NASA/TM-20210022168

Venus Global Reference Atmospheric Model (Venus-GRAM): User Guide

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September 2021

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Acknowledgments

The authors thank the NASA Science Mission Directorate (SMD) for their support of updating the Global Reference Atmospheric Models (GRAMs) including Venus-GRAM.

Venus-GRAM was originally developed under the leadership of Dr. Carl Gerald (Jere) Justus. The first release of Venus-GRAM occurred in March of 2005. In 2021, Venus-GRAM was re-released after being converted to the GRAM common framework. A complete history of Venus-GRAM version revisions is contained in appendix F.

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PREFACE

The 2021 version of the NASA Venus Global Reference Atmospheric Model (Venus-GRAM) was developed by the Natural Environments Branch, Spacecraft and Vehicle Systems Department, Engineering Directorate at NASA Marshall Space Flight Center and the Atmospheric Flight and Entry Systems Branch at NASA Langley Research Center.

Information on obtaining Venus-GRAM code and data can be found on the NASA Software Catalog at: https://software.nasa.gov.

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LIST OF ACRONYMS

ASCII	American Standard Code for Information Interchange
CSS	Cascading Style Sheets
CSV	comma separated value
ERT	Earth-receive time
GRAM	Global Reference Atmospheric Model
LTST	local true solar time
MSFC	Marshall Space Flight Center
NAIF	Navigation and Ancillary Information Facility
PET	planet event time
SMD	Science Mission Directorate
SPICE	Spacecraft Planet Instrument C-matrix Events
SZA	Solar Zenith Angle
TDB	Barycentric Dynamical Time
TDT	Terrestrial Dynamical Time
UTC	Coordinated Universal Time
Venus-GRAM	Venus Global Reference Atmospheric Model
VET	Venus-event time
VIRA	Venus International Reference Atmosphere

NOMENCLATURE

C_p specific heat capacity of a gaseous mixture for isobaric processes

C_v specific heat capacity of a gaseous mixture for isochoric processes

L_s solar longitude

P_F modeled perturbation factor

P_U user-supplied perturbation multiplier

R correlation factor for the previous time step

R' correlation factor for the current time step

S relative displacement from the last time step using NS, EW, vertical movement, and winds (when modeled)

X value provided by a random number generator

γ ratio of specific heats

ρ_0 mean value of atmospheric density

ρ' perturbed value of atmospheric density

TECHNICAL MEMORANDUM

VENUS GLOBAL REFERENCE ATMOSPHERIC MODEL (VENUS-GRAM): USER GUIDE

1. INTRODUCTION

1.1 Background and Overview

Engineers and mission planners designing vehicles that pass through Venus' atmosphere require an atmospheric model that calculates the mean values and variations of atmospheric properties. The Venus Global Reference Atmospheric Model (Venus-GRAM) is an engineering-oriented model that provides this critical information based on data from the Pioneer Venus Orbiter and Probe as well as Venera probe data. Venus-GRAM is designed to offer mission planners the flexibility to select input parameters such as time, latitude, and longitude. Venus-GRAM outputs mean values for atmospheric density, temperature, pressure, winds, and constituents along a user defined path. Venus-GRAM also provides dispersions of winds and density.

A Fortran version of Venus-GRAM was originally released in 2005. Recently the code has been updated and rearchitected in C++ to improve efficiencies in implementation, run time, and maintenance. Venus-GRAM now shares a common software core with other versions of the GRAMs. Additionally, documentation (including this User Guide, a Programmer's Manual, and trajectory code interfaces) has been made available with the software release.

This User Guide summarizes the atmospheric data model in Venus-GRAM and provides a guide for the user to obtain, set up, and run the code in various configurations. Section 2 describes the atmospheric data files and how they are used in Venus-GRAM. Section 3 explains the process to obtain the Venus-GRAM code, the data files, and how to set up and run the program. Appendices A through E provide additional details regarding the Venus-GRAM input and output files. Appendix F provides a history of Venus-GRAM revisions.

1.2 Significant Changes in Venus-GRAM

While the atmosphere model data used in Venus-GRAM has not changed from Venus-GRAM 2005, several major code modifications have been made to improve efficiencies in implementation, run time, and maintenance. The major updates to Venus-GRAM are as follows:

(1) The primary changes in this version of Venus-GRAM involve a rearchitecture from Fortran to a common object-oriented C++ framework called the GRAM Suite. This new architecture creates a common GRAM library of data models and utilities that reduces duplicated code, ensures consistent constants across all GRAMs, simplifies bug fixes, and streamlines the interface with trajectory codes. Users should refer to the GRAM Programmer's Manual for additional details.

(2) The Venus-GRAM input parameters have been renamed to be more descriptive. The legacy input parameter names are still accepted to maintain compatibility with existing NAMELIST input files from prior Venus-GRAM versions. Table 2 in section 3.3 provides the new and old input parameter names.

(3) The Navigation and Ancillary Information Facility (NAIF) Spacecraft Planet Instrument C-matrix Events (SPICE) library has been incorporated into the GRAM Suite for ephemeris calculations. Venus ephemeris values, such as longitude of the Sun and solar time, are now computed using the NAIF SPICE library for greater accuracy. The values generated by SPICE are slightly different from those generated in the original custom Venus-GRAM 2005 ephemeris engine. The use of NAIF SPICE requires the Venus-GRAM user to download the latest SPICE data before using Venus-GRAM. Instructions for doing so are provided in section 3.2.

(4) Due to the increase in computing power and memory since the original release of Venus-GRAM in 2005, the output files have been reformatted. The output is provided in two formats: (1) a comma separated value (CSV) file and (2) a LIST file (formerly LIST.txt, now LIST.md). The CSV file consolidates the column formatted output files from the original release of Venus-GRAM into a single file that can easily be loaded into data centric programs, such as Microsoft Excel or MATLAB®. A detailed list of CSV file parameters and definitions are provided in appendix A. Alternatively, the LIST file can be read using either a standard American Standard Code for Information Interchange (ASCII) reader or a Markdown syntax for enhanced rendering in a web browser. An example of both LIST file formats is provided in appendix C.

(5) The calculation of the speed of sound has been improved in Venus-GRAM. Venus-GRAM computes speed of sound based on a thermodynamic parameterization using density, pressure, and γ, the ratio of specific heats $\frac{C_p}{C_v}$, for a given constituent gas mixture. C_p is the specific heat capacity of a gaseous mixture for isobaric processes and C_v is the specific heat capacity of a gaseous mixture for isochoric processes. Venus-GRAM previously used a constant γ, which is physically unrealistic and over-estimates the speed of sound by as much as 10%. Venus-GRAM now uses an improved methodology for computing γ, involving temperature and pressure dependent tables of C_p and C_v evaluated in run-time for the current constituent combination[1].

2. VENUS-GRAM ATMOSPHERIC DATA

2.1 Venus-GRAM Atmospheric Data Description

Atmospheric density, temperature, pressure, chemical composition, and winds as a function of height are characterized by Venus International Reference Atmosphere (VIRA)[2]. The original version of VIRA in Venus-GRAM includes Pioneer Venus orbiter and probe data as well as Venera probe data, but does not include a solid planet model, nor a high resolution gravity model.[3] Other major data sources for Venus-GRAM include *Venus*[4], *Venus II*[5], *The Planet Venus*[6], and several journal articles[7-15].

For the lower atmosphere from 0 - 100 km, VIRA data depends on height and latitude. In the middle-atmosphere from 100 -150 km, VIRA data depends on height and local true solar time (LTST) (LTST = 0 or LTST = 12 Venus hours). At upper-altitudes from 150 - 250 km, VIRA data depends on height and solar zenith angle. Venus-GRAM insures smooth variation between height regions by averaging values at the two transition heights (100 km and 150 km).

VIRA data incorporated in Venus-GRAM includes: height, pressure, density, temperature, and number densities for CO_2, N_2, O, CO, He, N and H. Additionally, Venus-GRAM uses the atmospheric gas constant and the dimensionless compressibility factor that are contained in the low-altitude VIRA data file.

The Venus-GRAM thermosphere has been extended from the maximum VIRA height of 250 km to an altitude of 1000 km, by a Marshall Space Flight Center (MSFC) developed model[16] that is based on the following assumptions:

- VIRA conditions and constituents at 250 km are used as lower boundary values
- Constant (exospheric) temperature is assumed above 250 km (exospheric temperature = local VIRA temperature at 250 km)
- Hydrostatic conditions are computed separately for each constituent (diffusive separation)
- Total pressure is computed from constituent partial pressures
- Mass density is computed from constituent number densities

Variability in thermodynamic parameters, winds, and density are included in Venus-GRAM. For thermodynamic parameters, the variation of mean thermodynamic parameters with altitude is taken from the VIRA data. For heights up to 100 km, mean values are from the VIRA data for latitudes less than 30°. For heights between 100 and 150 km, mean values are from an average of VIRA daytime (LTST=12 hr) and nighttime (LTST=0 hr) data. For heights between 150 and 250 km, mean values are from VIRA data for a solar zenith angle of 90°.

Plots of sample Venus-GRAM temperature and pressure output data is provided in figures 1 and 2 of this document.

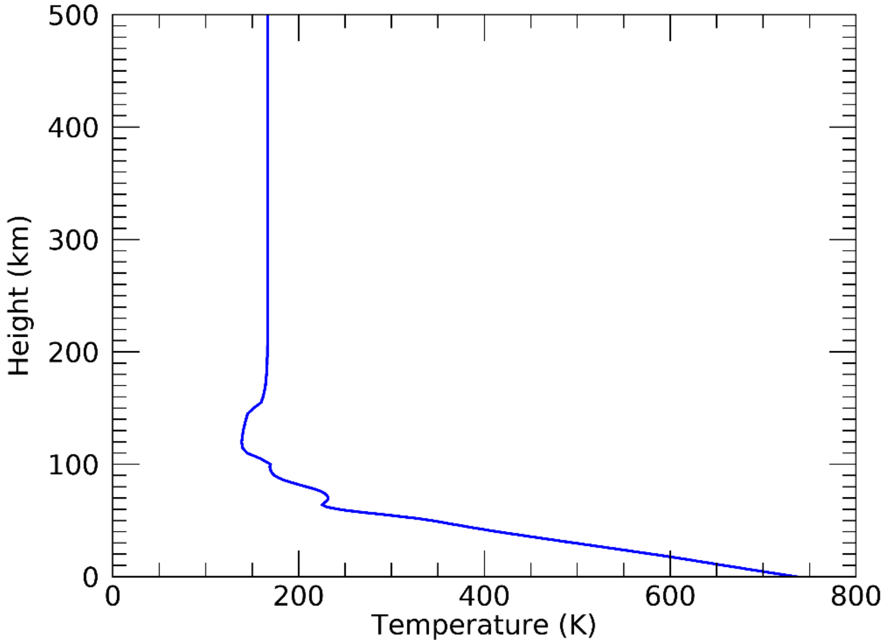

Figure 1. Height versus temperature from a sample Venus-GRAM output.

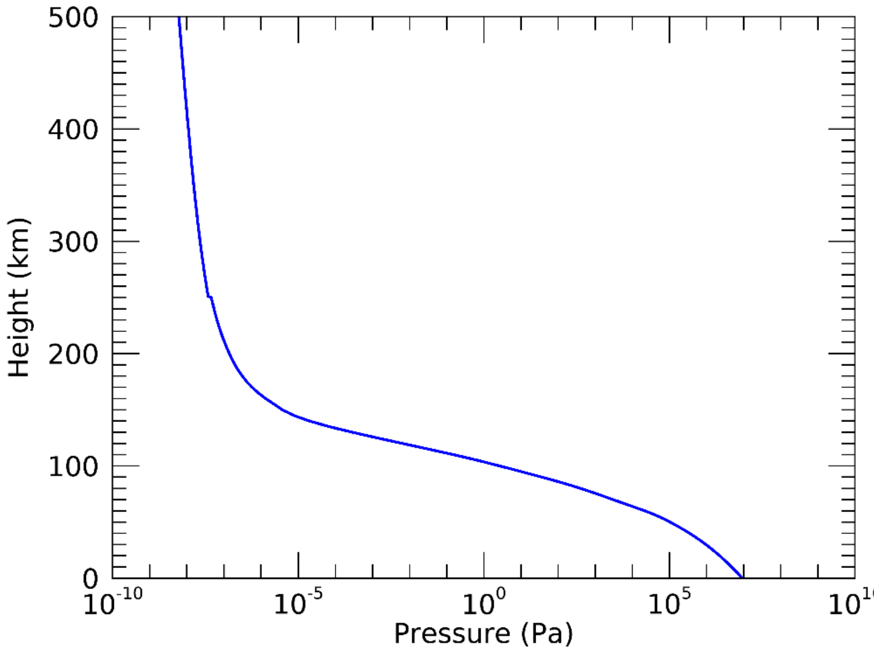

Figure 2. Height versus pressure from a sample Venus-GRAM output.

Venus-GRAM captures density variability in several ways. The magnitudes of density perturbations are estimated from temperature variations observed on Venus by: Pioneer probes[2,4,6], Pioneer orbiter[5], and Magellan radio occultation[7]. Horizontal scales of density perturbations were selected to be consistent with wavelength estimates from figure 6 of Bougher and Borucki[8], figure 2 of Mayr et al[9], Kasprzak et al.[10], and Kasprzak et al.[11]. Density variations for Venus are small below about 125 km. Variations of Venus density with Solar

Zenith Angle (SZA) (as SZA changes with time-of-day and latitude) are significant above about 150 km. Variations of Venus density with solar activity (solar cycle) are not large. For comparison, Earth density at Solar Max/Solar Min ~ 6.9 and Venus density at Solar Max/Solar Min, ~ 1.6 (i.e. varies between ~ 0.8 x Solar Average and ~ 1.25 x Solar Average). Due to the relatively small range of Venus density variation with solar activity, this effect was not explicitly included in the VIRA data or Venus-GRAM.

Venus-GRAM density perturbation magnitudes are estimated using

$$\rho' = \rho_0(1 + R' P_F P_U) \qquad (1)$$

and

$$R' = e^{-S}R + X\sqrt{1 - e^{-2S}} \qquad (2)$$

where:

ρ'	= perturbed value of atmospheric density
ρ_0	= mean value of atmospheric density
R'	= correlation factor for the current time step
P_F	= modeled perturbation factor (typically height dependent)
P_U	= user-supplied perturbation multiplier
S	= relative displacement from the last time step using NS, EW, vertical movement, and winds
R	= correlation factor for the previous time step
X	= value provided by a random number generator

Note that for small relative displacements, the new correlation factor is close to the previous correlation factor (R'≈R). For large relative displacements, the new correlation factor is essentially random (R'≈X).

The mean zonal wind versus height up to 80 km is based on approximations to VIRA data and from figure 5, page 469 of *Venus II*[5], with latitude variation from figure 8, page 696 of *Venus*[4]. The mean meridional wind versus height up to 80 km and versus latitude is from figure 3, page 466 of *Venus II*[5]. Up to 80 km, magnitudes of zonal and meridional wind perturbations are from approximations to VIRA data. The decrease in mean zonal wind above 80 km is parameterized from page 333 of Lellouch et al.[12] and figure 2 of Hou and Farrell[13]. Above 80 km, the zonal and meridional wind perturbation magnitudes are assumed to increase proportionally with increases in the mean wind. This assumption and proportional increase are from figure 2 of Zhang et al.[14]. At higher altitudes, the sub-solar to anti-solar diurnal wind is parameterized from figure 2 of Zhang et al.[14] and figure 4 of Bougher et al.[15] Sample wind perturbation outputs from Venus-GRAM are shown in figures 3 and 4 of this document.

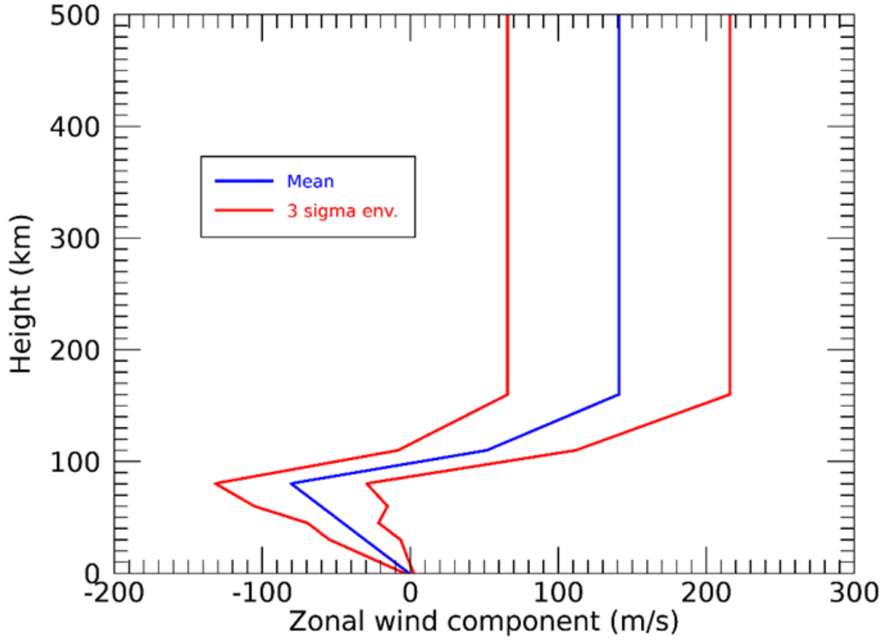

Figure 3. Three-sigma envelope of sample Venus-GRAM east (positive)/west (negative) zonal wind outputs for 60° N latitude and 225° E longitude.

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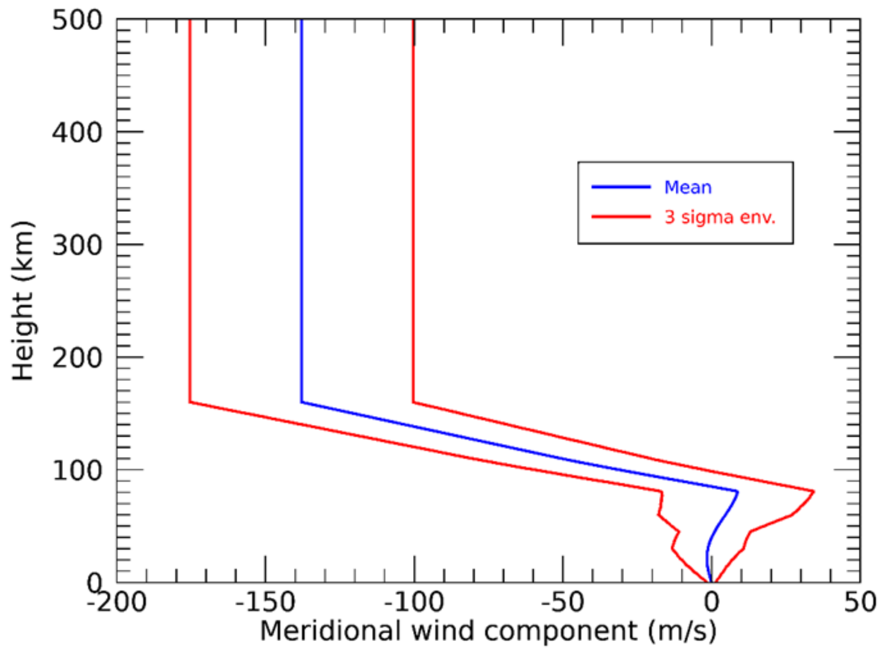

Figure 4. Three-sigma envelope of sample Venus-GRAM north (positive)/south (negative) meridional wind outputs for 60° N latitude and 225° E longitude.

Constituent information is from VIRA data.[2] A sample output of constituent contributions are shown in Figure 5 of this document.

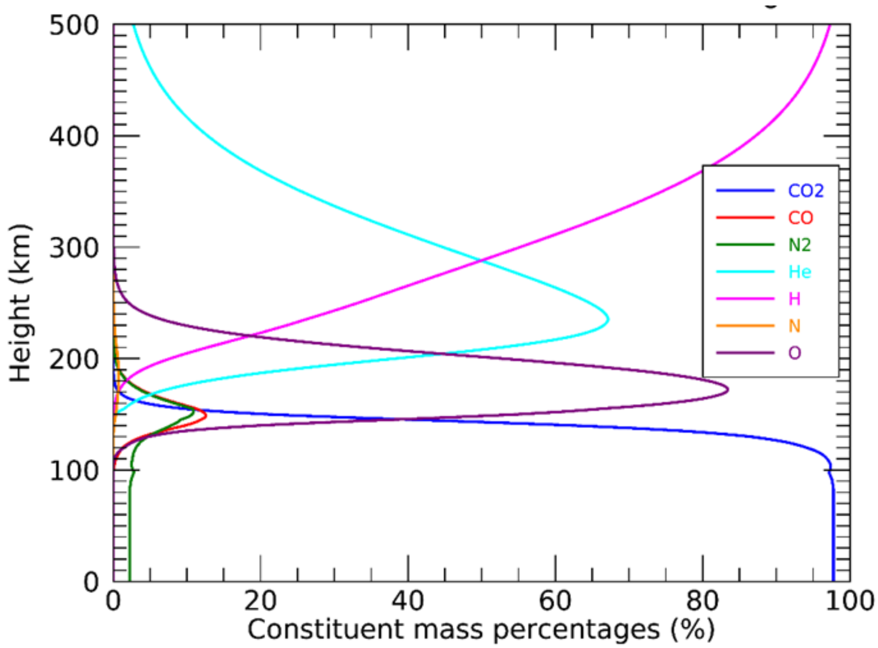

Figure 5. Sample Venus-GRAM mean constituent contributions by percent.

Planetary constants (radius, gravity, etc.) are from the NASA Space Science Data Coordinated Archive Planetary Fact Sheet for Venus Web page: https://nssdc.gsfc.nasa.gov/planetary/factsheet/venusfact.html.

Table 1 provides the Venus gravity parameter data that are utilized in Venus-GRAM.

Table 1. Venus gravity parameters.

Venus	**Label**	**Units**	**Value**
Gravitational Parameter	GM	km^3/s^2	324858.592
Mean Equatorial Radius	R_e	km	6051.8
Mean Polar Radius	R_p	km	6051.8
J2 harmonic	J_2	km^5/s^2	4.458e-6
Period		s	-20997360.0

2.2 Querying Atmosphere Data

The Venus-GRAM user defined path can be generated in multiple ways. The first is to run Venus-GRAM in standalone mode which uses an automated increment approach based on inputs specified in the NAMELIST input file for the initial time and position (e.g. *Year, Month, Day, Hour, Seconds, InitialHeight, InitialLatitude,* and *InitalLongitude*) and the deltas (e.g., *DeltaTime, DeltaHeight, DeltaLatitude*, and *DeltaLongitude*). Refer to section 3.3 for input parameter definitions and appendix B for a sample file. In standalone mode, Venus-GRAM steps automatically in user-defined increments of altitude, latitude, longitude, and time to generate a constantly incremented profile. Each point in the profile will have a corresponding atmospheric value for density, temperature, pressure, winds, and constituents. A second path generation option is to run the model in trajectory evaluation mode where the user provides a trajectory file, specified using *TrajectoryFileName.* The trajectory file contains a specified time history of altitude, latitude, and longitude and removes the constant increment constraint criteria of the previous option. Additional information about trajectory file input can be found in section 2.5. A third method is to incorporate the Venus-GRAM code directly into a user's trajectory code. This version of Venus-GRAM contains both C and Fortran interfaces. The GRAM libraries can be incorporated directly in the user's trajectory (or orbit propagation) code for atmospheric evaluations along a trajectory or orbital positions. Documentation of the GRAM libraries, interfaces, and examples are provided in the GRAM Programmer's Manual.

Regardless of the path generation option selected, Venus-GRAM writes output to two files: a CSV output file and a LIST file output. These output files are detailed in appendices A and C.

2.3 Monte Carlo Capability

Using the *NumberOfMonteCarloRuns* option in the NAMELIST input file, Venus-GRAM will generate the user-specified number of trajectories that disperse density, speed of sound, and winds. The resulting data are written to the output CSV file discussed in section 3.4. Each run is independent. The multiple methods for providing the trajectory input data (i.e. time, altitude, latitude, and longitude) to generate the individual Monte Carlo trajectories is described in section 2.2.

Using a user-generated trajectory file as described in section 2.5 allows varying trajectory increments to be defined by the user. The Venus-GRAM perturbation model uses the time, altitude, latitude, and longitude changes from the previous perturbation update to provide the perturbations and will result in a trajectory evaluation method that provides more realistic perturbations than the *NumberOfMonteCarloRuns* option.

Running Venus-GRAM directly in a trajectory simulation code is the preferred method to generate the atmospheric perturbation data. Doing so allows perturbations to be generated at each time step in an individual Monte Carlo trajectory. Steps for incorporating Venus-GRAM into a user's trajectory simulation code are described in the C++, C, and Fortran Interface sections of the GRAM Programmer's Manual.

2.4 Auxiliary Atmosphere Profile Option

The auxiliary atmosphere profile option provides the user the ability to overwrite the atmosphere model in Venus-GRAM with a profile of atmosphere quantities versus altitude (note: constituent data cannot be over-written using this option). This option is controlled by setting input parameters *AuxiliaryAtmosphereFileName, InnerRadius*, and *OuterRadius* in the NAMELIST input file. Each line of the auxiliary atmosphere profile input file must consist of: (1) height, in km, (2) latitude, in degrees, (3) longitude, in degrees, (4) temperature, in K, (5) pressure, in Pa, (6) density, in kg/m^3, (7) eastward wind, in m/s, and (8) northward wind, in m/s. Longitudes are east or west positive, as set by input parameter *EastLongitudePositive*. Standard Venus-GRAM input data for temperature, pressure, or density data are used if the auxiliary atmosphere profile inputs for temperature, pressure, or density are zero. Standard Venus-GRAM input wind data are used if both wind components in the auxiliary atmosphere profile file are set to zero.

A weighting factor for the auxiliary atmosphere profile data (*ProfileWeight*), having values between 0 and 1, is applied between the *InnerRadius* and *OuterRadius*. The *InnerRadius* is the latitude-longitude radius (degrees) within which weight for the auxiliary atmosphere profile is 1.0 (e.g., the data in the auxiliary profile is used as provided). The *OuterRadius* is the latitude-longitude radius (degrees) beyond which the weight for the auxiliary atmosphere profile is 0.0 (e.g., the model uses standard Venus-GRAM data). Mean conditions are specified by the auxiliary atmospheric profile input file if the desired point is within the *InnerRadius*; mean conditions are given by the standard Venus-GRAM data if the desired point is beyond the *OuterRadius*. Linear interpolation of pressure and density occurs at each altitude increment between the *InnerRadius* and *OuterRadius*. An illustration of the fairing that occurs between the *InnerRadius* and *OuterRadius* is provided in figure 6. If *InnerRadius* = 0, then the auxiliary atmosphere profile data are not used. In addition to faring in latitude and longitude, fairing of the auxiliary atmosphere profile altitude is performed. This only occurs at the beginning and end of the file. The profile weight factor (*ProfileWeight*) for the auxiliary atmosphere profile varies between 0 at the first auxiliary atmosphere profile altitude level and 1 at the second auxiliary atmosphere profile altitude level (and between 1 at the next-to-last auxiliary atmosphere profile altitude level and 0 at the last auxiliary atmosphere profile altitude level). Therefore, care must be taken when selecting the altitude spacing at the beginning and end of the auxiliary atmosphere profile (e.g., selected to be far enough apart in altitude) to ensure that a smooth transition occurs as *ProfileWeight* changes from 0 to 1 near these auxiliary atmosphere profile beginning and end points.

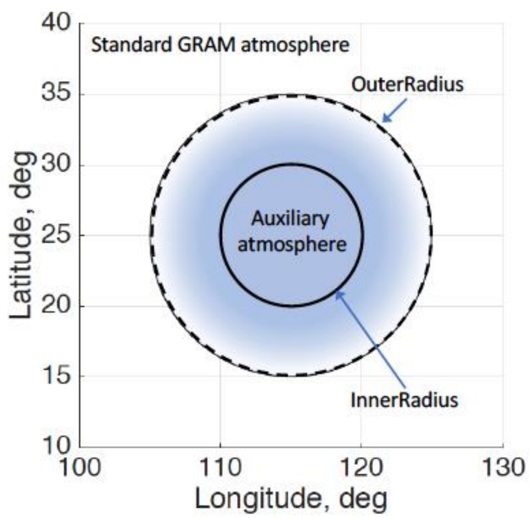

Figure 6. Illustration of two-dimensional auxiliary profile faring implementation with *InnerRadius* = 5° and *OuterRadius* = 10° for a vertical auxiliary profile located at latitude = 25° and longitude = 115°.

2.5 Trajectory File Input

The trajectory file is only utilized when a trajectory, rather than an automatically determined profile, is desired.

To utilize a trajectory file in a Venus-GRAM run, simply assign the desired trajectory file name to the NAMELIST variable *TrajectoryFileName*. The trajectory file may contain an unlimited number of individual list-directed (free-field) records, or lines, consisting of four real values:

(1) Time (s) past the start time specified in the NAMELIST input.
(2) Height (km).
(3) Latitude (± 90°, with southern latitudes being negative).
(4) Longitude (± 360°, with positive longitude designated by the input parameter *EastLongitudePositive*).

Any additional information included on each line of the trajectory file (e.g. orbit number, measured density, etc.) is ignored. Trajectory increments in these files do not have to be at small time or space steps. For example, a trajectory file may consist of successive periapsis times and positions for a simulated or observed aerobraking operation. Trajectory files may also contain arrays of locations used for computing height-latitude cross sections or latitude-longitude cross sections.

3. HOW TO RUN VENUS-GRAM

3.1 How to Obtain the Program

Venus-GRAM is available through the NASA Software Catalog: https://software.nasa.gov. The software is offered free of charge. See appendices D and E for summaries of the program and data files available in the downloaded package.

3.2 Running the Program

The Venus-GRAM installation includes a set of Windows and Linux 64-bit executable libraries located in the GRAM/Windows and GRAM/Linux folders. The Venus-GRAM programs in these folders may be relocated to any folder on the appropriate operating system. For those wishing to build their own executables or those running on another operating system, build instructions are provided in appendix E.

Before running Venus-GRAM, the NAIF SPICE data files must be downloaded. These data are available via FTP from ftp://naif.jpl.nasa.gov/pub/naif/generic_kernels. Information about the SPICE data is available from https://naif.jpl.nasa.gov/naif/data.html and help downloading is available from https://naif.jpl.nasa.gov/naif/download_tip.html. NAIF recommends that the entire collection be downloaded, but these files can be rather large. The files required by Venus-GRAM are listed in boldface below. They should be downloaded using the same folder structure as on the NAIF site.

```
/spice    (FTP source folder is /generic_kernels)
 └───────/lsk    (entire folder, less than 100KB)
              └───────/naif0012.tls    (time data, all GRAMs)
 └───────/pck  (entire folder except for a_old_versions, about 27MB)
              └───────/pck00010.tpc    (planetary size/shape data, all GRAMs)
 └───────/spk  (massive, consider getting subfolders only)
                   └───────/planets    (entire folder except for a_old_versions, about
                                         3.3GB)
                          └───────/de430.bsp    (Venus-GRAM)
              └───────/satellites    (entire folder except for a_old_versions, about
                                       5.8GB)
                          └───────/jup310.bsp    (Jupiter-GRAM)
                          └───────/mar097.bsp    (Mars-GRAM)
                          └───────/nep081.bsp    (Neptune-GRAM)
                          └───────/sat375.bsp    (Saturn-GRAM, Titan-GRAM)
                          └───────/ura111.bsp    (Uranus-GRAM)
```

The default location of the SPICE data files is in the root folder, /spice, on the current disk. If another location is desired, then be certain to set the *SpicePath* input parameter in the NAMELIST file to the desired location.

To run Venus-GRAM, simply double-click the VenusGRAM.exe file or enter 'VenusGRAM.exe' from a command prompt. The program will prompt for the path to an input parameter file in NAMELIST format (see section 3.3). The path may be entered as an absolute path or relative to the current folder. Sample input parameter files, ref_input.txt and traj_input.txt, can be found in the /GRAM/Venus/sample_inputs folder. Both files are plain text and can be viewed in a text editor, such as WordPad, with no word wrapping. On exit, the program will name the output files generated. In this case, they will be myref_LIST.md and myref_OUTPUT.csv. The myref_OUTPUT.csv file is best viewed using a spreadsheet program such as Microsoft Excel. See appendix C for optional methods for viewing the myref_LIST.md markdown file. Appendix C also shows examples of the myref_LIST.md output. The input parameter file may also be specified on the Venus-GRAM command line. The format of this option is 'VenusGRAM.exe –file ref_input.txt'. The sample_inputs folder contains pregenerated outputs ref_LIST.md and ref_OUTPUT.csv. These files are provided so that users may compare their output with the expected output.

3.3 Program Input

Venus-GRAM requires an input file in the format of a Fortran NAMELIST file. Appendix B gives a sample of the NAMELIST format input file for Venus-GRAM. All input parameter names are case insensitive. Input parameters whose values are supplied in the input file are as follows (the legacy Venus-GRAM input parameters names are still supported and appear in parentheses):

Table 2. Venus-GRAM input parameters.

Input Parameter	Description	Default
File Path and Names		
SpicePath or SpiceDir	The location of the NAIF SPICE data files. Absolute paths are recommended. Relative paths are acceptable.	/spice
ListFileName (LSTFL)	Name of list formatted file with no file extension. The appropriate file extension will be appended to this name. An example of a LIST file is given in appendix C.	LIST
ColumnFileName (OUTFL)	Name of the column formatted file with no file extension. The appropriate file extension will be appended to this name. A complete description of this file is contained in appendix A.	OUTPUT
TrajectoryFileName (TRAJFL)	(Optional) The trajectory input file name. This file contains time (seconds) relative to start time, height (km), latitude (degrees), and longitude (degrees, see below).	<empty>
Time Parameters		
TimeFrame (IERT)	Sets the time frame for the start time. 1 for Earth-receive time (ERT) 0 for planet event time (PET)	1
TimeScale (IUTC)	Sets the time scale for the start time. 0 for Terrestrial Dynamical Time (TDT). 1 for Coordinated Universal Time (UTC). 2 for Barycentric Dynamical Time (TDB).	1
Year (MYEAR)	Integer year for the start time. Typically, a 4-digit year. Alternately, years 1970 - 2069 can be input as a 2-digit number.	2000
Month	Integer month (1 through 12) for the start time.	1
Day (MDAY)	Integer day of month for the start time.	1

Input Parameter	Description	Default
Hour (IHOUR, IHR)	Integer hour (0 through 23) for the start time in the chosen *TimeScale* and *TimeFrame*.	0
Minute (IMIN)	Integer minute (0 through 59) for the start time in the chosen *TimeScale* and *TimeFrame*.	0
Seconds (SEC)	Real seconds (less than 60.0) for the start time in the chosen *TimeScale* and *TimeFrame*.	0.0
Perturbation Parameters		
InitialRandomSeed (NR1)	The integer seed value for the random number generator. The allowable range is 1 to 29999. Changing the seed will alter the perturbed values in trajectory. In Monte Carlo runs, the first trajectory uses the *InitialRandomSeed*. New seeds are generated automatically for all subsequent trajectories.	1001
DensityPerturbationScale	Random density perturbation scale factor (0.0 – 2.0, 1.0 = 3 sigma).	1.0
EWWindPerturbationScale	Random east/west wind perturbation scale factor (0.0 – 2.0, 1.0 = 3 sigma).	1.0
NSWindPerturbationScale	Random north/south wind perturbation scale factor (0.0 – 2.0, 1.0 = 3 sigma).	1.0
PerturbationScales (RPSCALE)	Random perturbation scale factor applied in place of the three scale factors listed above (0.0 – 2.0, 1.0 = 3 sigma). Note: This is a legacy input parameter only utilized for legacy NAMELIST input files.	1.0
MinRelativeStepSize (CORLMIN)	The minimum relative step size for perturbation updates (0.0-1.0). Perturbations are updated whenever the relative step size is greater than *MinRelativeStepSize*. *MinRelativeStepSize* = 0.0 means always update perturbations.	0.0
Trajectory Parameters		
EastLongitudePositive (LONEAST)	This flag controls the convention for input and output of longitudes. East positive convention if *EastLongitudePositive* = 1. West positive convention if *EastLongitudePositive* = 0.	1
NumberOfPositions (NPOS)	The number of positions to generate and evaluate, if an automatically-generated profile is to be produced. This parameter is ignored if a *TrajectoryFileName* is provided.	21
InitialHeight (FHGT)	Height (km) of the initial position.	0.0
InitialLatitude (FLAT)	Latitude (degrees, north positive) of the initial position.	0.0

Input Parameter	Description	Default
InitialLongitude (FLON)	Longitude (degrees) of the initial position. The direction of positive longitudes is determined by the *EastLongitudePositive* parameter.	0.0
DeltaHeight (DELHGT)	Height increment (km) between successive steps in an automatically generated profile (positive upward).	10.0
DeltaLatitude (DELLAT)	Latitude increment (degrees, north positive) between successive steps in an automatically generated profile.	0.0
DeltaLongitude (DELLON)	Longitude increment (degrees) between successive steps in an automatically generated profile. The direction of positive longitudes is determined by the *EastLongitudePositive* parameter.	0.0
DeltaTime (DELTIME)	Time increment (seconds) between steps in an automatically generated profile.	0.0
Monte Carlo Parameters		
NumberOfMonteCarloRuns (NMONTE)	Number of Monte Carlo runs during one execution of the program. New/different starting random numbers are automatically generated for each of the Monte Carlo profiles or trajectories.	1
Auxiliary Atmosphere Parameters		
AuxiliaryAtmosphereFileName (PROFILE)	(Optional) Input file name of the profile data for the auxiliary atmosphere.	<empty>
InnerRadius (PROFNEAR)	(Optional) Latitude-longitude radius (degrees) within which weight for the auxiliary profile is 1.0 (A value of 0.0 implies no auxiliary atmosphere data is present.)	0.0
OuterRadius (PROFFAR)	(Optional) Latitude-longitude radius (degrees) beyond which weight for the auxiliary profile is 0.0.	0.0
Output Parameters		
FastModeOn	Controls the speed and accuracy of ephemeris calculations. 0: More accurate, but slower. 1: Faster, but less accurate.	0
ExtraPrecision	For the new column output format, this parameter adds precision to all outputs.	0
UseLegacyOutputs	Flags which outputs to generate. 0: Use the new output formats. 1: Use output formats closely matching those of the Legacy Venus-GRAM.	0
DensityPrintScale (LOGSCALE)	Parameter to control units of output values of density and pressure to the legacy output files. This parameter has no effect if *UseLegacyOutputs* is 0. 0: use regular density and pressure units (kg/m^3 and N/m^2) 1: use logarithm (base-10) of the regular units	0

Input Parameter	Description	Default
	2: use percent deviation from mean model values of density and pressure 3: use SI units, with density in kg/km^3 (suitable for high altitudes)	

3.4 Program Output

There are two general types of program output provided by Venus-GRAM. The first output file is a listing format with the file name specified by input parameter *ListFileName*. This file contains header and descriptor information which is suitable for printing or viewing by an analyst. The list file is output using a Markdown format. Markdown is a lightweight markup language that is designed to be readable in plain text format and offers improved formatting when converted to other file formats (typically html). Markdown viewer apps are available on all platforms. While not yet natively supported, most web browsers offer an extension/add-on that adds the Markdown capability. Markdown viewing options and an example of the list output file format are given in appendix C.

The second output file is in a CSV format with the file name specified by the input parameter *ColumnFileName*. This file contains one header line and one line per output position and is suitable for reading into another program for additional analysis. The precision of the outputs can be increased using the input parameter *ExtraPrecision*. The CSV format can be easily loaded into most spreadsheet programs. It can also be imported into programs, such as MATLAB®, for analysis. A description of each of the output fields in the CSV file format can be found in appendix A.

3.5 Reference Test Run

The Venus-GRAM distribution includes sample files ref_input.txt and traj_input.txt for application in a reference test run. To verify the Venus-GRAM build, execute *VenusGRAM.exe* using ref_input.txt as the input parameter file. The files myref_LIST.md and myref_OUTPUT.csv, generated during the test run, should be identical to the supplied ref_LIST.md and ref_OUTPUT.csv files.

3.6 FindDates Utility

Venus-GRAM gives the user the option to find the date and time for a particular solar longitude (L_s) and Venus LTST through the *FindDates* utility. It also computes the Earth date and time of the next closest occurrence to the initial input date and time for which L_s and LTST are the user desired values. The SPICE data are required for this capability. The *FindDates* capability is contained within the Venus-GRAM program and controlled by the *FindDates* input parameter (see table 3). The utility will return three dates and times: the date and times of the target L_s and the two dates and times of the target LTST that immediately precede and follow the target L_s date. A sample *FindDates* input file can be found in the sample_inputs file.

Table 3. FindDates input parameters.

Input Parameter	Description	Default
SpicePath or SpiceDir	The location of the NAIF SPICE data files. Absolute paths are recommended. Relative paths are acceptable.	/spice
FindDates	The parameter flags the use of the FindDates auxiliary capability. Use the FindDates capability if *FindDates* = 1. Use Venus-GRAM if *FindDates* = 0.	0
EastLongitudePositive (LONEAST)	This flag controls the convention for input and output of longitudes. East positive convention if *EastLongitudePositive* = 1. West positive convention if *EastLongitudePositive* = 0.	1
Time Parameters		
TimeFrame (IERT)	Sets the time frame for the start time. 1 for Earth-receive time (ERT) 0 for planet event time (PET)	1
TimeScale (IUTC)	Sets the time scale for the start time. 0 for Terrestrial Dynamical Time (TDT) 1 for Coordinated Universal Time (UTC) 2 for Barycentric Dynamical Time (TDB)	1
Year (MYEAR)	Integer year for the start time. Typically, a 4-digit year. Alternately, years 1970 - 2069 can be input as a 2-digit number.	2000
Month	Integer month (1 through 12) for the start time.	1
Day (MDAY)	Integer day of month for the start time.	1
Hour (IHOUR, IHR)	Integer hour (0 through 23) for the start time in the chosen *TimeScale* and *TimeFrame*.	0
Minute (IMIN)	Integer minute (0 through 59) for the start time in the chosen *TimeScale* and *TimeFrame*.	0
Seconds (SEC)	Real seconds (less than 60.0) for the start time in the chosen *TimeScale* and *TimeFrame*.	0.0
Position Parameters		
InitialHeight (FHGT)	Height (km) of the initial position.	0.0
InitialLatitude (FLAT)	Latitude (degrees, North positive) of the initial position.	0.0
InitialLongitude (FLON)	Longitude (degrees) of the initial position. The direction of positive longitudes is determined by the *EastLongitudePositive* parameter.	0.0
FindDates Parameters		
TargetLongitudeSun	The desired longitude of the sun in degrees.	0.0
TargetSolarTime	The desired true local solar time in hours (0 to 24).	0.0

APPENDIX A – HEADERS FOR VENUS-GRAM OUTPUT FILE

Venus-GRAM produces a CSV output file (see table 4) suitable for passing to a data-centric program for plotting and further analysis. The field names purposely lack any special characters other than an underscore separating the units. Thus, for some fields, such as Gravity_ms2, the precise units must be inferred, as in m/s^2.

Table 4. OUTPUT.csv (or as prescribed in the *ColumnFileName* input parameter).

Time_s	Seconds past the start time
Height_km	Height above the reference ellipsoid
Latitude_deg	Geocentric latitude
LongitudeE_deg LongitudeW_deg	East (or west) longitude, as controlled by input value *EastLongitudePositive*
TotalRadius_km	Radial distance from planetary center of mass to the current position (latitude radius plus altitude)
LatitudeRadius_km	Planetary radius at current latitude.
Gravity_ms2	Local acceleration of gravity (m/s^2)
Temperature_K	Mean temperature (K)
Pressure_Nm2	Mean pressure (Pa)
Density_kgm3	Mean density (kg/m^3)
PressureScaleHeight_km	The height range over which pressure decreases by a factor of *e*
DensityScaleHeight_km	The height range over which density decreases by a factor of *e*
SpeedOfSound_ms	The speed of sound (m/s)
PressureAtSurface_Nm2	Pressure at the zero altitude surface (Pa)
SigmaLevel	The ratio of pressure to pressure at the surface.
PressureAltitude_km	Pressure altitude
ReferenceTemperature_K	Temperature of the reference atmosphere
ReferencePressure_Nm2	Pressure of the reference atmosphere (N/m^2)
ReferenceDensity_kgm3	Density of the reference atmosphere (kg/m^3)
ProfileWeight	Weight factor for auxiliary input profile data
LowDensity_kgm3	Mean density - 1 standard deviation (kg/m^3)
HighDensity_kgm3	Mean density + 1 standard deviation (kg/m^3)
PerturbedDensity_kgm3	Mean density + density perturbation (kg/m^3)
DensityPerturbation_pct	Density perturbation (kg/m^3)
DensityStandardDeviation_kgm3	Standard deviation of the density (kg/m^3)
PerturbedSpeedOfSound_ms	The speed of sound at the current perturbed density (m/s)
RelativeStepSize	Fraction of minimum step size for accuracy of perturbations (should be > 1 for insured accuracy of perturbations)
DensityDeviation_pct	Percent deviation of the mean density from the reference density
LowDensityDeviation_pct	Percent deviation of the low density from the reference density
HighDensityDeviation_pct	Percent deviation of the high density from the reference density
PerturbedDensityDeviation_pct	Percent deviation of the perturbed density from the reference density
EWWind_ms	Mean eastward wind component (m/s)

NSWind_ms	Mean northward wind component (m/s)
EWWindPerturbation_ms	Eastward wind perturbation (m/s)
NSWindPerturbation_ms	Northward wind perturbation (m/s)
PerturbedEWWind_ms	Total (mean plus perturbed) eastward wind (m/s)
PerturbedNSWind_ms	Total (mean plus perturbed) northward wind (m/s)
EWStandardDeviation_ms	Standard deviation of eastward wind perturbations (m/s)
NSStandardDeviation_ms	Standard deviation of northward wind perturbations (m/s)
LongitudeOfTheSun_deg	The planetocentric longitude of the sun, L_s
SubsolarLatitude_deg	The latitude of the sub-solar point at the current time
SubsolarLongitudeE_deg SubsolarLongitudeW_deg	The longitude of the sub-solar point at the current time. East positive or west positive as controlled by the input value *EastLongitudePositive*
LocalSolarTime_hr	The local solar time using 24 “hour” intervals
SolarZenithAngle_deg	The solar zenith angle
OneWayLightTime_min	One way light time to/from Earth and the current position
OrbitalRadius_AU	The current orbital radius of the planet
SecondsPerSol	The number of seconds in a local sol (planetary day)
TotalNumberDensity_m3	Number density of the atmosphere (#/m^3)
AverageMolecularWeight	Average molecular weight of the atmosphere (amu)
CompressibilityFactor	Compressibility factor (or zeta). This quantifies the deviation of a real gas from ideal gas behavior (zeta = 1 for ideal gases).
SpecificGasConstant_JkgK	Specific gas constant (J/(kg K))
SpecificHeatRatio	Specific heat ratio of the gas mixture.
CO2nd_m3	Number density of carbon dioxide (#/m^3)
CO2mass_pct	Carbon dioxide concentration, percent by mass
CO2mole_pct	Mole fraction (%) of carbon dioxide concentration (or % by volume)
CO2amw	Average molecular weight of carbon dioxide (amu)
COnd_m3	Number density of carbon monoxide (#/m^3)
COmass_pct	Carbon monoxide concentration, percent by mass
COmole_pct	Mole fraction (%) of carbon monoxide concentration (or % by volume)
COamw	Average molecular weight of carbon monoxide (amu)
N2nd_m3	Number density of molecular nitrogen (#/m^3)
N2mass_pct	Molecular nitrogen concentration, percent by mass
N2mole_pct	Mole fraction (%) of molecular nitrogen concentration (or % by volume)
N2amw	Average molecular weight of molecular nitrogen (amu)
Hend_m3	Number density of helium (#/m^3)
Hemass_pct	Helium concentration, percent by mass
Hemole_pct	Mole fraction (%) of helium concentration (or % by volume)
Heamw	Average molecular weight of helium (amu)
Hnd_m3	Number density of atomic hydrogen (#/m^3)
Hmass_pct	Atomic hydrogen concentration, percent by mass
Hmole_pct	Mole fraction (%) of atomic hydrogen concentration (or % by volume)
Hamw	Average molecular weight of atomic hydrogen (amu)
Nnd_m3	Number density of atomic nitrogen (#/m^3)
Nmass_pct	Atomic nitrogen concentration, percent by mass

Nmole_pct	Mole fraction (%) of atomic nitrogen concentration (or % by volume)
Namw	Average molecular weight of atomic nitrogen (amu)
Ond_m3	Number density of atomic oxygen (#/m^3)
Omass_pct	Atomic oxygen concentration, percent by mass
Omole_pct	Mole fraction (%) of atomic oxygen concentration (or % by volume)
Oamw	Average molecular weight of atomic oxygen (amu)

APPENDIX B – EXAMPLE NAMELIST FORMAT INPUT FILE

The following is an example of the NAMELIST format input file required by Venus-GRAM. Input data given here are provided as file ref_input.txt. Values given are the default values assigned by the program. Only values that differ from the defaults actually have to be included in the NAMELIST file.

```
$INPUT
 SpicePath              = '\spice'
 ListFileName           = 'NewLIST'
 ColumnFileName         = 'NewOUTPUT'
 EastLongitudePositive = 0

 TimeFrame = 1
 TimeScale = 1
 Month     = 8
 Day       = 25
 Year      = 2021
 Hour      = 15
 Minute    = 45
 Seconds   = 0.0

 InitialRandomSeed        = 1001
 DensityPerturbationScale = 1.0
 EWWindPerturbationScale  = 1.0
 NSWindPerturbationScale  = 1.0
 MinimumRelativeStepSize  = 0.0

 TrajectoryFileName = 'null'
 NumberOfPositions  = 201
 InitialHeight      = 0.0
 InitialLatitude    = 22.0
 InitialLongitude   = 48.0
 DeltaHeight        = 2.0
 DeltaLatitude      = 0.3
 DeltaLongitude     = 0.5
 DeltaTime          = 500.0

 AuxiliaryAtmosphereFileName = 'null'
 InnerRadius = 0.0
 OuterRadius = 0.0

 NumberOfMonteCarloRuns = 1

 FastModeOn        = 0
 ExtraPrecision    = 0
 UseLegacyOutputs  = 0
 DensityPrintScale = 0
$END

Explanation of variables:
 SpicePath         =  Path to NAIF Spice data
 ListFileName      =  List file name
 ColumnFileName    =  Output file name
 EastLongitudePositive =  0 for input and output West longitudes positive
                          1 for East longitudes positive

 TimeFrame = 0 Planet event time (PET)
             1 for time input as Earth-receive time (ERT)

 TimeScale = 0 for Terrestrial (Dynamical) Time (TDT)
             1 for time input as Coordinated Universal Time (UTC)
```

```
            2 for Barycentric Dynamical Time (TDB)
 Month     = month of year
 Day       = day of month
 Year      = year (4-digit, or 1970-2069 can be 2-digit)
 Hour      = hour of day (meaning controlled by TimeFrame and TimeScale)
 Minute    = minute of hour (meaning controlled by TimeFrame and TimeScale)
 Seconds   = seconds of minute (meaning controlled by TimeFrame and TimeScale)

 InitialRandomSeed        = starting random number (0 - 30000)

 DensityPerturbationScale = random perturbation scale factor for density (0 - 2)
 EWWindPerturbationScale  = random perturbation scale factor for east/west winds (0 -
2)
 NSWindPerturbationScale  = random perturbation scale factor for north/south winds (0
- 2)
 PerturbationScales       = sets all perturbation scale factors (0 - 2)
 MinimumRelativeStepSize = Minimum relative step size for perturbations(0 - 1)
                           0.0 means always update perturbations,
                           x.x means only update perturbations when relative
                           step size > x.x

 TrajectoryFileName = (Optional) Trajectory input file name
                      If present, then the values below are ignored
 NumberOfPositions  = number of positions to evaluate
 InitialHeight      = initial height (km)
 InitialLatitude    = initial latitude (N positive), degrees
 InitialLongitude   = initial longitude, degrees
                      (depends on EastLongitudePositive)
 DeltaHeight        = height increment (km) between steps
 DeltaLatitude      = latitude increment (deg) between steps
 DeltaLongitude     = longitude increment (deg) between steps
                      (depends on EastLongitudePositive)
 DeltaTime          = time increment (seconds) between steps


 AuxiliaryAtmosphereFileName = (Optional) auxiliary profile input file name
 InnerRadius = Lat-lon radius within which weight for auxiliary profile is 1.0
              (Use InnerRadius = 0.0 for no profile input)
 OuterRadius = Lat-lon radius beyond which weight for auxiliary profile is 0.0

 NumberOfMonteCarloRuns = the number of Monte Carlo runs

 FastModeOn        = Flags use of faster ephemeris computations (less accurate)
                     0 Most accurate ephemeris computations are used
                     1 Faster computations with slight loss in accuracy
 ExtraPrecision    = For the new column output format, this parameter
                     adds precision to all outputs
 UseLegacyOutputs  = Flags which outputs to generate
                     0 Use the new output formats
                     1 Use output formats closely matching those of the
                       legacy VenusGram
 DensityPrintScale = For legacy outputs only
                     0 regular SI units
                     1 log-base-10 scale
                     2 percentage deviations from Mean model
                     3 SI units with density in kg/km**3
```

The legacy form of the input parameters are supported for backwards compatibility. Some of the legacy input parameters are no longer used, such as *IUP*, *DATADIR*, *NVARX*, and *NVARY*. An example of the legacy input format is shown below.

```
$INPUT
  LSTFL     = 'LIST'
  OUTFL     = 'OUTPUT'
```

```
  TRAJFL    = 'TRAJDATA.txt'
  profile   = 'null'
  IERT      = 1
  IUTC      = 1
  Month     = 8
  Mday      = 25
  Myear     = 2021
  Ihr       = 0
  Imin      = 0
  Sec       = 0.0
  NPOS      = 201
  LonEast   = 0
  NR1       = 1001
  NVARX     = 1
  NVARY     = 0
  LOGSCALE  = 0
  FLAT      = 22.0
  FLON      = 48.0
  FHGT      = 0.0
  DELHGT    = 2.0
  DELLAT    = 0.3
  DELLON    = 0.5
  DELTIME   = 500.0
  profnear  = 0.0
  proffar   = 0.0
  rpscale   = 1.0
  NMONTE    = 1
  corlmin   = 0.0
$END

 Explanation of variables:
  LSTFL     =  List file name (CON for console listing)
  OUTFL     =  Output file name
  TRAJFL    =  (Optional) Trajectory input file name
  profile   =  (Optional) auxiliary profile input file name
  IERT      =  1 for time input as Earth-receive time (ERT), or 0
                Venus-event time (VET)
  IUTC      =  1 for time input as Coordinated Universal Time (UTC),
                or 0 for Terrestrial (Dynamical) Time (TT)
  MONTH     =  month of year
  MDAY      =  day of month
  MYEAR     =  year (4-digit, or 1970-2069 can be 2-digit)
  IHR       =  Hour of day (ERT or NET, controlled by IERT
                and UTC or TT, controlled by IUTC)
  IMIN      =  minute of hour (meaning controlled by IERT and IUTC)
  SEC       =  seconds of minute (meaning controlled by IERT and
                IUTC).  IHR:IMIN:SEC is time for initial position to
                be evaluated
  NPOS      =  max # positions to evaluate (0 = read data from
                trajectory input file)
  LonEast   =  0 for input and output West longitudes positive; 1 for
                East longitudes positive
  NR1       =  starting random number (0 < NR1 < 30000)
  LOGSCALE  =  0=regular SI units, 1=log-base-10 scale, 2=percentage
                deviations from Mean model, 3=SI units with density in
                kg/km**3
  FLAT      =  initial latitude (N positive), degrees
  FLON      =  initial longitude (West positive if LonEast=0 or East
                positive if LonEast = 1), degrees
  FHGT      =  initial height (km)
  DELHGT    =  height increment (km) between steps
  DELLAT    =  latitude increment (deg) between steps
  DELLON    =  longitude increment (deg) between steps (West positive
                if LonEast = 0, East positive if LonEast = 1)
```

```
DELTIME   =  time increment (seconds) between steps.  Time increment
              is in ERT or NET, as controlled by input parameter
              IERT, and UTC or TT, as controlled by input parameter
              IUTC
profnear  =  Lat-lon radius within which weight for auxiliary profile
              is 1.0 (Use profnear = 0.0 for no profile input)
proffar   =  Lat-lon radius beyond which weight for auxiliary profile
              is 0.0
rpscale   =  random perturbation scale factor (0-2)
NMONTE    =  number of Monte Carlo runs
corlmin   =  Minimum relative step size for perturbations
              (0.0 - 1.0); 0.0 means always update perturbations,
              x.x means only update perturbations when corlim > x.x
```

APPENDIX C – SAMPLE OUTPUT LIST FILE

Following is a portion of the LIST file output produced by the standard input parameters given in appendix B. The output data given below is provided in the file ref_LIST.md. This file allows users to complete a test run after compiling Venus-GRAM on their own computer and to electronically check their output by a file-compare process (e.g. the ‘diff’ command in UNIX or the ‘fc’ command from a Windows Command Prompt). Please note that, due to machine-dependent or compiler-dependent rounding differences, some output values may differ slightly from those shown here. These differences are usually no more than one unit in the last significant digit displayed.

Field	Value	Field	Value
Time Frame	Earth Receive Time (ERT)	Initial Random Seed	1001
Time Scale	Coordinated Universal Time (UTC)	Minimum Relative Step Size	0.000
Start Date	3/25/2020	Density Perturbation Scale	1.00
Start Time	12:30:00.00	EW Wind Perturbation Scale	1.00
Julian Day	2458934.020833	NS Wind Perturbation Scale	1.00

Record #1

Field	Value	Field	Value
Elapsed Time (s)	0.00	Elapsed Time (sols)	0.00
Height Above Ref. Ellipsoid (km)	0.000	Reference Radius (km)	6051.8
Latitude (deg)	22.000	Local Solar Time (hrs)	11.43
Longitude W (deg)	48.00	Longitude of the Sun (deg)	262.53
Pressure Scale Height (km)	15.819	Orbital Radius (AU)	0.72
Density Scale Height (km)	19.555	One Way Light Time (min)	5.86
Temperature (K)	735.3	Subsolar Latitude (deg)	-2.62
Pressure (Pa)	9.209e+06	Subsolar Longitude W (deg)	56.59
Sigma Level	1.000	Solar Zenith Angle (km)	26.01
Pressure Altitude (km)	-0.000	Gravity (m/s^2)	8.870
Surface Pressure (Pa)	9.209e+06	Speed of Sound (m/s)	419.043
Compressibility Factor (zeta)	1.0100	Specific Gas Constant (J/(kg K))	191.400
Specific Heat Ratio	1.235	Profile Weight	0.000

Density	Low	Average	High
Density (kg/m^3)	6.3520e+01	6.4790e+01	6.6086e+01
Density Deviation (%)	-2.0	0.0	2.0
Perturbed Density (kg/m^3)	6.5334e+01	Perturbation (%)	0.8
Perturbed Density Deviation (%)	0.84	Perturbed Speed of Sound (m/s)	417.30

Winds	Mean	Perturbation	Perturbed
Eastward Wind (m/s)	-1.0	-0.8	-1.8
Northward Wind (m/s)	-0.1	-0.1	-0.2

Gases	Number Density (#/m^3)	Mass (%)	Mole (%)	Avg Mol Wgt
Carbon Dioxide (CO2)	8.6675e+26	97.7	96.5	44.00
Carbon Monoxide (CO)	0.0000e+00	0.0	0.0	28.00
Dinitrogen (N2)	3.1437e+25	2.3	3.5	28.00
Helium (He)	0.0000e+00	0.0	0.0	4.00
Hydrogen (H)	0.0000e+00	0.0	0.0	1.01
Nitrogen (N)	0.0000e+00	0.0	0.0	14.00
Oxygen (O)	0.0000e+00	0.0	0.0	16.00
Total	8.9819e+26	100.0	100.0	43.44

Record #2

Field	Value	Field	Value
Elapsed Time (s)	500.00	Elapsed Time (sols)	0.00
Height Above Ref. Ellipsoid (km)	2.000	Reference Radius (km)	6051.8
Latitude (deg)	22.300	Local Solar Time (hrs)	11.46
Longitude W (deg)	48.50	Longitude of the Sun (deg)	262.54
Pressure Scale Height (km)	15.628	Orbital Radius (AU)	0.72
Density Scale Height (km)	19.290	One Way Light Time (min)	5.86
Temperature (K)	720.2	Subsolar Latitude (deg)	-2.62

Pressure (Pa)	8.109e+06	Subsolar Longitude W (deg)	56.57
Sigma Level	0.881	Solar Zenith Angle (km)	26.14
Pressure Altitude (km)	1.988	Gravity (m/s^2)	8.864
Surface Pressure (Pa)	9.209e+06	Speed of Sound (m/s)	413.884
Compressibility Factor (zeta)	1.0065	Specific Gas Constant (J/(kg K))	191.400
Specific Heat Ratio	1.235	Profile Weight	0.000

Density	Low	Average	High
Density (kg/m^3)	5.7304e+01	5.8450e+01	5.9619e+01
Density Deviation (%)	-2.0	-0.0	2.0
Perturbed Density (kg/m^3)	5.8677e+01	Perturbation (%)	0.4
Perturbed Density Deviation (%)	0.39	Perturbed Speed of Sound (m/s)	413.08

Winds	Mean	Perturbation	Perturbed
Eastward Wind (m/s)	-3.5	-2.1	-5.6
Northward Wind (m/s)	-0.2	-0.4	-0.6

Gases	Number Density (#/m^3)	Mass (%)	Mole (%)	Avg Mol Wgt
Carbon Dioxide (CO2)	7.8193e+26	97.7	96.5	44.00
Carbon Monoxide (CO)	0.0000e+00	0.0	0.0	28.00
Dinitrogen (N2)	2.8360e+25	2.3	3.5	28.00
Helium (He)	0.0000e+00	0.0	0.0	4.00
Hydrogen (H)	0.0000e+00	0.0	0.0	1.01
Nitrogen (N)	0.0000e+00	0.0	0.0	14.00
Oxygen (O)	0.0000e+00	0.0	0.0	16.00
Total	8.1030e+26	100.0	100.0	43.44

(Snipped for brevity)

Record #200

Field	Value	Field	Value
Elapsed Time (s)	99500.00	Elapsed Time (sols)	0.01
Height Above Ref. Ellipsoid (km)	398.000	Reference Radius (km)	6051.8
Latitude (deg)	81.700	Local Solar Time (hrs)	18.30
Longitude W (deg)	147.50	Longitude of the Sun (deg)	264.40
Pressure Scale Height (km)	135.114	Orbital Radius (AU)	0.72
Density Scale Height (km)	87.455	One Way Light Time (min)	5.78
Temperature (K)	220.0	Subsolar Latitude (deg)	-2.63
Pressure (Pa)	3.173e-09	Subsolar Longitude W (deg)	53.01
Sigma Level	0.000	Solar Zenith Angle (km)	93.25
Pressure Altitude (km)	4810.665	Gravity (m/s^2)	7.809
Surface Pressure (Pa)	9.209e+06	Speed of Sound (m/s)	1326.095
Compressibility Factor (zeta)	1.0000	Specific Gas Constant (J/(kg K))	4795.327
Specific Heat Ratio	1.667	Profile Weight	0.000

Density	Low	Average	High
Density (kg/m^3)	2.6148e-15	3.0070e-15	3.4581e-15
Density Deviation (%)	-1.8	13.0	29.9
Perturbed Density (kg/m^3)	2.6847e-15	Perturbation (%)	-10.7
Perturbed Density Deviation (%)	0.86	Perturbed Speed of Sound (m/s)	1403.45

Winds	Mean	Perturbation	Perturbed
Eastward Wind (m/s)	-75.8	-18.8	-94.6
Northward Wind (m/s)	-18.3	10.3	-8.0

Gases	Number Density (#/m^3)	Mass (%)	Mole (%)	Avg Mol Wgt
Carbon Dioxide (CO2)	2.7143e-07	0.0	0.0	44.00
Carbon Monoxide (CO)	6.1375e+00	0.0	0.0	28.00
Dinitrogen (N2)	4.8449e+00	0.0	0.0	28.00
Helium (He)	2.5274e+11	55.8	24.2	4.00
Hydrogen (H)	7.9165e+11	44.2	75.8	1.01
Nitrogen (N)	1.5935e+06	0.0	0.0	14.00
Oxygen (O)	2.0449e+07	0.0	0.0	16.00
Total	1.0444e+12	100.0	100.0	1.73

Record #201

Field	Value	Field	Value
Elapsed Time (s)	100000.00	Elapsed Time (sols)	0.01

```
| Height Above Ref. Ellipsoid (km)  | 400.000    | Reference Radius (km)            | 6051.8      |
| Latitude (deg)                    | 82.000     | Local Solar Time (hrs)           | 18.33       |
| Longitude W (deg)                 | 148.00     | Longitude of the Sun (deg)       | 264.41      |
| Pressure Scale Height (km)        | 136.445    | Orbital Radius (AU)              | 0.72        |
| Density Scale Height (km)         | 88.220     | One Way Light Time (min)         | 5.78        |
| Temperature (K)                   | 219.9      | Subsolar Latitude (deg)          | -2.63       |
| Pressure (Pa)                     | 3.136e-09  | Subsolar Longitude W (deg)       | 52.99       |
| Sigma Level                       | 0.000      | Solar Zenith Angle (km)          | 93.30       |
| Pressure Altitude (km)            | 4859.618   | Gravity (m/s^2)                  | 7.804       |
| Surface Pressure (Pa)             | 9.209e+06  | Speed of Sound (m/s)             | 1332.197    |
| Compressibility Factor (zeta)     | 1.0000     | Specific Gas Constant (J/(kg K)) | 4842.977    |
| Specific Heat Ratio               | 1.667      | Profile Weight                   | 0.000       |

| Density                           | Low        | Average                          | High        |
|-----------------------------------|------------|----------------------------------|-------------|
| Density (kg/m^3)                  | 2.5613e-15 | 2.9454e-15                       | 3.3873e-15 |
| Density Deviation (%)             | -1.4       | 13.3                             | 30.3        |
| Perturbed Density (kg/m^3)        | 2.7174e-15 | Perturbation (%)                 | -7.7        |
| Perturbed Density Deviation (%)   | 4.57       | Perturbed Speed of Sound (m/s)   | 1386.97     |

| Winds                             | Mean          | Perturbation  | Perturbed     |
|-----------------------------------|---------------|---------------|---------------|
| Eastward Wind  (m/s)              | -73.4         | -14.8         | -88.2         |
| Northward Wind  (m/s)             | -20.5         | 11.7          | -8.8          |

| Gases                 | Number Density (#/m^3) | Mass (%) | Mole (%) | Avg Mol Wgt |
|-----------------------|------------------------|----------|----------|-------------|
| Carbon Dioxide (CO2)  | 1.7817e-07             | 0.0      | 0.0      | 44.00       |
| Carbon Monoxide (CO)  | 4.7023e+00             | 0.0      | 0.0      | 28.00       |
| Dinitrogen (N2)       | 3.7140e+00             | 0.0      | 0.0      | 28.00       |
| Helium (He)           | 2.4414e+11             | 55.1     | 23.6     | 4.00        |
| Hydrogen (H)          | 7.8903e+11             | 44.9     | 76.4     | 1.01        |
| Nitrogen (N)          | 1.3946e+06             | 0.0      | 0.0      | 14.00       |
| Oxygen (O)            | 1.7570e+07             | 0.0      | 0.0      | 16.00       |
| Total                 | 1.0332e+12             | 100.0    | 100.0    | 1.72        |

--------------------
## End of data
--------------------
```

The list file is formatted using the Markdown syntax. The file can also be displayed using a Markdown viewer. A sample of the Markdown output is shown below. Most web browsers support Markdown via extensions/add-ons or through online Markdown editors. The ‘Markdown Viewer’ extension is suggested for Chrome and the ‘Markdown Viewer Webext’ works well in Firefox. Installable Markdown viewers are available on all platforms. On Windows, the Notepad++ application has a ‘Markdown++’ plugin which displays Markdown with exports to html or pdf formats. For command line users, Pandoc will convert Markdown (use –f gfm) to a host of familiar rich text formats. The example below used Pandoc to convert Markdown to Open Document format.

Field	**Value**	**Field**	**Value**
Time Frame	Earth Receive Time (ERT)	Initial Random Seed	1001
Time Scale	Coordinated Universal Time (UTC)	Minimum Relative Step Size	0.000
Start Date	3/25/2020	Density Perturbation Scale	1.00
Start Time	12:30:00.00	EW Wind Perturbation Scale	1.00
Julian Day	2458934.020833	NS Wind Perturbation Scale	1.00

Record #1

Field	**Value**	**Field**	**Value**
Elapsed Time (s)	0.00	Elapsed Time (sols)	0.00
Height Above Ref. Ellipsoid (km)	0.000	Reference Radius (km)	6051.8
Latitude (deg)	22.000	Local Solar Time (hrs)	11.43

Longitude W (deg)	48.00	Longitude of the Sun (deg)	262.53
Pressure Scale Height (km)	15.819	Orbital Radius (AU)	0.72
Density Scale Height (km)	19.555	One Way Light Time (min)	5.86
Temperature (K)	735.3	Subsolar Latitude (deg)	-2.62
Pressure (Pa)	9.209e+06	Subsolar Longitude W (deg)	56.59
Sigma Level	1.000	Solar Zenith Angle (km)	26.01
Pressure Altitude (km)	-0.000	Gravity (m/s^2)	8.870
Surface Pressure (Pa)	9.209e+06	Speed of Sound (m/s)	419.043
Compressibility Factor (zeta)	1.0100	Specific Gas Constant (J/(kg K))	191.400
Specific Heat Ratio	1.235	Profile Weight	0.000

Density	**Low**	**Average**	**High**
Density (kg/m^3)	6.3520e+01	6.4790e+01	6.6086e+01
Density Deviation (%)	-2.0	0.0	2.0
Perturbed Density (kg/m^3)	6.5334e+01	Perturbation (%)	0.8
Perturbed Density Deviation (%)	0.84	Perturbed Speed of Sound (m/s)	417.30

Winds	**Mean**	**Perturbation**	**Perturbed**
Eastward Wind (m/s)	-1.0	-0.8	-1.8
Northward Wind (m/s)	-0.1	-0.1	-0.2

Gases	**Number Density (#/m^3)**	**Mass (%)**	**Mole (%)**	**Avg Mol Wgt**
Carbon Dioxide (CO2)	8.6675e+26	97.7	96.5	44.00
Carbon Monoxide (CO)	0.0000e+00	0.0	0.0	28.00
Dinitrogen (N2)	3.1437e+25	2.3	3.5	28.00
Helium (He)	0.0000e+00	0.0	0.0	4.00
Hydrogen (H)	0.0000e+00	0.0	0.0	1.01
Nitrogen (N)	0.0000e+00	0.0	0.0	14.00
Oxygen (O)	0.0000e+00	0.0	0.0	16.00
Total	8.9819e+26	100.0	100.0	43.44

Many of the Markdown viewers allow customization of the table formats using Cascading Style Sheets (CSS). The following CSS snippet will give the table layout a nice look and feel. Search the options of the Markdown viewer for custom CSS.

```
table {
  width: 100%;
  margin-top: 10px;
  border-collapse: collapse; }
table tr {
  border-top: 1px solid silver;
  background-color: white; }
table tr:nth-child(2n) {
  background-color: whitesmoke; }
table tr th {
```

```
  font-weight: bold;
  border: 1px solid silver;
  background-color: lightgray;
  text-align: left;
  padding: 2px 8px; }
table tr td {
  border: 1px solid silver;
  text-align: left;
  padding: 1px 8px;}
```

APPENDIX D – SUMMARY OF FILES PROVIDED WITH VENUS-GRAM

The following are provided with the Venus-GRAM distribution:

- Build: A makefile system for building the GRAM Suite.
- MSVS: A Visual Studio solution for building the GRAM Suite (no Fortran).
- Documentation: A User Guide, a Programmer's Manual, and a GRAM Suite change log.
- Windows: Binary executables and libraries (64-bit) for Windows.
- Linux: Binary executables and libraries (64-bit) for Linux.
- common: A framework shared by all GRAM models:
    - include: Header files for the model
    - source: Source code for the model
    - examples: Generic example functions
    - unittest: Source code for unit tests
    - cspice: Headers and libraries for the NAIF SPICE toolkit
    - googletest: Headers and source for the unit test framework
- Venus: The model-specific code, examples, and tests for each planet
    - include: Header files for the model
    - source: Source code for the model
    - examples: Examples and the GRAM program for this model
    - unittest: Source code for unit tests
    - sample_inputs: Sample input parameter files and resulting outputs
    - md files: Markdown files used to build the Programmer's Manual
- GRAM: Source files for examples that combine all GRAM models.
- Doxyfile and DoxygenLayout.html: Configuration files used to generate the Programmer's Manual

APPENDIX E – BUILDING VENUS-GRAM

The Venus-GRAM distribution contains 64-bit executables and libraries for Windows in the folder /GRAM/Windows. These binaries were compiled with Microsoft Visual Studio 2017 using the solution /GRAM/MSVS/GRAMs.sln. To rebuild these binaries:

(1) Open the solution in MSVS 2017.
(2) Set the Solution Configuration to *Release*.
(3) Set the Solution Platform to *x64*.
(4) From the Build menu, select *Rebuild Solution*.

The resulting binaries will be found in /GRAM/MSVS/x64/Release. It is possible to use MSVS 2015 to build Venus-GRAM. Instructions can be found in the first chapter of the GRAM Programmer's Manual.

To build Venus-GRAM on other operating systems or other compilers, a GNU makefile system is provided in the /GRAM/Build folder. The process for building the executables and libraries is:

(1) Set the build environment in makefile.defs.
(2) Enter the command “make clean”.
(3) Enter the command “make –j”.

The resulting executables will be placed in /GRAM/Build/bin. Libraries will be placed in /GRAM/Build/lib. The makefile system parameters are defined in the file makefile.defs. The current settings work on a Linux platform or under MSYS2 using the GCC compiler suite version 6.3 or later. The key parameters in this file are:

- CXX, CC, FF, LNK
    - The command that invokes the C++ compiler, C compiler, Fortran compiler, and the linker, respectively.
- CXX_FLAGS
    - Must be set to use the C++11 standard.
- C_FLAGS
    - Must be set to use the C99 standard.
- F_FLAGS
    - Must be set to use the Fortran 2003 standard.
- SPICE_LIB
    - Path to the NAIF CSPICE library.

The above processes use pre-built SPICE libraries that were compiled following the cspice instructions (version N0066). These libraries are found in /GRAM/common/cspice/lib. To rebuild these libraries, please refer to the README.txt file that comes with the appropriate CSPICE toolkit. The toolkits can be obtained from https://naif.jpl.nasa.gov/naif/toolkit_C.html.

APPENDIX F – HISTORY OF VENUS-GRAM VERSION REVISIONS

Table 5. Venus-GRAM version revisions.

Version	Date	Comments
2004 beta	3/2004	First release for Aerocapture Systems Analysis Team. Dependence of mean atmospheric parameters on height, latitude, and time-of-day (or solar zenith angle) is based on Kliore, A. J., V. I. Moroz, and G. M. Keating (1986), "The Venus International Reference Atmosphere", Advances in Space Research, vol. 5, no. 11, 1985, pages 1-304, Pergamon Press, Oxford, referred to in comments within the program code as VIRA. To facilitate comparisons with Venus probe data (Veneras, Pioneers, Vegas), a new feature was added to output temperature +/- 1-sigma, and perturbed temperature on the TPresHgt.txt file.
2005 Version 1	3/2005	Added option to substitute auxiliary input profile of thermodynamic and/or wind data for VIRA climatology, within user-specified region. Use of this option is controlled by (optional) input profile file name and parameters profnear and proffar. Converted to option for long file names for LIST, OUTPUT, TRAJECTORY files, etc. (up to character*60). In order for users implementing multiple atmospheric models into one trajectory code to avoid duplication of names for source code files, subroutines, functions, and common blocks, suffix '_V05' was appended to all these names. No suffix was appended in source code for auxiliary programs (e.g. finddate.f). Modified routine to automatically generate random seed numbers. Added time effect on perturbation model correlation.
2005 Version 2	10/2009	Modified northward wind component factor times eastward wind component. Corrected low-altitude (0-82 km) interpolation in subroutine LowTerp.
2021	8/2021	The ephemeris engine has been replaced with the NAIF SPICE library. Code has been converted to a C++ framework. LIST and OUTPUT file formats have been updated. Input parameter names have been updated to be more descriptive. Planetary constants have been updated. Venus-GRAM now computes speed of sound based on a thermodynamic parameterization using density, pressure, and γ, the ratio of specific heats, for a given constituent gas mixture. Venus-GRAM previously used a constant γ, which is physically unrealistic and overestimates the speed of sound by as much as 10%. Venus-GRAM now uses an improved methodology for computing γ, involving temperature and pressure dependent tables of C_V and C_P evaluated in run-time for the current constituent combination.

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