

# SMARTS code, version 2.9.5

## For Linux

### USER'S MANUAL



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Please report any problem (or success stories...) to the author!

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# 1. INTRODUCTION

SMARTS (*Simple Model of the Atmospheric Radiative Transfer of Sunshine*) is a spectral model and Fortran code to predict the direct beam, diffuse, and global irradiance incident on surfaces of any geometry at the Earth's surface. It covers the whole shortwave solar spectrum (280 to 4000 nm), and thus includes the UVA, UVB, Visible and Near-Infrared bands. Besides the regular irradiance predictions needed for many possible applications, it can be used to simulate the spectral or broadband irradiance that would be measured by a radiometer, such as a spectroradiometer, a pyranometer, or a pyrheliometer. It can also predict the photosynthetically active components of radiation, the illuminance on any surface, the luminous efficacy of direct, diffuse, and global radiation, the UV index, as well as various UV action weighted spectra.

Version 2.0 of SMARTS was released in 1994 and was described in (Gueymard, 1994b, 1995). A peer-reviewed journal paper (Gueymard, 2001) also gives a partial but updated description of the model, current with version 2.8 released November 1996. A separate file ('History.txt') details the changes that occurred in the successive versions of the code prior to version 2.9.

This User's Manual covers version 2.9.5, which includes considerable improvements over previous versions (see Section 14). Background information on the new algorithms and on possible applications of the code in various fields is described elsewhere (Gueymard, 2005; Gueymard and Kambezidis, 2004; Gueymard et al., 2002; Myers and Gueymard, 2004).

The previous official release was version 2.9.2. Versions 2.9.3 and 2.9.4 have only been distributed to a few beta testers. As can be understood from Section 16, this new version offers many new features improvements over the previous ones. Consequently, the spectra predicted with this new version may differ slightly from those obtained with older versions even for the exact same conditions—at least over some wavebands.

Also new to this version is the choice between three platforms: Mac OSX, Linux and Windows. To simplify reading, each platform has now separate Manuals (this User's Manual and the QuickStart guide). Contrarily to previous versions, the functionality and purpose of each platform's version is now slightly different. The Windows version is aimed at novice users (particularly with the help of the graphical User Interface). Conversely, the Mac OSX and Linux versions are aimed at power users who want to take advantage of the powerful Unix scripting capabilities. The core model's features and Fortran code themselves, however, are strictly the same for all platforms.

Dr. Fotis Mavromatakis has been instrumental in preparing this Linux version. His volunteer help is deeply appreciated.

## 2. FORTRAN LANGUAGE AND EXECUTABLES

Standard Fortran 77 has been used with only a few extensions. The source file ('smarts295.f') now contains nearly 6000 lines of code. It calls 27 data files during a typical run. The executables have been prepared with the open-source g77 compiler. Two slightly different executables are provided: one for "Standard" execution and one for "Batch" execution. They are produced from the same source file just by modifying a single line of code. (Note to power users: See instructions on lines 184-185 of 'smarts295.f'.) The two executables only differ in the way they are invoked and the way the user is involved during execution. See Section 4 for all necessary details.

## 2.1 Standard execution

This execution is called “standard” because it provides significant user interaction, i.e., a way to manage file names at run time. The executable is ‘smarts295.exe’.

## 2.2 Batch execution

This execution is commanded by a different executable (‘smarts295bat.exe’). When it is invoked, execution is done transparently and directly (without any user intervention), using the default input/output file names. It provides maximum speed of execution.

# 3. HARDWARE AND SOFTWARE REQUIREMENTS

Typically, any recent computer will produce results in a few tenths of a second to a few seconds, depending on case complexity and processing power. *Daily calculations* are extremely processor intensive, but results should appear within less than a minute or so.

The source code has been successfully compiled and run under Linux RedHat 7, Fedora Core 2, Fedora Core 3, Debian 3.1, SunOS Core 5.9 and Cygwin, using the supplied g77 compiler. Binary executables for either standard execution or batch mode are provided at the root of the main directory. These binaries have been produced under Fedora Core 3.

No special hardware or software is required apart from a text editor. The standard g77 compiler is only required if it is necessary to recompile the code.

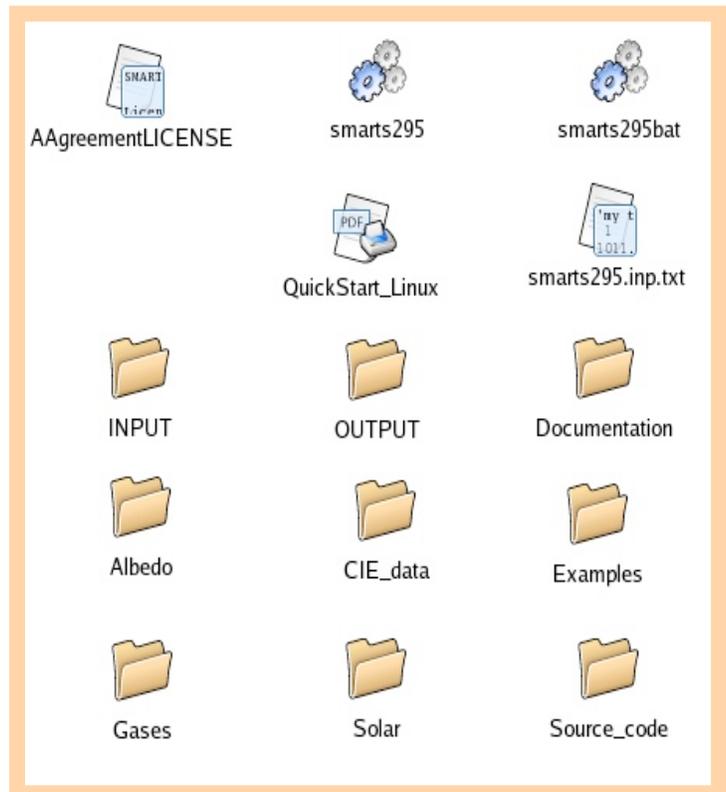
# 4. SOFTWARE INSTALLATION AND USE

The distribution package is compressed. After decompression, the SMARTS\_295\_Linux folder is created.

Read the **License Agreement** and, if you agree with its terms, proceed further as described below.

A typical screenshot of the folder is shown here. The exact appearance depends on the window manager you use and its settings.

All files and subfolders need to be in a unique folder (which by default is SMARTS\_295\_Linux, but can be renamed). The ‘smarts295.inp.txt’ file is a sample input file that can be used to familiarize oneself with the two execution modes described below.



To use a sample input files contained in one of the subfolders within the **Examples** folder, move the desired ‘smarts295.inp.txt’ file to the root of the **SMARTS\_295\_Linux** folder, thus replacing any pre-existing file of the same name.

Use `vi`, `xemacs`, `nedit`, or any similar text or word editor to modify the input file (‘smarts295.inp.txt’) according to your needs, based on the detailed explanations provided in Section 6, and save it as **TEXT**. The default input filename is ‘smarts295.inp.txt’. Keep in mind that filenames are case sensitive in Linux. This implies that folder names below the root directory and data names should not be altered.

#### **4.1 Standard execution**

To run SMARTS, open a Terminal window or an xterm and move to the directory where you have extracted the package:

```
cd /install_path/SMARTS_295_Linux
```

and hit Enter. Then type

```
./smarts295.exe
```

and hit Enter. A welcome message appears:

```
*****
Welcome to SMARTS, version 2.9.5!
*****
$$$ SMARTS_295> Use standard mode with default input file?
[If YES (or Y), execution will start immediately
using the default input file smarts295.inp.txt]
(Y/N) ==>
```

- If you type “y” or “yes” and hit Enter, execution begins immediately. A final message similar to this one is displayed when execution ends:

```
Total CPU time: 0.142 sec
```

It is clear that the actual execution time will vary according to your computational power.

Execution of the preloaded sample input file must have created two separate output files: ‘smarts295.out.txt’ and ‘smarts295.ext.txt’, both located at the root of the **SMARTS\_295\_Linux** folder.

- If you rather type “n” or “no” and hit Enter, the following message appears:

```
$$$ SMARTS_295> What is the path to the input file?
* Type only "." if in the same folder
* Do NOT type the last "/" of the chain
* 2000 characters max. ==>
```

Type the path and filename of the input file you want to use or type “.” if the file resides in the current folder. For instance, type “INPUT” if it is located in the **INPUT** folder of **SMARTS\_295\_Linux**, or type something like “**SMARTS\_inputs/Solar/First\_tests**” in the case of nested folders elsewhere, etc. Hit Enter and the program will ask for the proper filename:

```
$$$ SMARTS_295> Generic name for all input/output files
* without any extension
* 100 characters max.)? ==>
```

For instance, type “**Test\_for\_July**” if the input file is ‘**Test\_for\_July.inp.txt**’. Hitting Enter results in:

```

$$$ SMARTS_295> You chose the following filenames:
Input: INPUT/Test_for_July.inp.txt
Output: INPUT/Test_for_July.out.txt
Spreadsheet-ready: INPUT/Test_for_July.ext.txt
Smoothed results: INPUT/Test_for_July.scn.txt
$$$ SMARTS_295> Is this OK? (Y/N) ==>

```

Type “y” if it is OK, or “n” if not, and hit Enter. If you choose “yes”, execution starts normally and finishes identically as before. If you choose to reply “no”, the previous message reappears and the cycle continues until you reply “yes”. The output files will be located in the same folder as the input file, e.g., in the INPUT folder for this example.

To use any sample input file contained in one of the subfolders within the **Examples** folder, move it to the root of the **SMARTS\_295\_Linux** folder, thus replacing any pre-existing file of the same name. However, before undertaking the execution of any new run using an input file with the same name, it is imperative to either rename the existing output files, or to move them to the **OUTPUT** folder or any other folder. Failing to do so would prevent proper execution and generate the following error message:

```

open: 'new' file exists
apparent state: unit 16 named smarts295.out.txt
last format: list io
lately reading sequential formatted external IO
Abort (core dumped)

```

Power users can change this feature by altering the appropriate **OPEN** statements in the Fortran code, so that at anytime they are overwritten, and by recompiling. The source code, ‘smarts295.f’, resides in the **Source\_Code** folder, and can be compiled with any Fortran77 compiler. For example, the command

```
g77 -O -o smarts295.exe smarts295.f
```

should complete without any errors and create an optimized executable called ‘smarts295.exe’. Finally, move or copy this new executable to the **SMARTS\_295\_Linux** folder.

#### **4.2 Batch execution**

In batch mode the program runs without user interaction. It assumes that the correct input file is ‘smarts295.inp.txt’ at the root of the main folder. This means that once the command “./smarts295bat.exe” is issued, the program will read the default input file (‘smarts295.inp.txt’), make its spectral calculations, and pass the results to the default output files (e.g. ‘smarts295.out.txt’, ‘smarts295.ext.txt’, and ‘smarts295.scn.txt’). The file ‘smarts295bat.exe’ has been produced by activating the command “batch=.TRUE.” (line 188 of the code) and recompiling the code. Move or copy this new executable to the **SMARTS\_295\_Linux** folder. If you wish to avoid typing the “./” before the executables and you are using csh or tcsh, you can add the following line in your “.login”:

```
set PATH = ( $PATH /install_path/SMARTS_295_Linux).
```

After the execution command is issued this first message appears:

```

*****
Welcome to SMARTS, version 2.9.5!
*****

```

and, when the program stops, a final message similar to this one is displayed:

Total CPU time: 0.190 sec

Execution of the sample input file must have created two output files: ‘smarts295.out.txt’ and ‘smarts295.ext.txt’ at the root of the main folder. To avoid problems, it is recommended to move the output files to the OUTPUT folder (or any other folder) before the next run.

### ***4.3 Advanced scripts for batch processing***

Unix offers a series of shell commands that can enhance the batch capabilities of the SMARTS code. A sample shell file, called ‘smarts295script.csh’, is provided in the Source\_code folder. In order to use it, copy it to the root of the SMARTS\_295\_Linux directory. It makes use of the ‘smarts295bat.exe’ executable (see previous Section). The content of this file is listed below. A user familiar with shell scripting can take further advantage of the batch mode and create even more complicated scripts.

```
#!/bin/csh
# Use "source smarts295script.csh" to execute this file
# or
# "chmod u+x smarts295script.csh"
# and then
# "./smarts295script.csh"
#
foreach i (01 02 03 04 june july 20050914)
cp -f smarts_${i}.inp.txt smarts295.inp.txt
./smarts295bat.exe
mv smarts295.out.txt smarts_${i}.out.txt
mv smarts295.scn.txt smarts_${i}.scn.txt
mv smarts295.ext.txt smarts_${i}.ext.txt
end
```

This example script assumes that seven input files are present in the root folder, with a variety of naming conventions (for demonstration purposes): ‘smarts\_01.inp.txt’, ‘smarts\_02.inp.txt’, ‘smarts\_03.inp.txt’, ‘smarts\_04.inp.txt’, ‘smarts\_june.inp.txt’, ‘smarts\_july.inp.txt’, and ‘smarts\_20050914.inp.txt’.

When the script is activated (after it is moved to the root of the main folder, and the instructions from the comments in the first few lines of the script are followed), the content of each of these files is copied to the default input file with the help of the “cp” command (copy). Then the ‘smarts295script’ executable reads this input file, make the appropriate calculations and pass the output to the default files. In order not to overwrite the default output files, they are renamed with the help of the “mv” command (move). Once the “end” statement is reached, the “foreach” command will move to the next argument. If all arguments are used, the user will be returned to the standard prompt.

It is clear that the user can change the arguments of the “foreach” command to suit his/her needs. All text files and the executable are assumed to reside in the root directory of the code.

### ***4.4 Compiler issues***

Commercial Fortran compilers are generally more powerful than g77. Therefore, the executables provided here might not be the fastest possible. This is not a problem in normal use because execution takes only a few tenths of a second. For extremely intensive batch jobs (e.g., thousands of chained runs at a time), it would be advisable to recompile the code with one of these high-performance compilers.

Users of Pentium processors can download the Intel Fortran compiler. The specific compiler is free for the Linux OS, while it is a commercial product for Windows. The installation of the compiler is

easily performed. The compilation time is increased but the execution time is substantially reduced. The code would be compiled with the command

```
ifort -o smarts295.exe smarts295.f
```

An example of extremely intensive use of SMARTS is in the mesoscale radiation analysis project STRÅNG, <http://produkter.smhi.se/strang/>.

Another issue is that compilers may not interpret code the same way, depending on user-defined options or platform. This may therefore lead to varying results from one compiler to the other or one platform to the other. So far, this problem has been avoided, but it is always a good thing to double check that your results are correct. This is the role of the solved examples. Please report any discrepancy to the author!

## 5. RUNNING THE CODE

The only delicate step involved before actually running the code is to prepare a correct input file. *Careful reading of Section 6 is thus recommended in a first step.* Then, it is advised to start using one of the resolved examples that are provided in the **Examples** subfolder. Their input files are commented for clarity.

### **IMPORTANT NOTES:**

1. An incorrect input file will result either in incorrect results, or in a runtime error. In the latter case, the executable will either quit abruptly, or engage in an infinite loop that needs to be stopped manually by forcing the application to quit.
2. **Results** are located in one to three **output files** depending on the desired sophistication. The standard output displays only input echo and broadband results in **File 16** (e.g., 'smarts295.out.txt'). Two optional spreadsheet-ready output files with spectral results can be requested: **File 17** (e.g., 'smarts295.ext.txt') and **File 18** (e.g., 'smarts295.scn.txt'). File 17 contains spectral results for up to 43 user-selectable variables. File 18 contains spectral smoothed results for 5 fixed variables.
3. Previous users will notice a major overhaul in the file naming conventions. This is to streamline the use of extensions, accelerate filename typing in command lines, and avoid coexistence problems if an older version (e.g., 2.9.2) needs to be used concurrently.

Each of the sample runs resides in a single Example folder/subdirectory, with corresponding comments in a ReadMe file. These sample runs can be extremely valuable to get accustomed to the code and preview its capabilities.

In any case, it is important to become familiar with the different variables that constitute the input file. This is the goal of the next Section.

Once the input file is ready (e.g., 'smarts295.inp.txt' or 'Test\_for\_July.inp.txt') and correctly located in the main folder/directory, the program can be launched using the various alternative methods described in the previous Section.

 **IMPORTANT NOTE:**

The program will NOT execute if any output file (e.g., 'smarts295.out.txt', 'smarts295.ext.txt', or 'smarts295.scn.txt') already exists in this folder. An error message would result, as described in Section 4.1. It is thus important to RENAME the output files before proceeding to a new run, or to move them to a different folder.

## 6. INPUT PREPARATION

All inputs are contained in file 'smarts295.inp.txt', but, as mentioned above, it can be renamed to 'filename.inp.txt' where 'filename' stands for any user-defined name (e.g., 'Test\_for\_July').

The input file is constituted of a series of lines representing as many virtual "Input Cards". Their total number is variable, depending on the complexity of the requested calculations. *If a Card contains inputs for more than one variable, they must be separated by a blank space or a coma.* For clarity, commas are used to separate variables in this manual.

All Card images and their content are described here in their prescribed order of appearance in the input file. Variable names, and their character value, if applicable, appear in **COURIER bold** for easier recognition.

Quotes around text characters can be omitted (e.g., on Cards 1, 3a, and 8).

There are two types of Cards: the *Main Cards*, which are mandatory and should exist in any input file, and the *Optional Cards*, whose presence and contents depend on the options selected on the preceding Main Card.

This is a sample Main Card:

**CARD 3**: **IATMOS**

This is a sample Optional Card:

**CARD 3a** (if **IATMOS** = 1): **ATMOS**

Important discussions about the correct use of variables and data, sources of data, etc., appear in blue type with a red vertical border, just like this paragraph.

 **IMPORTANT NOTES:**

Some input cards and content have been modified since version 2.9.2. They appear in yellow and are marked with a 'blue star' symbol, ★. Existing input files from version 2.9.2 or earlier will not be valid without proper alteration of these input cards. Conversely, however, all 2.9.5 input files are backward compatible with versions 2.9 and later. Consult Section 16 for changes that occurred between versions 2.8 and 2.9.5.

New features in this version appear in red.

**CARD 1: COMNT**

**COMNT** is a text string that can be any title for the current run, or any user's comments on atmospheric conditions, etc. It is limited to 64 characters max. Do not use spaces but rather underscores ('\_') to separate words or character strings if necessary.

**CARD 2: ISPR**

**ISPR** is an option for site's pressure.

**ISPR** = 0 to input **SPR** on Card 2a;

**ISPR** = 1 to input **SPR**, **ALTIT** and **HEIGHT** on Card 2a;

**ISPR** = 2 to input **LATIT**, **ALTIT** and **HEIGHT** on Card 2a.

The program calculates **ALTIT** from **SPR** (assuming **HEIGHT** = 0) if **ISPR** = 0, or calculates **SPR** from **LATIT**, **ALTIT** and **HEIGHT** if **ISPR** = 2. The option **ISPR** = 1 provides more accurate results and is recommended.

**CARD 2a** (if **ISPR** = 0): **SPR**

**SPR**: Surface pressure (mb), **must be > 0.0004 mb**.

★ **CARD 2a** (if **ISPR** = 1): **SPR**, **ALTIT**, **HEIGHT**

**SPR**: Surface pressure (mb).

**ALTIT**: Site's altitude, i.e., elevation of the ground surface above sea level (km); **must be ≤ 100 km**. In case of a flying object, **ALTIT** refers to the ground surface below it.

**HEIGHT**: Height of the simulated object above the ground surface underneath (km); must be ≤ 100 km (**new input**).

The total **ALTIT** + **HEIGHT** is the altitude of the simulated object above sea level and must be ≤ 100 km.

★ **CARD 2a** (if **ISPR** = 2): **LATIT**, **ALTIT**, **HEIGHT**

**LATIT**: Site's latitude (decimal degrees, positive North, negative South); e.g., -17.533 for Papeete, Tahiti. If **LATIT** is unknown, enter 45.0.

**ALTIT**: Site's altitude, i.e., elevation of the ground surface above sea level (km); **must be ≤ 100 km**. In case of a flying object, **ALTIT** refers to the ground surface below it.

**HEIGHT**: Height of the simulated object above the ground surface underneath (km); must be ≤ 100 km (**new input**).

The total **ALTIT** + **HEIGHT** is the altitude of the simulated object above sea level and must be ≤ 100 km.

Note 1: If **ISPR** = 1 on Card 2, **SPR** is used as the main input for all pressure-related calculations. To study the effect of *varying* altitude (through **ALTIT** or **HEIGHT**) on irradiance, it is therefore *imperative* to use one of the following two options: (i) use **ISPR** = 2, forcing **SPR** to be recalculated each time **ALTIT** or **HEIGHT** varies; or (ii) use **ISPR** = 1, but each time **ALTIT** or **HEIGHT** varies, provide the re-evaluated **SPR** that corresponds to the effective altitude, **ALTIT** + **HEIGHT**.

Note 2: If **ISPR** = 2 on Card 2 and **IATMOS** = 1 on Card 3, the default **SPR** value generated by the reference atmosphere will ultimately replace the estimate from **ALTIT** and **LATIT** based on Card 2a information.

### **CARD 3: IATMOS**

**IATMOS** is an option to select the proper default atmosphere. Its value can be either 0 or 1. Set **IATMOS** = 0 to define a realistic (i.e., non-reference) atmosphere. Card 3a will then have to provide **TAIR**, **RH**, **SEASON**, **TDAY**.

Set **IATMOS** = 1 to select one of 10 default reference atmospheres (i.e., for ideal conditions). The shortened name of this atmosphere must be provided by **ATMOS** on Card 3a.

If **IATMOS** = 0 is selected, then **IH2O** should be 0 or 2; **IO3** and **IGAS** should be 0.

If **IATMOS** = 1 is selected, then **IH2O**, **IO3**, and **IGAS** may take any value. All user inputs have precedence over the defaults.

**CARD 3a** (if **IATMOS** = 0): **TAIR**, **RH**, **SEASON**, **TDAY**.

**RH**: Relative humidity at site level (%).

**SEASON**: Can be either 'WINTER' or 'SUMMER', for calculation of precipitable water and stratospheric temperature. If the true season is *Fall*, select **WINTER**. Select **SUMMER** if the true season is *Spring*. **SEASON** slightly affects the ozone effective temperature and the aerosol optical characteristics.

**TAIR**: Atmospheric temperature at site level (°C). Acceptable range:  $-120 < \mathbf{TAIR} < 50$ .

**TDAY**: Average daily temperature at site level (°C). For a flying object (**HEIGHT** > 0), this is a *reference* temperature for various calculations, therefore it is important to provide a realistic value in this case in particular. Acceptable range:  $-120 < \mathbf{TDAY} < 50$ .

**CARD 3a** (if **IATMOS** = 1): **ATMOS**

**ATMOS** is the name of the selected reference atmosphere; 4 characters max. This name can be one of the following:

- 'USSA' (U.S. Standard Atmosphere)
- 'MLS' (Mid-Latitude Summer)
- 'MLW' (Mid-Latitude Winter)
- 'SAS' (Sub-Arctic Summer)
- 'SAW' (Sub-Arctic Winter)
- 'TRL' (Tropical)
- 'STS' (Sub-Tropical Summer)
- 'STW' (Sub-Tropical Winter)
- 'AS' (Arctic Summer)
- 'AW' (Arctic Winter)

Note 1: Only the 6 first atmospheres are available in LOWTRAN or MODTRAN.

Note 2: The reference atmospheres determine pressure, temperature, relative humidity, ozone, and precipitable water *in the free atmosphere* at the total altitude specified on Card 2 (**ALTIT + HEIGHT**). If this altitude is > 0, the reference atmospheres will consider the site as an aircraft or a very tall tower, i.e., will not consider any boundary-layer effect, which tends to increase temperature, relative humidity, and precipitable water. For better results at most sites, it is preferable to define a non-reference atmosphere on Card 3 and specify precipitable water on Card 4 and ozone on Card 5.

#### **CARD 4: IH2O**

**IH2O** is an option to select the correct water vapor data. All water vapor calculations involve precipitable water, **W**. The following values of **IH2O** are possible:

0, to input **W** on Card 4a;

1, if **W** is to be defaulted to a value prescribed by the selected reference atmosphere and the site altitude (thus if **IATMOS** = 1 on Card 3). If **IATMOS** ≠ 1, **USSA** will be defaulted for this step.

2, if **W** is to be calculated by the program from **TAIR** and **RH** (thus if **IATMOS** = 0 on Card 3). This calculation is only approximate (particularly if **HEIGHT** > 0) and therefore this option is not recommended.

CARD 4a (if **IH2O** = 0): **W**

**W** is precipitable water *above the site altitude* in units of cm, or equivalently, g/cm<sup>2</sup>; it must be ≤ 12.

Precipitable water can be determined from radiosonde soundings, radiometric methods, remote sensing from space, or by using GPS positioning delay information. In the general case, such datasets are not specifically available for the exact desired time and site. It is possible to use climatological averages, or empirical equations predicting **W** as a function of surface temperature, humidity and pressure. See (Garrison and Adler, 1990; Gueymard, 1994a; Myers and Maxwell, 1992) more specifically for U.S. or Canadian conditions, and many other references for empirical determinations in various other countries. **W** represents the total column of water vapor (if condensed) in the atmosphere above *site level*. This value is to be input directly if **IH2O** = 0. Alternatively, it will be calculated by the program from either the user-selected reference atmosphere if **IH2O** = 1 (*assuming free-atmosphere conditions in this case—*in reality, precipitable water might be higher for an elevated site because of boundary-layer effects), or from surface data of temperature and humidity if **IH2O** = 2. In the latter case the author's empirical model (Gueymard, 1994a) is used. The validity of such estimates at high-altitude sites (including flying objects), or at sites outside North America, cannot be guaranteed.

#### **CARD 5: IO3**

**IO3** is an option to select the appropriate ozone abundance input.

**IO3** = 0 to input **IALT** and **AbO3** on Card 5a;

**IO3** = 1 to use a default value for **AbO3** according to the reference atmosphere selected by **IATMOS**. If **IATMOS** ≠ 1, **USSA** will be defaulted for this calculation.

CARD 5a (if **IO3** = 0): **IALT**, **AbO3**

**IALT** is an option to select the appropriate ozone column altitude correction.

**IALT** = 0 bypasses the altitude correction, so that the value of **AbO3** on Card 5a is used as is.

**IALT** = 1 should be rather used if a vertical profile correction needs to be applied (in case of an elevated site when the value of **AbO3** is known only at sea level).

This option is useful, for instance, when using ozone data from a ground-based instrument located at sea level to estimate the ozone abundance at a distant and elevated site (e.g., on top of an island mountain), or in the case of a flying object (**HEIGHT** > 0).

**AbO3**: site-level (if **IALT** = 0) or sea-level (if **IALT** = 1) ozone total-column abundance, normally excluding tropospheric pollution (atm-cm).

The normal range for **AbO3** is 0.2 to 0.5 atm-cm. The present record lows over Antarctica are just below 0.1 atm-cm. The range for the 10 reference atmospheres is 0.28 to 0.38, with an average of 0.3341 (close to USSA's value: 0.34379 atm-cm). Van Heuklon (1979) proposed an equation to obtain the average ozone column as a function of latitude, longitude and day of the year. A better alternative is to use measured data, either from satellite-based sensors such as TOMS ([http://jwocky.gsfc.nasa.gov/teacher/ozone\\_overhead.html](http://jwocky.gsfc.nasa.gov/teacher/ozone_overhead.html)) and GOME ([http://www.knmi.nl/gome\\_fd/tm3/vl4.html](http://www.knmi.nl/gome_fd/tm3/vl4.html)), or from ground-based spectrophotometers from the WOUDC network ([http://www.woudc.org/data\\_e.html](http://www.woudc.org/data_e.html)).

Most measured total-column data in the present era are expressed in Dobson units (DU). 1000 Dobson units are equivalent to 1 atm-cm.

**AbO3** represents the total-column abundance of ozone above site level. It may be corrected by the program if **IALT** is set to 1. A correction with altitude is then applied to **AbO3** so that the apparent ozone column from an elevated site can be obtained from available sea-level data. Tropospheric ozone may be present in polluted areas, but it is normally a small fraction of the total ozone. Reference atmospheres indicate a sea-level ozone concentration of 0.018–0.030 ppmv. If the site's ozone concentration is appreciably higher and is known to be excluded from the columnar abundance specified by **AbO3**, SMARTS has an option to take this additional contribution into account through **ApO3** (see Cards 6 and 6a).

#### **CARD 6**: **IGAS**

**IGAS** is an option to define the correct conditions for gaseous absorption and atmospheric pollution.

**IGAS** = 0 if **ILOAD** on Card 6a is to be read so that extra gaseous absorption calculations (corresponding to the gas load in the lower troposphere due to pollution—or absence thereof) can be initiated;

**IGAS** = 1 if all gas abundances (except carbon dioxide, ozone and water vapor—see Cards 4a, 5a, and 7) are to be defaulted, using average vertical profiles.

#### **CARD 6a** (if **IGAS** = 0): **ILOAD**

**ILOAD** is an option for tropospheric pollution, only used if **IGAS** = 0.

For **ILOAD** = 0, Card 6b will be read with the concentrations of 10 pollutants.

**ILOAD** = 1 selects default *PRISTINE ATMOSPHERIC* conditions, leading to slightly *reduced* abundances of some gases compared to the initial default obtained with the selected reference atmosphere.

Setting **ILOAD** to 2–4 will increase the concentration of the 10 pollutants to possibly represent typical urban conditions: *LIGHT POLLUTION* (**ILOAD** = 2), *MODERATE POLLUTION* (**ILOAD** = 3), and *SEVERE POLLUTION* (**ILOAD** = 4).

Note that these additional gas loads may not all correspond to realistic conditions because each site is different, and pollution conditions change rapidly over time. Thus, it may well happen that, for a specific site and time, some gases are in reality more abundant than what the default

proposes, whereas other gases are less abundant. These loads must therefore only be considered as subjective guidelines. If measured data are accessible, the option **ILOAD** = 0 is preferable.

The following table indicates the defaulted *additional* tropospheric concentrations (in ppmv) for each pollutant. The number within brackets indicates the value of **ILOAD**. Note that in the case of CH<sub>2</sub>O, CO, HNO<sub>2</sub>, NO<sub>3</sub>, and O<sub>3</sub>, their ground-level concentration under a Pristine Atmosphere is lower than that for the standard conditions of the reference atmosphere, hence the *negative* values for the additional concentrations.

Gas	(1) Pristine	(2) Light Pollution	(3) Moderate	(4) Severe
CH <sub>2</sub> O	-0.003	0.001	0.007	0.01
CH <sub>4</sub>	0	0.2	0.3	0.4
CO	-0.1	0	0.35	9.9
HNO <sub>2</sub>	-9.9E-4	0.0005	0.002	0.01
HNO <sub>3</sub>	0	0.001	0.005	0.012
NO	0	0.075	0.2	0.5
NO <sub>2</sub>	0	0.005	0.02	0.2
NO <sub>3</sub>	-4.9E-4	1E-5	5E-5	2E-4
O <sub>3</sub>	-0.007	0.023	0.053	0.175
SO <sub>2</sub>	0	0.01	0.05	0.2

**CARD 6b** (if **IGAS** = 0 and **ILOAD** = 0): **ApCH2O**, **ApCH4**, **ApCO**, **ApHNO2**, **ApHNO3**, **ApNO**, **ApNO2**, **ApNO3**, **ApO3**, **ApSO2**

**ApCH2O**: Formaldehyde volumetric concentration in the assumed 1-km deep tropospheric pollution layer (ppmv).

**ApCH4**: Methane volumetric concentration in the assumed 1-km deep tropospheric pollution layer (ppmv).

**ApCO**: Carbon monoxide volumetric concentration in the assumed 1-km deep tropospheric pollution layer (ppmv), Card 6b.

**ApHNO2**: Nitrous acid volumetric concentration in the assumed 1-km deep tropospheric pollution layer (ppmv).

**ApHNO3**: Nitric acid volumetric concentration in the assumed 1-km deep tropospheric pollution layer (ppmv).

**ApNO**: Nitric oxide volumetric concentration in the assumed 1-km deep tropospheric pollution layer (ppmv).

**ApNO2**: Nitrogen dioxide volumetric concentration in the assumed 1-km deep tropospheric pollution layer (ppmv).

**ApNO3**: Nitrogen trioxide volumetric concentration in the assumed 1-km deep tropospheric pollution layer (ppmv).

**ApO3**: Ozone volumetric concentration in the assumed 1-km deep tropospheric pollution layer (ppmv).

**ApSO2**: Sulfur dioxide volumetric concentration in the assumed 1-km deep tropospheric pollution layer (ppmv).

SMARTS considers separate gaseous absorption calculations for tropospheric gases typically trapped in a pollution layer. This layer is assumed to be 1-km thick above ground, and well-mixed. Default values for the concentration of ten tropospheric gases are transparently used in

the program when **IGAS** = 0 and **ILOAD** = 1–4. However, selecting **IGAS** = 0 and **ILOAD** = 0 allows the user to provide measured or otherwise estimated concentrations for these 10 gases through variables **ApCH2O**, **ApCH4**, **ApCO**, **ApHNO2**, **ApHNO3**, **ApNO**, **ApNO2**, **ApNO3**, **ApO3**, **ApSO2**. These concentrations need to be given in ppmv (parts per million per volume). The program converts these concentrations to equivalent total-column abundances, on the basis that each gas concentration is constant within the 1-km pollution layer. When data of average pollutant concentration are used and the pollution layer is known to be of a different thickness than 1 km, the user needs to make a preliminary conversion, i.e., by multiplying the observed average concentration for a H-km layer by H.

To use concentration data provided in atm-cm for a H-km layer, multiply these values by (10 / H) to obtain the correspondence in ppmv.

To use concentration data provided in  $\mu\text{g}/\text{m}^3$ , multiply these values by (0.022414 / M) for any H to obtain the correspondence in ppmv, where M is the molar mass of the gas in grams.

Molar masses of the basic species are as follows:

C = 12, H = 1, N = 14, O = 16, S = 32.

Hence the molar mass of ozone is 48 g and that of NO is 30 g.

#### **CARD 7**: **qCO2**

**qCO2** is the carbon dioxide columnar volumetric concentration (ppmv).

The current average CO<sub>2</sub> concentration is about 370 ppmv, but fluctuates seasonally and increases over time (by about 2 ppmv/year). It was about 330 ppmv in 1976, hence the default value of 330 ppmv used in the U.S. Standard Atmosphere (Anon., 1976) and the LOWTRAN/MODTRAN family of atmospheric codes. Note that this concentration does *not* vary appreciably with altitude, but does vary slightly with location and date (season and year).

#### ★ **CARD 7a**: **ISPCTR**

**ISPCTR** is an option to select the proper extraterrestrial spectrum. This option allows to choose one out of ten possible spectral files ('Spctrm\_n.dat', where n = 0–8 or n = U).

The following table lists the source for each file, and the corresponding solar constant. The original data have been resampled and degraded to the best resolution achievable with SMARTS, i.e., 0.5 nm between 280 and 400 nm, 1 nm between 400 and 1700 nm, and 5 nm between 1705 and 4000 nm.

**Option 0 (NEW)** is for a synthetic spectrum recently proposed (Gueymard, 2004) and is recommended for normal use.

Option 1 is for a synthetic spectrum (revised from the previous SMARTS 2.8 spectrum) which was recommended for use with versions 2.9. to 2.9.2.

Options 2–7 are directly derived from the six high-resolution spectra selectable in MODTRAN 4.0 and thus allow better compatibility with any irradiance prediction obtained with this code.

Option -1 (*NEW*) is for a user-defined spectrum, to be read in file ‘Spctrm\_U.dat’. This file is originally a copy of ‘Spctrm\_0.dat’ but can be altered by the user, inasmuch as the original format, wavelengths and units are conserved. See Section 8 for more details.

Option 8 (*NEW*) is for an *interpolated* version of the ASTM E490 standard spectrum (ASTM, 2000). It has been specially prepared by Daryl Myers for those applications that require compliance with this ASTM standard.

See Section 13 and (Gueymard, 2004) for more details and intercomparisons between the solar spectra offered here.

Option	File	MODTRAN 4 name	Source	Solar Constant (W/m <sup>2</sup> )
-1	‘Spctrm_U.dat’	N/A	User	User
0	‘Spctrm_0.dat’	N/A	Gueymard, 2004 (synthetic)	1366.10
1	‘Spctrm_1.dat’	N/A	Gueymard, unpublished (synthetic)	1367.00
2	‘Spctrm_2.dat’	cebchkur	MODTRAN, Cebula/Chance/Kurucz	1362.12
3	‘Spctrm_3.dat’	chkur	MODTRAN, Chance/Kurucz	1359.75
4	‘Spctrm_4.dat’	newkur	MODTRAN, New Kurucz	1368.00
5	‘Spctrm_5.dat’	oldkur	MODTRAN, Old Kurucz	1373.16
6	‘Spctrm_6.dat’	thkur	MODTRAN, Thuillier/Kurucz	1376.23
7	‘Spctrm_7.dat’	MODTRAN2	Wehrli/WRC/WMO, 1985	1367.00
8	‘Spctrm_8.dat’	N/A	ASTM E490, 2000 (synthetic)	1366.10

★ **CARD 8**: **AEROS**

**AEROS** selects the aerosol model, with one of the following twelve possible choices:

‘S&F\_RURAL’  
‘S&F\_URBAN’  
‘S&F\_MARIT’  
‘S&F\_TROPO’

These four choices refer respectively to the Rural, Urban, Maritime and Tropospheric aerosol models (Shettle and Fenn, 1979), which are humidity dependent and common with MODTRAN.

‘SRA\_CONTL’  
‘SRA\_URBAN’  
‘SRA\_MARIT’

These three choices refer respectively to the Continental, Urban, and Maritime aerosol models of the IAMAP preliminary standard atmosphere (IAMAP, 1986).

‘B&D\_C’  
‘B&D\_C1’

These two choices refer respectively to the Braslau & Dave aerosol type C and C1, themselves based on Deirmendjian’s Haze L model.

‘DESERT\_MIN’  
‘DESERT\_MAX’

These two choices are *new* in version 2.9.5. **DESERT\_MIN** corresponds to background (normal) conditions in desert areas, whereas **DESERT\_MAX** corresponds to extremely turbid conditions (sand storms).

The optical characteristics of all these default aerosol models are calculated by the program from wavelength, as well as relative humidity in the case of the Shettle & Fenn aerosols.

#### 'USER'

This last option is to be used if none of the above default aerosol model is appropriate, i.e., to describe realistic (as opposed to ideal) conditions. Card 8a is then necessary to input user-supplied aerosol information.

CARD 8a (if **AEROS** = 'USER'): **ALPHA1**, **ALPHA2**, **OMEGL**, **GG**

**ALPHA1**: Average value of Ångström's wavelength exponent  $\alpha$  for wavelengths < 500 nm (generally between 0.0 and 2.6).

**ALPHA2**: Average value of Ångström's wavelength exponent  $\alpha$  for wavelengths  $\geq$  500 nm (generally between 0.0 and 2.6).

**OMEGL**: Aerosol single scattering albedo (generally between 0.6 and 1.0).

**GG**: Aerosol asymmetry parameter (generally between 0.5 and 0.9).

CAUTION: These 4 variables must represent broadband average values only!

#### ★ **CARD 9**: **ITURB**

**ITURB** is an option to select the correct turbidity data input. The different options are:

0, to read **TAU5** on Card 9a

1, to read **BETA** on Card 9a

2, to read **BCHUEP** on Card 9a

3, to read **RANGE** on Card 9a

4, to read **VISI** on Card 9a

5, to read **TAU550** on Card 9a (*new* option).

CARD 9a (if **ITURB** = 0): **TAU5**

**TAU5**: Aerosol optical depth at 500 nm,  $\tau_5$ .

CARD 9a (if **ITURB** = 1): **BETA**

**BETA**: Ångström's turbidity coefficient,  $\beta$  (i.e., aerosol optical depth at 1000 nm).

CARD 9a (if **ITURB** = 2): **BCHUEP**

**BCHUEP**: Schüepp's turbidity coefficient,  $B$  (i.e., decadic aerosol optical depth at 500 nm).

CARD 9a (if **ITURB** = 3): **RANGE**

**RANGE**: Meteorological range,  $V_R$ , based on Koschmieder's equation, must be between 1 and 999 km.

CARD 9a (if **ITURB** = 4): **VISI**

**VISI**: Prevailing visibility,  $V$ , as observed at airports, must be between 0.77 and 764 km.

★ **CARD 9a** (if **ITURB** = 5): **TAU550**

**TAU550**: Aerosol optical depth at 550 nm,  $\tau_{550}$ .

All values appearing on Card 9a must correspond to the *aerosol total column* between the receiver's altitude and the top of the atmosphere. This may represent a challenge when dealing with an aircraft-based receiver, for instance, due to the lack of data at high altitude. For a receiver at altitudes above about 6 km, it is possible to obtain **TAU550** from the effective altitude  $z$  (i.e., **ALTIT** + **HEIGHT**) in km, by using the following empirical relationship:

$$\tau_{550} = \exp(-3.2755 - 0.15078 z).$$

Under 6 km, aerosol conditions are highly variable over time and space, hence a better estimate of the turbidity input is necessary.

If **BETA** is not input, all possible alternatives (**BCHUEP**, **RANGE**, **TAU5**, **TAU550**, **VISI**) are converted by the program first to  $\beta$ , then to a spectral aerosol optical depth,  $\tau_{a\lambda}$ , by use of equations such as:

$$\tau_5 = 2.302585 B$$

$$\beta = (0.5^{\alpha_2}) \tau_5 = (0.55^{\alpha_2}) \tau_{550}$$

$$V_R = 1.306 V$$

$$\tau_{a\lambda} = \beta (0.5^{\alpha_1 - \alpha_2}) \lambda^{\alpha_1}, \text{ if } \lambda < 0.5 \mu\text{m}; \tau_{a\lambda} = \beta \lambda^{\alpha_2}, \text{ if } \lambda \geq 0.5 \mu\text{m}.$$

$$\beta = (0.55^{\alpha_2}) f(V_R).$$

In the special case when **IATMOS** = 1 and **AEROS** = **S&F\_RURAL**, however,  $\tau_{a\lambda}$  is evaluated with Ångström's equation,  $\tau_{a\lambda} = \beta \lambda^{-\alpha}$ , where  $\alpha$  is obtained as a stepwise fit of the original data in (Shettle and Fenn, 1979). If this particular calculation does not appear appropriate, either set **IATMOS** to 0 (rather than 1) to define a **USER** atmosphere with **AEROS** = '**S&F\_RURAL**', or set **AEROS** = '**USER**' to define a user aerosol along with **IATMOS** = 1.

★ **CARD 10**: **IALBDX**

**IALBDX** is an option to select the correct *zonal (or far-field) albedo*, **RHOX**, for backscattering calculations.

From the reflectance standpoint, the ground surface can be treated either as Lambertian (L) or non-Lambertian (NL). A Lambertian (or isotropic) surface reflects the incident irradiance equally in all directions. Most natural surfaces have a directional reflectance pattern (they reflect more in the direction of the solar beam) and are thus non-Lambertian to some degree.

The possible values of **IALBDX** are:

-1, to input a fixed broadband, Lambertian albedo, **RHOX**, on Card 10a.

0, to read user-defined spectral reflectance from file 'Albedo.dat' with Lambertian characteristics (L);

1, if the same dataset from file 'Albedo.dat' is to be considered non-Lambertian (NL);

2, if a spectral, non-Lambertian reflectance for water is to be *calculated* by the program at run time;

3 to 66, if spectral reflectance data are to be read from one of the available 64 default files described below, and considered non-Lambertian (NL). **New:** The albedo library has 28 new files in this version; they are indicated by a red color in the Table below.

All reflectance data are read in an appropriate data file, except for codes -1 and 2 (see above). All the possible codes are listed in the table below, with the corresponding file names and spectral ranges. Note that most spectral ranges are significantly shorter than the maximum range supported by the code. If the requested spectral range for the calculations extends beyond the spectral range of an albedo file, all missing reflectance values are set equal to the nearest known value at run time.

Code	Description	File name (.DAT extension)	Reflection type*	Spectral range ( $\mu\text{m}$ )	Category*
-1	Fixed broadband albedo	—	L	0.28–4.0	U
0	User-defined spectral reflectance	Albedo	L	User- defined	U
1	User-defined spectral reflectance	Albedo	NL	User- defined	U
2	Water or calm ocean	(calculated)	SP	0.28–4.0	W
3	Fresh dry snow	Snow	NL	0.3–2.48	W
4	Snow on a mountain neve	Neve	NL	0.45–1.65	W
5	Basalt rock	Basalt	NL	0.3–2.48	S
6	Dry sand	Dry_sand	NL	0.32–0.99	S
7	Sand from White Sands, NM	WiteSand	NL	0.5–2.48	S
8	Bare soil	Soil	NL	0.28–4.0	S
9	Dry clay soil	Dry_clay	NL	0.5–2.48	S
10	Wet clay soil	Wet_clay	NL	0.5–2.48	S
11	Alfalfa	Alfalfa	NL	0.3–0.8	V
12	Green grass	Grass	NL	0.3–1.19	V
13	Perennial rye grass	RyeGrass	NL	0.44–2.28	V
14	Alpine meadow	Meadow1	NL	0.4–0.85	V
15	Lush meadow	Meadow2	NL	0.4–0.9	V
16	Wheat crop	Wheat	NL	0.42–2.26	V
17	Ponderosa pine tree	PineTree	NL	0.34–2.48	V
18	Concrete slab	Concrete	NL	0.3–1.3	M
19	Black loam	BlckLoam	NL	0.4–4.0	S
20	Brown loam	BrwnLoam	NL	0.4–4.0	S
21	Brown sand	BrwnSand	NL	0.4–4.0	S
22	Conifer trees	Conifers	NL	0.302–4.0	V
23	Dark loam	DarkLoam	NL	0.46–4.0	S
24	Dark sand	DarkSand	NL	0.4–4.0	S
25	Deciduous trees	Decidous	NL	0.302–4.0	V
26	Dry grass (sod)	DryGrass	NL	0.38–4.0	V
27	Dune sand	DuneSand	NL	0.4–4.0	S
28	Fresh fine snow	FineSnow	NL	0.3–4.0	W
29	Green rye grass (sod)	GrnGrass	NL	0.302–4.0	V
30	Granular snow	GrnlSnow	NL	0.3–4.0	W
31	Light clay	LiteClay	NL	0.4–4.0	S

32	Light loam	LiteLoam	NL	0.431–4.0	S
33	Light sand	LiteSand	NL	0.4–4.0	S
34	Pale loam	PaleLoam	NL	0.4–4.0	S
35	Sea water	Seawater	NL	2.079–4.0	W
36	Solid ice	SolidIce	NL	0.3–4.0	W
37	Dry soil	Dry_Soil	NL	0.28–4.0	S
38	Light soil	LiteSoil	NL	0.28–4.0	S
39	Old runway concrete	RConcrte	NL	0.3–4.0	M
40	Old runway asphalt	Asphalt	NL	0.3–4.0	M
41	Terracota roofing clay tile	RoofTile	NL	0.3–4.0	M
42	Red construction brick	RedBrick	NL	0.3–4.0	M
43	Gravel	Gravel	NL	0.32-1.3	S
44	Sand & gravel	SndGravl	NL	0.45-1.04	S
45	Fallow field	Fallow	NL	0.32-1.19	S
46	Tall green corn	TallCorn	NL	0.36-1.0	V
47	Birch leaves	Birch	NL	0.36-2.48	V
48	Wet sandy soil	WetSSoil	NL	0.48-2.48	S
49	Wet red clay	WetClay2	NL	0.52-2.48	S
50	Wet silt	WetSilt	NL	0.52-2.48	S
51	Dry long grass	LngGrass	NL	0.52-2.48	V
52	Lawn grass (generic bluegrass)	LwnGrass	NL	0.277-2.976	V
53	Deciduous oak tree leaves	OakTree	NL	0.305-2.944	V
54	Pinion pintetree needles	Pinion	NL	0.35-2.5	V
55	Melting snow (slush)	MeltSnow	NL	0.301-2.592	W
56	Plywood sheet (new, pine, 4-ply)	Plywood	NL	0.35-2.5	M
57	White vinyl plastic sheet, 0.15 mm	WiteVinl	NL	0.35-2.5	M
58	Clear fiberglass greenhouse roofing	FibrGlss	NL	0.35-2.5	M
59	Galvanized corrugated sheet metal, new	ShtMetal	NL	0.35-2.5	M
60	Wetland vegetation canopy, Yellowstone	Wetland	NL	0.409-2.478	V
61	Sagebrush canopy, Yellowstone	SageBrsh	NL	0.409-2.478	V
62	Fir trees, Colorado	FirTrees	NL	0.353-2.592	V
63	Coastal seawater, Pacific	CSeaWatr	NL	0.277-2.976	W
64	Open ocean seawater, Atlantic	OSeaWatr	NL	0.277-2.976	W
65	Grazing field (unfertilized)	GrazingField	NL	0.401-2.499	V
66	Young Norway spruce tree (needles)	Spruce	NL	0.39-0.845	V

**\*KEY**

L	Lambertian
NL	Non-Lambertian
SP	Specular
M	Manmade materials
S	Soils and rocks
U	User defined
V	Vegetation
W	Water, snow, or ice

The non-Lambertian effect is modeled as an increase of reflectance with zenith angle, such as:

$$\text{R}_{\text{hob}} = \text{R}_{\text{hob0}} [1 - \cos Z \ln(1 + 1/\cos Z)] / 0.35$$

$$\text{R}_{\text{hod}} = 1.167 \text{R}_{\text{hob0}}$$

for all surfaces except snow (codes 3, 4, 28 and 30), for which the following model is used:

$$\begin{aligned} \text{Rhob} &= \text{Rhob0} (1 - 0.176 \cos Z) / 0.94 \\ \text{Rhod} &= 0.939 \text{Rhob0}. \end{aligned}$$

In these equations, Rhob is the reflectance for beam radiation, Rhod the reflectance for diffuse radiation, Rhob0 the reference reflectance in the data files, and cosZ the cosine of the zenith angle, **ZENIT**. The measured data are supposed to have been measured at zenith angles of about 20 deg. for snow, and about 53 deg. for all other surfaces, including the user-defined data in file 'Albedo.dat'.

The spectral reflectance for water (code 2) is calculated for each wavelength by the program and uses the Fresnel formula for specular reflectance. However, codes 35 and 63-64 can be used to select actual measured sea-water albedo data along with a non-Lambertian—rather than specular—spatial reflectance distribution.

**CARD 10a** (if **IALBDX** = -1): **RHOX**

**RHOX**: Zonal broadband Lambertian ground albedo (for backscattering calculations); must be between 0 and 1. Observed values are usually between 0.12 and 0.60. See also the discussion about **RHOG** for Card 10d below.

**CARD 10b**: **ITILT**

**ITILT** is an option for tilted surface calculations. Select **ITILT** = 0 for no such calculation, **ITILT** = 1 to initiate these calculations using information on Card 10c.

★ **CARD 10c** (if **ITILT** = 1): **IALBDG**, **TILT**, **WAZIM**

**IALBDG** is identical to **IALBDX** (see Card 10) except that it relates to the foreground local albedo seen by a tilted surface. The list of options is identical to that of **IALBDG** and thus extends from -1 to 64 (*new*).

**TILT**: Tilt angle of the receiving surface (0 to 90 decimal deg.); e.g. 90.0 for a vertical plane. Use -999 for a *sun-tracking surface*.

**WAZIM**: Surface azimuth (0 to 360 decimal deg.) counted clockwise from North; e.g., 270 deg. for a surface facing West. Use -999 for a *sun-tracking surface*.

**CARD 10d** (if **ITILT**=1 and **IALBDG**=-1): **RHOG**

**RHOG**: Local broadband Lambertian foreground albedo (for tilted plane calculations), Card 10d (if **IALBDG** = -1); usually between 0.05 and 0.90.

Under realistic conditions, **RHOX** (on Card 10a) is generally different from **RHOG** (on Card 10d). Both may have large seasonal variations at high latitudes and in cold regions, due to snow. The difference between **RHOG** and **RHOX** may seem subtle; they are frequently—but incorrectly—used interchangeably in the literature. **RHOX** corresponds to the *zonal albedo* (large scale, e.g., 10-100 km<sup>2</sup>) used in backscattering calculations. **RHOG** rather corresponds to the *local albedo* (small scale, e.g., 1-1000 m<sup>2</sup>) required when converting irradiance incident on a

horizontal plane to that incident on a tilted plane. **RHOG** is then the broadband reflectance of the horizontal foreground immediately in front of the tilted receiver, itself assumed of small dimensions (e.g., a solar collector, a window...). In general, **RHOG** and **RHOX** have different values because the ground surface is rarely uniform over large areas. However, the value of **RHOX** can be used for **RHOG** if the tilted “receiver” has a nearly infinite area (e.g., a mountain slope).

Note also that **RHOG** and **RHOX** are both broadband-average albedo values, i.e., spectrally-fixed reflectances. Such a case is almost never found in nature, so that calculations based on these values will be simplistic. For more realistic spectral calculations, use the library of 64 spectral reflectance files for natural surfaces, all obtained from spectral measurements (see **IALBDG** and **IALBDX**), or use site-specific spectral albedo values with the user-defined ‘Albedo.dat’ file.

#### **CARD 11**: **WLMN**, **WLMX**, **SUNCOR**, **SOLARC**

**WLMN**, **WLMX**: Spectral range (in nm), or min and max wavelengths between which all spectral calculations will be performed. **WLMN** should be  $\geq 280.0$  nm and **WLMX** should be  $\leq 4000$  nm; e.g., **WLMN** = 300.5, **WLMX** = 1810.

**SUNCOR** is a correction factor equal to the inverse squared actual radius vector, or true Sun-Earth distance; e.g., **SUNCOR** = 1.024.

**SUNCOR** varies naturally between 0.966 and 1.034, adding 3.4% to the irradiance in January and reducing it by 3.4% in July. It is calculated by the program if the solar position is calculated from date & time, i.e., if **IMASS** = 3 on Card 17, thus overwriting the input **SUNCOR** value on Card 11. If solar position is directly input instead (**IMASS**  $\neq$  3), **SUNCOR** should be set to 1.0 if the average extraterrestrial irradiance (or “solar constant”, see **SOLARC**) is to be used, or to any other number between 0.966 and 1.034 to correct it for distance if so desired.

**SOLARC** is the selected Solar constant ( $\text{W}/\text{m}^2$ ). The current ASTM-standard value is  $1366.1 \text{ W}/\text{m}^2$  and the WMO-accepted value is  $1367 \text{ W}/\text{m}^2$ . At runtime, all spectral irradiances are uniformly multiplied by a constant scaling factor equal to **SOLARC** divided by the total extraterrestrial irradiance corresponding to the selected spectrum. This one is chosen among the eight possible data files ‘Sptrm\_n.dat’ with **ISPCTR** (Card 7a).

These eight files contain the best current estimates of the extraterrestrial spectrum in the 280–4000 nm spectral range. For each of these files, the solar constant is slightly larger than the integrated irradiance from 280 to 4000 nm because it also includes the contributions for wavelengths below 280 nm and above 4000 nm. The second line of each file indicates the corresponding solar constant, which is read by the program. For each wavelength, the program then multiplies the extraterrestrial irradiance by the scaling factor described above. This scaling process is identical to what is done in MODTRAN 4.0. See **ISPCTR** (Card 7a) for a description of each of the eight spectrum files.

#### **CARD 12**: **IPRT**

**IPRT** is an option to select the results to be printed on Files 16 and 17. Only broadband results are output (to File 16) if **IPRT** = 0. Spectral results are added to File 16, and Card 12a is read, if **IPRT** = 1. Spectral results are rather printed to File 17 (in a spreadsheet-like format) if **IPRT** = 2. Finally,

spectral results are printed to both File 16 and 17 if **IPRT** = 3. Cards 12b and 12c are read if **IPRT** = 2 or 3 (see **IOTOT** and **IOUT**).

Note that the spectral results printed on File 16 with **IPRT** = 1 are limited in scope to the direct, diffuse, and global irradiances. For improved control and a larger choice of printable variables, use **IPRT** = 2 or 3. Note also that the spectral results of the smoothing postprocessor (Card 14) are printed on another spreadsheet-ready file, File 18, irrespective of **IPRT**.

**CARD 12a** (if **IPRT** ≥ 1): **WPMN, WPMX, INTVL**

**WPMN, WPMX**: Spectral range, or min and max wavelengths (nm) between which results will be printed on File 16 ('SMARTS295\_OUT.txt'), and/or File 17 ('smarts295.ext.txt'), if **IPRT** = 1 to 3 on Card 12. These conditions must be respected: **WPMN** ≥ **WLMN**; **WPMX** ≤ **WLMX**. Example: **WPMN** = 320.5, **WPMX** = 1100.

**INTVL**: Interval for printing spectral results on Files 16 and 17.

Example 1: if **INTVL** = 0.5, the effective interval used by the program will automatically adapt to the maximum possible resolution in each spectral region: 0.5 nm (280–400 nm), 1 nm (400–1700 nm), and 5 nm (1705–4000 nm).

Example 2: if **INTVL** is set to 2 nm, the effective interval will be 2 nm (280–1702 nm) and 5 nm (1705–4000 nm).

Example 3: if **INTVL** is set to 10 nm, the effective interval will be 10 nm for all possible bands (280–4000 nm).

★ **CARD 12b** (if **IPRT** = 2 or 3): **IOTOT**

**IOTOT** is the total number of output variables to print on File 17; it must be between 1 and 43 (*new*: up from 32 in version 2.9.2). A code defining these variables is read on Card 12c. Variables will be printed in the order selected.

★ **CARD 12c** (if **IPRT** = 2 or 3): **IOUT**

**IOUT** is a code number (1–43) to select the spectral variables to print on File 17. This code is to be selected among the following list.

<b>IOUT</b>	<b>Output variable</b>	<b>Unit</b>
1	Extraterrestrial spectrum	$\text{W m}^{-2}$
2	Direct normal irradiance	$\text{W m}^{-2}$
3	Diffuse horizontal irradiance	$\text{W m}^{-2}$
4	Global horizontal irradiance	$\text{W m}^{-2}$
5	Direct horizontal irradiance	$\text{W m}^{-2}$
6	Direct tilted irradiance	$\text{W m}^{-2}$
7	Diffuse tilted irradiance	$\text{W m}^{-2}$
8	Global tilted irradiance	$\text{W m}^{-2}$
9	Experimental direct normal irradiance (with circumsolar)	$\text{W m}^{-2}$
10	Experimental diffuse horizontal irradiance	$\text{W m}^{-2}$
11	Circumsolar irradiance within radiometer field of view	$\text{W m}^{-2}$
12*	Global tilted photon flux per wavelength	$\text{cm}^{-2} \text{s}^{-1} \text{nm}^{-1}$
13	Direct normal photon flux per wavelength	$\text{cm}^{-2} \text{s}^{-1} \text{nm}^{-1}$
14	Diffuse horizontal photon flux per wavelength	$\text{cm}^{-2} \text{s}^{-1} \text{nm}^{-1}$
15	Rayleigh transmittance	—
16	Ozone transmittance	—
17	Transmittance from all trace gases	—
18	Water vapor transmittance	—
19	Mixed gas transmittance	—
20	Aerosol transmittance	—
21	Beam radiation transmittance	—
22	Rayleigh optical thickness	—
23	Ozone optical thickness	—
24	Optical thickness from all trace gases	—
25	Water vapor optical thickness	—
26	Mixed gas optical thickness	—
27	Aerosol optical thickness	—
28	Aerosol single scattering albedo	—
29	Aerosol asymmetry factor	—
30	Zonal surface reflectance	—
31	Local ground reflectance	—
32	Atmospheric reflectance	—
33*	Global foreground reflected irradiance on tilted surface	$\text{W m}^{-2}$
34*	Upward hemispheric ground-reflected irradiance	$\text{W m}^{-2}$
35*	Global horizontal photosynthetic photon flux	$\mu\text{mol m}^{-2} \text{s}^{-1} \text{nm}^{-1}$
36*	Direct normal photosynthetic photon flux	$\mu\text{mol m}^{-2} \text{s}^{-1} \text{nm}^{-1}$
37*	Diffuse horizontal photosynthetic photon flux	$\mu\text{mol m}^{-2} \text{s}^{-1} \text{nm}^{-1}$
38*	Global tilted photosynthetic photon flux	$\mu\text{mol m}^{-2} \text{s}^{-1} \text{nm}^{-1}$
39*	Spectral photonic energy	eV
40*	Global horizontal photon flux per eV	$\text{cm}^{-2} \text{s}^{-1} \text{eV}^{-1}$
41*	Direct normal photon flux per eV	$\text{cm}^{-2} \text{s}^{-1} \text{eV}^{-1}$
42*	Diffuse horizontal photon flux per eV	$\text{cm}^{-2} \text{s}^{-1} \text{eV}^{-1}$
43*	Global tilted photon flux per eV	$\text{cm}^{-2} \text{s}^{-1} \text{eV}^{-1}$

\* New (or modified for #12) in this version

Changes in this version are:

- Output #12 is now for global tilted (rather than global horizontal) photon flux
- Outputs #33–43 are *new*.

The *trace gases* are: BrO\*, CH<sub>2</sub>O\*, ClNO<sub>3</sub>\*, HNO<sub>2</sub>\*, HNO<sub>3</sub>\*, NH<sub>3</sub>, NO, NO<sub>2</sub>, NO<sub>3</sub>\*, SO<sub>2</sub>\*. The *mixed gases* are: CH<sub>4</sub>, CO, CO<sub>2</sub>, N<sub>2</sub>, N<sub>2</sub>O, O<sub>2</sub>, and O<sub>4</sub>\*. An asterisk indicates a gas that is not considered, or only partially considered, in MODTRAN4.

### **CARD 13**: **ICIRC**

**ICIRC** is an option controlling the calculation of circumsolar radiation, which is useful when simulating any type of radiometer (spectral or broadband) equipped with a collimator.

**ICIRC** = 0 bypasses these calculations.

**ICIRC** = 1 indicates that a typical radiometer needs to be simulated. The geometry of its collimator must then be defined on Card 13a.

#### **CARD 13a** (if **ICIRC** = 1): **SLOPE**, **APERT**, **LIMIT**

**SLOPE**: Slope angle (half cone) of the simulated radiometer, between 0.1 and 10 deg.

**APERT**: Half aperture (or “opening”) angle of the simulated radiometer (deg.), between 0.1 and 10 deg.

**LIMIT**: Limit angle (half cone) of the simulated radiometer, between 0.1 and 10 deg.

These half angles fully define the geometry of the simulated radiometer and are bound by the condition: **SLOPE** < **APERT** < **LIMIT**.

If **SLOPE** or **LIMIT** is set to 0.0, the missing value will be calculated by the program.

If **SLOPE** and **LIMIT** are set to 0.0, the penumbra function will be set to 1.0 (an average geometry is thus considered).

If **APERT** is unknown, it should be set to 0.0; the penumbra function will be calculated transparently from **SLOPE** and **LIMIT** only.

Precise values for these quantities are provided in Table 1 of (Gueymard, 1998), reproduced below, in the case of the most widely used pyrheliometers. For instance, **SLOPE** = 1.78 deg., **APERT** = 2.91 deg., and **LIMIT** = 4.03 deg. for the Eppley NIP instrument. **APERT** and **LIMIT** are rarely known for spectroradiometers.

The precise definition of **SLOPE**, **APERT**, **LIMIT** is illustrated in the figure below, where **SLOPE** is noted  $\epsilon_S$ , **APERT** is noted  $\epsilon_A$  and **LIMIT** is noted  $\epsilon_L$ .

Make & model	Slope	Opening	Limit
Eppley NIP	1.78	2.91	4.03
Eppley H-F	0.804	2.5	4.19
Kipp & Zonen Linke-Feussner	1.0	5.08	9.11
Kipp & Zonen CH1	1.0	2.5	4.0
Abbott silver disk	0.8	2.9	4.9

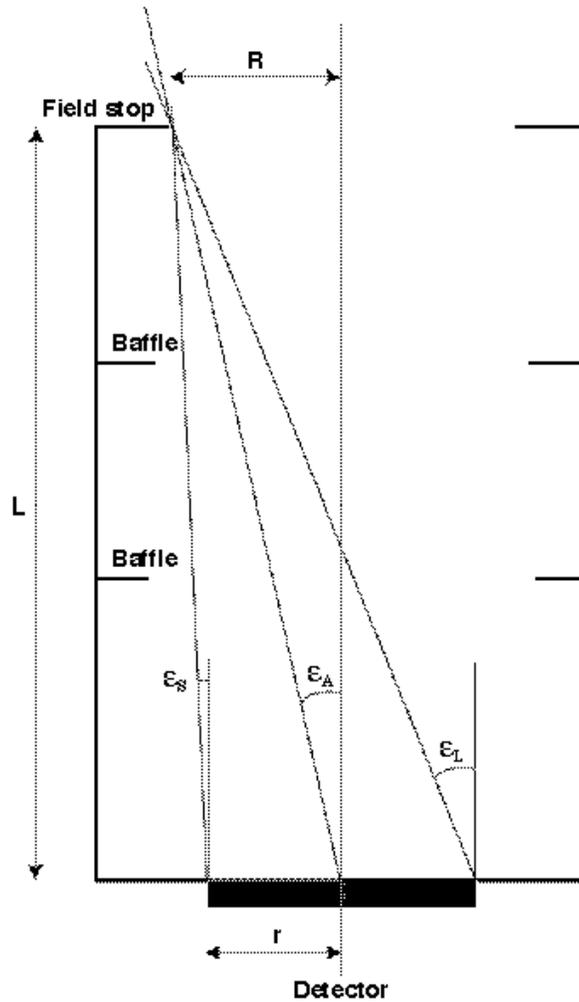


Fig.1 Geometry of a collimated radiometer.

**CARD 14**: **ISCAN**

**ISCAN**: Option for using the scanning/smoothing virtual filter of the postprocessor. The smoothed results are output on a spreadsheet-ready file, File 18 ('smarts295.scn.txt'). This postprocessor is activated if **ISCAN** = 1, not if **ISCAN** = 0. Card 14a is read if **ISCAN** = 1.

**CARD 14a** (if **ISCAN** = 1): **IFILT**, **WV1**, **WV2**, **STEP**, **FWHM**

**IFILT**: Option for the transmittance shape of the radiometer's optics. Select **IFILT** = 0 for a triangular shape; **IFILT** = 1 for a Gaussian (bell) shape.

**WV1**: Min wavelength (nm) to output the smoothed results.

**WV2**: Max wavelength (nm) to output the smoothed results.

Example: **WV1** = 320.5, **WV2** = 1100.

To avoid transitional problems near these limits and the main simulation limits defined on Card 11, the following rules must be followed:

**WV1** > **WLMN**+**FWHM**

**WV2** < **WLMX**-**FWHM**

**WV2**-**WV1** > 2\***FWHM**.

**STEP:** Interval (nm) at which the smoothed irradiance results will be printed; e.g., **STEP** = 2.5.

**FWHM:** Full Width at Half Maximum, i.e., characteristic bandwidth of the filter transmittance or radiometer spectral response chosen to smooth the output spectral data; e.g., **FWHM** = 6.15.

★ **CARD 15: ILLUM**

**ILLUM:** Option for illuminance, luminous efficacy and photosynthetically active radiation (PAR) calculations. These calculations take place if **ILLUM** = -1, 1, -2 or 2, and are bypassed if **ILLUM** = 0. With **ILLUM** = -1 or 1, illuminance calculations are based on the CIE photopic curve (or V $\lambda$  curve) of 1924, as supplied in File 'VLambda.dat'. With **ILLUM** = -2 or 2, the same calculations are done but the revised CIE photopic curve of 1988 is rather used (from File 'VMLambda.dat'). Note that selecting **ILLUM** = 1 or -1 will override **WLMN** and **WLMX** (see Card 11) so that calculations are done between at least 360 and 830 nm.

Moreover, if **ILLUM** = 1 or 2, luminous efficacy calculations are added to the illuminance calculations. This overrides the values of **WLMN** and **WLMX** on Card 11, and replaces them by 280 and 4000, respectively.

*New:* Broadband PAR calculations are performed whenever **ILLUM**  $\neq$  0. (Spectral PAR calculations are *always* performed—see outputs corresponding to **IOUT** = 35–38 on Card 12c.) The two series of broadband results that are provided for the 400–700 nm spectral range are the photosynthetic irradiance ( $\text{W m}^{-2}$ ) and the photosynthetic photon flux density ( $\mu\text{mol m}^{-2} \text{s}^{-1}$ ).

**CARD 16: IUUV**

**IUV:** Option for special broadband UV calculations. Select **IUV** = 0 for no special UV calculation, **IUV** = 1 to initiate such calculations. These include UVA, UVB, UV index, and different action weighted irradiances of interest in photobiology.

Note that **IUV** = 1 overrides **WLMN** and **WLMX** so that calculations are done between at least 280 and 400 nm. The spectral results are also printed between at least 280 and 400 nm, irrespective of the **IPRT**, **WPMN**, and **WPMX** values.

**CARD 17: IMASS**

**IMASS:** Option for solar position and air mass calculations. Set **IMASS** to:

0, if inputs are to be **ZENIT**, **AZIM** on Card 17a

1, if inputs are to be **ELEV**, **AZIM** on Card 17a

2, if input is to be **AMASS** on Card 17a

3, if inputs are to be **YEAR**, **MONTH**, **DAY**, **HOUR**, **LATIT**, **LONGIT**, **ZONE** on Card 17a

4, if inputs are to be **MONTH**, **LATIT**, **DSTEP** on Card 17a (for a *daily* calculation).

**CAUTION:** The option **IMASS** = 2 does not completely define the sun's position; therefore, the sun's azimuth is defaulted to 180.0 (south facing). If tilted irradiance calculations are necessary (**ITILT** = 1), it is better avoiding the **IMASS** = 2 option. However, a tracking surface can be simulated with this option without problem.

CARD 17a (if **IMASS** = 0): **ZENIT, AZIM**

**ZENIT:** Apparent solar zenith angle (0 to 90 decimal deg.), i.e., true astronomical zenith angle MINUS refraction correction.

**AZIM:** Solar azimuth (0 to 360 decimal deg.), counted clockwise from North (0.0) toward West (270.0).

Note: **AZIM** is only used to calculate radiation on a tilted plane. If such calculation is not relevant, any value (e.g., 0.0) can be input for this variable.

CARD 17a (if **IMASS** = 1): **ELEV, AZIM**

**ELEV:** Solar elevation (0 to 90 decimal deg.), i.e., true astronomical elevation PLUS refraction correction.

**AZIM:** Solar azimuth (0 to 360 decimal deg.), counted clockwise from North (0.0) toward West (270.0).

Note: **AZIM** is only used to calculate radiation on a tilted plane. If such calculation is not relevant, any value (e.g., 0.0) can be input for this variable.

CARD 17a (if **IMASS** = 2): **AMASS**

**AMASS:** Relative (i.e., non pressure-corrected) air mass, or Rayleigh optical mass (must be between 1.0 and 38.2),

CARD 17a (if **IMASS** = 3): **YEAR, MONTH, DAY, HOUR, LATIT, LONGIT, ZONE**

**YEAR:** A four-digit integer, e.g., 2002.

**MONTH:** Any integer between 1 and 12.

**DAY:** Day of the month (1–31).

**HOUR:** Local Standard Time (LST) in decimal hour (CAUTION: not to be confused with Local Apparent Time, Daylight Saving Time, or Universal Time).

**LATIT:** Site latitude (decimal degrees, positive North, negative South); e.g., -17.533 for Papeete, Tahiti.

**LONGIT:** Site longitude (decimal deg.). Counted positive East of Greenwich, negative West of Greenwich; e.g., -104.667 for Denver's International Airport, Colorado.

**ZONE:** International Time Zone relative to Greenwich, with the same sign convention as **LONGIT**; e.g., **ZONE** = -5 for Eastern Standard Time (North America), **ZONE** = 2 for Greece.

The Local Apparent Time (LAT) corresponding to the input's Local Standard Time (LST) is calculated and printed to the main output file ('smarts295.out.txt', or "File 16"). However, for some applications it might be necessary to relate to LAT rather than Local Standard Time (LST) as used here. Predicting irradiances exactly at solar noon (i.e., 12:00 LAT) is a typical example. Such a calculation is possible, but requires a preliminary run, where **HOUR** would be set to 12. From the LAT value that is printed on File 16, it is easy to obtain the difference between LAT and LST. The final run would be done after adjusting **HOUR** for this difference.

When **IMASS** = 3 the actual sun-earth distance is calculated from the supplied date and overwrites the **SUNCOR** value from Card 11.

CARD 17a (if **IMASS** = 4): **MONTH**, **LATIT**, **DSTEP**

**MONTH** : Any integer between 1 and 12.

**LATIT**: Site latitude (decimal degrees, positive North, negative South); e.g., -17.533 for Papeete, Tahiti.

**DSTEP**: Time interval (min) for the numerical integration of irradiation when a daily calculation is requested. **DSTEP** must be a real number and divisor of 60, hence this (non-exhaustive) list of possible values of **DSTEP**: 1, 2, 3, 4, 5, 6, 7.5, 10, 12, 15, 20, 30, 60.

**DSTEP** ≤ 6 is recommended for better accuracy, whereas **DSTEP** ≥ 15 is recommended for speedier results. Tests have indicated that no real improvement in accuracy is obtained when **DSTEP** < 5.

Because of the large quantity of calculations involved with this daily option, only *broadband* results are output, irrespective of the value of **IPRT** on Card 12.

**IMPORTANT NOTES:**

- As many 17a cards can be piled up as desired; the program will perform the spectral calculations sequentially. All other variables remain constant during these successive runs.
- It is recommended to insert a blank line after the last input card, or that card might not be read!

## 7. INPUT VARIABLES LIST

For cross-reference purposes, all possible input variables are listed below in alphabetical order with the Card number on which they appear.

Variable	Card #	Variable	Card #	Variable	Card #	Variable	Card #
<b>AbO3</b>	5a	<b>COMNT</b>	1	<b>IOTOT</b>	12b	<b>SOLARC</b>	11
<b>AEROS</b>	8	<b>DAY</b>	17a	<b>IOUT</b>	12c	<b>SPR</b>	2a
<b>ALPHA1</b>	8a	<b>DSTEP</b>	17a	<b>IPRT</b>	12	<b>STEP</b>	14a
<b>ALPHA2</b>	8a	<b>ELEV</b>	17a	<b>ISCAN</b>	14	<b>SUNCOR</b>	11
<b>ALTIT</b>	2a	<b>FWHM</b>	14a	<b>ISPCTR</b>	7a	<b>TAIR</b>	3a
<b>AMASS</b>	17a	<b>GG</b>	8a	<b>ISPR</b>	2	<b>TAU5</b>	9a
<b>ApCH2O</b>	6b	<b>HEIGHT</b>	2a	<b>ITILT</b>	10b	<b>TAU550</b>	9a
<b>ApCH4</b>	6b	<b>HOUR</b>	17a	<b>ITURB</b>	9	<b>TDAY</b>	3a
<b>ApCO</b>	6b	<b>IALBDG</b>	10c	<b>IUV</b>	16	<b>TILT</b>	10c
<b>APERT</b>	13a	<b>IALBDX</b>	10	<b>LATIT</b>	2a, 17a	<b>VISI</b>	9a
<b>APHNO2</b>	6b	<b>IALT</b>	5a	<b>LIMIT</b>	13a	<b>W</b>	4a
<b>APHNO3</b>	6b	<b>IATMOS</b>	3	<b>LONGIT</b>	17a	<b>WAZIM</b>	10c
<b>ApNO</b>	6b	<b>ICIRC</b>	13	<b>MONTH</b>	17a	<b>WLMN</b>	11
<b>ApNO2</b>	6b	<b>IFILT</b>	14a	<b>OMEGL</b>	8a	<b>WLMX</b>	11
<b>ApNO3</b>	6b	<b>IGAS</b>	6	<b>qCO2</b>	7	<b>WPMN</b>	12a
<b>ApO3</b>	6b	<b>IH2O</b>	4	<b>RANGE</b>	9a	<b>WPMX</b>	12a
<b>ApSO2</b>	6b	<b>ILLUM</b>	15	<b>RH</b>	3a	<b>WV1</b>	14a
<b>ATMOS</b>	3a	<b>ILOAD</b>	6a	<b>RHOG</b>	10d	<b>WV2</b>	14a
<b>AZIM</b>	17a	<b>IMASS</b>	17	<b>RHOX</b>	10a	<b>YEAR</b>	17a
<b>BCHUEP</b>	9a	<b>INTVL</b>	12a	<b>SEASON</b>	3a	<b>ZENIT</b>	17a
<b>BETA</b>	9a	<b>IO3</b>	5	<b>SLOPE</b>	13a	<b>ZONE</b>	17a

## 8. USER-DEFINED DATA FILES

Albedo data in File 19 ('Albedo.dat', located in the Albedo subfolder) are user modifiable but need to follow a specific format. This file must contain two columns and any number of rows up to a maximum of 3000 (up from 2002 in previous versions), and must be saved as TEXT. These two columns are respectively for: Wavelength ( $\mu\text{m}$ ), Reflectance (0.0 to 1.0). A hard return is needed at the end of the last row, otherwise the file might be read incorrectly.

Similarly, the extraterrestrial spectrum data in File 15 ('Spctrm\_U.dat', located in the Solar subfolder) are now user modifiable. They need to respect the *same format and units* as all other similar files ('Spctrm\_n.dat'). No interpolation or extrapolation is performed on the spectrum, so the irradiance values may be changed but not their wavelength attribution. This file must therefore contain 2002 spectral values from 280 to 4000 nm, and must terminate with a hard return.

## 9. OUTPUT FILES

The OUTPUT to File 16 (e.g., 'smarts295.out.txt') is well documented and, thus, self-explanatory. It gives an echo of the input data, as well as a series of results from the spectral and broadband calculations. The content of this output file is fixed.

The OUTPUT to File 17 (e.g., 'smarts295.ext.txt') is formatted to create a spreadsheet-formatted file, the content of which can be tailored to the user's specific needs, according to:

- column 1: Wavelength (nm)
- columns 2 to last (i.e., **IOTOT** + 1): depending on user's choice of 43 possible variables (see **IOUT** on Card 12c).

Columns of data are separated by a space and have a heading of 24 characters each.

The OUTPUT to File 18 (e.g., 'smarts295.scn.txt') is also formatted to create a spreadsheet-formatted file, but its content is fixed, according to:

- column 1: WVLGTH [Wavelength (nm)]
- column 2: ET\_SPCTRUM [Extraterrestrial Irradiance ( $\text{W}/\text{m}^2$ )]
- column 3: BEAM\_NORM [True Direct Beam Irradiance at Normal Incidence ( $\text{W}/\text{m}^2$ )]
- column 4: BEAM\_NORM+ [Experimental Beam Irradiance at Normal Incidence ( $\text{W}/\text{m}^2$ )]
- column 5: GLOB\_HORIZ [Global Horizontal Irradiance ( $\text{W}/\text{m}^2$ )]
- column 6: GLOBL\_TILT [Global Tilted Irradiance ( $\text{W}/\text{m}^2$ )].

Columns of data are separated by a space. A two-line header recapitulates the instrumental characteristics selected.

Output files 17 and 18 can be read directly (in TEXT format) by a spreadsheet program such as Microsoft Excel, or by plotting software such as Synergy's Kaleidagraph. Select a space separator in the Open or Import window if format recognition is not automatic.

## 10. TROUBLESHOOTING, WARNING & ERROR MESSAGES

If the code crashes, does not stop properly, or only provides an echo of the input, it is highly probable that the input file has not been prepared correctly. A missing line, a missing input on a line, an unphysical or unreadable input value, or a misplaced line are typical culprits. Double-checking the input file is the best way to correct the problem.

A run-time error happens any time the output files that have been created in a previous run are still in the same directory and have not been renamed. Deleting or renaming them will simply solve the problem.

More subtle problems may surface if the numerical values of some inputs are not appropriate. In the most minor cases, the code will run anyway, but will output WARNING messages to signal the problem and possibly inform the user of any interpretation or extrapolation it had to do. In more severe cases, an ERROR message is issued and the run is aborted. Most of these messages are relatively self-explanatory but they are all listed and discussed below for further reference.

### WARNING messages

#1 The calculated ozone temperature ... was below the most probable minimum of ... for this altitude. The latter value has been used for optimum results. Suggestion: double check the daily temperature on input Card 3a.

*The effective ozone temperature is now calculated from the daily average temperature at the altitude of the simulated receiver. A good estimate of the latter is therefore necessary.*

#2 The calculated ozone temperature ... was above the most probable maximum of ... for this altitude. The latter value has been used for optimum results. Suggestion: double check the daily temperature on input Card 3a.

*Symmetrical to #1 just above.*

#3 The ozone columnar amount, ... atm-cm, is outside the most probable limits of ... and ... for this altitude. This may produce inconsistent results. Suggestion: double check the values of **IALT** and **AbO3** on input Card 5a.

*Consistency between **IALT** and **AbO3** is important, particularly for a high-flying object. In such a case, either the ground value of **AbO3** is used and **IALT** set to 1, or the local value of **AbO3** is used and **IALT** set to 0. See Card 5a for discussion.*

#4 Pressure cannot be < 0.00041 mb and has been increased to this value.

*See Card 2.*

#5 Precipitable water was not provided and no reference atmosphere was specified! **USSA** conditions have been used here.

*See Card 4.*

#6 The ozone amount was not provided and no reference atmosphere was specified! **USSA** conditions have been used here.

*See Card 5.*

#7 The aerosol type has been changed to "**S&F\_TROPO**" because the height above ground is > 2 km.

*Only the aerosols in the well-mixed layer (assumed to have a fixed thickness of 2 km, independent from the ground altitude above sea level) are allowed to have very variable physical and optical characteristics. Above this layer, all aerosols are considered obeying to the "tropospheric" model. Hence, the aerosol column above an object flying at more than 2 km above ground is always forced to respond to the tropospheric model.*

#8 The aerosol optical depth at 550 nm, ... is outside the most probable limits of ... and ... for this altitude, assuming a slight background amount of volcanic aerosols. This may produce inconsistent results. Suggestion: double check the value of your turbidity input on Card 9a.

*This message is generated if the geometric altitude of the simulated object above sea level (i.e., **HEIGHT + ALTIT**) is between 15 and 22 km, where more volcanic aerosols than normal (background) may exist. In practice, it may be difficult to estimate the aerosol abundance above a high-flying object. The typical minimum and maximum limits provided in this message may be used as a guideline.*

#9 The aerosol optical depth at 550 nm, ... is outside the most probable limits of ... and ... for this altitude. This may produce inconsistent results. Suggestion: double check the value of your turbidity input on Card 9a.

*Same as message #8 just above, but for altitudes below 15 km or above 22 km. No volcanic aerosol is normally present at these altitudes.*

#10 The values of both **APERT** and **SLOPE** or **LIMIT** for the circumsolar correction are incorrectly less than or equal to 0. This calculation is therefore skipped!

*The collimator's geometry must be better defined... See Card 13.*

#11 The radiometer's **SLOPE** and **LIMIT** angles are not provided. Circumsolar calculations will therefore be performed for an average geometry corresponding to the **APERTURE** angle.

*See Card 13. When the geometry of the collimator tube is not known entirely but its aperture is known (which is the most important variable and the most likely to be known), circumsolar calculations are performed without significant loss of accuracy.*

#12 Circumsolar calculations cannot be done for this geometry. All half angles must be < 10 deg.

*See Card 13a.*

#13 Ground reflectance data for ... extend only from ... to ...  $\mu\text{m}$ , whereas the wavelength limits for this run are ... and ...  $\mu\text{m}$ . Consequently, reflectance is fixed at ... below ...  $\mu\text{m}$  and at ... above ...  $\mu\text{m}$ .

*This message is very frequent. It is displayed in nearly all cases where an albedo file is selected rather than a fixed value. All these files have been obtained from measurements, whose spectral range is relatively limited. In particular, measurements below 300 nm are*

nearly impossible due to the weakness of the signal. Three files contain data for the full simulation range (280–4000 nm) because extrapolation has been used to fill the missing data: #8 (SOIL), #37 (DRY SOIL) and #38 (LITE SOIL). Furthermore, calculations for **IALBDX** =2 or **IALBDG** = 2 (SEA or LAKE) are done for the full spectral range. If the simple extrapolation scheme used at run time and described in the message is not appropriate, the use of a custom-built ALBEDO.DAT file is recommended. See Card 10 for more details.

#14 Lower limit for scans needs to be  $> \mathbf{WV1} + 0.5*\mathbf{FWHM}$ !

*This is in fact a non-fatal error more than a warning: specifying a too large spectral range for the scan bypasses the smoothing post-processor, but all other calculations and results are not affected. See Card 14a.*

#15 Lower limit for scans is not  $> \mathbf{WV1} + \mathbf{FWHM}$ . This will reduce accuracy in the results for the first wavelengths.

*The post-processor can operate but the accuracy at the shorter wavelengths is not guaranteed. See Card 14a.*

#16 Upper limit for scans needs to be  $< \mathbf{WV2} - 0.5*\mathbf{FWHM}$ !

*Symmetrical to message #14 above.*

#17 Upper limit for scans is not  $< \mathbf{WV2} - \mathbf{FWHM}$ . This will reduce accuracy in the results for the last wavelengths.

*Symmetrical to message #15 above.*

#18 Parameter **INTVL** on Card 12a is too low and will be defaulted to 0.5 nm.

*Spectral outputs cannot be reported at a spectral step less than the calculation step.*

#19 Error in albedo file #..: Number of data rows is ... but should be  $\leq 3000$ .

*High-resolution albedo data files cannot be used! This test prevents the inadvertent corruption of data files from the library, and the construction of a too long ALBEDO.DAT file by the user. See Section 8.*

#20 Receiver is at more than 6 km above sea level, hence the aerosol optical depth has been fixed to a default value, dependent only on altitude.

*Whenever the elevation above sea level,  $z$ , is more than 6 km, **TAU550** is calculated from*

$$\mathbf{TAU550} = \exp(-3.2755-0.15078 z)$$

*and the turbidity input from Card 9a is ignored.*

#21 Receiver is at more than 0.5 km above ground, hence the calculation of the reflected irradiance from the ground to the tilted plane is not accurate.

*The albedo specified on Card 10c is for the tilted surface foreground, whose area may be relatively small. The higher the Receiver is above ground, the lesser the effect of this foreground is on the reflected irradiance to the receiver.*

## **ERROR messages**

#1 The altitude cannot be > 100 km! RUN ABORTED!

*This corresponds to the assumed outer limit of the atmosphere... See Card 2a.*

#2 The value selected or calculated for precipitable water, **W**, is ..., which is above the allowed maximum value of 12 cm. RUN ABORTED!

*This message is displayed if an incorrect value is entered on Card 4a, or if extremely hot and humid conditions are entered on Card 3a.*

#3 Input value for **ITURB** on Card 9 is > 5. Please specify a smaller value. RUN ABORTED!

***ITURB** should be between 0 and 5. See Card 9.*

#4 Input value for turbidity is too large (**TAU550** = ...). Please specify a smaller value. RUN ABORTED!

*The maximum allowed value of **TAU550** is 5.0.*

#5 Input value for Meteorological Range is < 1 km. Please specify a larger value. RUN ABORTED!

*This message is displayed if a too low value is entered on Card 9a. The minimum value for **RANGE** is 1 km, and 0.77 km for **VISI**.*

#6 Sun is too low for the specified date.

[This condition must be fulfilled: |declination - latitude| < 85 deg.

The input data for this day are such that |declination - latitude| = ... deg.]

RUN ABORTED!

*Daily calculations can only be done if the sun is high enough during the average day of the month.*

#7 Value of **ZENIT** = ... is > 90 deg. RUN ABORTED!

*Calculations can only be done during sunup hours. See Card 17a.*

#8 Value of **AMASS** = ... is > 38.2. RUN ABORTED!

*Calculations can only be done during sunup hours. See Card 17a.*

## 11. SAMPLE RUNS AND PRINTOUT

Sample runs are provided and reside in separate *Example* folders/directories. Each one is documented with a ReadMe file. The input and output files are provided so that the user can test if his/her results are in complete agreement with these sample runs.

The printouts of files ‘SMARTS295\_INP.txt’ and ‘SMARTS295\_OUT.txt’ corresponding to the particular case described in *Example 6* of this package appear in the Appendix for reference purposes.

### **IMPORTANT NOTE:**

Example 6 allows to *approximate* the most recent reference spectra at air mass 1.5 adopted in 2003 by ASTM under standard G173-03, which was based on version 2.9.2 of this code.

## 12. UV ACTION-WEIGHTED IRRADIANCES

Extra UV calculations are invoked when the option **IUV** is set to 1. For each wavelength, the global horizontal irradiance is then convolved with a specific biological action spectrum. When summed over all UV wavelengths, this provides an action-weighted irradiance, which can be of interest in different photobiological applications.

Fourteen such action-weighted irradiances are calculated by the program, as detailed below.

- Erythema irradiance, according to five different studies. The most widely used erythema spectrum is that of (McKinley and Diffey, 1987), also known as the CIE erythema spectrum. Separate results using older erythema spectra are also reported by the program for comparative purposes. These include the fit proposed by (Green and Mo, 1975) from the original data of (Coblentz and Stair, 1934), the Diffey erythema spectrum (Diffey, 1982) modified by (Björn, 1989), the equation of (Green *et al.*, 1974) derived from the data of (Komhyr and Machta, 1973), and the equation of (Björn, 1989) obtained by fitting the data of (Parrish *et al.*, 1982).
- The biological action curve of (Caldwell, 1971) as fitted by (Green *et al.*, 1974).
- The ACGIH safety spectrum (ACGIH, 1978) as fitted by (Wester, 1981, 1984).
- The photosynthesis inhibition spectrum and the polychromatic action spectrum for higher plants, according to (Caldwell *et al.*, 1986).
- The plant DNA spectrum fit of (Green and Mo, 1975) from data of (Setlow, 1974).
- The systematic immunosuppression spectrum of (De Fabo *et al.*, 1990).
- The skin carcinogenesis spectra for humans and mice of (de Gruijl and Van der Leun, 1994).
- The spectrum for DNA to protein crosslinks by (Peak and Peak, 1982).

The three latter datasets have been fitted to manageable functions by this author.

Two other results are further obtained from the CIE erythema irradiance. The UV dose in MED/hr (where 1 MED = 210 J/m<sup>2</sup>) is calculated to simulate the output of a Robertson-Berger biometer. Finally, the UV index—which is now used regularly in many meteorological reports and forecasts for public protection purposes—is obtained as 40 times the erythema irradiance. Note that previous versions of SMARTS have been used in different countries to predict the UV index (Koepke *et al.*, 1998; Lehmann, 2001).

### 13. REVISED EXTRATERRESTRIAL SPECTRUM

A significant revision of the extraterrestrial spectrum is now proposed and recommended. It has been obtained as a synthesis from the most recent sources, using data with the least uncertainty possible and appropriate corrections (Gueymard, 2004). This new spectrum covers the region 0.5 nm to 1000  $\mu\text{m}$ , and integrates to 1366.1  $\text{W}/\text{m}^2$ , the currently accepted value of the solar constant.

Figure 2 shows how the newly proposed spectrum compares to other existing spectra, namely the previous SMARTS spectrum (Gueymard, 2002, unpublished), the newer Kurucz spectrum used in MODTRAN (“newkur”), and the ASTM standard (ASTM, 2000). The Kurucz spectrum integrates to 1368.0  $\text{W}/\text{m}^2$ , whereas the ASTM spectrum integrates to 1366.1  $\text{W}/\text{m}^2$ , like the newly proposed spectrum. Note that the IR part of all these spectra are based on a version or another of the Kurucz spectrum, hence their good agreement there (not shown).

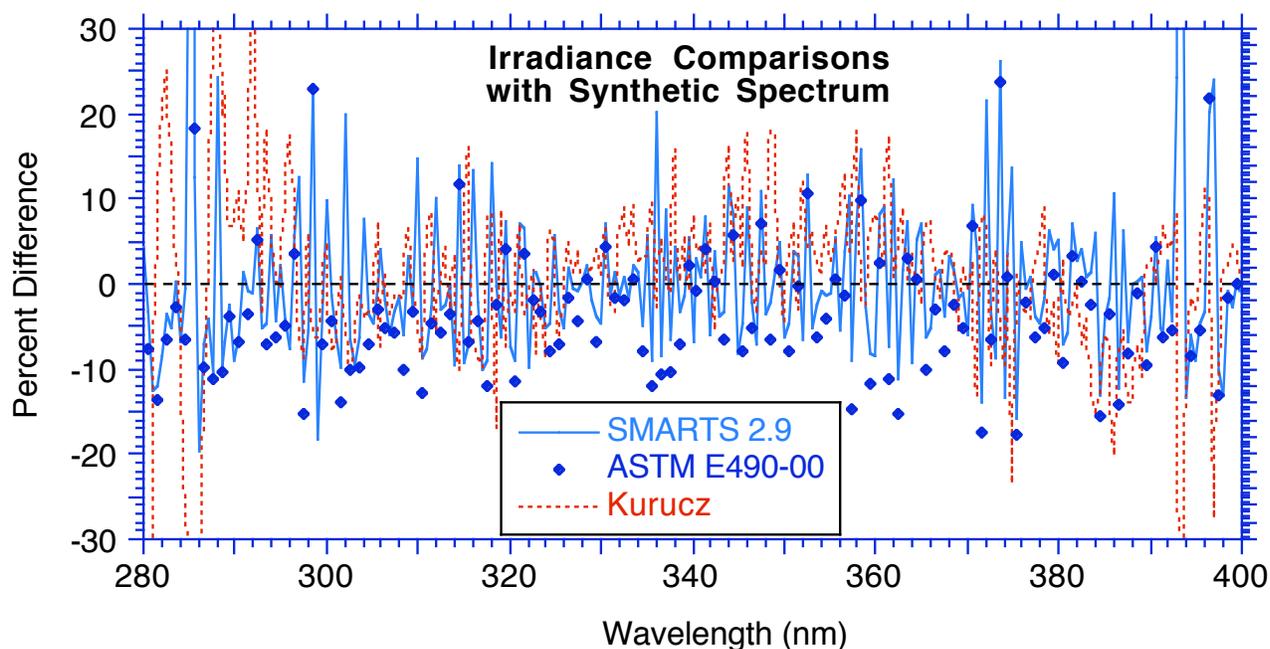


Fig. 2a Wavelength-by-wavelength irradiance difference between some existing spectra and the new default spectrum of SMARTS in the UV region.

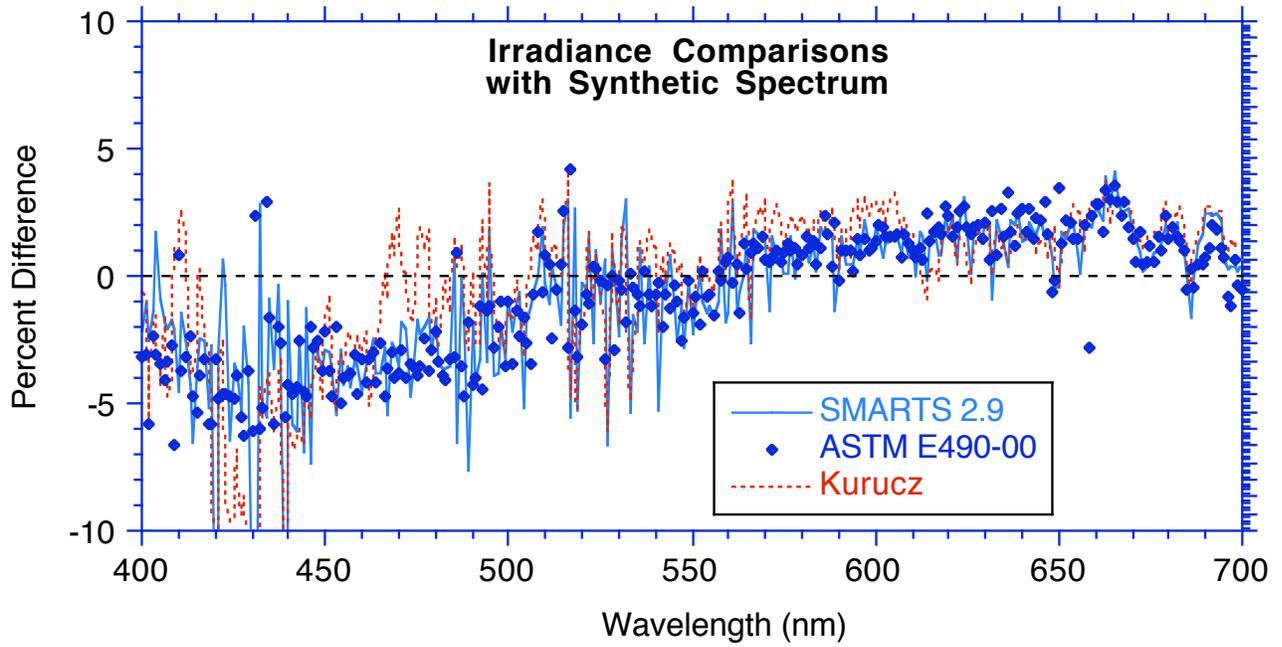


Fig. 2b Wavelength-by-wavelength irradiance difference between some existing spectra and the new default spectrum of SMARTS in the visible region.

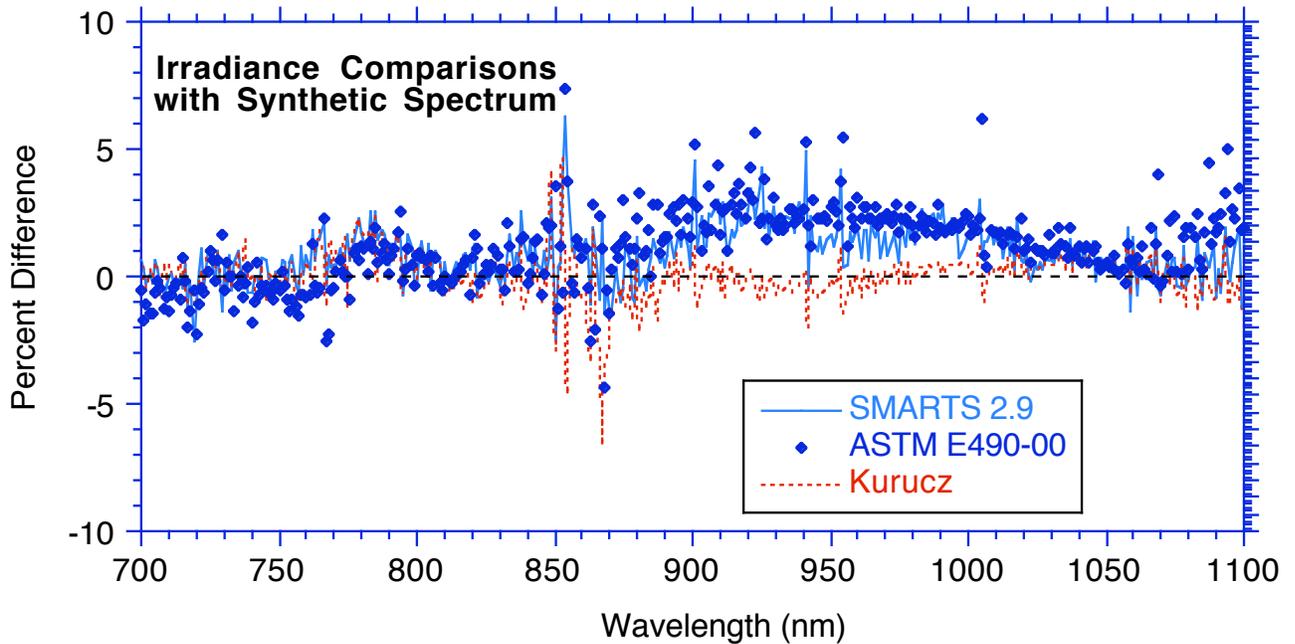


Fig. 2c Wavelength-by-wavelength irradiance difference between some existing spectra and the new default spectrum of SMARTS in the near IR region from 700 to 1100 nm.

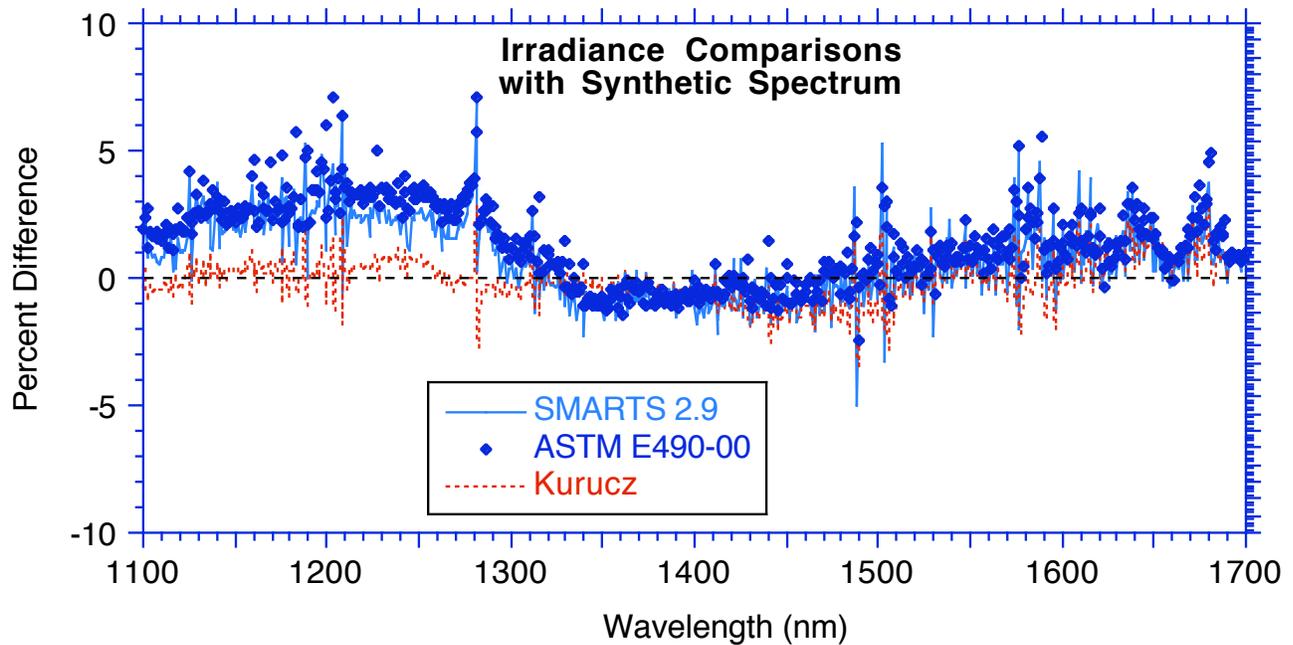


Fig. 2d Wavelength-by-wavelength irradiance difference between some existing spectra and the new default spectrum of SMARTS in the near IR region from 1100 to 1700 nm.

## 14. COMPARISONS WITH MODTRAN

It would be difficult to argue against the statement that the currently pre-eminent—if not *de facto* standard—radiative transfer code in atmospheric sciences is MODTRAN, developed by the Air Force Geophysics Laboratory of Hanscom, MA. The SMARTS algorithms have been revised in this version to improve the agreement between its predictions and those of MODTRAN, version 4.0. Although the algorithms in SMARTS are completely different than those in MODTRAN, both codes have some common ground, described below.

1. The six reference atmospheres used in MODTRAN are part of the library of ten reference atmospheres in SMARTS.
2. The different Shettle & Fenn aerosol models used in MODTRAN are also part of the library of default aerosols in SMARTS. Note, however, that only an approximate fit of the spectral variation of the optical characteristics of these aerosols has been voluntarily used in SMARTS. A notable exception has been made for the Rural Aerosol model, whose optical depth spectral variations have been closely reproduced with a stepwise regression method.
3. Absorption coefficients for some gases have been derived from MODTRAN4 results. This is the case for CH<sub>4</sub>, CO, CO<sub>2</sub>, H<sub>2</sub>O, NH<sub>3</sub>, NO, N<sub>2</sub>, N<sub>2</sub>O over the whole spectrum, and for O<sub>3</sub> and SO<sub>2</sub> in the IR only. In all other cases, cross section data from the recent spectroscopic literature have been used, and temperature correction functions have been considered wherever possible.
4. The optical masses for all extinction processes in SMARTS have been fitted to a common equation from slant column abundances obtained by varying the zenith angle in a series of MODTRAN runs.
5. The six default extraterrestrial spectra offered in MODTRAN are now also available in SMARTS for comparative and compatibility purposes. However, the revised, non-MODTRAN spectrum described in Section 13 is recommended for normal use.

Because MODTRAN4 incorporates many changes and improvements over MODTRAN2, on which the previous versions of SMARTS were based, it is interesting to compare the predictions of SMARTS (versions 2.8 and 2.9) to those of MODTRAN4 for typical atmospheric conditions. Such a comparison is not directly possible because MODTRAN's outputs are in equal steps of wavenumbers (with a minimum step of  $1 \text{ cm}^{-1}$ ), rather than wavelengths. Thus it has been necessary to resample and degrade MODTRAN's outputs (using its maximum resolution) to fit SMARTS's own resolution so that wavelength-by-wavelength correspondence could be achieved. The atmospheric conditions were chosen according to ASTM standard E891-87, reissued as standard G159-98 (ASTM, 1987, 1998) and ISO 9845-1 (ISO, 1992). These same conditions are used in Examples 1 and 3 for the user's benefit.

Figure 3 shows the percent deviation between the direct atmospheric transmittance predicted by the two versions of SMARTS and by MODTRAN. The improvement from version 2.8 to 2.9 is particularly obvious over the whole spectrum. A more detailed comparison between SMARTS 2.9 and MODTRAN 4.0 appears in Fig. 4. Structure in the difference curve is caused by different possible causes: the simplified algorithms used in SMARTS which can affect results in strong absorption bands (e.g., the water vapor bands around 940-nm and 1150-nm), the use of more recent or complete absorption data in this version of SMARTS (e.g., for the UV and visible ozone bands), and the consideration of more absorbing gases by SMARTS. Eight absorbing species now considered in SMARTS are not in MODTRAN yet: BrO,  $\text{CH}_2\text{O}$ ,  $\text{ClONO}_2$ ,  $\text{HNO}_2$ ,  $\text{HNO}_3$ ,  $\text{NO}_3$ ,  $\text{O}_4$ , as well as  $\text{SO}_2$  in the UV. As demonstrated by Fig. 4, the dips in the difference curve are attributable to the additional absorption caused by these gases, particularly  $\text{O}_4$ .

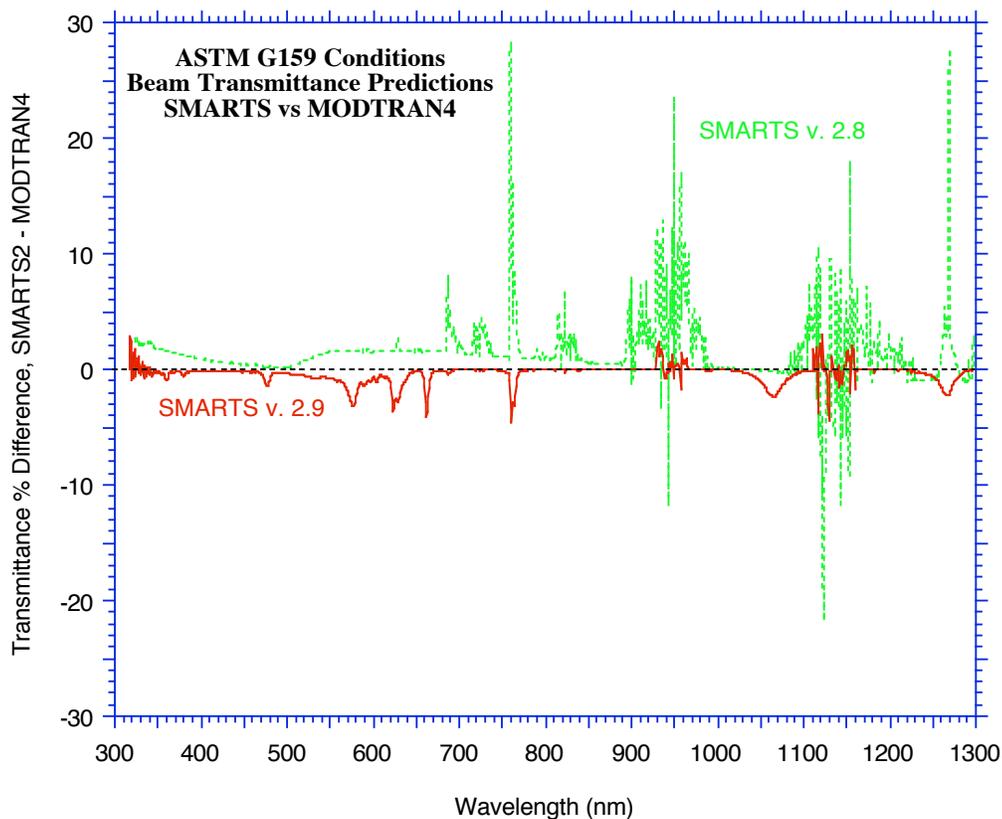


Fig. 3 Percent difference between the direct transmittance predicted by SMARTS, versions 2.8 and 2.9, and MODTRAN, version 4.0, for the same standard conditions.

Figure 5 shows a comparison between the direct irradiance for an air mass 1.5 and standard atmospheric conditions predicted by SMARTS, and the absolute spectral difference (in  $\text{W/m}^2 \text{ nm}$ ) between the irradiance predictions of SMARTS and MODTRAN4. For this comparison, the Cebula/Chance/Kurucz spectrum has been used in both codes.

Finally, the data in Fig. 5 are shown in greater detail in Fig. 6, where the irradiance difference between the predictions of the Monte-Carlo BRITE code (that was originally used to develop the spectra in standards ASTM G159 and ISO 9845-1) and those of MODTRAN, is added for comparative purposes. It can be concluded that the gain in accuracy between BRITE and SMARTS is about an order of magnitude, at least for these particular conditions.

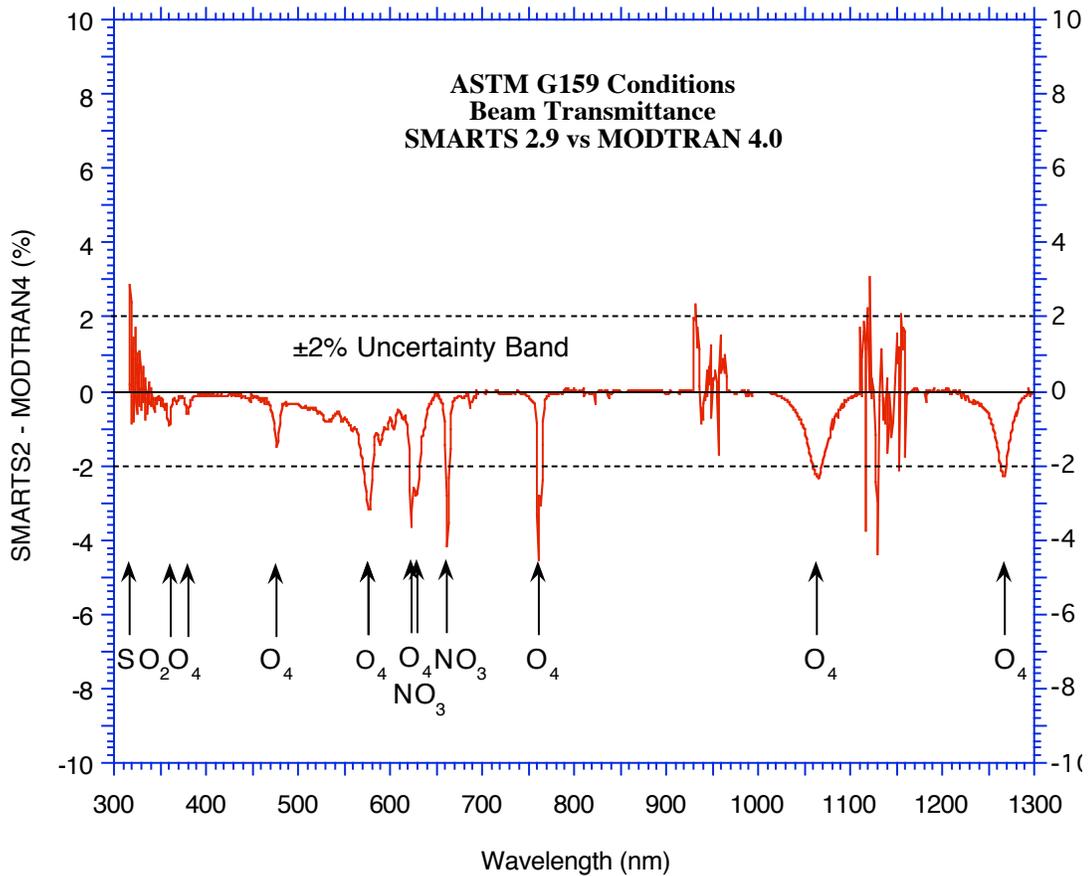


Fig. 4 Percent difference between the direct transmittance predicted by SMARTS 2.9 and MODTRAN 4.0, showing the additional absorption bands (indicated by arrows and the corresponding gases) considered in SMARTS.

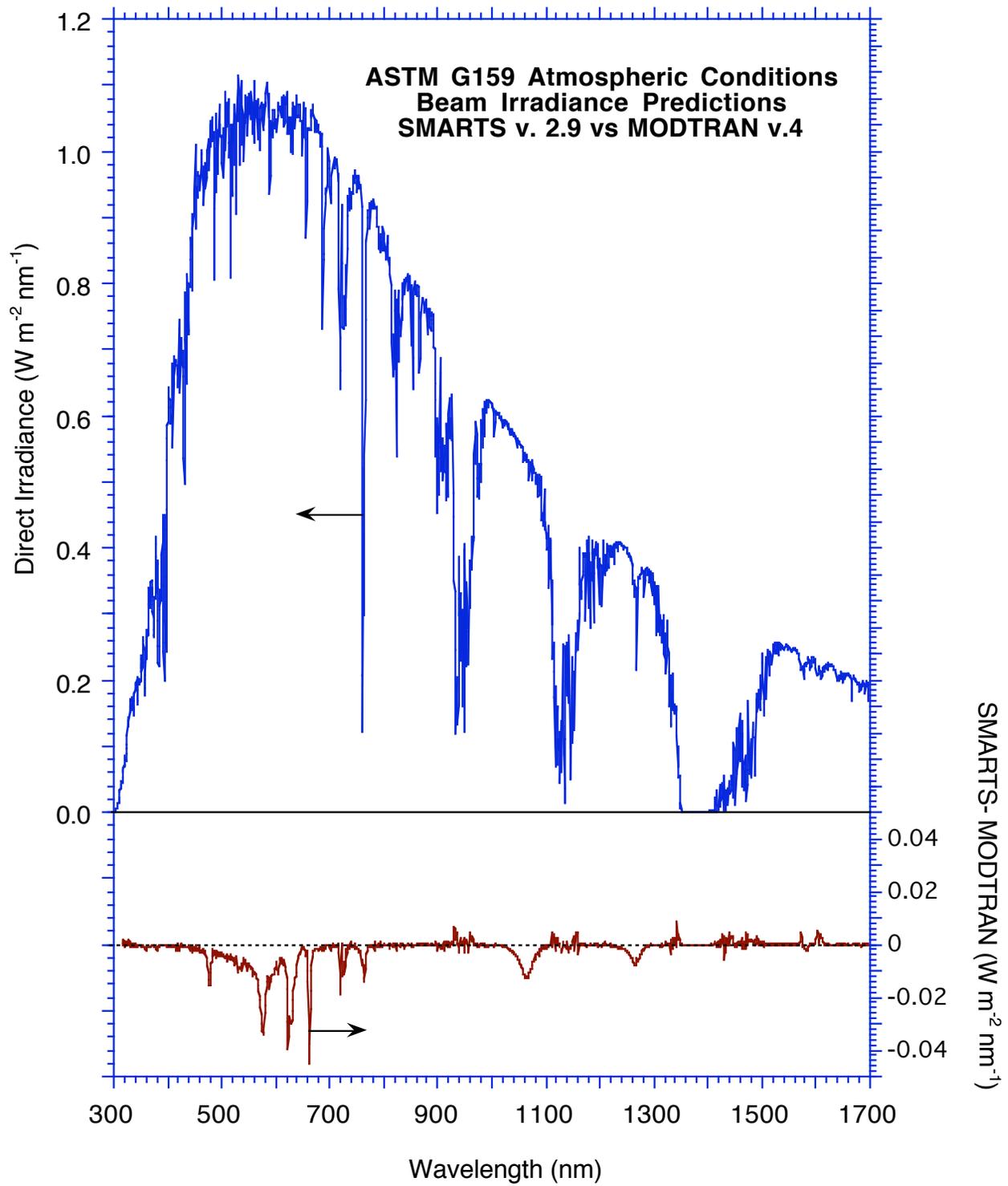


Fig. 5 Direct irradiance at normal incidence predicted by SMARTS (top panel) and its absolute difference with that predicted by MODTRAN 4.0 (bottom panel) for the same standard conditions.

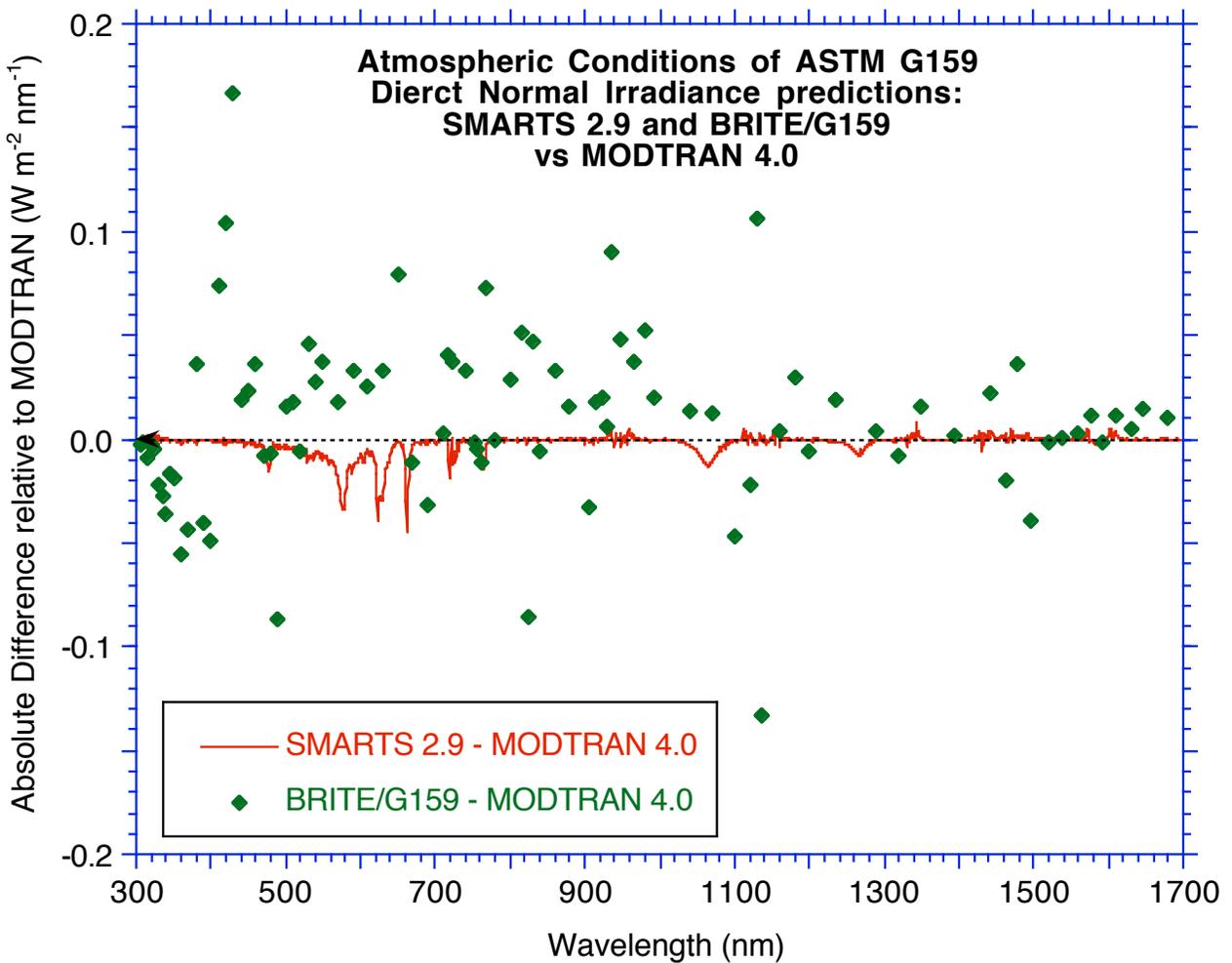


Fig. 6 Absolute difference between the direct irradiance predicted by SMARTS 2.9, BRITE (as per the ASTM G159 standard tabulations), and MODTRAN 4.0.

## 15. APPLICATIONS

Because of its versatility, SMARTS can be used in a large number of applications, covering a broad spectrum of activities. A detailed review is available elsewhere (Gueymard, 2005). One of these applications in particular is worth mentioning here because of its long-term impact. Following the development of SMARTS-based reference spectra (Gueymard et al., 2003), the American Society for Testing and Materials (ASTM) has recently adopted these reference spectra to replace those in the existing G159 standard (mentioned in Section 14). Another reference “high UV” global spectrum has also been standardized. The two new spectra and the new UV spectrum in these standards (G173-03 and G177-03, respectively) are specifically based on version 2.9.2 of the code. It will be kept in a “frozen” state for permanent reference, even if new updates continue to be developed, leading to slightly different results for identical conditions, like in the present case. ASTM also plans to offer version 2.9.2 as an “adjunct standard” on CD-ROM. Please refer to <http://www.astm.org/> and <http://rredc.nrel.gov/solar/models/SMARTS/> for further information.

## 16. SUMMARY OF NEW FEATURES IN VERSION 2.9.x

### *Version 2.9.5*

- *Bug correction*

A bug in all previous versions that affected the calculation of pressure in the southern hemisphere has been corrected. Another bug, that affected versions 2.9, 2.9.1 and early 2.9.2, where a request for more than 24 spectral outputs crashed the program, has been corrected. Another corrected bug is one that affected all previous versions, where incorrect spectral values of direct tilted irradiance were printed on File 17 when a zero tilt (horizontal plane) was defined. The incorrect value that was displayed for the N<sub>2</sub> abundance in the main OUT file has been corrected. Finally, two bugs affecting the illuminance results in versions 2.9 to 2.9.2 was discovered and corrected. The data files VLambda.dat and VMLambda.dat have been modified accordingly.

- *Extraterrestrial spectrum*

It is now possible to use two new synthetic spectra. One is based on the most up-to-date data (Gueymard, 2004), and the other one is interpolated from a standard spectrum (ASTM, 2000). (See Card 7a and Section 13.)

A user-defined extraterrestrial spectrum has been added to the available choices, but its preparation must follow strict guidelines (see Card 7a and Section 8).

- *Aerosol models*

Two new aerosol models have been added: **DESERT\_MIN** (for background desert conditions) and **DESERT\_MAX** (for sand-storm conditions); see Card 8.

- *Turbidity inputs*

A new turbidity input option has been added: the aerosol optical depth at 550 nm, **TAU550**. It is convenient because often reported in satellite-based aerosol datasets, for instance. See Card 9.

A more precise relationship between turbidity and visibility is now used. It depends on season and takes into account the presence of tropospheric aerosols above an altitude of 2 km.

- *Altitude inputs*

An additional input variable has been added to describe the vertical position of the object (e.g., aircraft) under scrutiny: its **HEIGHT** above ground. See Card 2 and other details below.

- *Albedo library*

Twenty-eight files have been added to the library; see Card 10. The maximum number of lines in each user-defined spectral albedo file has been increased to 3000.

- *Irradiance calculations*

The algorithm used to evaluate diffuse irradiance has been streamlined. As a result, irradiance predictions appear to be improved compared to spectral measurements, particularly in the UV.

Calculations are now possible for any ground site or to simulate objects/instruments whose **HEIGHT** above sea level is < 100 km, see Card 2. For sites at more than 6 km above sea level, turbidity is calculated internally.

For flying objects, the columnar amount of absorbing gases aloft, their temperature, and other atmospheric variables are extrapolated from ground-level defaults if necessary. If such values are rather provided by the user, they are checked for consistency as a function of altitude.

Pressure calculations as a function of altitude and latitude have been improved.

More spectral output options are possible (see Card 12c). In particular, various components of photon fluxes and photosynthetic active radiation (PAR) are now calculated. Optionally, broadband PAR energy flux and quantum flux can also be output (see Card 15).

More tests are done on the input data to avoid unphysical situations. The existing Warning and Error messages have been streamlined, and more have been added (see Section 10).

Two new sets of sample calculations (Examples 10 and 11) have been added.

- *File management*

File naming has been streamlined, with all input and output files now having a .txt extension. All extraterrestrial spectra are now in the **Solar** folder, all absorption data files are in the **Gases** folder, all albedo data files are in the **Albedo** folder, and all examples (including two new examples) are in the **Examples** folder. The user interaction during execution, as well as the method to invoke the executables, have also been streamlined.

### **Version 2.9.2**

- *Bug correction*

A bug in version 2.9.1 that affected calculations with one albedo file (**IALBDX** and **IALBDG** = 2) has been corrected. Another fix was a bug that potentially affected *all* previous versions and was causing numerical instability when calculating irradiances at large air masses. The spectral optical depths for water vapor and other gases are now correctly reported when more than one sub-run (solar position) is requested. The aerosol optical depths are now correctly reported on the main output file ('filename.OUT') and correspond exactly to the spectral values reported on the optional output file ('filename.EXT'). Finally, the output details for Day of Month and Day of Year are now correctly reported for both Local Time and Universal Time.

- *Turbidity inputs*

An improved relationship between turbidity and meteorological range is now used, for better correspondence with MODTRAN results. It is season-dependent and takes the influence of tropospheric aerosols above the boundary layer into account.

The aerosol optical depth at 550 nm is now calculated and printed in the input echo section of 'filename.OUT'. This wavelength corresponds to the peak of the photopic curve and is the effective wavelength used when deriving the aerosol optical depth from the meteorological range.

### **Version 2.9.1**

- *Bug correction*

A bug in version 2.9 affected calculations with all reference atmospheres except USSA. It prevented the correct value of the default precipitable water to be used, so that the USSA value was rather used in all cases if **IH2O** = 1 was selected on Card 4.

- *Output variables*

The number of spectral variables is no more limited to 24 by **IOTOT** on Card 12b. All 32 variables can now be printed on File 17 ('filename.EXT').

- *Scanning/smoothing output*

Results of the scanning/smoothing routine (if **ISCAN** = 1 on Card 14) are now printed on a separate spreadsheet-ready output file, File 18 ('filename.SCN'), for more flexibility.

- *Main output file*  
Labelling and content of the main output file, File 16 ('filename.OUT'), has been slightly revamped for clarity.

### **Version 2.9**

- *New algorithm for the sun position*  
The authors of the new algorithm (Blanco-Muriel et al., 2001) claim that it is more accurate than Michalsky's algorithm that was used in previous versions. *Month* and *Day of month* are now used as inputs rather than *day of year*, which might be easier. Local Apparent Time (LAT) is now an output of the program. The time zone sign convention has been reversed to become consistent with the longitude sign convention.
- *Improved resolution*  
Resolution has been doubled in the UV, below 400 nm (0.5 nm rather than 1 nm). The total number of wavelengths is now 2002, from 280 to 4000 nm.
- *Revised extraterrestrial solar spectrum*  
The new spectrum corresponds more closely to the currently accepted solar constant (1367 W/m<sup>2</sup>). Additionally, there are 6 optional spectra, from as many possible default spectra in MODTRAN4 (Wehrli/WRC/WMO, oldkur, newkur, chkur, cebchkur, and thkur). These datasets have been resampled and degraded from their original resolution (1 cm<sup>-1</sup>) to that of SMARTS, to accommodate the latter's resolution. As in MODTRAN, these spectral irradiances can now be scaled to 1367 W/m<sup>2</sup> or any other solar constant value if so desired.
- *Revised Rayleigh scattering function*  
The coefficients in the Rayleigh optical depth formulation,

$$\tau_R = (p / p_0) / (a_0 \lambda^4 + a_1 \lambda^2 + a_2 + a_3 \lambda^{-2})$$

have been revised to take new fundamental determinations into account (Bucholtz, 1995; Bodhaine et al., 1999). The functional form above guarantees a significantly better fit to the theoretical data than the polynomial ratio recommended by Bodhaine et al.

- *Revised optical masses*  
Each extinction process has now a separate optical mass, obtained as a function of zenith angle. The air mass takes the atmosphere's curvature and the vertical profile of each absorber or scatterer into account, and thus alleviates the limitations of the usual plane-parallel approximation.
- *New absorption coefficients*  
All absorption coefficients are either new or revised in this version, and are based on the latest spectroscopic data. There is now a total of 19 absorbing gases (a number of them new to SMARTS; some of them not considered in MODTRAN yet). Wherever possible, the absorption coefficients are temperature dependent. All gases are treated individually, with a separate input data file (hence the far larger number of data files in the present version).
- *Pollution mode*

The abundance of all gases is defaulted to “standard” conditions calculated from pressure and temperature. The abundance of those 10 gases that are highly variable due to tropospheric pollution (e.g., O<sub>3</sub>, NO<sub>2</sub>, SO<sub>2</sub>) can be modified with a “pollution index”. Their real tropospheric abundance can be either user defined (in ppm), or defaulted to four representative levels (pristine conditions, light pollution, moderate pollution, and severe pollution).

- *Variable CO<sub>2</sub> concentration*  
Like in MODTRAN, the atmospheric CO<sub>2</sub> concentration (which is slowly increasing over time) is a user input.
- *Revised relationship between visibility and aerosol optical depth*  
It is now based on MODTRAN4 results.
- *Improved fits for Ångström’s wavelength exponent*  
More accurate fits of  $\alpha = f(\text{wavelength, humidity})$  have been obtained for Shettle & Fenn’s aerosol models.
- *Improved albedo library*  
The number of albedo data files has been doubled, now incorporating some wide-range spectral datasets from JPL’s ASTER Spectral Library, Version 1.2 (available on line or on CD-ROM from the Jet Propulsion Laboratory, <http://speclib.jpl.nasa.gov>).
- *More accurate smoothing*  
Improved accuracy and functionality for the SCAN smoothing postprocessor have been implemented. It has a better tail rejection (for wavelengths away from the peak wavelength), and can now cover the whole spectrum in one pass.
- *Daily run*  
A daily run can now be specified, to calculate the mean daily *broadband* irradiation (in MJ/m<sup>2</sup>) for any month at a specified location.
- *UV Index*  
The *UV Index* is now reported when requesting the optional extra UV calculations.
- *Faster batch runs*  
A simpler interface is used to expedite batch runs.
- *Corrections*  
A few bugs that have been reported by users of version 2.8 have been corrected.
- *Examples*  
Nine documented Examples are now available with all the related input/output files, and a description in a ReadMe file.
- This User’s Manual!

## 17. REFERENCES

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# APPENDIX: PRINTOUTS FOR EXAMPLE 6

## • *INPUT FILE*

'Example_6:USSA_AOD_0.084'	!Card 1 Comment
1	!Card 2 ISPR
1013.25 0. 0.	!Card 2a Pressure, altitude, height
1	!Card 3 IATMOS
'USSA'	!Card 3a Atmos
1	!Card 4 IH2O
1	!Card 5 IO3
1	!Card 6 IGAS
370.0	!Card 7 qCO2
0	!Card 7a ISPCTR
'S&F_RURAL'	!Card 8 Aeros
0	!Card 9 ITURB
0.084	!Card 9a Turbidity coeff. (TAU5)
38	!Card 10 IALBDX
1	!Card 10b ITILT
38 37 180	!Card 10c Tilt variables
280 4000 1.0 1367.0	!Card 11 Input wavelengths; solar spectrum
2	!Card 12 IPRT
280 4000 .5	!Card 12a Print limits
4	!Card 12b # Variables to Print
8 9 10 30	!Card 12c Variable codes
1	!Card 13 ICIRC
0 2.9 0	!Card 13a Receiver geometry
0	!Card 14 ISCAN
0	!Card 15 ILLUM
0	!Card 16 IUUV
2	!Card 17 IMASS
1.5	!Card 17a Air mass

• **OUTPUT FILE**

\*\*\*\*\* SMARTS, version 2.9.5 \*\*\*\*\*  
Simple Model of the Atmospheric Radiative Transfer of Sunshine  
Chris A. Gueymard, Solar Consulting Services  
December 2005

This model is documented in FSEC Report PF-270-95  
and in a Solar Energy paper, vol. 71, No.5, 325-346 (2001)

NOTE: These references describe v. 2.8 or earlier!!!  
See the User's Manual for details on the considerable  
changes that followed...

\*\*\*\*\*

Reference for this run: Example\_6:USSA\_AOD=0.084

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\* ATMOSPHERE : USSA      AEROSOL TYPE: S&F\_RURAL

\* INPUTS:

Pressure (mb) = 1013.250    Ground Altitude (km) = 0.000  
Height above ground (km) = 0.000  
Relative Humidity (%) = 46.040    Precipitable Water (cm) = 1.4160  
Ozone (atm-cm) = 0.3438 or 343.8 Dobson Units  
AEROSOLS: Optical Depth at 500 nm = 0.0840    Optical depth at 550 nm = 0.0764  
Angstrom's Beta = 0.0333    Schuepp's B = 0.0365  
Meteorological Range (km) = 124.2    Visibility (km) = 95.1  
Alpha1 = 0.9640    Alpha2 = 1.4314    Mean Angstrom's Alpha = 1.1977  
Season = SPRING/SUMMER

\* TEMPERATURES:

Instantaneous at site's altitude = 288.1 K  
Daily average (reference) at site's altitude = 288.1 K  
Stratospheric Ozone and NO2 (effective) = 225.3 K

The following spectral variables will be output to file: SMARTS2.EXT

- \* Global\_tilted\_irradiance
- \* Beam\_normal\_+circumsolar
- \* Difuse\_horiz-circumsolar
- \* Zonal\_ground\_reflectance

Spectral ZONAL albedo data: LIGHT\_SANDY\_SOIL  
with a reflection process: NON\_LAMBERTIAN

\* GEOMETRY (half-angles) OF THE SIMULATED RADIOMETER (deg.):

Slope = 0.00    Aperture = 2.90    Limit = 0.00

\*\* WARNING #11\*\*\*\*\*

\The radiometer's Slope and Limit angles are not provided.  
\Circumsolar calculations will therefore be performed for  
\an average geometry corresponding to the Aperture angle.

Spectral LOCAL albedo data: LIGHT\_SANDY\_SOIL  
with a reflection process: NON\_LAMBERTIAN

=====

=====

\* SOLAR POSITION (deg.):  
Zenith Angle (apparent) = 48.236 Azimuth (from North) = 180.00

RELATIVE OPTICAL MASSES:

- Rayleigh = 1.500
- Water Vapor = 1.501
- Ozone = 1.498
- NO2 = 1.500
- Aerosols = 1.501

CO2 Mixing Ratio at sea level (ppmv): 370.0

Total column abundances (atm-cm) for all gases except H2O, and for normal/standard conditions:

BrO	CH2O	CH4	CINO3	CO	CO2	HNO2	HNO3	NH3
0.2500E-05	0.3000E-03	0.1325E+01	0.1200E-03	0.8859E-01	0.2970E+03	0.1000E-03	0.3637E-03	0.1751E-03
NO	NO2	NO3	N2	N2O	O2	O3	O4	SO2
0.3145E-03	0.2044E-03	0.5000E-04	0.3827E+06	0.2473E+00	0.1678E+06	0.3438E+00	0.1678E+06	0.1100E-03

\* ANGLES (deg.) FOR TILTED SURFACE CALCULATIONS:  
Surface Tilt = 37.000 Surface Azimuth (from North) = 180.000  
Incidence Angle = 11.236

Diffuse irradiance ratios (tilted plane/horizontal):  
0.8993 (isotropic approximate conversion--for reference)  
1.2420 (anisotropic conversion model--used here)

\* \* \* \* \*

\*\* SPECTRUM:  
Total (0-100  $\mu\text{m}$ ) Extraterrestrial Irradiance used here = 1367.00 W/m<sup>2</sup>  
(i.e., 1.0000 times the selected solar constant, 1367.00 W/m<sup>2</sup>, due to the actual Sun-Earth distance.)  
Source for selected solar spectrum: Gueymard\_2004

To account for the chosen Solar Constant value, the selected solar spectrum has been uniformly multiplied by this scaling coefficient = 1.0007

Wavelength Range = 280.0 to 4000.0 nm; Number of Wavelengths = 2002

\*\*\* BROADBAND IRRADIANCES (W/m<sup>2</sup>):

\* DIRECT BEAM AT NORMAL INCIDENCE:  
Extraterrestrial = 1348.92 Terrestrial = 896.54 Atmospheric Transmittance = 0.6646

\* FOR THE HORIZONTAL PLANE:  
Direct Beam = 597.16 Diffuse = 100.13 Global = 697.29 Clearness index, KT = 0.5101  
Diffuse irradiance origination details:  
Sky diffuse = 87.17 Back-scattered diffuse = 12.96

\* FOR THE TILTED PLANE:  
Direct Beam = 879.36 Sky Diffuse = 124.57 Ground Reflected = 23.83 Global = 1003.93

\* EXPERIMENTAL (WITH CIRCUMSOLAR CORRECTION):  
Direct Beam, Normal Incidence = 898.78 Diffuse Horizontal = 98.64 Global Horizontal = 697.29