $\int_{\nu} f_{\nu} d\nu = \int_{\lambda} (f_{\lambda} C / \lambda^2) d\lambda$  with  $\lambda = C / \nu$

*Full Channel Equivalent Width* in wavelength  $\lambda$  [ $\mu\text{m}$  or nm]:  $\int_{\lambda} f_{\lambda} d\lambda = \int_{\nu} (f_{\nu} C / \nu^2) d\nu$  with  $\nu = C / \lambda$

*First Spectral Moment*:  $\int_x (x f_x) dx / \int_x f_x dx$  with  $x = \nu$  or  $\lambda$

*Absorptivity*:  $\int_x (1 - t_x) f_x dx / \int_x f_x dx$  with  $t_x$  = spectral transmittance

*Transmittance*:  $1 - \text{Absorptivity}$

*Channel Radiance* ( $\text{W cm}^{-2}$  / sr) or *Irradiance* ( $\text{W cm}^{-2}$ ):  $\int_x (R_x f_x) dx$  with  $R_x$  = spectral (ir)radiance

*Channel Spectral Radiance* or *Irradiance*: *Channel (Ir)radiance* over Full Channel Equivalent Width

The constant  $C$  is a conversion factor equal to either  $10^4 \mu\text{m} / \text{cm}$  or  $10^7 \text{nm} / \text{cm}$ . TRANSMITTANCE in CHANNEL\_SPECTRA generally contains molecular absorptivities (1 – molecular transmittances), while TRANSMITTANCE in [SPECTRAL](#) contains transmittances. Test case CirrusProfile uses the MODTRAN repeat run option to demonstrate use of 4 distinct outputs that result from different input options.

Besides [ITEMSCT](#), there are other inputs which affect the output in CHANNEL\_SPECTRA. One important input is the first character on the first line of the selected \*.flt sensor filter file. If that first character is “M” (for microns) or “N” (for nanometers), then the spectral response function  $f_{\lambda}$  for each channel is defined on a wavelength ( $\lambda$ ) grid and the corresponding channel output is computed as spectral integrals over wavelength with  $f_{\lambda}$  interpolated linearly in wavelength between spectral grid points. Similarly, if the first character in the selected sensor filter file is “W” (for wavenumbers), then the spectral response function  $f_{\nu}$  for each channel is defined on a frequency ( $\nu$ ) grid and the corresponding channel output is computed as spectral integrals over frequency with  $f_{\nu}$  interpolated linearly in frequency between spectral grid points.

The CHANNEL\_SPECTRA content is also affected by the input value of [NOPRNT](#) in [FILEOPTIONS](#). If [NOPRNT](#)  $\leq -1$ , then output is generated for each sensor channel whether or not the calculation spectral range overlaps at all with the channel’s spectral response function. If [NOPRNT](#) = 0, then output is generated for any spectral channel for which there is at least some overlap with the spectral range. If [NOPRNT](#)  $\geq 1$ , then output is generated only for the spectral channels for which the calculation spectral range completely covers the channels response function spectral range.

**Table 4.8.** Keywords in CHANNELS structure, included in all channel output options.

Keyword	Type	Header	Description
CHAN_INDEX	Integer	CHANNEL NO.	Spectral channels are numbered, starting from one, based on the order they are listed in the spectral response

<b>Keyword</b>	<b>Type</b>	<b>Header</b>	<b>Description</b>
CHAN_CENTER	Float	1ST SPECTRAL MOMENT	function file. A negative value is output if the spectral range of the MODTRAN calculation did not completely cover the spectral range of the response function.
CHAN_WIDTH	Float	FULL CHANNEL EQUIVALENT WIDTH	Defined using the equations above, with its units [ $\text{cm}^{-1}$ , $\mu\text{m}$ or nm] chosen to be spectral grid unit of the Spectral Response Function (SRF). This value does not depend on the spectral range of the MODTRAN calculation, only on the SRF itself. The 1 <sup>st</sup> spectral moment is used as the channel reference frequency or wavelength, not the spectral point at which the SRF is maximum.
CHAN_WIDTH_FREQ	Float	FULL CHANNEL EQUIVALENT WIDTH	Channel width in wavelengths with units of $\mu\text{m}$ unless the spectral grid of the response function is in nm units.
CHAN_MIN	Float	SPECTRAL MINIMUM	Channel width in frequency with units of $\text{cm}^{-1}$
CHAN_MAX	Float	SPECTRAL MAXIMUM	The minimum frequency or wavelength of the spectral response function
CHAN_DESCRIP	String[]	CHANNEL DESCRIPTION	The maximum frequency or wavelength of the spectral response function
			Header line for the current channel from the spectral response function (filter) file.

**Table 4.9.** TRANSMITTANCE in CHANNEL\_SPECTRA keywords with associated types and descriptions

Keyword	Type	Header	Description
UNITS_FREQ	Table 4.2		Units of Spectral Response Function (SRF), [cm <sup>-1</sup> , μm or nm]
NUM_HEAVYSPC	Integer		Number of MODTRAN "X" cross-section species
NUM_USERSPC	Integer		Number of MODTRAN 'Y' auxiliary species
NUM_CHAN	Integer		Number of SRF channels
CHANNELS	JSON Array		See Table 4.8
AVE_EXTINCTION	Float[]	AVERAGE EXTINCTION (1-TRANS)	One minus the absorbance plus scattering attenuation computed from the band model resolution TOT_TRANS, the direct transmittance for the line-of-sight (LOS) path including all sources of molecular and particulate extinction
CHAN_EXTINCTION	Float[]	CHANNEL EXTINCTION (CM <sup>-1</sup> )	Product of AVERAGE EXTINCTION and FULL CHANNEL EQUIVALENT WIDTH (CM <sup>-1</sup> )
ABSORP_H2O	Float[]	H2O (NO CONT)	Absorptivity computed from the band model resolution TRANS_H2O, the water vapor transmittance for LOS path
		ABSORBANCE	excluding water continuum contributions
ABSORP_UMIX	Float[]	UNIFORMLY MIX GASES	Absorptivity computed from the band model resolution TRANS_UMIX, the uniformly mixed gases transmittance for LOS path. In MODTRAN, the uniformly mixed gases include CO <sub>2</sub> , CO, CH <sub>4</sub> , N <sub>2</sub> O and O <sub>2</sub> .
		ABSORBANCE	
ABSORP_O3	Float[]	O3	Absorptivity computed from the band model resolution TRANS_O3 output, i.e. the LOS path ozone transmittance
		ABSORBANCE	
ABSORP_TRACE	Float[]	TRACE GASES	Absorptivity computed from the band model resolution TRACE TRANS, the trace gas transmittance for LOS path. In MODTRAN, the trace gases include NH <sub>3</sub> , NO, NO <sub>2</sub> , SO <sub>2</sub> and HNO <sub>3</sub> . Water vapor, ozone, the uniformly mixed gases and the trace gases together constitute the 12 MODTRAN default band model species.
		ABSORBANCE	
ABSORP_N2_CONT	Float[]	N2 CONTINUUM	Absorptivity computed from the band model resolution ABSORBANCE CONT_N2, the LOS path nitrogen continuum transmittance
		CONTINUUM	
ABSORP_H2O_CONT	Float[]	H2O	Absorbance computed from the band model resolution CONT_H2O, the LOS path water vapor continuum transmittance
		CONTINUUM	
		ABSORBANCE	
MOL_SCATTER	Float[]	MOLECULAR (RAYLEIGH)	Extinction computed from the band model resolution MOLEC SCAT, the LOS path molecular scattering (Rayleigh) transmittance
		SCATTERING	
EXT_AERCLD	Float[]	AEROSOL PLUS CLOUD	One minus the absorbance plus scattering attenuation computed from the band model resolution TRANS_AERCLD output, i.e. the EXTINCTION LOS path aerosols plus clouds transmittance
		EXTINCTION	
ABSORP_HNO3	Float[]	HNO3	Absorptivity computed from the band model resolution ABSORBANCE TRANS_HNO3, the LOS path nitric acid transmittance
		ABSORBANCE	
ABSORP_AERCLD	Float[]	AEROSOL PLUS CLOUD	Absorptivity computed from the band model resolution ABSORBANCE ABTRNS_AERCLD, the LOS path attenuation arising from aerosol and cloud absorption. This term excludes the attenuation from aerosol and cloud scattering.
		ABSORBANCE	
ABSORP_CO2	Float[]	CO2	Absorptivity computed from the band model resolution ABSORBANCE TRANS_CO2, the LOS path carbon dioxide transmittance
		ABSORBANCE	
ABSORP_CO	Float[]	CO	Absorptivity computed from the band model resolution ABSORBANCE TRANS_CO, the LOS path carbon monoxide transmittance
		ABSORBANCE	
ABSORP_CH4	Float[]	CH4	Absorptivity computed from the band model resolution ABSORBANCE TRANS_CH4, the LOS path methane transmittance
		ABSORBANCE	
ABSORP_N2O	Float[]	N2O	Absorptivity computed from the band model resolution ABSORBANCE TRANS_N2O, the LOS path nitrous oxide transmittance
		ABSORBANCE	

<b>Keyword</b>	<b>Type</b>	<b>Header</b>	<b>Description</b>
ABSORP_O2	Float[]	O2 ABSORBANCE	Absorptivity computed from the band model resolution TRANS_O2, the LOS path oxygen gas transmittance
ABSORP_NH3	Float[]	NH3 ABSORBANCE	Absorptivity computed from the band model resolution TRANS_NH3, the LOS path ammonia transmittance
ABSORP_NO	Float[]	NO ABSORBANCE	Absorptivity computed from the band model resolution TRANS_NO, the LOS path nitric oxide transmittance
ABSORP_NO2	Float[]	NO2 ABSORBANCE	Absorptivity computed from the band model resolution TRANS_NO2, the LOS path nitrogen dioxide transmittance
ABSORP_SO2	Float[]	SO2 ABSORBANCE	Absorptivity computed from the band model resolution TRANS_SO2, the LOS path sulfur dioxide transmittance
	Float[]	CLOUD EXTINCTION	Absorbance plus scattering attenuation computed from the band model resolution TRANS_CLOUD, the LOS path cirrus plus water cloud transmittance
ABSORP_CFC11	Float[]	CFC11 ABSORBANCE	Absorptivity computed from the band model resolution CFC11 TRANS, the LOS path trichlorofluoromethane transmittance
ABSORP_CFC12	Float[]	CFC12 ABSORBANCE	Absorptivity computed from the band model resolution CFC12 TRANS, the LOS path dichlorodifluoromethane transmittance
ABSORP_CFC13	Float[]	CFC13 ABSORBANCE	Absorptivity computed from the band model resolution CFC13 TRANS, the LOS path chloro-trifluoromethane transmittance
ABSORP_CFC14	Float[]	CFC14 ABSORBANCE	Absorptivity computed from the band model resolution CFC14 TRANS output, the LOS path carbon tetrafluoride transmittance
ABSORP_CFC22	Float[]	CFC22 ABSORBANCE	Absorptivity computed from the band model resolution CFC22 TRANS, the LOS path chlorodifluoromethane transmittance
ABSORP_CFC113	Float[]	CFC113 ABSORBANCE	Absorptivity computed from the band model resolution CFC113 TRANS, the LOS path 1,1,2-trichlorotrifluoroethane transmittance
ABSORP_CFC114	Float[]	CFC114 ABSORBANCE	Absorptivity computed from the band model resolution CFC114 TRANS, the LOS path 1,2-dichlorotetrafluoroethane transmittance
ABSORP_CFC115	Float[]	CFC115 ABSORBANCE	Absorptivity computed from the band model resolution CFC115 TRANS, the LOS path chloropentafluoroethane transmittance
ABSORP_CLONO2	Float[]	CLONO2 ABSORBANCE	Absorptivity computed from the band model resolution ClONO <sub>2</sub> TRANS, the LOS path chlorine nitrate transmittance
ABSORP_HNO4	Float[]	HNO4 ABSORBANCE	Absorptivity computed from the band model resolution HNO <sub>4</sub> TRANS, the LOS path hydroxyl nitrate transmittance
ABSORP_CHCL2F	Float[]	CHCL2F ABSORBANCE	Absorptivity computed from the band model resolution CHCl <sub>2</sub> F TRANS, the LOS path dichlorofluoromethane transmittance
ABSORP_CCL4	Float[]	CCL4 ABSORBANCE	Absorptivity computed from the band model resolution CCl <sub>4</sub> TRANS, the LOS path carbon tetrachloride transmittance
ABSORP_N2O5	Float[]	N2O5 ABSORBANCE	Absorptivity computed from the band model resolution N <sub>2</sub> O <sub>5</sub> TRANS, the LOS path dinitrogen pentoxide transmittance
ABSORP_H2_H2	Float[]	H2-H2 ABSORBANCE	Absorptivity computed from the band model resolution H <sub>2</sub> -H <sub>2</sub> TRANS, the LOS path H <sub>2</sub> -H <sub>2</sub> Collision-Induced Absorption
ABSORP_H2_HE	Float[]	H2-He ABSORBANCE	Absorptivity computed from the band model resolution H <sub>2</sub> -He TRANS, the LOS path H <sub>2</sub> -H <sub>2</sub> Collision-Induced Absorption
ABSORP_H2_CH4	Float[]	H2-CH4 ABSORBANCE	Absorptivity computed from the band model resolution H <sub>2</sub> -CH <sub>4</sub> TRANS, the LOS path H <sub>2</sub> -CH <sub>4</sub> Collision-Induced Absorption
ABSORP_CH4_CH4	Float[]	CH4-CH4 ABSORBANCE	Absorptivity computed from the band model resolution CH <sub>4</sub> -CH <sub>4</sub> TRANS, the LOS path CH <sub>4</sub> -CH <sub>4</sub> Collision-Induced Absorption
ABSORP-USERSPC	Float[]	Aux Species ABSORBANCE	Absorptivity computed from the band model resolution TRANS_USERSPC, the LOS path transmittance arising from the input set of auxiliary species
NAMES_USERSPC	String[]		Names of the user species

**Table 4.10.** RADIANCE in CHANNEL\_SPECTRA keywords with associated types and descriptions.

Keyword	Type	Header	Description
UNITS_FREQ	Table 4.2		Units of Spectral Response Function (SRF), [cm <sup>-1</sup> , μm or nm]
NUM_LOS	Integer		Number of lines-of-sight
NUM_CHAN	Integer		Number of SRF channels
CHANNELS	JSON Array		See Table 4.8
TOTAL_RAD_FREQ	Float[]	SPECTRAL RADIANCE	Total sensor channel spectral radiance (W cm <sup>-2</sup> sr <sup>-1</sup> / cm <sup>-1</sup> ) computed from band model resolution TOTAL_RAD and earlier equations.
TOTAL_RAD_WAVLN	Float[]	SPECTRAL RADIANCE	Total sensor channel spectral radiance (W cm <sup>-2</sup> sr <sup>-1</sup> / μm unless UNITS_FREQ is nm; in that case, W cm <sup>-2</sup> sr <sup>-1</sup> / nm); computed from band model resolution TOTAL_RAD and earlier equations.
BR_TEMP	Float[]	BRIGHTNESS TEMP	Brightness temperature in Kelvin, defined as the temperature a blackbody would need to have to emit the CHANNEL_RAD radiance.
CHANNEL_RAD	Float[]	CHANNEL RADIANCE	Total sensor channel in-band radiance (W cm <sup>-2</sup> sr <sup>-1</sup> ) computed from band model resolution TOTAL_RAD and earlier equations. Equals the sum of THRML_EM, THRML_SCAT, SURF_EMIS, MULT_SCAT, SING_SCAT and GRND_RFLT.
THRML_EM	Float[]	PATH EMISSION	Channel in-band sensor path thermal emission (W sr <sup>-1</sup> cm <sup>-2</sup> ), computed from band model resolution THRML_EM.
THRML_SCAT	Float[]	SCATTERED EMISSION	Channel in-band thermal radiation atmospherically scattered directly into the LOS and transmitted to the sensor (W sr <sup>-1</sup> cm <sup>-2</sup> ), computed from band model resolution THRML_SCT.
SURF_EMIS	Float[]	TRANSM GROUND EMISSION	Channel in-band surface emission directly transmitted to the sensor (W sr <sup>-1</sup> cm <sup>-2</sup> ), computed from band model resolution SURF_EMIS. If the LOS terminates at the ground, this term is the product of the Planck surface emission, the directional emissivity and the path transmittance. If the LOS does not terminate at the ground but <a href="#">TPTEMP</a> is a positive temperature in SURFACE, SURF_EMIS will contain the transmitted surface emission of a target object. Otherwise, SURF_EMIS is zero.
MULT_SCAT	Float[]	PATH MULT SCAT SOLAR	Channel in-band solar/lunar radiation multiple scattered by the atmosphere and ground, and directly transmitted to the sensor (W sr <sup>-1</sup> cm <sup>-2</sup> ), computed from band model resolution MULT_SCAT. Excludes SING_SCAT.
SING_SCAT	Float[]	PATH SINGLE SCAT SOLAR	Channel in-band solar/lunar radiation single scattered by the atmosphere and directly transmitted to the sensor (W sr <sup>-1</sup> cm <sup>-2</sup> ), computed from band model resolution SING_SCAT.
GRND_RFLT	Float[]	TOTAL TRANSM GRND REFLECT	Channel in-band ground reflected radiation directly transmitted to the sensor (W sr <sup>-1</sup> cm <sup>-2</sup> ), computed from band model resolution GRND_RFLT. Includes reflection of the three downward flux components – direct solar, diffuse solar and diffuse thermal.
DRCT_RFLT	Float[]	DIRECT TRANSM GRND REFLECT	Channel in-band ground reflected radiation arising from solar photons that travel along the direct sun to ground to sensor path without being scattered or absorbed by the atmosphere (W sr <sup>-1</sup> cm <sup>-2</sup> ), computed from band model resolution DRCT_RFLT.
REF_SOL	Float[]	TRANSM SOLAR LOS+SUN PATH	Channel in-band irradiance computed from band model resolution REF_SOL, the product of the TOA solar irradiance (W cm <sup>-2</sup> ) and the sensor-to-final_altitude-to-sun transmittance (final_altitude is the ground, the TOA or input <a href="#">H2ALT</a> ). It excludes the surface reflectance.

Keyword	Type	Header	Description
SOL_AT_OBS	Float[]	TRANSM SOLAR TO SENSOR	Channel in-band TOA solar irradiance transmitted to <a href="#">H1ALT</a> , the sensor ( $\text{W cm}^{-2}$ ), computed from band model resolution SOL_AT_OBS.
DRCT_COEFF	Float[]	A	The spectral channel convolved product of the top-of-atmosphere (TOA) solar irradiance, the solar path total (direct + diffuse) transmittance and the LOS direct transmittance, all normalized by the spectral channel convolved TOA solar irradiance. A is only non-zero for a LOS terminating at the solar illuminated ground.
DIFF_COEFF	Float[]	B	The spectral channel convolved product of the TOA solar irradiance, the solar path total transmittance and the LOS diffuse transmittance, all normalized by the spectral channel convolved TOA solar irradiance. B is only non-zero for a LOS terminating at the solar illuminated ground.
SPH_ALBEDO	Float[]	S	Channel spherical albedo at ground calculated as a quotient of spectrally convolutions. The numerator is the product of the TOA solar irradiance, the solar path total transmittance, the LOS total transmittance and the spherical albedo; the normalizing denominator excludes the spherical albedo term. S is only non-zero for a LOS terminating at the solar illuminated ground
TOT_TRANS	Float[]	SENSOR PATH TRANSM	Channel LOS direct molecular + particulate transmittance, computed from band model resolution TOT_TRANS.
DIR_EM	Float[]	SURFACE DIRECTIONAL EMISSIVITY	Channel directional emissivity at ground towards sensor (between 0 and 1 inclusive) computed from band model resolution DIR_EM.

**Table 4.11.** IRRADIANCE in CHANNEL\_SPECTRA keywords with associated types and descriptions.

Keyword	Type	Header	Description
UNITS_FREQ	Table 4.2		Units of Spectral Response Function, [ $\text{cm}^{-1}$ , $\mu\text{m}$ or nm]
NUM_CHAN	Integer		Number of Spectral Response Function (SRF) channels
CHANNELS	JSONArray		See Table 4.
TR_IRRAD_WAVLN	Float[]	TRANSMITTED SPECTRAL SOLAR IRRADIANCE	Channel transmitted spectral solar/lunar irradiance, computed from band model resolution TR_IRRAD, the product of the band model resolution direct transmittance and the top-of-atmosphere solar irradiance ( $\text{W cm}^{-2} / \mu\text{m}$ unless UNITS_FREQ is nm, in that case, $\text{W cm}^{-2} / \text{nm}$ ).
TR_IRRAD_FREQ	Float[]	TRANSMITTED SPECTRAL SOLAR IRRADIANCE	Channel transmitted spectral solar/lunar irradiance, computed from band model resolution TR_IRRAD, the product of the band model resolution direct transmittance and the top-of-atmosphere solar/lunar irradiance ( $\text{W cm}^{-2} / \text{cm}^{-1}$ ).
TR_IRRAD_CHAN	Float[]	TRANSMITTED SOLAR IRRADIANCE	Channel in-band transmitted solar/lunar irradiance computed from band model resolution TR_IRRAD, the product of the band model resolution direct transmittance and the TOA solar/lunar irradiance ( $\text{W cm}^{-2}$ ).
TOA_IRRAD	Float[]	TOP OF ATMOS SOLAR IRRAD	Channel in-band solar/lunar irradiance computed from band model resolution TOA_IRRAD, the band model resolution TOA solar/lunar irradiance ( $\text{W cm}^{-2}$ ).
TR_PATH	Float[]	SOLAR PATH TRANSM	Channel solar/lunar path transmittance computed from band model resolution TRANS, the band model resolution TO solar irradiance ( $\text{W cm}^{-2}$ ).

## 4.5 Spectral Flux Output in [FLUXES](#)

The [FLUXES](#) JSONObject contains the spectral flux data at multiple altitude levels. Spectral flux data are generated whenever a multiple scattering line-of-sight radiance calculation is performed, i.e. when [IMULT](#) is does not equal [RT\\_NO\\_MULTIPLE\\_SCATTER](#) (or 0). The spectral flux data is placed in [FLUXES](#) whenever it is generated and [FLAGS](#)[6] is not blank.

The content of [FLUXES](#) can be quite large: by default, it contains spectral flux data for each spectral grid point and at each atmospheric altitude level. For many applications, the totality of information is not required. The keyword [MLFLX](#) in [SPECTRAL](#) allows the user to limit the number of output altitude levels. If [MLFLX](#) is a positive integer less than the total number of atmospheric levels, then spectral flux information is only included for the first [MLFLX](#) atmospheric levels and for the top-of-atmosphere (TOA). For example, if [MLFLX](#) is set to “1”, then the [FLUXES](#) will only contain ground and TOA spectral flux data. If [FLAGS](#)[0] is input as blank or “W”, then the spectral flux data is generated on a wavenumber [ $\text{cm}^{-1}$ ] grid from [V1](#) to [V2](#)  $\text{cm}^{-1}$  with a [DV](#)  $\text{cm}^{-1}$  step size ([V1](#), [V2](#) and [DV](#) are all in [SPECTRAL](#)). Spectral flux values are in units of [ $\text{W cm}^{-2} / \text{cm}^{-1}$ ]. The spectral resolution of the flux output is [FWHM](#)  $\text{cm}^{-1}$ , where the [FWHM](#) input provides the full width at half maximum of the scanning or filter function. The value of [FLAGS](#)[1] determines the type of slit function. If [FLAGS](#)[1] is blank, then a rectangular slit function is used if the [FWHM](#) is less than twice the band model resolution, and a triangular slit function is used otherwise. If [FLAGS](#)[1] is not blank, then its value determines the type of slit function (“1” or “T” for triangular, “2” or “R” for rectangular, “3” or “G” for Gaussian, “4” or “S” for Sinc, “5” or “C” for Sinc-squared, and “6” or “H” for Hamming). If input [FLAGS](#)[0] is “M” for microns (“N” for nanometers), then the spectral flux data is generated on a  $\mu\text{m}$  (nm) grid from [V1](#) to [V2](#)  $\mu\text{m}$  (nm) with a [DV](#)  $\mu\text{m}$  (nm) step size, respectively. Spectral flux values are in units of  $\text{W cm}^{-2} / \mu\text{m}$  [ $\text{W cm}^{-2} / \text{nm}$ ]. The spectral resolution of the flux output is [FWHM](#)  $\mu\text{m}$  [nm].

**Table 4.11.** FLUXES keywords with associated types and descriptions.

Keyword	Type	Description
<a href="#">UNITS_FREQ</a>	Table 4.2	Spectral unit
<a href="#">NUM_FREQ</a>	Integer	Number of spectral grid points
<a href="#">NUM_ALT</a>	Integer	Number of altitude grid points
<a href="#">ALT</a>	Float[]	Altitude grid (km)
<a href="#">FREQ</a>	Float[]	Spectral Abscissa
<a href="#">FLUX_UP</a>	Float[]	Upward diffuse (scattered) flux, $F^+$
<a href="#">FLUX_DOWN</a>	Float[]	Downward diffuse (scattered) flux, $F^-$
<a href="#">FLUX_SOLAR</a>	Float[]	Direct solar flux

There are three primary spectral flux outputs in the [FLUXES](#) JSONObject: upward diffuse flux,  $F_z^+$ , downward diffuse flux,  $F_z^-$ , and downward direct solar flux. The direct solar flux is the product of 3 terms: the top-of-atmosphere (TOA) solar irradiance,  $F^{dir}$ , the solar path direct transmittance from the TOA to the current atmospheric altitude level, and the cosine of the solar zenith angle at that level. The spectral diffuse flux terms are calculated from the MODTRAN plane-parallel multiple scattering modules, either 2-stream Isaacs [32, 42] or the discrete ordinate DISORT [55, 56] algorithm. The basic equation is

$$F_z^\pm = 2\pi \int_0^1 \mu I^0(z, \pm\mu) d\mu , \quad (4.1)$$

Where  $z$  is the altitude level,  $\mu$  is the positive cosine of the hemisphere view angle, and  $I^0(z, \pm\mu)$  is the zero order coefficient of the azimuth angle  $\phi$  Fourier cosine series for the line-of-sight diffuse radiation intensity  $I(z, \mu, \phi)$ :

$$I(z, \mu, \phi) = \sum_{m=0}^{2M} I^m(z, \mu) \cos(\phi - \phi_0) . \quad (4.2)$$

In this equation,  $\phi_0$  is the solar azimuth angle and  $2M$  is the number of azimuth moments included in the calculation.

In the 2-stream model, the flux values are proportional to the  $60^\circ$  intensities and equal to  $\pi I^0(z, \pm\frac{1}{2})$ . DISORT computes the upward and downward fluxes of Eq. (4.1) with a Gaussian quadrature integral, and only requires solving the radiative transfer equations for the first ( $m = 0$ ) azimuth moment.

MODTRAN scattered radiance calculations can be run in a thermal radiance only mode or in a thermal plus solar/lunar radiance mode. In the thermal radiance only mode, IEMSCT set to RT\_THERMAL\_ONLY, the diffuse flux terms only include thermal contributions; the direct and diffuse solar/lunar flux terms are zero. In the thermal plus solar/lunar radiance modes, IEMSCT set to RT\_SOLAR\_AND\_THERMAL or RT\_LUNAR\_AND\_THERMAL, the diffuse flux terms include both the thermal and solar/lunar contributions. The unit of the *band pass* flux is W/cm<sup>2</sup>.

#### **4.5.1 Use of FLUXES Data for Modeling the Flux Impinging on a Surface MOVE TO FAQ**

For a flat ground, the sum of the downward diffuse and the direct solar/lunar flux values at the ground level is the flux impinging on the ground. The question arises as to whether data from FLUXES can be used to compute the spectral flux impinging on an arbitrarily oriented facet within the atmosphere. The correct method for calculating this flux requires integrating the impinging radiance over the hemisphere normal to the facet. If a target with many thousands of facets is to be modeled, the full set of calculations can become unmanageable.

In the 2-stream approximation, the assumption is made that downward and upward diffuse radiances are each isotropic. Obviously, this is not an optimal assumption, but it may suffice for some applications. Using the 2-stream approach, the diffuse spectral flux impinging on a facet, with normal zenith angle  $\theta$  ( $\theta$  equals  $0^\circ$  for an upward facing facet and equals  $180^\circ$  for a downward facing facet) is given by

$$F(z, \theta) = F^-(z) \cos^2(\theta/2) + F^+(z) \sin^2(\theta/2) , \quad (4.3)$$

where  $F^+$  is the upward diffuse flux and  $F^-$  is the downward diffuse flux.

The direct solar flux is zero unless the facet faces the sun, i.e., the dot product of the facet normal,  $\hat{r}_f$ , and the solar direction unit vector,  $\hat{r}_s$ , is positive. Since the MODTRAN direct solar flux includes the cosine solar zenith angle factor, the direct solar flux impinging on a facet is computed as follows:

$$F^{dir}(z, \hat{r}_f, \hat{r}_s) = \begin{cases} F^{dir}(z) \hat{r}_f \bullet \hat{r}_s / \mu_0 & \text{for } \hat{r}_f \bullet \hat{r}_s > 0 \\ 0 & \text{otherwise} \end{cases} \quad (4.4)$$

Here,  $\mu_0$  is the cosine of the solar zenith angle, equal to the z-component of  $\hat{r}_s$ .

#### **4.6 Atmospheric Correction Data Output in <ROOTNAME>.acd Files**

#### **4.7 Line-By-Line and Correlated-k Data Output**

#### **4.8 Segment Spectral Data Output**

#### **4.9 Spectral Cooling Rate Data Output**

#### **4.10 DISORT Multiple Scatter Data Output**

## 5. FAQ

Add a Introduction

### 5.1 General

#### 5.1.1 What is MODTRAN?

MODTRAN is radiative transfer software designed to model the propagation, emission and scattering of the infrared, visible and ultraviolet light that passes through a planet's atmosphere, in particular, Earth's terrestrial atmosphere. Traditionally, MODTRAN solved the fundamental radiative transfer equation using a “narrow band model” approach, although higher fidelity models are now provided for applications that do not require the speed the band model algorithm provides. The atmosphere is modeled as spherically stratified (horizontally homogeneous) based on a local Earth radius, and its constituent vertical profiles, both molecular and particulate, may be defined either using built-in models or by user-specified vertical profiles. Spectral coverage extends from the UV through the far-infrared ( $0 - 50,000 \text{ cm}^{-1}$ , i.e.  $> 0.2 \mu\text{m}$ ), providing band model resolution as fine a  $0.2 \text{ cm}^{-1}$  [arbitrarily fine spectral resolution is provided by the line-by-line (LBL) algorithm]. MODTRAN solves the radiative transfer equation including the effects of molecular and particulate absorption/emission and scattering, surface reflections and emission, solar/lunar illumination, and spherical refraction. Outputs include narrow spectral band direct and diffuse transmittances, path component and total radiances, transmitted and top-of-atmosphere solar/lunar irradiances, horizontal fluxes, cooling rates, and more. With over a 30-year heritage, MODTRAN has been extensively validated, and it serves as the community standard atmospheric band model radiative transfer algorithm. See the 2017 JQSRT paper and references therein [Berk and Hawes, 2017].

#### 5.1.2 Who developed MODTRAN?

LOWTRAN was the precursor of MODTRAN, a low spectral resolution ( $20 \text{ cm}^{-1}$ ) 1-parameter band model radiative transfer algorithm developed by the Air Force Geophysics Laboratories, now the Air Force Research Laboratories (AFRL). Spectral Sciences, Inc. (SSI) integrated a narrow ( $1.0 \text{ cm}^{-1}$ ) band model into LOWTRAN as part of an Air Force sponsored effort, creating MODTRAN in the later half of 1980's. SSI has continued development of MODTRAN over the past 3+ decades with support and validation from AFRL. MODTRAN6 was released in August of 2016.

#### 5.1.3 How do I get a copy of MODTRAN6?

MODTRAN6 can be ordered from [www.modtran.spectral.com](http://www.modtran.spectral.com). Select the **Order** tab for further instructions.

#### 5.1.4 How much does MODTRAN6 cost?

The baseline price of MODTRAN6 for commercial and non US government agencies with 1 year maintenance is \$2,500.00. Reduced prices are offered to educational institutions and to U.S. government agencies and their contractors. Long-term maintenance agreements are also available. A higher cost also results if MODTRAN is to be used in large production processing of data.

#### 5.1.5 How accurate is MODTRAN6?

The accuracy of MODTRAN depends on the scenario of one's calculation and the specific output quantities being examined. It is recommended that the user perform a benchmark MODTRAN6 line-by-line (LBL) calculation to quantify the error introduced by the MODTRAN statistical methods for a given application. Additional uncertainties can arise because of inexact specification of the atmosphere, but the LBL calculation will determine the error introduced by the band model or statistical correlated- $k$  algorithms.

### **5.1.6 What reference(s) should be use for MODTRAN6?**

The best current generally available reference for MODTRAN6 and its validation is Berk A and Hawes F. "Validation of MODTRAN®6 and its line-by-line algorithm." J Quant Spectrosc Radiat Transfer (2017), <http://dx.doi.org/10.1016/j.jqsrt.2017.03.004>.

The integration of the DISORT scattering algorithm into MODTRAN is briefly described in Berk A, Stamnes K and Lin Z. "MODTRAN® Scattering: Extracting Spherical-Refractive Path Contributions from Plane-Parallel DISORT." Accepted for presentation and publication at the IEEE International Geoscience and Remote Sensing Symposium (IGARSS), Fort Worth, Texas, USA, 23-28 July 2017.

An extensive description of MODTRAN algorithms is included in Berk A, van den Bosch J, Acharya P, Adler-Golden S, Anderson G, Bernstein L, *et al.* "Algorithm Theoretical Basis Document (ATBD) for Next Generation MODTRAN." Spectral Sciences, Inc. Rpt. No. SSI-TR-688 (3247), Contract No. FA9453-12-C-0262, Summited to AFRL for publication, June 2016.

The MODTRAN Interface Control Document (ICD) is a useful reference for users of MODTRAN looking to interface the model through an Application Program Interface (API): Perkins T, Berk A and van den Bosch J. "MODTRAN®6 Interface Control Document." Spectral Sciences, Inc. Rpt. No. SSI-TR-520 (3247), Contract No. FA9453-12-C-0262, Summited to AFRL for publication, June 2016.

### **5.1.7 What is the MODTRAN version number convention?**

Currently (April 2017), the public release version of MODTRAN is MODTRAN6.0.0.6. The leading number is only incremented when a major change to the model is developed. For example, MODTRAN4 introduced a statistical correlated- $k$  algorithm into MODTRAN, MODTRAN5 increased the spectral resolution of the MODTRAN band model to  $0.1\text{ cm}^{-1}$ , and MODTRAN6 provides a modernization of the MODTRAN model along with a LBL algorithm. The second number is incremented when significant new features are added to the model. When MODTRAN5.3 was released, it included the Spectral Aerosol Profile (SAP) model that improved the modeling of aerosols and an ocean bidirectional reflection distribution function (BRDF). The third number is incremented when a new release of MODTRAN is made available. The fourth and final number is incremented when corrections and minor code changes are introduced.

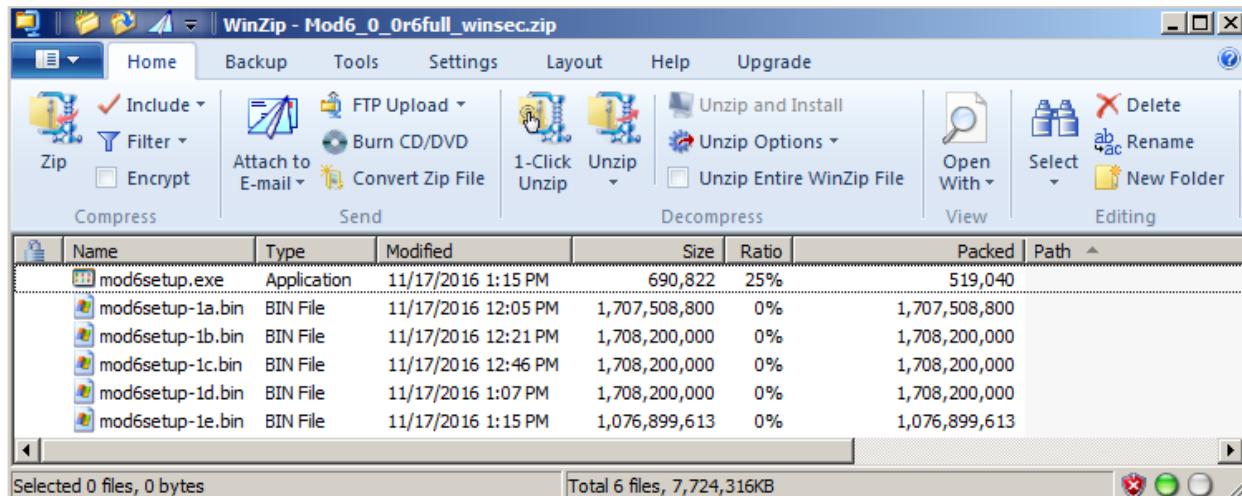
## **5.2 Installation and Trouble Shooting**

### **5.2.1 How do I install the MODTRAN6 software package?**

After receiving a user name and password, log into the MODTRAN download site:

The screenshot shows the "Download MODTRAN®" page. At the top left is the SPECTRAL SCIENCES, INCORPORATED logo. The main title is "Download MODTRAN®". Below the title are navigation links: HOME, About MODTRAN®, Features, FAQ, MODTRAN® Web App, Order, and Add-ons. A message says "Please select a software version for your platform." Under "Windows Installer", there are two sections: "Full (Windows 7/8/10 32/64-bit)" and "Update (Windows 7/8/10 32/64-bit)". Each section lists a standard version and a secure version with download links. Under "Linux/Mac/Windows Combined Archive", there are two sections: "Full (64-bit)" and "Update (64-bit)". Each section lists compressed tar archive and 7zip archive options with download links. At the bottom left is a copyright notice: "Copyright © 2016 Spectral Sciences Inc. All rights reserved. The MODTRAN® trademark is being used with the express permission of the owner, the United States of America, as represented by the United States Air Force." At the bottom right are the AFRL logo and the AFRL website address.

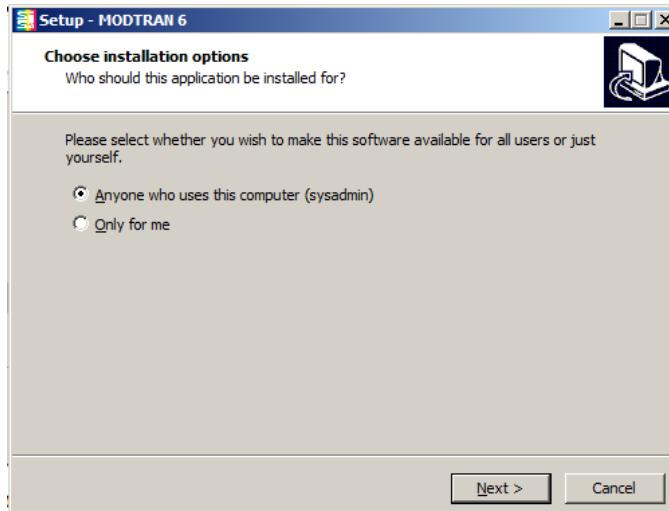
Windows users should download either the Standard or Secure WinZip file by clicking on the appropriate file. It is suggested that you use Save As to place the file in your chosen location. Open the WinZip file:



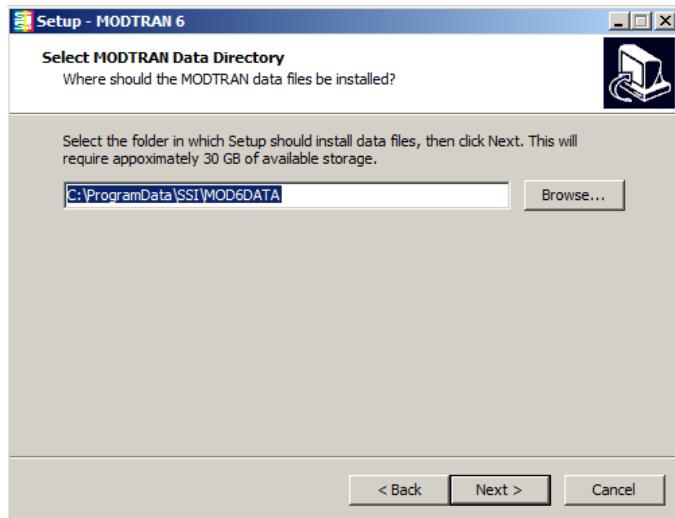
Extract the 6 files to your desired location. Clicking on mod6setup.exe, the following window will appear:



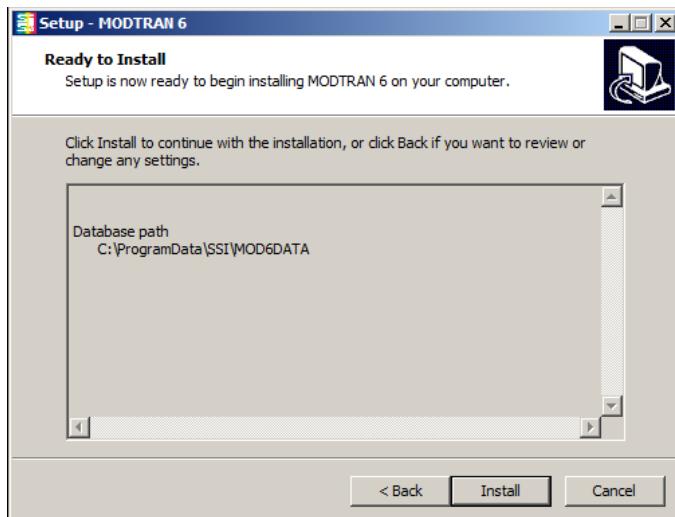
You may need administrative privileges to proceed. After which the following window will appear:



If you wish to restrict MODTRAN usage to yourself, click on “Only for me” before hitting next. The subsequent window,



Allows user to select the location of the MODTRAN6 DATA directory. The default location is listed, but the user can select a different folder if desired or required. After clicking on Next, the Ready to Install window will be displayed.



Click on Install to complete the Window installation.

Linux and Mac users should download either the tar gzip or 7zip file by clicking on the appropriate file. The 7zip file is about 2/3 the size of the tar gzip version. It is suggested that you use Save As to place the compressed file in your chosen location. Use 7zip to uncompress the \*.7z file, or use the tar command (tar -xvf \*.gz) to extract MODTRAN6 from a console/linux window. The installation [without the atmospheric generator toolkit (AGT)] will include the following directory structure:

```

lex@right:/work/lex/Mod6_0_0r6full_allplat
/wk...lex/Mod6_0_0r6full_allplat 1274$ ls -R|grep :
.:
./MODTRAN6.0.0:
./MODTRAN6.0.0/bin:
./MODTRAN6.0.0/bin/linux:
./MODTRAN6.0.0/bin/linux/lib:
./MODTRAN6.0.0/bin/macos:
./MODTRAN6.0.0/bin/macos/lib:
./MODTRAN6.0.0/bin/windows:
./MODTRAN6.0.0/DATA:
./MODTRAN6.0.0/DATA/HITRANtrace2013:
./MODTRAN6.0.0/DATA/IRSL:
./MODTRAN6.0.0/DATA/NOAA:
./MODTRAN6.0.0/dev:
./MODTRAN6.0.0/dev/examples:
./MODTRAN6.0.0/dev/include:
./MODTRAN6.0.0/dev/include/modtran:
./MODTRAN6.0.0/dev/include/modtran/arch:
./MODTRAN6.0.0/dev/include/modtran/modlib:
./MODTRAN6.0.0/dev/include/modtran/tape5:
./MODTRAN6.0.0/dev/mpi:
./MODTRAN6.0.0/doc:
./MODTRAN6.0.0/TEST:
./MODTRAN6.0.0/TEST/COMPARE:
./MODTRAN6.0.0/TEST_c:
./MODTRAN6.0.0/TEST_c/COMPARE:
./MODTRAN6.0.0/util:
./MODTRAN6.0.0/util/aerosol_toolkit:
./MODTRAN6.0.0/util/aerosol_toolkit/COMPARE:
./MODTRAN6.0.0/util/aerosol_toolkit/data:
./MODTRAN6.0.0/util/aerosol_toolkit/examples:
./MODTRAN6.0.0/util/floating_license_servers:
/wk...lex/Mod6_0_0r6full_allplat 1275$
```

### 5.2.2 Who do I contact if I have problems with the software?

For installation or technical questions, please email Spectral Sciences, Inc. (SSI) at [modtran@spectral.com](mailto:modtran@spectral.com). Typically, Ms. Paula Wing responds to questions regarding the ordering of MODTRAN6, Mr. Tim Perkins responds to installation issues, Dr. Marsha Fox handles licensing issues, and Dr. Alexander (Lex) Berk responds to technical inquiries. Users requiring a US Government point of contact (POC) should send email inquiries to [ARFL.RVBYI.MODTRANOrgMailbox@us.af.mil](mailto:ARFL.RVBYI.MODTRANOrgMailbox@us.af.mil). If your maintenance contract is up-to-date, you will generally receive an email response within one business day.

## **5.3 Inputs**

### 5.3.1 How does one set up an input file?

The easiest way to set up a MODTRAN6 input file is by running the MODTRAN GUI. The procedure for running the GUI is described in Chapter 2 of this User's Manual.

Some input options require a large number of entries, and using the GUI to set up these runs can be tedious. The atmospheric generator toolkit (AGT) and the aerosol toolkit (ATK) are designed to generate [ATMOSPHERE](#) and [AEROSOLS](#) inputs.

For other inputs requiring a large number of entries, it can be helpful to read a MODTRAN6 test case into the GUI. The JSON input files are stored in the `<modtran6_directory>/TEST/TEST.json` directory for the Linux and Mac operating systems,. Here `<modtran_directory>` is the full or relative path to the MODTRAN6 directory. On Windows, the same set of test case JSON input files are stored in the `Documents\MODTRAN6\TestCases\JSON\` folder.

### 5.3.2 How does one convert radiosonde data into MODTRAN6 vertical profiles?

An Atmosphere Generator Toolkit (AGT) utility can be purchased with MODTRAN6. One function of the AGT is conversion of radiosonde data in a number of formats into MODTRAN6 compatible inputs. See Chapter 8 for a full description of the AGT utility.

### 5.3.3 What chemical species are included in MODTRAN6?

The MODTRAN standard atmospheres include 12 band model molecules ( $H_2O$ ,  $O_3$ ,  $CO_2$ ,  $CO$ ,  $CH_4$ ,  $N_2O$ ,  $O_2$ ,  $NH_3$ ,  $NO$ ,  $NO_2$ ,  $SO_2$ ,  $HNO_3$ ) and 13 cross-section species (CFC11, CFC12, CFC13, CFC14, CFC22, CFC113, CFC114, CFC115, ClONO<sub>2</sub>, HNO<sub>4</sub>, CHCl<sub>2</sub>F, CCl<sub>4</sub> and N<sub>2</sub>O<sub>5</sub>). Collision induced absorption (CIA) is modeled for four dimers: H<sub>2</sub>-H<sub>2</sub>, H<sub>2</sub>-He, H<sub>2</sub>-CH<sub>4</sub> and CH<sub>4</sub>-CH<sub>4</sub>. An additional 16 molecules (OH, HF, HCl, HBr, HI, ClO, OCS, H<sub>2</sub>CO, HOCl, N<sub>2</sub>, HCN, CH<sub>3</sub>Cl, H<sub>2</sub>O<sub>2</sub>, C<sub>2</sub>H<sub>2</sub>, C<sub>2</sub>H<sub>6</sub>, PH<sub>3</sub>) are included in the MODTRAN6 atmosphere by setting [RTOPTIONS](#) keyword [LYMOLC](#) to “TRUE”.

Auxiliary molecular species can be added by defining their (vertical or line-of-sight) profiles and absorption data. Absorption data has been generated for the full set of Pacific Northwest National Laboratory (PNNL) Infra-Red Spectral Library (IRSL) species. These data files are not included in the standard MODTRAN distribution, but are available for purchase (contact [modtran@spectral.com](mailto:modtran@spectral.com) for more information).

### 5.3.4 Can aerosol and/or clouds be defined with sharp boundaries?

MODTRAN has four aerosol regions, nominally defined with positive 550 nm extinction coefficients defined at the following altitudes:

1. Boundary Layer Aerosol: 0, 1 and 2 km
2. Tropospheric Aerosol: 3, 4, 5, 6, 7, 8, 9 and 10 km
3. Stratospheric Aerosol: 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25 and 30 km
4. Meteoric Dust / Volcanic Aerosols: 35, 40, 45, 50, 55, 60, 65, 70, 80 and 100 km

This general structure is illustrated in Table 5.1. Between 2 and 3 km altitude, the boundary layer aerosol extinction decreases linearly with altitude to zero and the tropospheric aerosol extinction increases linearly from zero. A similar transition occurs from 10 to 11 km for the tropospheric and stratospheric aerosols. The transition region for the stratospheric and meteoric dust / volcanic aerosols is even larger, extending from 30 to 35 km. These profiles, including the transition regions, are illustrated on the left in Figure 5.1.

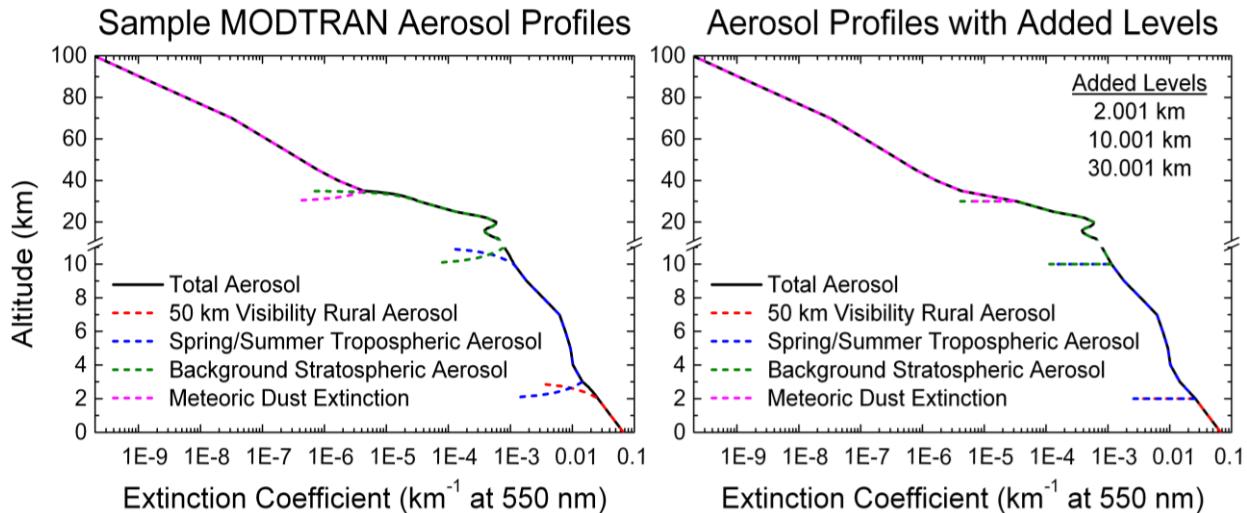
Naturally occurring atmospheric aerosols often have sharper vertical boundaries than those illustrated in Figure 5.1. For MODTRAN built-in aerosols, sharp boundaries can be defined by inserting altitude levels just above the bottom of the tropospheric, stratospheric and meteoric dust / volcanic aerosol layers, e.g. 2.001, 10.001 and 30.001 km. Adding these altitude levels producing the aerosol profiles are illustrated on the right in Figure 5.1.

One can also define sharp aerosol boundaries by explicitly entering the aerosol extinction profiles. This can be accomplished either within the [ATMOSPHERE](#) input array by defining

Z(KM)	AEROSOL 1	AEROSOL 2	AEROSOL 3	AEROSOL 4
0.	6.670E-02	0.000E+00	0.000E+00	0.000E+00
1.	4.150E-02	0.000E+00	0.000E+00	0.000E+00
2.	2.600E-02	0.000E+00	0.000E+00	0.000E+00
3.	0.000E+00	1.460E-02	0.000E+00	0.000E+00
4.	0.000E+00	1.020E-02	0.000E+00	0.000E+00
...	0.000E+00	...	0.000E+00	0.000E+00
9.	0.000E+00	1.820E-03	0.000E+00	0.000E+00
10.	0.000E+00	1.140E-03	0.000E+00	0.000E+00
11.	0.000E+00	0.000E+00	7.990E-04	0.000E+00
12.	0.000E+00	0.000E+00	6.410E-04	0.000E+00
...	0.000E+00	0.000E+00	...	0.000E+00
25.	0.000E+00	0.000E+00	1.310E-04	0.000E+00
30.	0.000E+00	0.000E+00	3.320E-05	0.000E+00
35.	0.000E+00	0.000E+00	0.000E+00	4.300E-06
40.	0.000E+00	0.000E+00	0.000E+00	1.670E-06
...	0.000E+00	0.000E+00	0.000E+00	...

**Table 5.1.** MODTRAN Aerosol Extinction ( $km^{-1}$  at 550 nm) Profile Transition Regions. Profiles were defined with the 50 km Visibility Rural Boundary Layer, Spring / Summer Tropospheric, and Background Stratospheric Aerosols.

PROFILES of TYPE PROF\_AHAZE, PROF\_AHAZE2, PROF\_AHAZE3 and PROF\_AHAZE4 or by setting ARUSS to "SAP" and defining a Spectral Aerosol Profiles input file, as described in Section 3.5.4. The CD2c3\_USS.json test case illustrates the use of the PROF\_AHAZE, PROF\_AHAZE2, PROF\_AHAZE3 and PROF\_AHAZE4 profiles within its ATMOSPHERE section:



**Figure 5.1.** MODTRAN Aerosol Extinction ( $\text{km}^{-1}$  at 550 nm) Profile defined with the 50 km Visibility Rural Boundary Layer, Spring / Summer Tropospheric, and Background Stratospheric Aerosols. On the right-hand side, altitude levels at 2.001, 10.001 and 30.001 km have been added to create sharp transitions between aerosol regions. Note there is a break in the vertical scale at 11 km altitude.

```

"ATMOSPHERE": {
    "MODEL": "ATM_USER_ALT_PROFILE",
    "M1": "ATM_MIDLAT_SUMMER",
    "M2": "ATM_MIDLAT_SUMMER",
    "M3": "ATM_MIDLAT_SUMMER",
    "M4": "ATM_MIDLAT_SUMMER",
    "M5": "ATM_MIDLAT_SUMMER",
    "M6": "ATM_MIDLAT_SUMMER",
    "MDEF": 1,
    "CO2MX": 3.80000000000000e+02,
    "H2OSTR": 0.00000000000000e+00,
    "H2OUNIT": " ",
    "O3STR": 0.00000000000000e+00,
    "O3UNIT": " ",
    "C_PROF": 3,
    "AERRH": 0.00000000000000e+00,
    "S_UMIX": [
        1.00, 1.00, 1.05, 1.00, 1.00, 1.00, 1.00, 1.00, 1.00 ],
    "S_XSEC": [
        1.85, 2.25, 1.00, 1.00, 2.75, 4.00, 1.00, 1.00, 1.00, 0.73, 1.00, 1.00, 0.00, 0.00 ],
    "HMODEL": "aer_profs",
    "AYRANG": false,
    "E_MASS": 0.00000000000000e+00,
    "AIRMWT": 0.00000000000000e+00,
    "NLAYERS": 36,
    "NPROF": 5,
    "PROFILES": [
        {
            "TYPE": "PROF_ALTITUDE",
            "UNITS": "UNT_KILOMETERS",
            "PROFILE": [
                0.000e+0, 1.000e+0, 2.000e+0, 3.000e+0, 4.000e+0, 5.000e+0,
                6.000e+0, 7.000e+0, 8.000e+0, 9.000e+0, 1.000e+1, 1.100e+1, 1.200e+1, 1.300e+1,
                1.400e+1, 1.500e+1, 1.600e+1, 1.700e+1, 1.800e+1, 1.900e+1, 2.000e+1, 2.100e+1,
                2.200e+1, 2.300e+1, 2.400e+1, 2.500e+1, 2.600e+1, 2.700e+1, 2.800e+1, 2.900e+1,
                3.000e+1, 3.500e+1, 4.000e+1, 5.000e+1, 7.000e+1, 1.000e+2 ]
        },
        {
            "TYPE": "PROF_AHAZE",
            "UNITS": "UNT_UNKNOWN",
            "PROFILE": [
                4.309e-2, 3.794e-2, 3.341e-2, 2.942e-2, 2.590e-2, 2.280e-2,
                2.007e-2, 1.767e-2, 1.386e-2, 9.238e-3, 4.619e-3, 0.000e+0, 0.000e+0, 0.000e+0,
                0.000e+0, 0.000e+0, 0.000e+0, 0.000e+0, 0.000e+0, 0.000e+0, 0.000e+0,
                0.000e+0, 0.000e+0, 0.000e+0, 0.000e+0, 0.000e+0, 0.000e+0, 0.000e+0,
                0.000e+0, 0.000e+0, 0.000e+0, 0.000e+0, 0.000e+0, 0.000e+0 ]
        },
        {
            "TYPE": "PROF_AHAZE2",
            "UNITS": "UNT_UNKNOWN",
            "PROFILE": [
                2.731e-2, 2.316e-2, 1.901e-2, 1.108e-2, 7.235e-3, 6.187e-3,
                5.197e-3, 3.260e-3, 1.970e-3, 1.256e-3, 7.631e-4, 0.000e+0, 0.000e+0, 0.000e+0,
                0.000e+0, 0.000e+0, 0.000e+0, 0.000e+0, 0.000e+0, 0.000e+0, 0.000e+0,
                0.000e+0, 0.000e+0, 0.000e+0, 0.000e+0, 0.000e+0, 0.000e+0, 0.000e+0,
                0.000e+0, 0.000e+0, 0.000e+0, 0.000e+0, 0.000e+0, 0.000e+0 ]
        },
        {
            "TYPE": "PROF_AHAZE3",
            "UNITS": "UNT_UNKNOWN",
            "PROFILE": [
                0.000e+0, 0.000e+0, 0.000e+0, 0.000e+0, 0.000e+0, 0.000e+0,
                0.000e+0, 0.000e+0, 0.000e+0, 0.000e+0, 7.990e-4, 6.410e-4, 5.170e-4,
                4.420e-4, 3.950e-4, 3.820e-4, 4.250e-4, 5.200e-4, 5.810e-4, 5.890e-4, 5.020e-4,
                4.200e-4, 3.000e-4, 1.980e-4, 1.310e-4, 3.320e-5, 0.000e+0, 0.000e+0, 0.000e+0,
                0.000e+0, 0.000e+0, 0.000e+0, 0.000e+0, 0.000e+0, 0.000e+0, 0.000e+0 ]
        },
        {
            "TYPE": "PROF_AHAZE4",
            "UNITS": "UNT_UNKNOWN",
            "PROFILE": [
                0.000e+0, 0.000e+0, 0.000e+0, 0.000e+0, 0.000e+0, 0.000e+0,
                0.000e+0, 0.000e+0, 0.000e+0, 0.000e+0, 0.000e+0, 0.000e+0, 0.000e+0,
                0.000e+0, 0.000e+0, 0.000e+0, 0.000e+0, 0.000e+0, 0.000e+0, 0.000e+0,
                0.000e+0, 0.000e+0, 0.000e+0, 0.000e+0, 4.300e-6, 1.670e-6, 8.000e-7,
                4.200e-7, 2.207e-7, 1.159e-7, 3.200e-8, 5.795e-9, 0.190e-9 ]
        }
    ]
},
}

```

Figure 5.2 illustrates the MODTRAN built-in cloud profiles. These profiles, similar to those of the aerosol models, are not defined with sharp boundaries. User-defined cloud profiles are defined using input array [CLDAL](#)T in [AEROSOLS](#). This is illustrated in Section 3.6.

One subtle precaution is noted. When fine vertical layering is introduced into MODTRAN, it is critical that one not create a large temperature or relative humidity (RH) gradient. The refractive index profile is defined as a function of temperature and RH. The MODTRAN spherical refractive geometry package can fail when large vertical gradients produce super-refraction or ducting. Warning and error messages are produced; the error messages lead to termination of processing.

### 5.3.5 Should the 550 nm vertical optical depth input include the Rayleigh molecular scattering contribution?

If a negative value is entered for the [AEROSOLS](#) keyword [VIS](#), the magnitude (absolute value) of that entry is the 550 nm aerosol optical depth. The value does not include a Rayleigh molecular scattering contribution. If the vertical optical depth at 550 nm is obtained from a measurement, the user must subtract the Rayleigh contribution. For vertical paths from sea-level ("[GNDALT](#)":0.0), the model atmosphere values for the Rayleigh vertical optical depth are

0.097547	Tropical	0.097310	Mid-Latitude Summer
0.097583	Mid-Latitude Winter	0.096780	Sub-Arctic Summer
0.097018	Sub-Arctic Winter	0.097102	U.S. Standard Atmosphere

A baseline MODTRAN multiple scattering run can be run to determine the 550 nm scattering optical depth for a given scenario if an independent measurement of the Rayleigh optical depth is not available. The value is included in the \*.tp6 output file:

TOTAL COLUMN ABSORBER AMOUNTS FOR A VERTICAL PATH FROM GROUND TO SPACE:

HNO <sub>3</sub> (ATM CM)	O <sub>3</sub> UV (ATM CM)	CNTMSLF1 (MOL CM-2)	CNTMSLF2 (MOL CM-2)	CNTMFRN (MOL CM-2)	N2 CONT	MOL SCAT ( 550 NM EXTINCTION )	TOTAL AER
3.7983E-04	2.7727E-01	1.9820E+21	1.5774E+20	1.1321E+23	3.6886E+00	0.09754515	0.28866288

### 5.3.6 When is it appropriate to use the ISAACS scaled to DISORT scattering option?

MODTRAN6 provides three [IMULT](#) multiple scattering model options, RT\_DISORT, RT\_ISAACS\_2STREAM and RT\_ISAACS\_SCALED (to DISORT). Each of these can be based at the latitude and longitude of the sensor or the [H2ALT](#). Running the DISORT scattering model (RT\_DISORT) is preferable if one can afford the computational costs. Also, if one is running an [IEMSCT](#) RT\_THERMAL\_ONLY calculation, 2-stream DISORT is no slower than 2-stream Isaacs so it should be used. For solar and lunar calculations, instances arise in which the accuracy of the 2-stream approach is insufficient but the computation time of DISORT processing is too long. MODTRAN provides the Isaacs 2-stream scaled to DISORT option (RT\_ISAACS\_SCALED). DISORT scattering calculations are performed for a handful of fixed spectral points in atmospheric window regions. The ratio of DISORT to Isaacs multiple scatter solar path radiances is calculated at each of these spectral grid point, creating a spectral correction curve. This curve is used to adjust the Isaacs multiple scatter solar path radiances at each spectral point. An analogous correction is made to the ground reflected downward diffuse flux for lines-of-sight that intersect the ground.

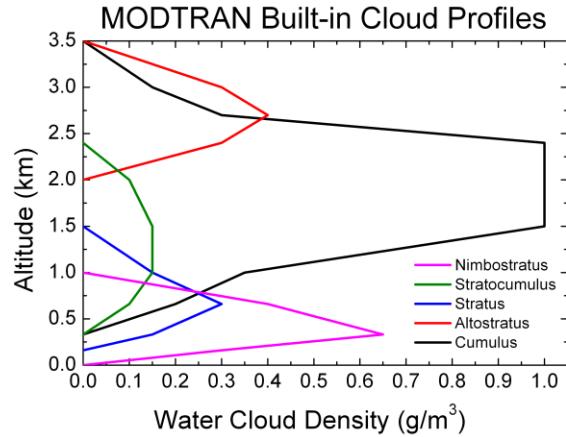


Figure 5.2: MODTRAN Built-in Cloud Profiles.

The Isaacs scaled to DISORT option should really only be used for the shortwave ( $< 4 \mu\text{m}$ ). Moreover, one should compare the scaled results to a full DISORT calculation for a subset of runs to verify that the accuracy of the approximation is sufficient for the application.

### 5.3.7 Can MODTRAN<sup>6</sup> be run with older band model data files?

MODTRAN6 can only be run with the 2013 band model data files based on HITRAN 2012. It is anticipated that 2017 band model data files will be generated based on HITRAN 2016. When that is complete, MODTRAN6 is expected to be compatible with both HITRAN 2012 and the HITRAN 2016 based sets of data.

### 5.3.8 What is the difference between [SPECTRAL](#) keywords [DV](#) and [FWHM](#)?

[DV](#) is the increment or step size at which output is generated. The Full Width at Half Maximum ([FWHM](#)) is the resolution of the slit function. Nyquist sampling dictates that [DV](#) be set to [FWHM](#) / 2.

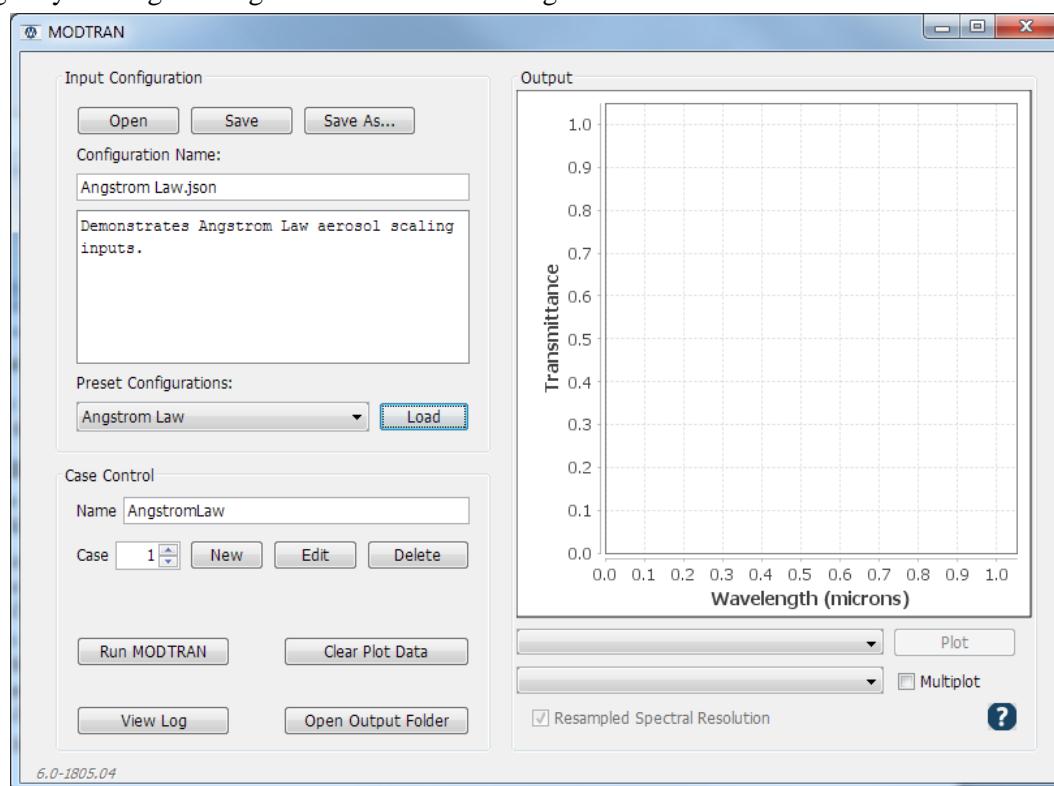
## 5.4 The Ground Surface

### 5.4.1 How can surface altitude, pressure, air temperature and relative humidity be specified as MODTRAN inputs?

Occasionally, MODTRAN users have surface data that they wish to insert into their MODTRAN calculations. These are not direct MODTRAN inputs. So how can they be incorporated into a MODTRAN run?

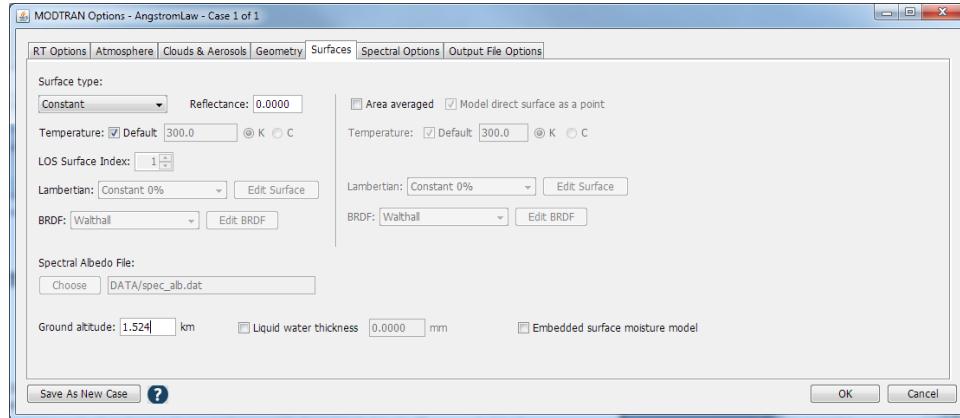
This is most easily done using the MODTRAN6 GUI with a baseline JSON input file. For this example, the Angstrom Law Preset Configuration will be loaded as the baseline case. Suppose surface measurements are as follows: 5,000 ft ground altitude, 0.85 atm pressure, 70 °F surface air temperature and a 66% RH.

Begin by loading the Angstrom Law Preset Configuration:

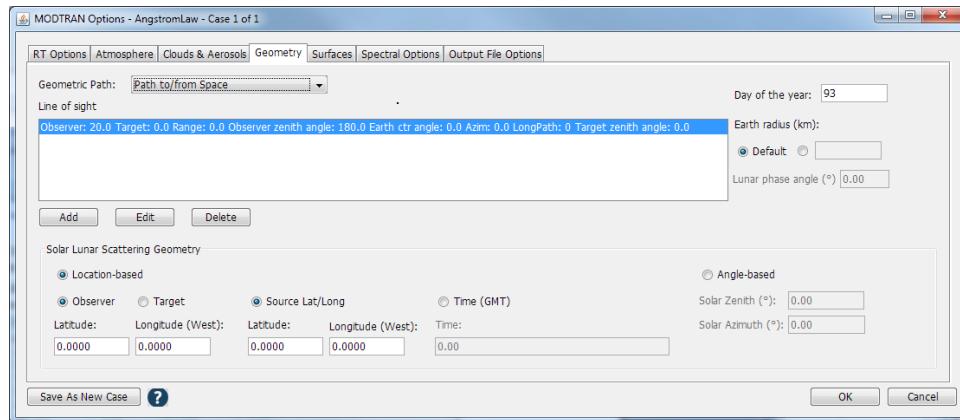


After hitting OK, click Edit and then OK to finalize loading of the Preset Configuration (this added step was required at the time at which these instruction were written).

Again click Edit and select the Surfaces tab to specify the ground altitude. The ground altitude of 5,000 ft corresponds to 1.524 km. Enter that value:

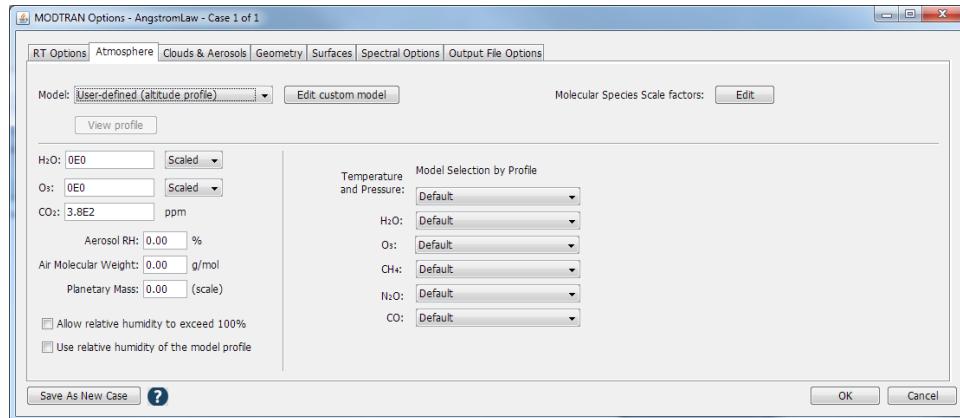


The Angstrom Law line-of-sight is a nadir path from 20.0 to 0.0 km. The final altitude cannot be below ground. Under the Geometry tab, switch the Geometric Path from Path between 2 altitudes to Path to/from Space.



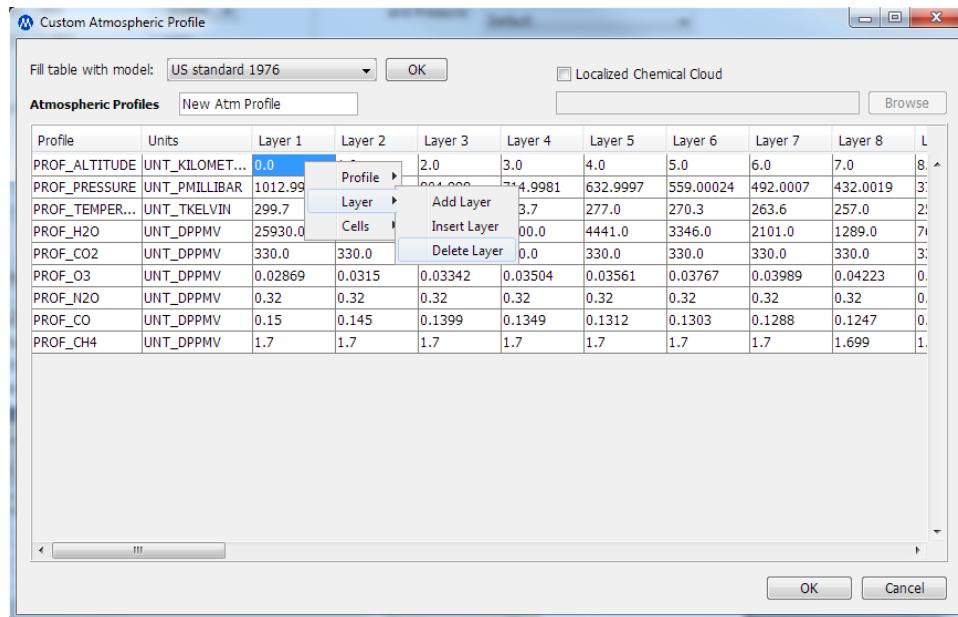
This will allow the nadir path from 20.0 km to terminate at the new ground altitude, 1.524 km.

Select the Atmosphere tab. The Angstrom Law case uses the Tropical model atmosphere. Switch to the User-defined (pressure-dependent) model:



With the User-defined (pressure-dependent) model, MODTRAN explicitly integrates the hydrostatic equation using the input pressure and temperature profile information and the ground altitude. The input altitude level profile is completely ignored. If surface properties were to be altered and no changes were made to the atmosphere, the hydrostatic equation would be violated.

From the Atmosphere tab, click on the Edit custom model button. The profiles are filled with the Tropical model atmosphere data. The first few atmospheric Levels are at 0.0, 1.0, 2.0, ... km altitude (the label Layer should actually be Level). Since the ground altitude is 1.524 km, Layer 1 at 0.0 km should be eliminated and Layer 2 should be edited with the surface data. To delete Layer 1, click on the 0.0 PROF\_ALTITUDE and then right click in one of the other cells in the same column to delete the Layer, as shown:



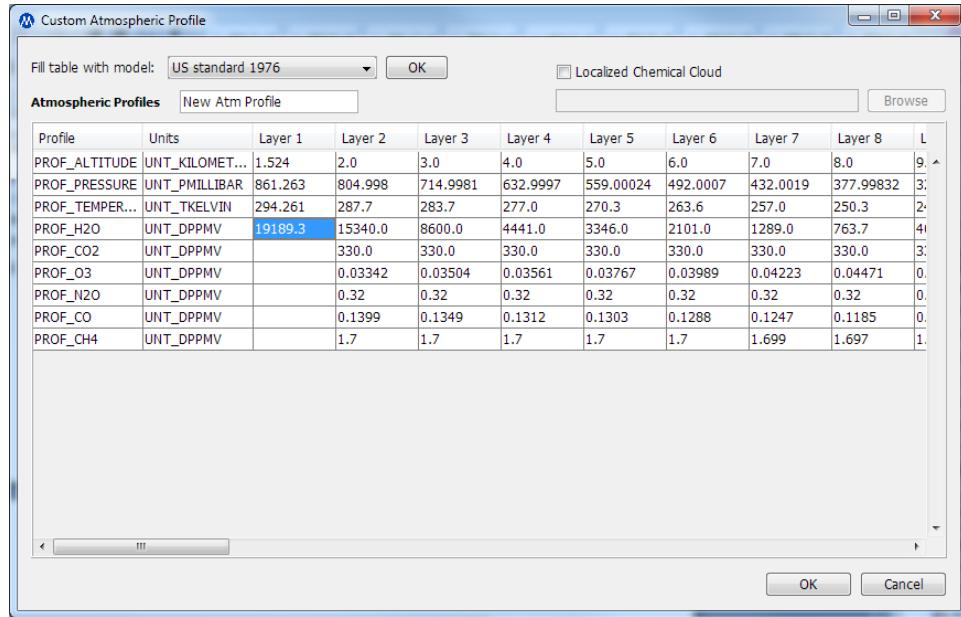
Next, change the new Layer 1 altitude to 1.524 km. Remove the Layer 1 entries for PROF\_CO2, PROF\_O3, PROF\_N2O, PROF\_CO and PROC\_CH4, so that Tropical model default values at 1.524 km will be defined. The pressure of 0.85 atm corresponds to 861.263 mbar; enter that value. The 70 °F temperature corresponds to 294.261 K; enter that value. The relative humidity (RH) of 66% must be converted to a mixing ratio in ppmV. MODTRAN models the water vapor saturation density,  $\rho_{sat}(T_0/T)$ , in g/m<sup>3</sup> as a function of the ambient to standard temperature ratio via the equation

$$\rho_{sat}(T_0/T) = \frac{T_0}{T} \exp [18.9766 - (14.9595 + 2.43882 T_0/T) T_0/T] ; \quad T_0 = 273.15 \text{ K} . \quad (5.1)$$

At 294.261 K, the water vapor saturation density is 18.4386 g/m<sup>3</sup>. A 66% RH implies a density of 12.1695 g/m<sup>3</sup>. The density in g/m<sup>3</sup> is converted to ppmV by

1. Dividing by the molecular weight of water (18.01528 g/mole),
2. Multiplying by the standard volume (22,413.83 cm<sup>3</sup> atm/mole),
3. Dividing by pressure (0.85 atm in this example), and
4. Dividing by the temperature ratio ( $T_0/T$  equals 0.92826 in this example)

The mixing ratio is 19,189.3 ppmV. After entering that value the Custom Atmospheric Profile has the following form.



If you click on OK twice, you will be brought back to the top MODTRAN6 GUI window. Use Save As... to create the modified \*.json input file. The Atmosphere section should have the form shown on the next page. The right side of the PROFILE data has been truncated to fit within the page. The input surface values are the first PROFILE entries for PROF\_ALTITUDE, PROF\_PRESSURE, PROF\_TEMPERATURE and PROF\_H2O. Also note that the first level PRO\_MASK value for PROF\_CO2, PROF\_O3, PROF\_N2O, PROF\_CO and PROF\_CH4 are all -1. This indicates that the value should be interpolated from the built-in model profile data.

```

"ATMOSPHERE": {
    "MODEL": "ATM_USER_PRESS_PROFILE",
    "M1": "ATM_TROPICAL",
    "M2": "ATM_TROPICAL",
    "M3": "ATM_TROPICAL",
    "M4": "ATM_TROPICAL",
    "M5": "ATM_TROPICAL",
    "M6": "ATM_TROPICAL",
    "MDEF": 1,
    "CO2MX": 380.0,
    "HMODEL": "New Atm Profile",
    "NPROF": 9,
    "NLAYERS": 49,
    "PROFILES": [
        {
            "TYPE": "PROF_ALTITUDE",
            "UNITS": "UNT_KILOMETERS",
            "PROFILE": [ 1.524, 2.0, 3.0, 4.0, 5.0, 6.0, 7.0, 8.0, 9.0, 10.0, 11.0, 12.0, 13.0, 14.0, 15.0, 16.0, 17.0, 18.0, 19.0, 20.0, 21.0, 22.0, 23.0, ...]
        },
        {
            "TYPE": "PROF_PRESSURE",
            "UNITS": "UNT_PMILLIBAR",
            "PROFILE": [ 863.263, 804.998, 714.9981, 632.9997, 559.00024, 492.0007, 432.0019, 377.99832, 329.00076, 285.9995, 247.00038, ...]
        },
        {
            "TYPE": "PROF_TEMPERATURE",
            "UNITS": "UNT_TKELVIN",
            "PROFILE": [ 294.261, 287.7, 283.7, 277.0, 270.3, 263.6, 257.0, 250.3, 243.6, 237.0, 230.1, 223.6, 217.0, 210.3, 203.7, 197.0, 194.8, ...]
        },
        {
            "TYPE": "PROF_H2O",
            "UNITS": "UNT_DPPMV",
            "PROFILE": [ 19189.3, 15340.0, 8600.0, 4441.0, 3346.0, 2101.0, 1289.0, 763.7, 409.8, 191.2, 73.06, 29.05, 9.9, 6.22, 4.0, 3.0, 2.9, 2.75, ...]
        },
        {
            "TYPE": "PROF_CO2",
            "UNITS": "UNT_DPPMV",
            "PROFILE": [ 0.0, 330.0, 330.0, 330.0, 330.0, 330.0, 330.0, 330.0, 330.0, 330.0, 330.0, 330.0, 330.0, 330.0, 330.0, 330.0, 330.0, 330.0, ...],
            "PRO_MASK": [-1, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0]
        },
        {
            "TYPE": "PROF_O3",
            "UNITS": "UNT_DPPMV",
            "PROFILE": [ 0.0, 0.03342, 0.03504, 0.03561, 0.03767, 0.03989, 0.04223, 0.04471, 0.05, 0.05595, 0.06613, 0.07815, 0.09289, 0.105, ...],
            "PRO_MASK": [-1, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0]
        },
        {
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            "UNITS": "UNT_DPPMV",
            "PROFILE": [ 0.0, 0.32, 0.32, 0.32, 0.32, 0.32, 0.32, 0.32, 0.32, 0.32, 0.3195, 0.3179, 0.314, 0.3095, 0.3048, 0.2999, 0.2944, 0.2877, 0.2783, 0.2671 ...],
            "PRO_MASK": [-1, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0]
        },
        {
            "TYPE": "PROF_CO",
            "UNITS": "UNT_DPPMV",
            "PROFILE": [ 0.0, 0.1399, 0.1349, 0.1312, 0.1303, 0.1288, 0.1247, 0.1185, 0.1094, 0.09962, 0.08964, 0.07814, 0.06374, 0.05025, ...],
            "PRO_MASK": [-1, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0]
        },
        {
            "TYPE": "PROF_CH4",
            "UNITS": "UNT_DPPMV",
            "PROFILE": [ 0.0, 1.7, 1.7, 1.7, 1.7, 1.7, 1.699, 1.697, 1.693, 1.685, 1.675, 1.662, 1.645, 1.626, 1.605, 1.582, 1.553, 1.521, 1.48, 1.424, ...],
            "PRO_MASK": [-1, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0]
        }
    ]
},

```

#### **5.4.2 Does MODTRAN support input of tabulated or user-defined surface BRDFs?**

MODTRAN Bi-directional Reflectance Distribution Function (BRDF) option supports a host of parameterized terrain models. The option was originally designed to allow tabulated surface BRDFs, but that option has never been implemented. If you require a BRDF input option not currently supported by MODTRAN, please forward your request to SSI ([modtran@spectral.com](mailto:modtran@spectral.com)) and AFRL ([ARFL.RVBYI.MODTRANOrgMailbox@us.af.mil](mailto:ARFL.RVBYI.MODTRANOrgMailbox@us.af.mil)).

#### **5.4.3 Even though my path does not terminate at the ground, my total radiance includes a surface emitted term. Why? [Alternatively: How do I set the ground temperature when my path does not terminate at the ground?]**

For a line-of-sight that intersects the Earth, the [SURFACE](#) keyword [TPTEMP](#) is the ground surface temperature in degrees Kelvin (if [TPTEMP](#) is  $\leq 0.$ , then the ground surface temperature is set to the surface air temperature). Occasionally a user will set [TPTEMP](#) to the desired ground temperature when running an up-look scenarios or a down-look scenarios that does not terminate at the ground. In these cases, MODTRAN interprets [TPTEMP](#) as the temperature of a grey body target at the end of the line-of-sight. Unless one is actually modeling a grey body target, [TPTEMP](#) should be set to zero for lines-of-sight not terminating at the ground. Otherwise, the target thermal emission is included in the total radiance.

One may still wish to set a surface ground temperature, distinct from the surface air temperature, for lines-of-sight not terminating at the ground. This value will indirectly contribute to the thermal multiple scattering radiance component. To define the ground surface temperature in these cases, set [SURFACE](#) keyword [SURREF](#) to either 'LAMBER' or 'BRDF'; set [SURFACE](#) keyword NSURF to 2 and set [SURFACE](#) keyword AATEMP to the desired surface ground temperature in degrees Kelvin.

#### **5.4.4 Why is the spectral ground reflected (GRND\_RFLT) output zero for paths that do not terminate at the ground?**

It may seem confusing that the GRND\_RFLT spectral radiance is always zero for lines-of-sight that do not intersect the ground. Radiation scattered off the ground can scatter into the line-of-sight, but that component is included in the multiple scattering (MULT\_SCAT) and/or thermal scattering (THRML\_SCT) path radiance terms. The GRND\_RFLT radiance only includes ground reflected radiance that directly transmits to the sensor.

### **5.5 Outputs**

#### **5.5.1 Is there documentation describing MODTRAN spectral output?**

MODTRAN5 did not include a description of its spectral output in the body of its user's manual. Instead, a frequently asked questions (FAQ) document was introduced that described the MODTRAN spectral outputs. The MODTRAN5 FAQ was incorporated into the MODTRAN5.3 user's manual as an appendix.

For MODTRAN6, the spectral output descriptions from the MODTRAN5 FAQ have been updated and incorporated into this MODTRAN6 user's manual as Chapter 4.

#### **5.5.2 What is the meaning of the atm-cm and atm-cm/km units used in MODTRAN output?**

See Section 3.4.1.

#### **5.5.3 Can the built-in scattering phase functions used by MODTRAN6 be written to a file?**

In the early 1980's, when aerosol models were being integrated into LOWTRAN, the precursor of MODTRAN, memory was at a premium. Storing the aerosol Mie theory spectral scattering phase functions in block data was not an option. To circumvent this problem, a compact master list of scattering phase functions was defined along with a function that mapped each aerosol type and spectral grid point to the entry in the master list that most closely matched original phase function. This heritage remains in

MODTRAN. MODTRAN does not generally output this information. In its most general form, the scattering phase functions would be written at every altitude level and spectral grid point; that is a lot of data. If you do need access to these functions, please email your request to [modtran@spectral.com](mailto:modtran@spectral.com) and a version of the MODTRAN6 executable will be provided that generates this output.

#### 5.5.4 Why is the product of molecular and particulate component transmittances generally not equal to the combined (total) transmittance?

The MODTRAN band model invokes the statistical assumption that the absorption from distinct species is randomly correlated. This implies that combined transmittance is the product of the individual species transmittances. Within MODTRAN, this assumption is applied at the band model resolution: 0.1, 1.0, 5.0 or 15.0 cm<sup>-1</sup>. When the output spectral resolution ([SPECTRAL](#) keyword [FWHM](#)) exactly equals the band model resolution, the product of the individual species transmittances generated when [IEMSCT](#) equals *RT\_TRANSMITTANCE* will equal the combined species transmittance. At any coarser output spectral resolution, this equality is not strictly obeyed.

#### 5.5.5 What is the difference between the combined transmittance and the total transmittance?

The attenuation along a path due to absorption and scattering losses is referred to as the direct transmittance. The diffuse transmittance is the amount of radiation that passes through a medium, such as a cloud or the total atmosphere, due to scattering. The sum of the direct and diffuse transmittance is defined as the *total transmittance*. The term *total transmittance* can be confusing because it is sometimes also used to define the direct transmittance due to the totality of extinction sources (H<sub>2</sub>O, CO<sub>2</sub>, O<sub>3</sub>, aerosols, clouds, Rayleigh scattering, etc.). The MODTRAN <ROOTNAME>.tp7 and <ROOTNAME>.7sc output files instead use the term *combined transmittance* to describe the direct transmittance due to the totality of extinction sources. Unfortunately, other MODTRAN output files, e.g. <ROOTNAME>.tp6 and <ROOTNAME>.csv, still use the term *total transmittance* for *combined transmittance*.

#### 5.5.6 Are vertical aerosol optical depth (AOD) values included in the MODTRAN output?

The <rootname>.tp6 file (also available from the View Log button on the MODTRAN GUI, Figure 2.1) always includes a section beginning with the phrase “TOTAL COLUMN ABSORBER AMOUNTS FOR THE LINE-OF-SIGHT PATH No. <#>:”. This section includes the line-of-sight 550 nm extinction optical depths for the four MODTRAN aerosol regions and for their total. If you are running a thermal infrared calculation, as an example, the output of aerosol optical depths in the center of the visible, i.e. 550 nm, may not be of great utility. Therefore, this section as include the LOS aerosol extinction optical depths at the central wavelength of the input bandpass.

Whenever multiple scattering is included in a MODTRAN run (RTOPTIONS keyword [IMULT](#) = RT\_DISORT, RT\_DISORT\_AT\_OBS, RT\_ISAACS\_2STREAM, RT\_ISAACS\_2STREAM\_AT\_OBS, RT\_ISAACS\_SCALED or RT\_ISAACS\_SCALED\_AT\_OBS), there is a separate section in the <rootname>.tp6 file (and in the log generated from the GUI) that begins with the phrase “TOTAL COLUMN ABSORBER AMOUNTS FOR A VERTICAL PATH FROM GROUND TO SPACE:”. There is one set of aerosol optical depths in this second section that contains the *vertical* aerosol optical depth (AOD) data at 550 nm; a second set contains the data at the central wavelength.

One can also determine the total vertical AOD without running a multiple scattering calculation, i.e. with RTOPTIONS keyword [IMULT](#) = RT\_NO\_MULTIPLE\_SCATTER. Simply set up a space-to-ground ([GEOMETRY](#) keywords [ITYPE](#) = 3, [H1ALT](#) = 100 and [OBSZEN](#) = 180) transmittance only calculation ([RTOPTIONS](#) keyword [IEMSCT](#) = RT\_TRANSMITTANCE) and sum the aerosol line-of-sight column absorber amounts.

## **5.5.6 Why does the total thermal spectral radiance generally decrease when multiple scattering is turned on?**

In thermal radiance mode ([RTOPTIONS](#) keyword `IEMSC`T = RT\_THERMAL\_ONLY), the total thermal radiance will generally decrease when multiple scattering is enabled ([RTOPTIONS](#) keyword `IMULT` changed from RT\_NO\_MULTIPLE\_SCATTER to any of the other selections). This is perplexing because the thermal emission cannot exceed the thermal emission plus thermal scatter. This occurs because MODTRAN invokes the conservative scattering approximation when no multiple scattering model is selected. The conservative scattering approximation assumes that the radiance scattered out of the LOS exactly equals the radiance that is scattered back into the LOS. This is implemented by setting the emissivity in each path segment to one. Generally, conservative scattering approximation predicts too much thermal scatter. For this reason, it is recommended that DISORT multiple scattering with at least two streams is run when RT\_THERMAL\_ONLY calculations are performed. Note that the Isaacs 2-stream thermal scatter model runs no faster than the higher fidelity DISORT 2-stream model.

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## **5.2 Specialized Applications**

### **5.1.1 Can MODTRAN6 be used for modeling laser wavelength transmittances?**

The MODTRAN6 line-by-line (LBL) option does allow laser wavelength to be modeled. Currently (MODTRAN6.0.0), however, a problem with the LBL line tails leads to a problem in the microwave spectral region. This problem will be fixed in MODTRAN6.1.0, which will include HITRAN 2016 based band model parameters.

### **5.1.2 Does MODTRAN atmospherically correct hyperspectral and/or multispectral imagery?**

If DISORT solar multiple scattering is used (by providing `IMULT` in [RTOPTIONS](#) set to RT\_DISORT or RT\_DISORT\_AT\_OBS) with a downward viewing line-of-sight, and if `DISALB` is set to TRUE, MODTRAN will generate an atmospheric correction data (<ROOTNAME>.acd) output file. This file contains the spectral spherical albedo and both solar and line-of-sight path diffuse and direct transmittance data required for mapping observed radiances into ground reflectances. However, MODTRAN itself does not process radiance imagery to generate surface reflectance maps. A number of software products are available for atmospherically correcting hyperspectral and/or multispectral imagery, most of which rely on MODTRAN radiative transfer to perform the radiance to reflectance mapping. In particular, we recommend the atmospheric correction code FLAASH®, developed by Spectral Sciences, Inc. and distributed as an add-on to the ITT ENVI Geospatial Software. For more information, see [http://www.harrisgeospatial.com/portals/0/pdfs/envi/flaash\\_module.pdf](http://www.harrisgeospatial.com/portals/0/pdfs/envi/flaash_module.pdf).

### **5.1.3 Does MODTRAN6 compute polarization radiance vectors?**

There is a version of MODTRAN4 that computes polarization radiance vectors using the vectorized version of DISORT, VDISORT [53]. This capability has yet to be integrated in MODTRAN6. For more information, contact Dr. Alexander (Lex) Berk at [lex@spectral.com](mailto:lex@spectral.com).

### **5.1.4 Is the extra-terrestrial planetary version of MODTRAN generally available?**

An initial MODTRAN derivative model known as MOD-ET has been developed by Spectral Sciences, Inc to model extra-terrestrial (ET) planetary atmospheres [16, 11, 27]. MOD-ET uses the MODTRAN band model and includes absorption sources that are insignificant for the terrestrial atmosphere but that are critical to ET atmospheres such as H<sub>2</sub>-H<sub>2</sub>, H<sub>2</sub>-He, H<sub>2</sub>-CH<sub>4</sub> and CH<sub>4</sub>-CH<sub>4</sub> collision induced absorption (CIA). MOD-ET also incorporates a broader temperature range of band model data, a generalized treatment of Rayleigh scattering, and input of planetary mass and air molecular weight for solving the hydrostatic equation. Atmospheric and aerosol models have been defined for Neptune, Saturn and Jupiter. MOD-ET has been validated against measurement data for the entire microwave through UV

spectral range. For more information, please contact Dr. Alexander (Lex) Berk at [lex@spectral.com](mailto:lex@spectral.com).

#### **5.1.5 Can MODTRAN be used to model sky radiance?**

For a stratified atmosphere, defined by molecular and particulate vertical profiles, MODTRAN can be used to model the downward surface spectral flux and/or the angular variation of the spectral radiance impinging on the ground. To generate the surface flux data, input [FLAGS\[6\]](#) in [SPECTRAL](#) should be set to “T” or “F” and [MLFLX](#) set to 1. This will generate [FLUXES](#) in [MODTRANOUTPUT](#). The angular radiance data is defined by placing the observer, [HIAUT](#) in [GEOMETRY](#), at the ground, setting the desired sensor zenith angle, [OBSZEN](#), and setting the relative solar/lunar azimuth angle, [TRUEAZ](#), if the Sun/Moon is being included in the simulation. Often times, sky radiance measurements are associated with modeling of partial cloud cover scenes. Because of its assumption of horizontal homogeneity, MODTRAN is not specifically designed to model broken cloud scenes. Many users have successfully pieced together cloud-free and semi-infinite cloud results to model the partial clouds, but the onus for those studies resides with the user.

#### **5.1.6 Does MODTRAN model airglow and other non-local thermodynamic equilibrium (NLTE) affects?**

MODTRAN is strictly a local thermodynamic equilibrium (LTE) model, meaning that the population of electronic, vibrational and rotational excitation states is determine solely on the basis of the local temperature. The LTE assumption is valid as long as the frequency of molecular collisions exceeds relaxation times. For the terrestrial atmosphere, this is essentially always true for altitudes below about 30 km. At higher altitudes, the LTE assumption is still valid in many spectral regions. However, for limb paths above 30 km, a radiative transfer model that treats NLTE phenomena such as SAMM®2 [25] is preferred over MODTRAN.

#### **5.1.7 Can MODTRAN be used to model solar terminator affects [Alternatively, does MODTRAN model twilight (low Sun) conditions]?**

MODTRAN calculates the refractive path to the sun for each altitude level along the sensor line-of-sight (LOS). If the hard Earth, which MODTRAN models as a sphere, intersects with the solar illumination path, then the LOS altitude level is labeled as being in shadow and the solar single scatter radiance at that point is set to zero. If, on the other hand, the LOS altitude level is solar illuminated, MODTRAN does calculate the single scatter solar for the refracted path. MODTRAN does not model the atmospheric chemistry that occurs across the terminator. Also, the scattering algorithms in MODTRAN do not accurately model the solar multiple scatter for low Sun conditions. Thus, MODTRAN can only be used to model solar terminator affects if the chemical changes in the atmosphere are inconsequential for one’s applications and multiple scatter is not the dominant source of radiation (above around 3  $\mu\text{m}$ ).

#### **5.1.8 Can the MODTRAN atmosphere be varied to match ground measurements of the direct and hemispherical solar flux?**

MODTRAN is a forward rather than inverse model. There is no option to input spectral radiance data and automatically retrieve atmospheric conditions. However, MODTRAN does provide input options which can be used to help retrieve atmospheric conditions. Suppose, for example, that you have made ground measurements of spectral channel direct and hemispherical solar flux values and you wish to retrieve the atmosphere. Given a baseline atmosphere definition, possibly based on local radiosonde data, one can use the aerosol Angstrom Law inputs ([CDASTM](#), [ASTMC](#), and [ASTMX](#) in [AEROSOLS](#)) to perturb the aerosol spectral extinction until the direct solar flux predictions match the data. In a second step, one could perturb the darkness of the aerosols by adjusting the spectral dependence of the aerosol single scattering albedo by setting up [AWAVLN](#) and [ASSALB](#) in [SSALB](#) in [AEROSOLS](#).

### 5.1.9 Can MODTRAN segment transmittances be multiplied together to get the total path transmittance?

MODTRAN originated as a statistical band model radiative transfer algorithm, although MODTRAN4 introduced a Correlated-k algorithm and MODTRAN6 introduces a line-by-line (LBL) capability. The MODTRAN band model algorithm does not solve the radiative transfer equation monochromatically. Instead, narrow spectral band transmittances are calculated based on a statistically modeled distribution of molecular transitions. Beer's Law states that monochromatic segment transmittances, such as those calculated by the MODTRAN6 LBL option, are multiplicative:

$$T_v^{AB} = T_v^A \times T_v^B \quad (5.2)$$

Here,  $T_v^A$  is the spectral transmittance through segment A at spectral frequency  $v$ ,  $T_v^B$  is the spectral transmittance through segment B, and  $T_v^{AB}$  is the spectral transmittance through combined segment AB. Unfortunately, transmittances integrated over a spectral band,  $\Delta v$ , are not multiplicative:

$$\int_{\Delta v} T_v^{AB} dv = \int_{\Delta v} T_v^A \times T_v^B \neq \int_{\Delta v} T_v^A dv \times \int_{\Delta v} T_v^B dv \quad (5.3)$$

MODTRAN does include a statistical k-distribution and Correlated-k (Ck) algorithm. With the k-distribution method, the band model transmittance is represented as a weighted sum of monochromatic transmittances:

$$\int_{\Delta n^u} T_v^A dv = \sum_i \Delta g_i T_i^A. \quad (5.4)$$

The Correlated-k ansatz states that each interval satisfies Beer's Law so that

$$\int_{\Delta v} T_v^{AB} dv = \sum_i \Delta g_i T_i^{AB} = \sum_i \Delta g_i T_i^A T_i^B \quad (5.5)$$

Thus, if the k-distributions are known for segments A and B, then one can calculate the total A+B path transmittance, but it still does not equal the product of the segment spectral band transmittances.

### 5.1.10 Can MODTRAN be used in the microwave through terahertz spectral region?

The MODTRAN band model data begins at 0 cm<sup>-1</sup>. In principle, the MODTRAN band model can provide as fine as 0.1 cm<sup>-1</sup> spectral resolution results in the microwave through terahertz spectral region. For some planetary atmosphere applications, this capability has been validated against measured data in regions where collision induced absorption (CIA) dominates. However, the MODTRAN6 LBL capability is preferred in the microwave through terahertz spectral region over the band model approach.

## 5.2 Model Features

### 5.2.1 Does MODTRAN6 use the DISORT BRDF option?

DISORT Version 2 includes an upgrade for treatment of the lower boundary condition using a Legendre expansion of the surface Bi-directional Reflectance Distribution Functions (BRDFs). MODTRAN6 was upgraded to interface the DISORT BRDF capability.

### 5.2.2 Does MODTRAN6 include an ocean surface model?

MODTRAN contains the "Ross-Sea" ocean surface model [46, 47]. The option is activated by using CBRDF and setting it to BRDF\_ROSS\_SEA. The Ross-Sea BRDF serves as the lower boundary condition for DISORT multiple scattering.

### 5.2.3 Does MODTRAN model mixed phase (water and ice) clouds?

MODTRAN does model mixed phase (water and ice) clouds. Whenever a water cloud model is selected,

*i.e. `ICLD` in `AEROSOLS` set to values 1 through 10, then the user can input distinct profiles for water and ice clouds using `CLDAWT`. These profiles can be chosen to be overlapping, creating mixed phase clouds.*

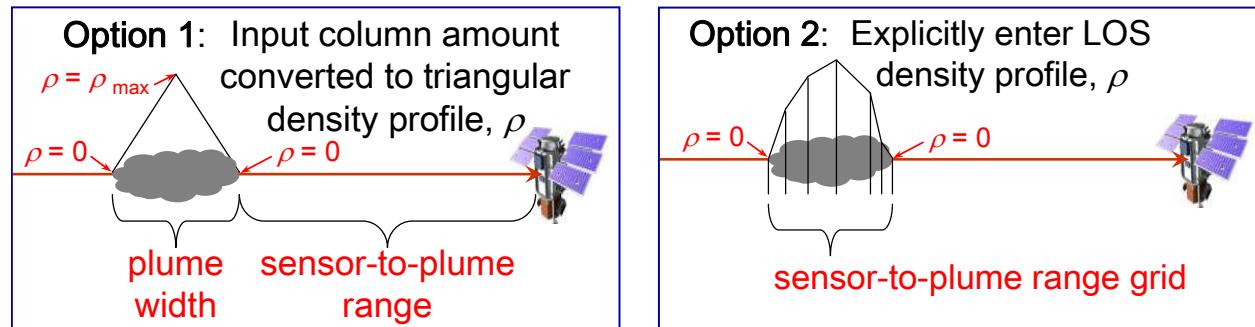
#### **5.2.4 Can MODTRAN model multiple cloud layers?**

*MODTRAN can model multiple cloud layers, but with a few caveats. The MODTRAN cloud option allows a user to define cloud profiles by setting up `CLDAWT`. The cloud profiles are read in whenever a water cloud is selected i.e. `ICLD` in `AEROSOLS` set to values 1 through 10, and `CLDAWT` is provided. One can define cloud profiles to contain multiple layers by simply setting the cloud density to zero between layers. However, this creates multiple cloud layers with common optical properties. For the two cloud layer scenario, each layer can be defined with distinct optical properties. `CLDAWT` nominally provides both a water and ice cloud profile. If default cloud optical properties are used, then indeed the input `CLD` will contain the profile of a cloud defined with water droplet optical data and the input `CLDICE` will contain the profile of a cloud defined with ice particle optical data. However, `CLDSPC` can be used to define the optical data for both `CLD` and `CLDICE`. Using this option, `CLD` and `CLDICE` can contain whatever type of cloud one wishes.*

## 6. LOCAL CHEMICAL CLOUDS AND SLANT RANGE PROFILE DATA

MODTRAN6 provides the capability to model local chemical plumes defined from the perspective of the observer/sensor and to generate outputs of ambient, with plume and contrast signature predictions. The local chemical plume capability is initiated by setting `AYRANG` in the `ATMOSPHERE` JSONObject to TRUE. In the `PROFILES` JSONArray of the `ATMOSPHERE` JSONObject, the `UNAME` keyword value for at least one auxiliary molecule must be preceded by a tilde (~) to indicate that it is to be modeled as a local chemical species. MODTRAN ambient species, such as H2O and CO, can be listed as local plume species (e.g.,  $\sim\text{H}_2\text{O}$  and  $\sim\text{CO}$ ) to model enhancements above background concentrations. All `UNAME` molecules with the tilde prefix must have slant range profile data defined in a `<ROOTNAME>.rng` file (or in file `yrange.asc` if no rootname is provided). This appendix describes the format of these files.

A goal of this effort was to design a format for the `<ROOTNAME>.rng` files that would be relatively easy to use. Data is read in using free formats. The source code for input of the data is routine `yrange.f`. As illustrated in Figure 6.1, two input options are available. The first and simpler option defines a triangle profile in which slant range densities are zero at the front of the cloud, increase linearly to a maximum at the midpoint slant range, and decrease linearly to zero at the back of the cloud. The user specifies column densities and a midpoint temperature; the end-point temperatures are both automatically set to ambient. The second option allows the user to explicitly enter the slant range profile data for the temperature and molecular densities; endpoint densities are set to zero and endpoint temperatures set to ambient.



**Figure 6.1.** Two options for defining local chemical cloud slant range profile data.

Sample `<ROOTNAME>.rng` input files for each option are included in Tables 6.1 and 6.2. Table 6.1 contains the Option 1 inputs used for the “plumeMLOStm” and “plumeMLOStmCK” test cases. If these were single line-of-sight runs, the entire `<ROOTNAME>.rng` file would only consist of the first 3 lines in Table 6.1. However, these test cases utilize the MODTRAN multiple line-of-sight (`MLOS`) option (JSONObject `SURFACE` keyword `SURFNLOS > 1`) to run 11 lines-of-sight using a single multiple scattering calculation. As a result, Table 6.1 contains 11 triplets of slant range profile data. For each line-of-sight, the Option 1 inputs are:

- *Line 1:* A “dummy” header that is not read in. The list of species is provided for clarity. The list and order of slant range molecules is determined from the `PROFILES` JSONArray; each molecule whose name is preceded by a tilde (~) must be included in the `<ROOTNAME>.rng` file and their density inputs must be entered in the same order as the names appeared in the `PROFILES` JSONArray.
- *Line 2:* A data line containing (a) the slant range [km] from the sensor to the front of the local chemical cloud [`Y_RANG(0,*)`], (b) the logical variable `LY_TMP`, which should be set to .TRUE. if an absolute temperature is to be entered and set to .FALSE. if a temperature relative to ambient is to be entered, and (c) the column densities [PPM-m] for each local chemical cloud

molecule [YCOL]. The “PPM-m” label which appears at the end on the Line 2 entries in Table 6.1 is not read in.

- *Line 3:* A data line containing (a) the slant range [km] from the sensor to the back of the local chemical cloud [Y\_RANG(1,\*)] and (b) the peak temperature [K] of the chemical cloud if LY\_TMP is .TRUE. or the increase over ambient temperature [K] if LY\_TMP is .FALSE. [RNG\_T(1,\*)].

**Table 6.1.** The Test Case Input File “plumeMLOStm.rng”

RANGE [ km ]	TEMP [ K ]	SF6	SO2	
19.9000000000000D0	F 2.50000	500.0000	PPM-m	
19.9050000000000D0	+36.000			
RANGE [ km ]	TEMP [ K ]	SF6	SO2	
19.9000190025645D0	F 2.45000	490.0000	PPM-m	
19.90490190025645D0	+36.000			
RANGE [ km ]	TEMP [ K ]	SF6	SO2	
19.90000760102761D0	F 2.40000	480.0000	PPM-m	
19.90480760102761D0	+36.000			
RANGE [ km ]	TEMP [ K ]	SF6	SO2	
19.90001710231895D0	F 2.35000	470.0000	PPM-m	
19.90471710231895D0	+36.000			
RANGE [ km ]	TEMP [ K ]	SF6	SO2	
19.90003040413955D0	F 2.30000	460.0000	PPM-m	
19.90463040413955D0	+36.000			
RANGE [ km ]	TEMP [ K ]	SF6	SO2	
19.90004750650215D0	F 2.25000	450.0000	PPM-m	
19.90454750650215D0	+36.000			
RANGE [ km ]	TEMP [ K ]	SF6	SO2	
19.90006840942313D0	F 2.20000	440.0000	PPM-m	
19.90446840942313D0	+36.000			
RANGE [ km ]	TEMP [ K ]	SF6	SO2	
19.90009311292249D0	F 2.15000	430.0000	PPM-m	
19.90439311292249D0	+36.000			
RANGE [ km ]	TEMP [ K ]	SF6	SO2	
19.90012161702390D0	F 2.10000	420.0000	PPM-m	
19.90432161702390D0	+36.000			
RANGE [ km ]	TEMP [ K ]	SF6	SO2	
19.90015392175461D0	F 2.05000	410.0000	PPM-m	
19.90425392175461D0	+36.000			
RANGE [ km ]	TEMP [ K ]	SF6	SO2	
19.90019002714557D0	F 2.00000	400.0000	PPM-m	
19.90419002714557D0	+36.000			

Table 6.2 contains the Option 2 slant range input file used in test cases “plumeDN,” “plumeUP” and “plumeCK”. The Option 2 input files contain 4 sets of input lines:

- A *dummy header*: This line is not read in. The list of species is provided for clarity. The list and order of slant range molecules is determined from the [PROFILES](#) JSONArray; each molecule whose name is preceded by a tilde (~) must be included in the <ROOTNAME>.rng file and their density inputs must be entered in the same order as the names appeared in the [PROFILES](#) JSONArray.

- *Cloud front*: The second line contains (a) the slant range [km] from the sensor to the front of the local chemical cloud [Y\_RANG(0,\*)], (b) the logical variable LY\_TMP, which should be set to .TRUE. if an absolute temperature is to be entered and set to .FALSE. if a temperature relative to ambient is to be entered, and (c) an **optional** list of the column densities [PPM-m] for each local chemical cloud molecule [YCOL]; if column density values are provided, they are used to scale the subsequent list of densities to match the input column amounts.
- *Cloud interior*: Each line from this section must include (a) a slant range [km] from the sensor to an interior point in the cloud [Y\_RANG(i,\*)], (b) the temperature [K] of the chemical cloud at the interior point if LY\_TMP is .TRUE. or the increase over ambient temperature [K] at the interior point if LY\_TMP is .FALSE. [RNG\_T(i,\*)], and (c) the density [PPM] of each local chemical cloud species at the specified slant range [YDEN]. The slant range values must increase monotonically.
- *Cloud back*: The last line contains the slant range [km] from the sensor to the back of the local chemical cloud [Y\_RANG(N,\*)].

If the multiple line-of-sight ([MLOS](#)) option (JSONObject [SURFACE](#) keyword SURFNLOS > 1) is used with Option 2, all 4 sets of lines should be repeated.

Internally, MODTRAN determines the altitude at each slant range and adds that altitude to its vertical profiles. If the number of added altitudes is too large, MODTRAN will stop with the following error message:

```
Error in routine ADDALT: Parameter LAYDIM from the include file "PARAMS.h"
must be increased above its current value of XXX.
```

In this case, MODTRAN must be recompiled with parameter LAYDIM increased.

**Table 6.2.** The Test Case Input File “plumeDN.rng”

RANGE [ km ]	TEMP [ K ]	CO [ PPM ]	SF6 [ PPM ]
0.10000D0	F 100.0000	200.0000	PPM-m
0.10120D0	+2.000	50.0000	80.0000
0.10200D0	+3.000	70.0000	200.0000
0.10300D0	+2.000	40.0000	60.0000
0.10500D0			

## 7. RUNNING MODTRAN6 IN PARALLEL USING MPI

MODTRAN6 provides the option to run the model in parallel using the message passing interface (MPI). The following README file describes the set up:

The "modmpi" application executes independent MODTRAN runs in parallel using MPI. The application code modmpi.cc in the MODTRAN6/bin/ directory is provided both as a utility and as an example of using the MODTRAN6 C++ API to coordinate the execution of multiple input configurations in parallel. It reads a sequence of MODTRAN cases defined in a JSON or TP5 input file and distributes each case to independent "worker" processes running within a distributed processing system.

Any input file compatible with the standard MODTRAN application will operate with this MPI program. However, to avoid overwriting of output, the case configurations should provide unique file names in the [FILEOPTIONS](#) section of the JSON input.

NOTE: This application performs automatic load balancing at the expense of a control process (the "master" process). Because the master process does not perform a MODTRAN calculation, choosing  $N + 1$  processes at runtime, where one process is duplicated on the "master" process, should yield better performance.

Dependencies:

MPI library (with compiler)

To build

1. Edit the Makefile:

Set MPICXX to the MPI compilation wrapper script installed on your system. For example: MPICXX = mpicxx

2. Build the executable:

make clean (optional)

make

The executable called mod6mpi.x will be created in the upper "bin" directory.

3. To run, cd to the bin directory

mpirun -np <n> ./mod6mpi.x input\_script.json [output\_path]

where <n> should be replaced by the number of processes (see NOTE) and "mpirun" by the appropriate MPI run script. The output path is an optional parameter used to specify a target directory for the output files.

## 8. THE MODTRAN6 ATMOSPHERIC GENERATOR TOOLKIT

The Atmosphere Generator Toolkit (AGT) provides MODTRAN6 users the ability to input custom atmospheres into MODTRAN in a straightforward manner. The command-line tool must be called with either location (latitude, longitude, date, and time) or radiosonde data. The AGT outputs the custom atmosphere in either the form of MODTRAN legacy (tape5) CARD 2C1 inputs or as text for a MODTRAN6 JSON input file.

The radiosonde AGT input can be either post-processed or raw data. A **raw radiosonde** typically consists of several thousand lines (or more) of altitude dependent pressures, temperatures and relative humidities, ranging from the near ground level to about 30 km. Altitude gaps or noisy profiles are common. A **post-processed radiosonde** typically consists of processed measurements at 100s (not thousands) of altitudes. Typically this data extends to 25-30 km, with fewer missing data points and minimal noise. As examples, NOAA/ERSL and The University of Wyoming both maintain actively updated collections of post-processed radiosondes. File formats are not consistent between data sources; the AGT understands the three most common file formats and regularizes the input stream prior to processing the data for usage within MODTRAN.

Long-term time-averaged global data is available from a database maintained by NOAA in the form of the NCEP/NCAR Reanalysis Monthly Means and Other Derived Variables. This publicly available database contains long-term time-averaged data sets covering the entire globe on a 2.5 degree latitude by 2.5 degree longitude grid at 17 pressure levels that span from ground level to an approximate altitude of 30 km. Temperature and geopotential height data are present at all levels while relative humidity is only available from the ground to an approximate altitude of 9 km. The long-term monthly data covers 12 months averaged from January 1948 to present. The four times daily data covers covers the globe at 6 hour intervals averaged from 1981-2010.

### **8.1 Installation Instructions**

The AGT is shipped as a pre-built binary. Three operating systems are supported:

- **Linux**
- **Windows**
- **Mac**

The compiled software is called either `sndtp5.out` (Linux and Mac) or `sndtp5.exe` (Windows). Binary files for all supported operating systems are located in a three sub-directories or folders, one for each supported operating system:

- `./bin/linux/`,
- `./bin/windows`, and
- `./bin/mac`.

Those sub-folders contain a single file: a binary for use with a particular operating system. For convenience, the binary can be placed within the operating system's search path. Typical user installs on Linux often reside in the `/usr/bin/` or `/usr/local/bin/` folder. Windows default search path contains `%SystemRoot%\system32\` (that is usually `c:\windows\system32\`). Mac default search path contains both `/usr/bin/` and `/usr/local/bin/` folders.

The temporal data required by AGT is stored in the MODTRAN data directory. The data exclusively pertains to the NCEP/NCAR database making the directory unnecessary when parsing radiosonde files. The directory holds temperature, pressure, and water vapor concentrations. While the AGT executable can be placed in any location convenient to the user, the AGT data directory does not have the same flexibility. The AGT executable expect the AGT data to be located in the directory defined by the `MODTRAN_DATA` environment variable. All MODTRAN users should have a `MODTRAN_DATA`

environment variable set as part of the install process so no further action should be necessary. (See MODTRAN install instructions for further details.)

Examples radiosonde files are included in the ./examples/ directory. One column-formatted radiosonde file (RAW\_SONDE.COL), two FSL-formatted radiosonde files (NEW\_MEXICO\_2011.FSL and CHATHAM\_2005.FSL), and two Wyoming-formatted radiosonde files (DENVER\_2002.WYO and SALEM\_2015.WYO) are provided. These examples are provided for testing the installation. They can be placed in any convenient location or deleted from a workspace.

## **8.2 Running the Code**

There are two main modes of operation for the AGT:

1. AGT can process an individual radiosonde file to create atmospheric data compatible with MODTRAN legacy tape5 files or the new JavaScript Object Notation (JSON) input format.
2. AGT can define NCEP/NCAR reanalysis database atmospheric profiles that depend on latitude, longitude, day-of-year and universal time. The NCEP/NCAR database contains global long-term time-averaged climatology data (air temperature, geopotential height, and H<sub>2</sub>O concentrations). The data is uniformly averaged over a 2.5 degree latitude × 2.5 degree longitude grid (144 × 73) at 17 pressure levels corresponding to values from the ground (1000 mb) to approximately 30 km (10 mb) [The NCEP/NCAR database is not dependent on year since it is providing multi-year averages].

The following subsections describe each mode of operation for AGT. along with possible combinations of user inputs. The summary of allowed user commands is shown in Table 8.1.

**Table 8.1.** Possible command-line combinations for radiosonde parsing.

Entry	Options	Radiosonde	NCEP/NCAR
Sonde File Name	-f {filename}	Yes	
Sonde File Format	-txt, -fsl, -wyo	Yes	
NCEP/NCAR Database	-noaa, -noaa_m, -noaa_d		Yes
Latitude (degrees N)	-lat, -lat_n		Yes
Latitude (degrees E)	-long, -long_e		Yes
Day of Year (1-365)	-day {day-of-year}		Yes
Time of Day (integer 0-23)	-time {time-of-day}		Yes
Output Format	-tp5, -json	Yes	Yes

### **8.2.1 Operating with Radiosonde Files**

The AGT accepts three inputs when operating on a radiosonde file. The inputs are:

1. **Radiosonde File Name:** The absolute or relative path to and name of the ASCII formatted file.
2. **Radiosonde File Format:** The AGT currently supports column-formatted, FSL, and Wyoming radiosondes. Column-formatted data must be supplied by the user and only one example is provided. FSL-formatted data can be obtained online from NOAA (<http://esrl.noaa.gov/raobs/>). Two FSL-formatted files are provided. WYO-formatted data can be obtained online from the University of Wyoming (<http://weather.uwyo.edu/upperair/sounding.html>).
3. **Output File Format:** Options are a partial MODTRAN \*.tp5 file or ATMOSPHERE section inputs to a JSON file.

There are six radiosonde and output combinations; an example of each combination is given in Table 8.2. The three example radiosonde files in the Table 2 are: RAW\_SONDE.COL is a column-formatted

radiosonde file, CHATHAM\_2005.FSL is an FSL-formatted radiosonde file and DENVER\_2002.WYO is a Wyoming-formatted radiosonde file. The user can specify any file extension desired with the exception of “fsl” and “wyo” which may override user selection. In addition, case sensitivity is dependent on the operating system being used. Linux and Mac users will need to provide radiosonde file names with proper case while Windows users may be case insensitive.

**Table 8.2.** Possible command-line combinations for radiosonde parsing.

Format	Output	Example Command
Columns	Tape 5	snntp5.out -f RAW_SONDE.COL -txt -tp5
Columns	JSON	snntp5.out -f RAW_SONDE.COL -txt -json
FSL	Tape 5	snntp5.out -f CHATHAM_2005.FSL -fsl -tp5
FSL	JSON	snntp5.out -f CHATHAM_2005.FSL -fsl -json
Wyoming	Tape 5	snntp5.out -f DENVER_2002.WYO -wyo -tp5
Wyoming	JSON	snntp5.out -f DENVER_2002.WYO -wyo -json

The three supported radiosonde formats each have their own method of specifying measured atmospheric conditions. We will briefly describe their formats below.

### 8.2.1.1 ASCII Radiosonde Format

The ASCII radiosonde file format is space delimited without any header information. Four columns of data are considered meaningful with any remaining information ignored. Radiosonde data is expected to appear in the following sequence:

- **Column 1:** Altitude in kilometers
- **Column 2:** Pressure in units of millibar
- **Column 3:** Temperature in units of degrees centigrade
- **Column 4:** Water vapor in units of relative humidity

One example is shown below.

0.315	968.700	14.100	50.000
0.325	967.500	13.400	50.000
0.338	966.100	12.500	52.000
0.350	964.700	11.700	54.000
0.362	963.300	11.600	55.000
0.374	961.900	11.400	56.000
0.387	960.500	11.200	57.000
0.397	959.300	11.100	57.000
0.407	958.100	11.000	58.000
0.417	957.000	10.900	58.000

Any additional information beyond column 4 is ignored and the only requirement for column formatting is that they be space-delimited. Consequently, this too is a valid example of an ASCII radiosonde:

0.005	.1005E+04	2.819E+02	1.094E+01	1
0.041	.1000E+04	2.831E+02	1.227E+01	2
0.246	.9760E+03	2.889E+02	1.795E+01	3
0.305	.9692E+03	2.888E+02	1.772E+01	4
0.610	.9351E+03	2.876E+02	1.629E+01	5
0.702	.9250E+03	2.874E+02	1.588E+01	6
0.914	.9020E+03	2.864E+02	1.458E+01	7
1.219	.8700E+03	2.849E+02	1.278E+01	8
1.316	.8600E+03	2.844E+02	1.227E+01	9
1.414	.8500E+03	2.848E+02	1.140E+01	10

### **8.2.1.2 Wyoming Radiosonde Format**

The University of Wyoming format has one line of header information followed by weather data in space-delimited ASCII format. Four columns of data are considered meaningful with any remaining information ignored. Radiosonde data is expected to appear in the following sequence:

- **Column 1:** Pressure in units of hPa
- **Column 2:** Altitude in meters
- **Column 3:** Temperature in units of degrees centigrade
- **Column 4:** Dew Point in units of degrees centigrade

All additional columns of data are ignored.

One example follows:

954.0	506	-5.5	-6.0	-5.3	96	102	2.57	50	5	...
950.0	539	-5.9	-7.2	-6.4	91	96	2.35	52	6	...
925.0	745	-7.5	-8.1	-7.2	95	103	2.25	65	9	...
905.0	914	-8.5	-8.9	-7.9	96	105	2.16	75	7	...
870.1	1219	-10.2	-10.4	-9.2	98	109	2.00	160	1	...
868.0	1238	-10.3	-10.5	-9.3	98	109	1.99	160	2	...
850.0	1400	-8.1	-8.3	-7.4	98	107	2.42	160	8	...
849.0	1409	-7.9	-8.1	-7.2	98	107	2.46	157	8	...
844.0	1455	-5.5	-6.1	-5.4	96	101	2.88	143	7	...

### **8.2.1.3 FSL Radiosonde Format**

The Global Systems Division [formerly the Forecast Systems Laboratory (FSL)] of the Earth System Research Laboratory (ESRL) at the National Oceanic and Atmospheric Administration (NOAA) introduced the FSL radiosonde format. A complete description of the format is available at [http://esrl.noaa.gov/raobs/intl/fsl\\_format-new.cgi](http://esrl.noaa.gov/raobs/intl/fsl_format-new.cgi); this information is briefly summarized.

The FSL format has four lines of header information followed by weather data in space-delimited ASCII format. The header lines are separated into seven columns of information and, as described by the NOAA repository, are laid out as shown below:

254	HOUR	DAY	MONTH	YEAR	(blank)	(blank)
1	WBAN#	WMO#	LAT D	LONG D	ELEV	RTIME
2	HYDRO	MXWD	TROPL	LINES	TINDEX	SOURCE
3	(blank)	STAID	(blank)	(blank)	SONDE	WSUNITS

A date-stamp is explicitly provided in line one of the header. The second line geolocates the station and notes the time (RTIME) the radiosonde balloon was released. The third and fourth lines provide information on the type of radiosonde used and key measurement values such as the assumed tropopause and maximum wind speed.

The data appears in seven fixed-width columns.

- **Column 1:** Identification line for a specific altitude. Common values include 4 (mandatory level), 5 (significant level) and 9 (surface altitude). Further information available at the NOAA website.
- **Column 2:** Pressure in units of either whole millibars (original format) or tenths of millibars (new format)
- **Column 3:** Height in whole units of meters
- **Column 4:** Temperature in tenths of degrees Celsius
- **Column 5:** Dew point temperature in tenths of a degree Celsius
- **Column 6:** Wind direction in degrees

- **Column 7:** Wind speed in either knots or tenths of a meter per second. The user can select the desired units for this variable. AGT does not use this data, so either choice is acceptable.

An example of a radiosonde file in this format is shown below:

254	23	14	FEB	2015			
1	99999	1241	63.70N	9.60E	7	2324	
2	300	200	1660	45	99999	3	
3		ENOL			99999	kt	
9	10210	7	24	-26	115	19	
4	10000	176	18	-42	120	27	
5	9690	428	-5	-49	99999	99999	
5	9530	562	40	-70	99999	99999	
5	9390	682	48	-72	99999	99999	
4	9250	806	38	-72	170	15	
4	8500	1486	-11	-91	190	15	
5	7370	2599	-107	-137	99999	99999	
4	7000	2999	-117	-197	235	17	
5	6850	3164	-123	-213	99999	99999	

### 8.2.2 Batch Processing Radiosonde Files

The AGT can process multiple radiosonde files in batch. To do so, the user must adhere strictly to the following rules:

- **Do not mix-and-match:** The AGT still needs to know the type of radiosonde file to be parsed. This is specified globally for the batch and not on a per-file basis. Consequently, all radiosonde files in a batch must be of the same type.
- **Path specification:** The path must be specified in the native format for an operating system. This means using a foward-slash for Linux and Mac systems and a backslash for Windows systems.
- **Work in a directory:** It is recommended that a path be specified. That is, do not execute in batch within the same directory as the AGT is executed.
- **Use quotes:** Be sure to include quotes around the directory string to be parsed. Failing to do so will not cause the program to crash. Instead, only the first element in the batch of files will be parsed.

Examples of valid batch execution statements are shown in Table 8.3.

**Table 8.3.** Possible command-line combinations for batch processing.

Description	Example Command
(Linux/Mac) All files in directory	sdntp5.out -f "sonde_dir/" -txt -tp5
(Linux/Mac) All files ending in ".SND"	sdntp5.out -f "sonde_dir/*.SND" -txt -tp5
(Linux/Mac) All files in directory	sdntp5.out -f "sonde_dir\**" -txt -tp5
(Windows) All files in directory	sdntp5.out -f "c:\sonde_dir\" -txt -tp5
(Windows) All files ending in ".SND"	sdntp5.out -f "sonde_dir\*.SND" -txt -tp5
(Windows) All files in directory	sdntp5.out -f "sonde_dir\**" -txt -tp5

### 8.2.3 Operating with the NCEP/NCAR Reanalysis Data

The NCEP/NCAR Reanalysis data precludes the need for a user-supplied radiosonde data file. Instead, a specific location, day-of-year and absolute time is required. Location is specified by a latitude (degrees North of the equator) and longitude (degrees East of Greenwich). The longitude convention differs from that of MODTRAN, which requires that longitudes be entered in degrees *West* of Greenwich. Time is specified by a date (calendar day of the year), and a time at Greenwich, England (UTC in units of decimal hours). As an example, the approximate location of Boston, Massachusetts is 42.4 degrees North and 289.0 degrees East. Sunrise on February 11<sup>th</sup> (the 42<sup>th</sup> day of the year) occurs at approximately 6:30 am, i.e. 11:30 am or 11.5 hours past midnight in Greenwich on the same day. Example inputs for the AGT are shown in Table 8.4.

**Table 8.4.** Command-line combinations for February 11 Boston sunrise using NCEP/NCAR data.

Data	Output	Example Command
Month	Tape 5	snntp5.out -noaa_m -lat_n 42.4 -long_e 289 -time 11.5 -day 42 -tp5
Month	JSON	snntp5.out -noaa_m -lat_n 42.4 -long_e 289 -time 11.5 -day 42 -json
Hour	Tape 5	snntp5.out -noaa_d -lat_n 42.4 -long_e 289 -time 11.5 -day 42 -tp5
Hour	JSON	snntp5.out -noaa_d -lat_n 42.4 -long_e 289 -time 11.5 -day 42 -json

Several features have been added to the date and time specification to give the user additional flexibility.

- The time at Greenwich can be specified outside of the usual 0-24 range. So, for example, if time is being registered locally then time zone information can be mechanically added and the AGT will adjust as appropriate. If a time at Greenwich is specified as being less than zero then the date will also be decremented by one day. If a time at Greenwich is specified as being greater than 24 then the date will be incremented by one day.
- The date can be specified either by the day of the year or by providing a month and day. Month must be specified before day, month values must be ASCII letters (not numbers 1-12), month values are case insensitive, and month values can be spelled out or only the first three letters given. So, “February 11”, “FEBRUARY 11”, “feb 11”, and “FEB 11” would all be valid means of entering a date for the example inputs shown in Table 8.4:

```
snntp5.out -noaa_m -lat_n 42.4 -long_e 289 -time 11.5 -day February 11 -tp5
snntp5.out -noaa_m -lat_n 42.4 -long_e 289 -time 11.5 -day FEBRUARY 11 -json
snntp5.out -noaa_d -lat_n 42.4 -long_e 289 -time 11.5 -day feb 11 -tp5
snntp5.out -noaa_d -lat_n 42.4 -long_e 289 -time 11.5 -day FEB 11 -json
```

An automated output file naming convention is used when NCEP/NCAR option is exercised. There are four salient pieces of information conveyed in the file name, represented as three numbers followed by a text string. The first number gives the latitude grid point closest to the user-request input latitude. The second number gives the longitude grid point closest to the user-requested input longitude. The third number gives either the month closest to the user-supplied date (for runs requesting monthly averages) or the time index closest to the user-supplied date (for runs using the four-times daily averages). The fourth element echoes the user choice of either four-times daily (“4Xd”) or monthly (“mon”) database usage.

## 8.3 Using AGT Output with MODTRAN

AGT writes atmospheric profiles in either standard tape5 format or a compliant JSON file. Both outputs then require some user interaction in order to be inserted into a valid MODTRAN input. Here we outline the procedure to use for both cases.

### 8.3.1 Inserting AGT output into a MODTRAN TAPE5 Input

The AGT provides three elements in its tp5 output. (See the MODTRAN manual for detailed information on TAPE5 input structure.) The three pieces of information within an AGT tp5 output are:

- Selected “CARD 1” information inputs on the first line,
- The full “CARD 2C” on the second line, and
- All the “CARD 2C1” lines on the remaining lines.

To edit an existing tp5 file, replace the column values with those in the radiosonde output file. There are five steps that need to be performed. They are as follows:

- **Step 1:** For CARD 1 (line 1), column 5 (input [MODEL](#)) should be set to 7
- **Step 2:** For CARD 1 (line 1), columns 35, 40, 45 and 50 (inputs M3, M4, M5 and M6) should be set to the listed values (a number between 1 and 6 inclusive for each entry)
- **Step 3:** For CARD 1 (line 1), columns 55 and 60 (inputs MDEF and I\_RD2C) should both be set to 1.
- **Step 4:** The CARD 2C1 lines follow CARD 2C. Often, these cards immediate precede the line-of-sight entry (CARD 3). Edit these lines (verbatim) into the tp5 file
- **Step 5:** Save the edited complete MODTRAN \*.tp5 file.

An example of a MODTRAN tp5 file modified with these changes is shown below. Each step in the process has been highlighted.

**Step 1**  
Set CARD1 column 5 to value from AGT (will always be 7)

**Step 2**  
Set CARD1 columns 35, 40, 45, 50 to values from AGT

**Step 3**  
Set CARD1 columns 55 and 60 to values from AGT (will always be 1)

**Step 4**  
(card 2c)  
Insert entire AGT atmospheric profile before MODTRAN line-of-sight information

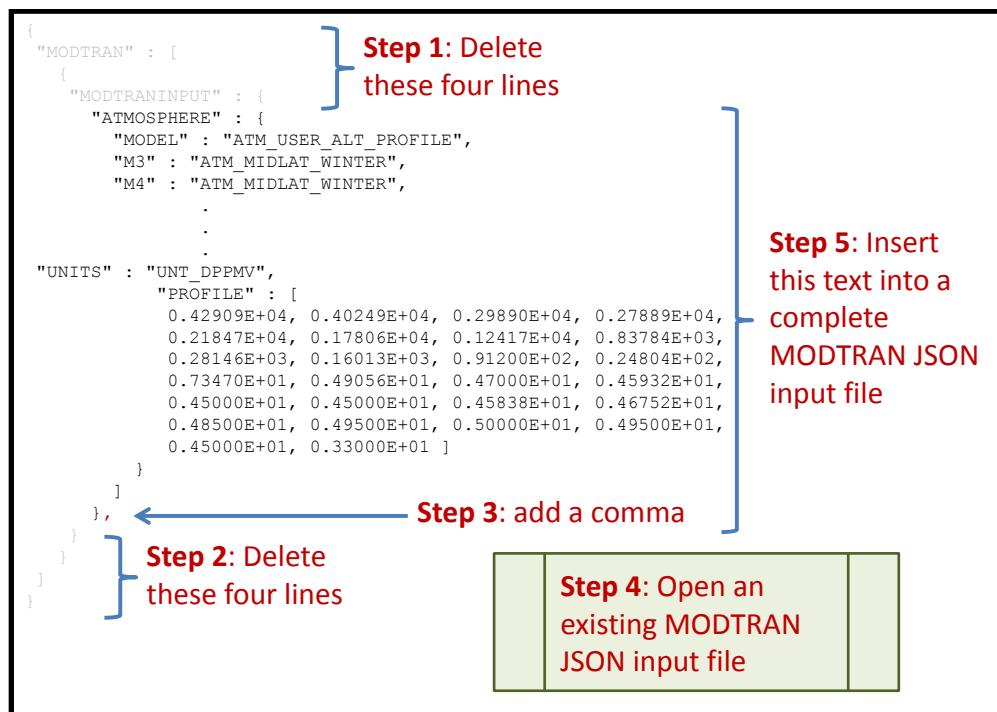
```
MMT 7 3 0 0 0 0 0.000 0.0000
FT 16 0 380.0000
01_2013
1.00 1.00 1.05 1.00 1.00 1.00 1.00 1.00 1.00 1.00
1.85 2.25 1.00 1.00 2.75 4.00 1.00 1.00 1.00 1.00
1 18 23.00000
0.7000 0.0000 0.0000
32 0 0_42.5_287.5__2_mon
0.000 1.0169E+03 2.715E+02 4.291E+03
0.132 1.0000E+03 2.709E+02 4.025E+03
0.748 9.2500E+02 2.680E+02 2.989E+03
.
.
100.00000 0.00000 180.00000
0.200 2.995 0.005 0.020TM MTAA
0
```

### 8.3.2 Inserting AGT output into a MODTRAN JSON Input

The user will need to make use of a text editor to manually insert the JSON code block generated by AGT into an existing MODTRAN JSON input file. The procedure involves five steps.

- **Step 1:** Delete the first 4 lines
- **Step 2:** Delete the last 4 lines of the AGT-generated JSON file.
- **Step 3:** Add a comma to the end of the new last line of the AGT-generated JSON file (that is the fifth-to-last line of the unedited AGT-generated JSON file).
- **Step 4:** Open an existing, complete MODTRAN JSON input file.
- **Step 5:** Insert the entire AGT-generated JSON into the complete MODTRAN JSON input file. The AGT-generated JSON file should have Step 1 and Step 2 applied, making it 8 lines shorter than what AGT outputs. The insertion point within the complete MODTRAN JSON input *must* be on the line **above** (before) the line beginning with ATMOSPHERE.
- **Step 6:** Save the edited complete MODTRAN JSON file.

The New MODTRAN JSON input file is now ready to be run using the `mod5c_cons` executable file. Notice that the new JSON input file contains two ATMOSPHERE data block definitions. This approach makes use of the standard JSON parsing rules. It is only the first ATMOSPHERE definition that is used. An illustration of the necessary steps is shown below.



## 9. THE MODTRAN6 AEROSOL TOOLKIT

As part of the MODTRAN6 development effort, an offline Aerosol Toolkit (ATK) was developed, to calculate optical properties from physical descriptions of aerosols with specified number density vertical profiles. The Aerosol Toolkit is a function library which calculates radiometric (scalar) or polarimetric (vector) optical properties; it also writes Spectral Aerosol Profile (SAP) scalar data files for use by MODTRAN6. The format of the SAP files is described in Chapter 3 of MODTRAN User's Manual. Since SAP files only contain scalar optical data, user codes must be written to link against the library and access the results of polarimetric calculations through the Fortran and C/C++ Application Programming Interfaces (APIs).

The Toolkit treats an aerosol as a superposition of "components", each component defined as a collection of particles with a specified size distribution, a shape, a set of spectral real and imaginary refractive indices, and a number density vertical profile. The particle size distributions can have one of several functional forms:

- lognormal,
- power-law,
- Modified power-law,
- Gamma, or
- Modified Gamma.

Calculations can be done either with a Mie code for spherical particles, or with a T-Matrix code for more general axisymmetric particle shapes. Both the Mie and T-Matrix codes are described in Chapter 5 of the Mishchenko, Travis and Lacis text [43].

The `src/tools/aerosol_toolkit/` directory contains the current version of the Aerosol Toolkit, with APIs for both Fortran and C.

There are also several test programs, demonstrating the use of the APIs to invoke the Toolkit's functions and perform calculations from Fortran and C. All but one of these are fixed example calculations. The one exception is a program that reads aerosol specifications from a text input file.

### 9.1 Directory Structure

The directories for the Aerosol Toolkit are set up as follows:

<code>src/tools/aerosol_toolkit/</code>	The top-level directory.
<code>src/</code>	Source files and Makefile to build the library and some test programs.
<code>data/</code>	Data files used in several test cases (spectral refractive index data for several aerosol materials, number density profiles, standard sets of output wavelengths and scattering angles, altitude profiles).
<code>examples/</code>	Text input files for some example cases, usable with the text-interface front end program <code>aerosoltoolkit_txtint</code> .
<code>COMPARE/</code>	Output files from the test programs, for use in testing.

## **9.2 Data/ Directory**

The data/ directory includes data files for use as inputs to the aerosol toolkit. Users are encouraged to add new data files tailored for their specific applications. The files delivered with the aerosol toolkit are as follows:

Spectral real and imaginary refractive index files:

```
longtin_quartz_ave.txt  
longtin_quartz_e.txt  
longtin_quartz_o.txt  
m_dustlike  
m_h2onew  
m_meteoric  
m_nh4so3  
m_quartze  
m_quartzo  
m_sandh10e  
m_sandh10o  
m_seasalt  
m_soot  
m_stbkg  
m_wtrsol  
peterson_quartz_ave.txt  
peterson_quartz_e_ray.txt  
peterson_quartz_o_ray.txt
```

Spectral wavelength files:

```
lwir002wlens  
lwir10wlens  
lwir129wlens  
sap_wlens
```

Number density profile files:

```
ndensityprofiledes4c  
ndensityprofiledes4ccbsoot  
ndensityprofiledes4cdustlk  
ndensityprofiledes4cnh4so3  
ndensityprofiledes4csand10e  
ndensityprofiledes4csand10o  
ndensityprofiledes4cv  
ndensityprofiledes4cwtrsol  
sap_test_zprof
```

Altitude profiles:

```
sap_alts  
sap_alts_des4c
```

Scattering angle grids:

```
scatangles  
stdangles  
stdangles_m
```

### **9.3 Test Programs**

There are four simple "canned" test programs, and a stand-alone program that reads aerosol specifications from a text input file.

-tatk01.f90	Is a simple test, setting up the "custom aerosol inputs" section of the aerosol toolkit, and then reading out the values of variables. This program writes to the console, but it does not generate any output files and does not link against the libAerosolToolkit.a library. It is a simple test to verify that inputs to the Toolkit are set correctly, and that spectral interpolation of refractive indices is done correctly.
-tatk02.f90	Sets up the inputs for a four-component test desert aerosol model at 10 km/s wind speed, with particle number densities varying with altitude. It calculates optical properties at 129 wavelengths in the thermal IR from 8 to 15 microns, and writes the SAP file, tatk02.sap. Number density profiles, refractive index data, altitudes, wavelengths, and scattering angles are given in files in the data/ directory. This does not link against libAerosolToolkit.a, but compiles and links all necessary files.
-tatkapi01.c	Performs the same calculation as tatk02.f90 for the four-component test desert aerosol model, but using a C API. It links against the library libAerosolToolkit.a. The resulting SAP file differs very slightly from that generated by tatk02.f90. In most cases the relative residuals are a few parts in $10^{14}$ , but some may be as large as a few parts in $10^6$ . These larger relative residuals only occur for high degree (order) SAP Legendre coefficients whose magnitudes are very small.
-tatkapi02.c	Performs calculations for the tatk02.f90 four-component test desert aerosol model, but uses the API functions to store calculated optical properties, including the polarization components, directly to arrays in memory. Results are returned at two long-wave IR wavelengths (8 and 15 microns) and at two altitudes (5 and 190 meters). This case also links against the precompiled library, libAerosolToolkit.a.
-aerosoltoolkit_txtint.f90	A text-interface front end for the Aerosol Toolkit. It reads a text file to get the aerosol specifications and calculation details, sets up the toolkit, runs the calculation, and writes the output to a file. Instructions are given below in the section "RUNNING THE TEXT-INTERFACE PROGRAM (Linux)". The input file format is described in detail, in comments in the text input files in examples/. This also links against the precompiled library, libAerosolToolkit.a.

### **9.4 Building the Code (Linux)**

This code is built with gnu make, from the Makefile in the src/ directory. The Makefile takes definitions of compilers and options from the file makedefs in the MODTRAN6 base directory.

The default makedefs uses gfortran and g++, with optimization level -O2, minimal error-checking; it is a copy of makedefs\_default\_gcc. There are other files, makedefs\_\*, with other options, in the base directory. To change definitions, just copy the preferred makedefs\_\* file to makedefs or edit makedefs itself.

In the following instructions, <enter> indicates to hit the Enter key, and <top\_directory> indicates the path to the top directory of the MODTRAN6 installation.

The library and test programs will be built automatically when you build with the command `make all` from the top directory.

Alternatively, to build just the library and test programs:

- change directories to `src/tools/aerosol_toolkit/src/`
- type `make all <enter>`

Important outputs are:

- |   |   |
|---|---|
| <code>-libAerosolToolkit.a,</code>          | The library file (for static linking).      |
| <code>-mach_mod.mod,</code>                 | Fortran-90 kind type parameter definitions. |
| <code>-aerosoltoolkit_mod.mod,</code>       | Explicit interfaces for the Fortran API.    |
| <code>-the test program executables.</code> |   |

The library is left in `<top_directory>/src/lib/`, and the executables are left in `<top_directory>/bin/`.

## **9.5 Running the Simple Test Programs (Linux)**

The test programs are all run from the command line. In the instructions below, `<path_to_bin>` is the directory path from the current working directory to `<top_directory>/bin/`.

Execution times mentioned here are approximate, and assume that the code is running on a modern PC with clock speed roughly 3 GHz, with full use of one processor core.

### **9.5.1 To run `tatk01`:**

Change directory (`cd`) to `src/`, then type

`<path_to_bin>/tatk01 <enter>`

The program will set up aerosols, and write information about their size distributions, refractive indices, and number density profiles to the console. A transcript of the console output is contained in `COMPARE/outs_tatk01`.

### **9.5.2 To run `tatk02`:**

Change directory (`cd`) to `src/`, then type

`<path_to_bin>/tatk02 <enter>`

The execution will run roughly two hours, and the program will write lines of ongoing status information to the console, and finally generate the file `tatkapi01.sap`. A transcript of the console output is contained in `COMPARE/outs_tatk02`.

### **9.5.3 To run `tatkapi01`:**

Change directory (`cd`) to `src/`, then type

`<path_to_bin>/tatkapi01 <enter>`

The execution will run roughly two hours, and the program will write lines of ongoing status information to the console, and finally generate the file `tatkapi01.sap`.

### **9.5.4 To run `tatkapi02`:**

Change directory (`cd`) to `src/`, then type

`<path_to_bin>./tatkapi02 <enter>`

The execution should run shortly over a minute; the program will write several lines of information to the console, and will then create sample files `tatkapi02_des4caNNwNN.sme` and

`tatkapi02_des4caNNwNN.cof`, where the characters NN are replaced by two-digit numbers. The string aNN is equal to a01 in a file name to denote altitude level 1 (counting from zero) data; in the file `sap_alts_des4c`, altitude level 1 has a value of 5 meters. The string aNN is equal to a12 in a file name to denote altitude level 12 (counting from zero); in the file `sap_alts_des4c`, altitude level 12 has a value of 200 meters. The string wNN is equal to w00 in a file name to denote wavelength 0; in the file `lwir002wlens`, wavelength 0 has a value of 8 microns. The string wNN is equal to w01 in a file name to denote wavelength 1; in the file `lwir002wlens`, wavelength 1 has a value of 15 microns. Files with suffix `.cof` are sets of Generalized Spherical Function (GSF) expansion coefficients. Files with suffix `.sme` are the non-zero scattering matrix elements in Mueller matrix form.

## 9.6 Running the Text-Interface Program (Linux)

To run the text-interface program with a text input file `inputfile`, change directory (`cd`) to the location of the input, and type

```
<path>/aerosoltoolkit_txtint inputfile<enter>
```

where `<path>` is the (absolute or relative) path to the directory containing the executable file. Alternatively, the executable can be moved to a `bin/` directory in your search path (`$PATH` or equivalently `$path`).

There are four example input files in the `examples/` directory:

```
ex1_rural_0rh_mie_expdec.in,  
ex2_tropo_0rh_tmat_expdec.in,  
ex3_tropo_0rh_mie_expdec.in, and  
ex1_allattop.in
```

They are fully commented, and thereby provide user instructions for setting up your own input stream. It is strongly recommended that the new user reads through these input files to understand the input to `aerosoltoolkit_txtint`

`ex1_rural_0rh_mie_expdec.in` generates a SAP file for a rural aerosol model at 0% relative humidity, with the number densities of the large particle modes decreasing exponentially with altitude. The particles are spherical, and the Mie code is used. The spectral range has 40 values from 0.2 to 40 microns, and the range of altitudes is from 0 meters altitude to 2.23 km.

`ex2_tropo_0rh_tmat_expdec.in` generates a SAP file for a two-component tropospheric aerosol model at 0% relative humidity. Both aerosol components use oblate spheroidal particles with aspect ratio 1.1:1 (horizontal axis/rotational axis), with lognormal particle size distributions; the T-Matrix code is used for the calculation. This input file can serve as a template for T-Matrix inputs, for aerosols with non-spherical axisymmetric particle shapes. The same wavelengths and altitudes are used as in the first (rural) example case.

`ex3_tropo_0rh_mie_expdec.in` generates a SAP file for a two-component tropospheric aerosol model at 0% relative humidity. The particles are spherical, and the Mie code is used. Otherwise, this example is the same as example case 2.

`ex1_allattop.in` is an edited version of the first input file `ex1_rural_0rh_mie_expdec.in`, in which the lines defining the aerosol calculation have been copied to the top of the file, for easier readability; the rest of the file contains the descriptive comments, as in the original input file.

To run the text-interface program with any of these, change directory (cd) to `examples/`, and type, e.g.,

```
./src/aerosoltoolkit_txtint ex1_rural_0rh_mie_expdec.in <enter>
```

or

```
./src/aerosoltoolkit_txtint ex2_tropo_0rh_tmat_expdec.in <enter>
```

or

```
./src/aerosoltoolkit_txtint ex3_tropo_0rh_mie_expdec.in <enter>
```

Running `ex1_rural_0rh_mie_expdec.in`:

Execution time is over an hour; the program writes several lines of status and progress information to the console, and creates a SAP file, `ex1_rural_0rh_mie_expdec.sap`. A transcript of the console output, and a copy of the SAP file, are available in the `COMPARE/` directory.

Running `ex2_tropo_0rh_tmat_expdec.in`:

Execution time is roughly 95 seconds; the program writes several lines of status and progress information to the console, and creates a SAP file, `ex2_tropo_0rh_tmat_expdec.sap`. A transcript of the console output, and a copy of the SAP file, are available in the `COMPARE/` directory.

Running `ex3_tropo_0rh_mie_expdec.in`:

Since this performs Mie calculations, the execution time is shorter, only a few seconds. The program writes status and progress messages to the console, and creates a SAP file, `ex3_tropo_0rh_mie_expdec.sap`. There will be slight differences in the extinction and scattering coefficients, etc., between this and the T-matrix case, due to the differences in particle shape. A transcript of the console output, and a copy of the SAP file, are available in the `COMPARE/` directory.

## 9.7 API Information for Developers

The API for both Fortran and C/C++ user programs is described in the MODTRAN6 Aerosol Toolkit (ATK) Interface Control Document (ICD).

The routines in `aerosoltoolkit_mod.f90` represent the Fortran API, and those in `aerosoltoolkitapi_mod.f90` represent the Fortran code underlying the C API.

Header `apifunctions.h` contains the C function declarations corresponding to the definitions in `aerosoltoolkitapi_mod.f90`.

Headers `inputstructs.h` and `outputstructs.h` define data structures and enumerated types which may be used in the future to rewrite the C API functions in `apifunctions.h`. Currently they are not used.

If one develops Fortran-90 programs to invoke the Toolkit functions, the precompiled modules `mach_mod` and `aerosoltoolkit_mod` can be used in "use" statements in your code, to provide the interfaces. The module `mach_mod` defines kind type parameters used in the API, and `aerosoltoolkit_mod` provides the routines themselves.

If you develop C/C++ programs to invoke the Toolkit functions, add this line to the include's at the top of your source code:

```
#include <apifunctions.h>
```

## 9.8 Aerosol Toolkit Status

The aerosol toolkit can perform Mie and T-matrix calculations for multi-component aerosols, and combine the results with weighting from aerosol number density profiles, to create altitude-dependent

spectral aerosol optical property data. The Fortran and C/C++ APIs are complete and have been successfully tested.

Calculations for large particle size parameters are quite time-consuming, and the maximum size or complexity of an aerosol particle size distribution is limited by several array-dimensioning parameters used by the Mie and T-Matrix subroutines.

The dimensioning parameters for the Mie routines are in `spher.par.f90`; `NMIE` is the maximum allowed degree of Riccati-Bessel functions, which limits the particle size; `NGRAD` is the maximum number of data points for integration over size distributions. The distribution is built with `NMIE = 30000` and `NGRAD = 500000`, so that spherical particles can have quite large sizes, however the calculation times (which are roughly proportional to the cube of the largest size parameter) are quite long.

The dimensioning parameters for the T-Matrix routines are in `tmd.par.f90`; `NPN1` sets the maximum allowed degree of GSF expansion coefficients, and `NGMX1` sets the maximum number of Gauss points for various integrations. The distribution is built with `NPN1 = 175` and `NGMX1 = 1000`. This allows e.g., calculations up to a maximum size parameter ~30, for oblate spheroids with axis ratio 1.5:1. However, as particle shapes become more deformed (larger axis ratio, or more complex shapes) the memory requirements increase disproportionately. Several other versions of `tmd.par.f90` with different values of `NPN1` up to 300 are provided in the distribution, and can be substituted for the default parameter file.

## 10. 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.

### 10.1 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 4, of the NOVAM manual. These inputs are the same as stated for positions 1 to 7. The revised Table 4 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)
- 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 6 and Table 7, of the NOVAM manual. Table 6 contains data, each line of which consists of an altitude (m), potential temperature ( $^{\circ}\text{C}$ ) and aerosol mixing ratio (g/kg). The relationship between the potential temperature ( $\Theta$ ) and the usual air temperature (T) is given by the formula:

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

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 7 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  $^{\circ}\text{C}$ , RH in percent and pressure in millibars multiplied by 10. As stated above, one needs the profile data either in the format of Table 6 and Table 7. Table 6 is said to be in 'n' format whereas Table 7 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:

40	<b>(number of wavelengths and wavelengths in microns)</b>								
.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	<b>(number of altitudes and altitudes in m )</b>								
20.9	123.6	226.3	329.1	393.8	458.6	523.4	572.0	620.7	669.3
<b>(temperature in K)</b>									
287.65	286.49	285.57	284.85	285.37	285.95	285.65	287.65	288.91	288.45
<b>(pressures in mb)</b>									
1010.70	999.40	988.10	976.80	969.66	962.55	955.50	949.60	943.73	937.90
<b>(RH)</b>									
88.80	91.41	95.39	95.60	81.88	66.69	65.60	50.08	37.44	35.80
<b>(spectral data for 0.2 microns)</b>									
.156E+00	.146E+00	.145E+00	.145E+00	.144E+00	.142E+00	.140E+00			
.377E-01	.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	.635E-06	(absorption)					
.801E+00	.798E+00	.797E+00	.797E+00	.797E+00	.797E+00	.797E+00			
.758E+00	.758E+00	.758E+00	.758E+00	(asymmetry)					

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<i>(spectral data for 0.3 microns)</i>							
.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					

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.

### **10.2 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 radiosonde 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. 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.

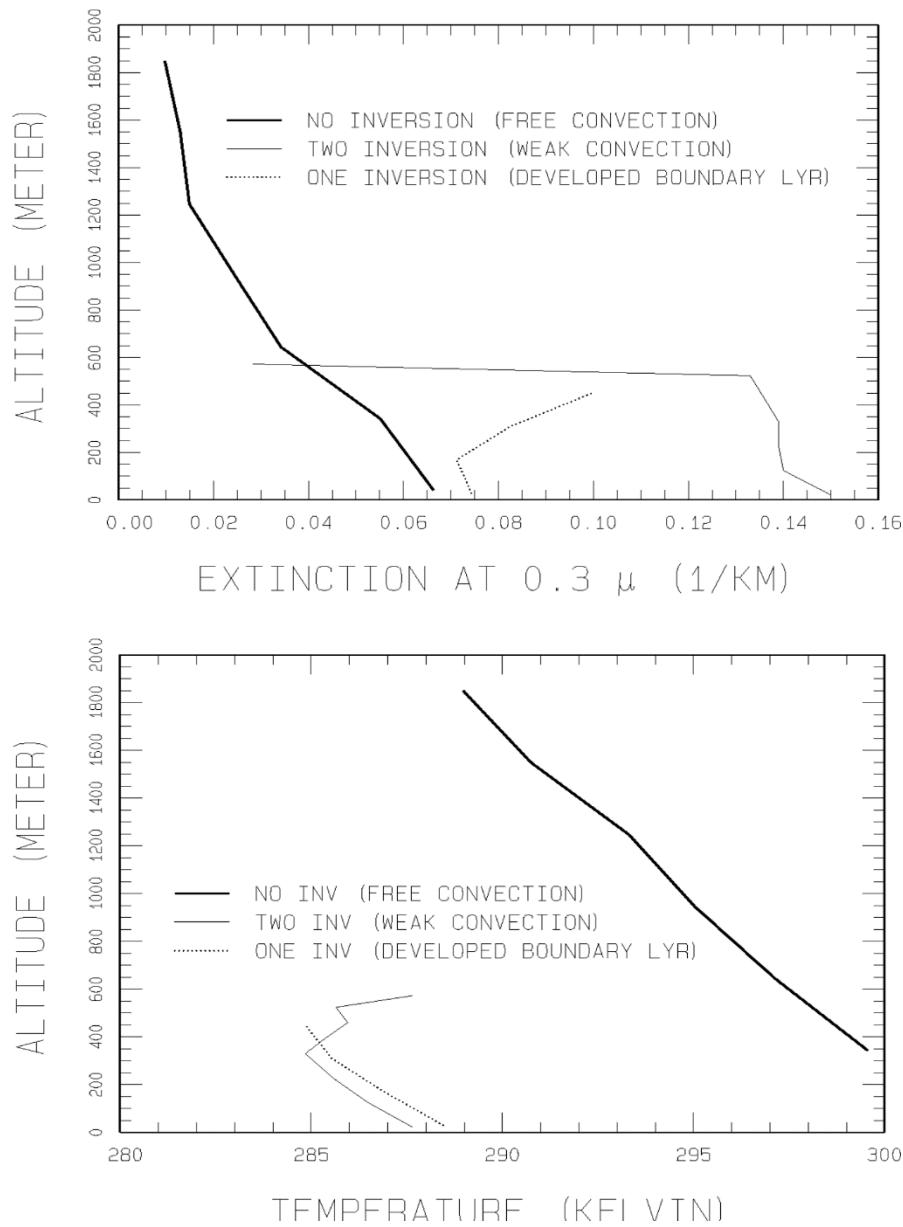
In summary, NOVAM is simply used to generate a database of marine aerosol profiles and spectral information for MODTRAN. NOVAM does not at present generate angular phase functions. Instead, it has a database of asymmetry parameters from which Henyey-Greenstein phase functions can be computed. In principle,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

### **10.3 Some Results**

Three typical (as provided in the NOVAM package) profiles of aerosol extinction and coincident temperature are shown if 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

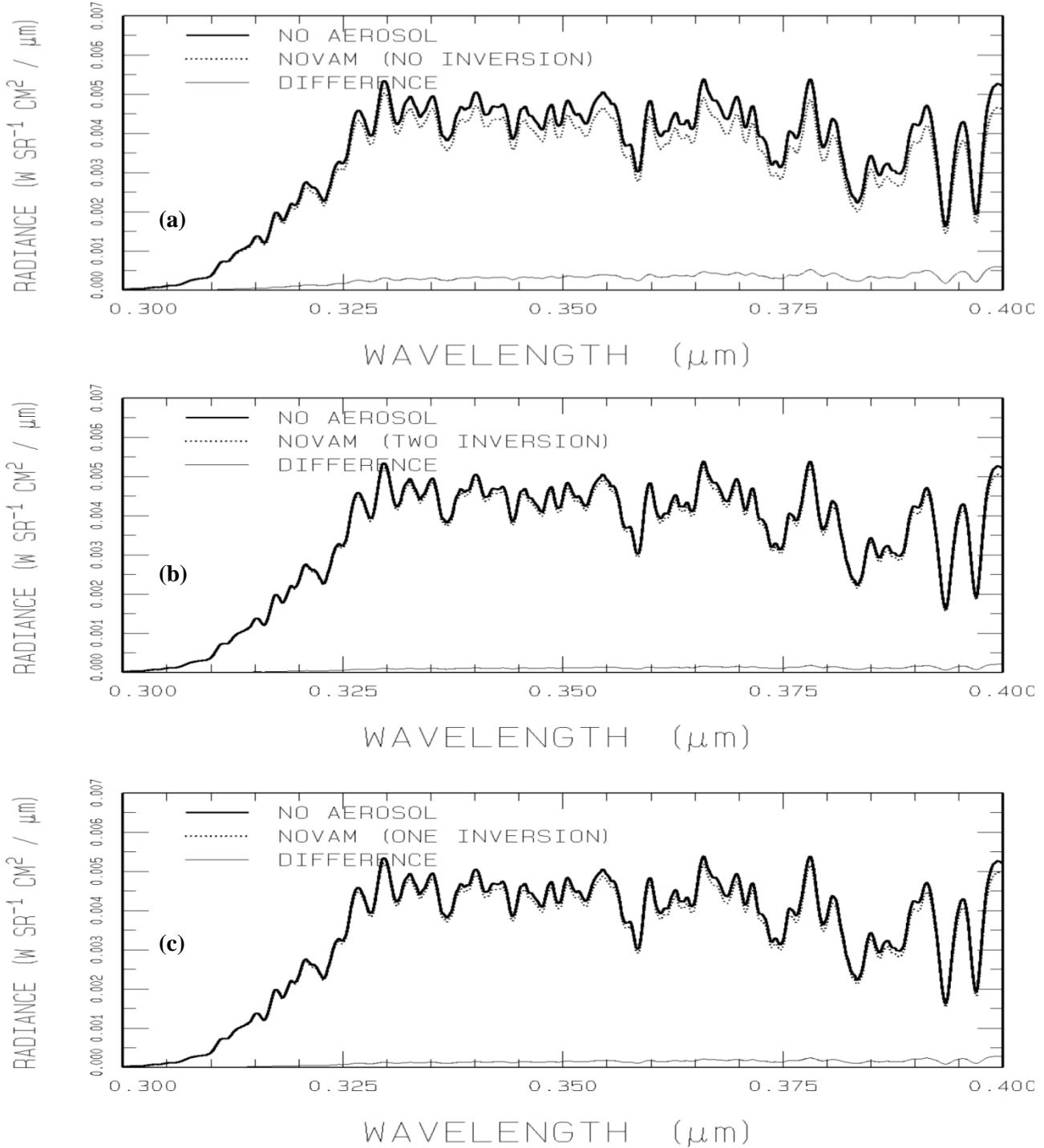
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calculations use all three types of temperature inversions modeled in NOVAM. The calculation with no aerosol includes only the Rayleigh scattering component and is used as the measure of change imparted to the backscattered signature by low-lying aerosols. 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.

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**Figure 2a, b and c.** As denoted, these represent typical sensitivity to the new NOVAM aerosol profiles shown in Figure 1. The plots are shown linearly to emphasize the impact at the longer wavelengths that ‘see’ to the surface, and, therefore, would be impacted by boundary-layer variability. At shorter wavelengths,  $<0.3 \mu\text{m}$ ), the stratospheric aerosol component might be important under extremes of volcanic loading. That sensitivity requires a logarithmic plot and has not been explored in this study.

### 10.4 NOVAM input and MODTRAN input Files

NOVAM files were described earlier. 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.

#### **10.5 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 H<sub>2</sub>SO<sub>4</sub> 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 radiosonde data will provide additional confidence in the procedure.

#### **10.6 Modifications to NOVAM to Code**

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 **gettim** 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.

#### **10.7 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).

## **11. DEDICATION AND ACKNOWLEDGEMENTS**

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## REFERENCES

- [1] Abreu, L.W. and G.P. Anderson, "The MODTRAN 2/3 Report and LOWTRAN 7 Model", Prepared by Ontar Corporation for PL/BPOS (1996).
- [28] Adler-Golden, S., M.W. Matthew, L.S. Bernstein, R.Y. Levine, A. Berk, S.C. Richtsmeier, P.K. Acharya, G.P. Anderson, G. Felde, J. Gardner, M. Hoke, L.S. Jeong, B. Pukall, A. Ratkowski, and H.-H. Burke, "Atmospheric Correction for Short-wave Spectral Imagery Based on MODTRAN4", Proc. SPIE, Optical Spectroscopy Techniques and Instrumentation for Atmospheric and Space Research, 3753 (1999).
- [2] Anderson, G.P., S.A. Clough, F.X. Kneizys, J.H. Chetwynd, E.P. Shettle, "AFRL Atmospheric Constituent Profiles (0-120 km)", AFRL-TR-86-0110 (1986).
- [3] 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).
- [4] Anderson G.P, J. Wang, M.L. Hoke, F.X. Kneizys, J.H. Chetwynd, L.S. Rothman, L.M. Kimball, R.A. McClatchey, E.P. Shettle, S.A. Clough, W.O. Gallery, "History of one family of atmospheric radiative transfer codes", Passive Infrared Remote Sensing of Clouds and the Atmosphere II, Rome, Italy, Proc. SPIE, Vol. 2309, 170 (1994).
- [5] Anderson, G.P, F.X. Kneizys, J.H. Chetwynd, L.S. Rothman, M.L. Hoke, A. Berk, L.S. Bernstein, P.K. Acharya, H.E. Snell, E. Mlawer, "Reviewing atmospheric radiative transfer modeling – New developments in high and moderate resolution FASCODE/FASE and MODTRAN", Optical spectroscopic techniques and instrumentation for atmospheric and space research II; Proceedings of the Meeting, Denver, CO; pp. 82-93 (1996).
- [6] Anderson, G.P., A. Berk, P.K. Acharya, L.S. Bernstein, S.M. Adler-Golden, J. Lee and L. Muratov, "Reformulated Atmospheric Band Model Method for Modeling Atmospheric Propagation at Arbitrarily Fine Spectral Resolution and Expanded Capabilities", Patent No. 7593835 (September 22, 2009).
- [13] 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.
- [7] 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).
- [8] 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).
- [9] Berk, A., P.K. Acharya, L.S. Bernstein, G.P. Anderson, J.H. Chetwynd, Jr., M.L. Hoke, "Reformulation of the MODTRAN band model for finer spectral resolution", proceedings of SPIE Vol. 4049, Orlando, Florida, (April, 2000).
- [10] Berk, A., G.P. Anderson, P.K. Acharya, L.S. Bernstein, M. Fox, "MODTRAN<sup>®</sup> 5: A Reformulated Atmospheric Band Model with Auxiliary Species and Practical Multiple Scattering Options", <http://handle.dtic.mil/100.2/ADA425699>, Defense Technical Information Center, 2004.
- [12] Berk, A., "Analytically derived conversion of spectral band radiance to brightness temperature", J. Quant. Spectrosc. Radiat. Transfer, v109, 1266-1276 (2008).
- [11] Berk, A., P.K. Acharya, L.S. Bernstein, G.P. Anderson, P. Lewis, J.H. Chetwynd, M.L. Hoke, "Band Model Method for Modeling Atmospheric Propagation at Arbitrarily Fine Spectral Resolution", Patent No. 7433806 (Oct 7, 2008).
- [6a] Berk, A., "Voigt equivalent widths and spectral-bin single-line transmittances: Exact expansions and

the MODTRAN®5 implementation”, J. Quant. Spectrosc. Radiat. Transfer, v118, 102-120 (2013) DOI: 10.1016/j.jqsrt.2012.11.026.

[13a] Berk, A., and F. Hawes, “Validation of MODTRAN6 and its line-by-line algorithm,” J. Quant. Spectrosc. Radiat. Transfer (2017), <http://dx.doi.org/10.1016/j.jqsrt.2017.03.004>.

[13b] Berk, A, Stamne

[14] Bernstein, L.S., “Treatment of the layer temperature-gradient issue in band-model emission codes”, Applied Optics, 34, 507-513 (1995).

[15] 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).

[16] Bernstein, L.S., A. Berk and R.L. Sundberg, “Application of MODTRAN® to Extra-Terrestrial Planetary Atmospheres,” 2007 AMOS Technology Conference, Maui, HI, 2007.

[17] Cebula, R., G. Thuillier, R.M. Vanhousier, E. Hilsenrath, M. Herse, and P.C. Simon, “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).

[18] 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).

[19] Clough, S.A. and F.X. Kneizys, “Convolution algorithm for the Lorentz function”, Applied Optics, 18, 2329 (1979).

[20] Clough, S.A., F.X. Kneizys, L.S. Rothman and W.O. Gallery, “Atmospheric spectral transmittance and radiance: FASCOD1B”, Proceedings of the SPIE 277, 152 (1981).

[22] Clough, S.A., M.J. Iacono, and J.-L. Moncet, “Line-by-line calculation of atmospheric fluxes and cooling rates: Application to water vapor”, J. Geophys. Res., 97, 15761-15785 (1992).

[23] Clough, S.A., and M.J. Iacono, “Line-by-line calculations of atmospheric fluxes and cooling rates II: Application to carbon dioxide, ozone, methane, nitrous oxide, and the halocarbons”, J. Geophys. Res., 100, 16,519-16,535 (1995).

[21] Clough, S.A., F.X. Kneizys, G.T. Anderson, E.P. Shettle, J.H. Chetwynd, L.W. Abreu, and L.A. Hall, “FASCOD3 Spectral Simulation”, Proceedings of the International Radiation Symposium, Lenoble and Galeyn, Deepak Publishing (1998).

[24] Clough, S.A., M.W. Shephard, E.J. Mlawer, J.S. Delamere, M.J. Iacono, K. Cady-Pereira, S. Boukabara and P.D. Brown, “Atmospheric radiative transfer modeling: a summary of the AER codes”, J. Quant. Spectrosc. Radiat. Transfer, 91, 233-244 (2005).

[25] Dothe, H., J.W. Duff, J.H. Gruninger, P.K. Acharya, A. Berk, J.H. Brown, R.D. Sharma, C. Parsons, “Users’ Manual for SAMM®2, SHARC-4 and MODTRAN4 Merged”, AFRL-VS-HA-TR-2004-1145 (June 2004).

[26] Fontenla, J.M., P.C. Stancil, and E. Landi, “Solar Spectral Irradiance, Solar Activity, and the Near-Ultra-violet”, Astrophysical Journal, 809, 157 (2015).

[27] Fox, M.J., A. Berk and L.S. Bernstein, “Atmospheric Characterization of Jupiter using a Planetary Radiation Transport Model Based on MODTRAN® 5”, AMOS Conf. Proc., (2009).

[29] 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).
- [30] Hapke, B.W., "Bidirectional reflectance spectroscopy 1. Theory", *J. Geophys. Res.*, 86, 3039-3054 (1981).
- [31] Hapke, B.W., "Bidirectional reflectance spectroscopy 1. The extinction coefficient and opposition effect", *Icarus*, 67, 264-280 (1986).
- [32] Isaacs, R.G., W.-C. Wang, R. D. Worsham, and S. Goldenberg, "Multiple scattering LOWTRAN and FASCODE models", *Applied Optics*, 26, 1272-1281 (1987).
- [33] 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).
- [34] 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.
- [35] 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 Mexican de Astronomia y Astrofisica*, 23 (1992).
- [36] 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).
- [37] Kurucz, R.L. Solar irradiance data set (1997).
- [38] Kurucz, R.L., "High Resolution Irradiance Spectrum from 300 to 1000 nm", presented at AFRL Transmission Meeting, 15-16 June 2005, Lexington, MA, in the proceedings (2005).
- [39] 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.* (2000).
- [40] Macke, A., personal communication to A. Berk (2001).
- [41] Matthew, M.W., S.M. Adler-Golden, A. Berk, S.C. Richtsmeier, R.Y. Levine, L.S. Bernstein, P.K. Acharya, G.P. Anderson, G.W. Felde, M.P. Hoke, A. Ratkowski, H.-H. Burke, R.D. Kaiser, and D.P. Miller, "Status of atmospheric correction using a MODTRAN4-based algorithm", SPIE Proceeding, Algorithms for Multispectral, Hyperspectral, and Ultraspectral Imagery VI, Vol. 4049 (2000).
- [42] Meador, W.E. and W.R. Weaver, "Two-Stream Approximations to Radiative Transfer in Planetary Atmospheres: A Unified Description of Existing Methods and a New Improvement", *J. Atmos. Sciences*, 37, 630-643 (1980).
- [43] Mishchenko, M.I., L.D. Travis and A.A. Lacis, "Scattering, Absorption, and Emission of Light by Small Particles," Third electronic release (NASA Goddard Institute for Space Studies), available at <http://www.giss.nasa.gov/~crmmr/books.html>.
- [44] Pinty, B. and M.M. Verstraete, "Extracting Information on surface properties from bidirectional reflectance measurements", *J. Geophys. Res.*, 96, 2865-2874, (1991).
- [45] 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).

- [47] Ross, V., and D. Dion, "Sea Surface Slope Statistics Derived from Sun Glint Radiance Measurements and Their Apparent Dependence on Sensor Elevation", *J. Geophys. Res.*, 112, C09015, DOI:10.1029/2007JC004137 (2007).
- [46] Ross, V., D. Dion and G. Potvin, "Detailed Analytical Approach to the Gaussian Surface Bidirectional Reflectance Distribution Function Specular Component Applied to the Sea Surface", *J. Opt. Soc. Am. A*, 22, 2442-2453 (2005).
- [48] 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", *J. Quant. Spectrosc. Radiat. Transfer*, 48, 469-507 (1992).
- [49] 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", *J. Quant. Spectrosc. Radiat. Transfer*, 60, 665-710 (1998).
- [50] Rothman, L.S., I.E. Gordon, A. Barbe, D. Chris Benner, P.F. Bernath, M. Birk, V. Boudon, L.R. Brown, A. Campargue, J.-P. Champion, K. Chance, L.H. Coudert, V. Danaj, V.M. Devi, S. Fally, J.-M. Flaud, R.R. Gamache, A. Goldman, D. Jacquemart, I. Kleiner, N. Lacome, W.J. Lafferty, J.-Y. Mandin, S.T. Massie, S.N. Mikhailenko, C.E. Miller, N. Moazzen-Ahmadi, O.V. Naumenko, A.V. Nikitin, J. Orphal, V.I. Perevalov, A. Perrin, A. Predoi-Cross, C.P. Rinsland, M. Rotger, M. Šimečková, M.A.H. Smith, K. Sung, S.A. Tashkun, J. Tennyson, R.A. Toth, A.C. Vandaele, J. VanderAuwera, "The HITRAN 2008 molecular spectroscopic database", *J. Quant. Spectrosc. Radiat. Transfer*, 110, 533-572 (2009).
- [51] Rothman, L.S., I.E. Gordon, Y. Babikov, A. Barbe, D. Chris Benner, P.F. Bernath, M. Birk, L. Bizzocchi, V. Boudon, L.R. Brown, A. Campargue, K. Chance, E.A. Cohen, L.H. Coudert, V.M. Devi, B.J. Drouin, A. Fayt, J.-M. Flaud, R.R. Gamache, J.J. Harrison, J.-M. Hartmann, C. Hill, J.T. Hodges, D. Jacquemart, A. Jolly, J. Lamouroux, R.J. Le Roy, G. Li, D.A. Long, O.M. Lyulin, C.J. Mackie, S.T. Massie, S. Mikhailenko, H.S.P. Müller, O.V. Naumenko, A.V. Nikitin, J. Orphal, V. Perevalov, A. Perrin, E.R. Polovtseva, C. Richard, M.A.H. Smith, E. Starikova, K. Sung, S. Tashkun, J. Tennyson, G.C. Toon, V.I.G. Tyuterev, and G. Wagner, "The HITRAN2012 molecular spectroscopic database", *J. Quant. Spectrosc. Radiat. Transfer*, 130, 4-50 (2013).
- [52] 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).
- [53] Schulz, F.M., K Stamnes and F. Weng, "VDISORT, an improved and generalized discrete ordinate method for polarized (vector) radiative transfer", *J. Quant. Spectrosc. Radiat. Transfer*, 61, 105-122 (1999).
- [54] Snell, H.E., G.P. Anderson, J. Wang, J.-L. Moncet, J.H. Chetwynd and S.J. English, "Validation of FASE (FASCODE for the Environment) and MODTRAN3: Updates and Comparisons with Clear-Sky Measurements", The European Symposium on Satellite Remote Sensing, Conf. of Passive IR Remote Sensing of Clouds and the Atmosphere III, Paris, France, (1995).
- [55] 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).
- [56] Stamnes, K., S.C. Tsay, W. Wiscombe, and I. Laszlo, "DISORT, a General-Purpose Fortran Program for Discrete-Ordinate-Method Radiative Transfer in Scattering and Emitting Layered Media: Documentation of Methodology" (2000), available on line at: [ftp://climate1.gsfc.nasa.gov/ridgway/Multiple\\_Scatt/DISORTReport1.1.pdf](ftp://climate1.gsfc.nasa.gov/ridgway/Multiple_Scatt/DISORTReport1.1.pdf).

- [57] Thuillier, G., M. Herse, P.C. Simon, D. Labs, H. Mandel, and D. Gillotay, “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).
- [58] 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).
- [59] 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).
- [60] Wang, J., G.P. Anderson, H.E. Revercomb, and R.O. Knuteson, “Validation of FASCOD3 and MODTRAN3: Comparison of model calculations with ground-based and airborne interferometer observations under clear-sky conditions”, *Applied Optics*, 35, 6028-6040 (1996).
- [61] 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).
- [62] 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).