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

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April 2020

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Neptune-GRAM was originally developed under the leadership of Dr. Carl Gerald (Jere) Justus. The first release of Neptune-GRAM occurred in September 2004. In 2020, Neptune-GRAM was rereleased after being converted to the GRAM common framework. A complete history of Neptune-GRAM version revisions is contained in appendix F.

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PREFACE

The 2020 version of the NASA Marshall Space Flight Center (MSFC) Neptune Global Reference Atmospheric Model (Neptune-GRAM) was developed by the Natural Environments Branch, Spacecraft and Vehicle Systems Department, Engineering Directorate of MSFC.

Information on obtaining Neptune-GRAM code and data can be found in 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
FTP	File Transfer Protocol
GRAM	Global Reference Atmospheric Model
IRIS	Infrared Interferometer Spectrometer and Radiometer
Ls	longitude of the Sun
LTST	local true solar time
MSFC	Marshall Space Flight Center
NAIF	NASA's Navigation and Ancillary Information Facility
Neptune-GRAM	Neptune Global Reference Atmospheric Model
NET	Neptune event time
SMD	Science Mission Directorate
SPICE	Spacecraft Planet Instrument C-matrix Events
UVS	Ultraviolet Spectrometer

TECHNICAL MEMORANDUM

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

1. INTRODUCTION

1.1 Background and Overview

Engineers and mission planners designing vehicles that pass through Neptune's atmosphere require an atmospheric model that calculates the mean values and variations of atmospheric properties. The Neptune Global Reference Atmospheric Model (Neptune-GRAM)[1] is an engineering-oriented model that provides this critical information based on data from Voyager observations. Neptune-GRAM is designed to offer mission planners the flexibility to select input parameters such as local solar time, latitude and longitude, and season. Neptune-GRAM outputs mean, maximum, and minimum values for atmospheric density, temperature, pressure, winds, and constituents along a user-defined path. Neptune-GRAM also provides dispersions of winds and density. The computation of density and its variability is vital as density directly affects the drag force and, thus, the trajectory of the vehicle.

A Fortran version of Neptune-GRAM was originally released in 2004. Recently, the code has been updated and rearchitected in C++ to improve efficiencies in implementation, run time, and maintenance. Neptune-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 Technical Memorandum summarizes the atmospheric data model in Neptune-GRAM and provides a guide for the user to obtain, set up, and run the code in various configurations. Section 2 describes the input atmospheric data files and how they are used in Neptune-GRAM. Section 3 explains the process to obtain the Neptune-GRAM code and data files and how to set up and run the program. Appendices A through E provide additional details regarding the Neptune-GRAM input and output files and how to interpret program results. Appendix F provides a history of Neptune-GRAM revisions. Finally, it is noted that, due to the lack of data at Neptune, Neptune-GRAM is not a 'global reference' model in its current form. However, future versions of Neptune-GRAM will include more comprehensive models as modeling techniques improve and additional data are available.

1.2 Significant Changes in Neptune-GRAM

While the atmosphere model data used in Neptune-GRAM have not changed from Neptune-GRAM 2004, several major code modifications have been made to improve efficiencies in implementation, run time, and maintenance. The major updates to Neptune-GRAM are as follows:

(1) The Neptune-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 Neptune-GRAM versions. Table 3 in section 3.3 provides the new and old input parameter names.

(2) The code has incorporated the Navigation and Ancillary Information Facility (NAIF) Spacecraft Planet Instrument C-matrix Events (SPICE) library for ephemeris calculations. Neptune 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 Neptune-GRAM 2004 ephemeris engine. While the values produced by the new and legacy Neptune-GRAMs will compare favorably, slight differences in the Min/Max Factor are observed. Details of the Min/Max Factor are discussed in section 2.1.2. Additionally, the use of NAIF SPICE requires the Neptune-GRAM user to download the latest SPICE data before using Neptune-GRAM. Instructions for doing so are provided in section 3.2.

(3) Due to the increase in computing power and memory since the original release of Neptune-GRAM in 2004, 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 all of the column formatted output files from the original release of Neptune-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 an 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.

(4) The primary changes in this version of Neptune-GRAM involve a rearchitecture from Fortran to a common object-oriented C++ framework. The new architecture creates a common GRAM library of data models and utilities. Additionally, upon release of all the rearchitected GRAM models the user will be able to compile the GRAMs into a single library containing GRAM atmospheric data for multiple destinations. The common C++ framework 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. NEPTUNE-GRAM ATMOSPHERIC DATA

2.1 Neptune-GRAM Input Data

2.1.1 Overview of Neptune-GRAM Data

The atmospheric input data for the Neptune-GRAM model are from figures in *Neptune and Triton*.[2] These data are based on observations from Voyager radio science, Infrared Interferometer Spectrometer and Radiometer (IRIS), and the Ultraviolet Spectrometer (UVS). The data profiles provide an adequate fit to all three sources of variations and uncertainties: (1) uncertainties in the analysis of the Voyager data, (2) estimated range of latitudinal variations in atmospheric structure, and (3) temporal changes in the atmosphere due to seasonal and diurnal variations.

The data consist of profiles of average, minimum, and maximum temperature values. Additional thermodynamic values have been derived from the data using hydrostatics and the ideal gas law. The data have been extended in altitude by utilizing a simple thermospheric model that includes diffusive separation.

The temperature profile data for the middle and upper atmosphere are taken directly from Bishop et al.,[3] the troposphere from Gautier et al.,[4] and the troposphere and stratosphere (including gravity wave perturbations) from Ingersoll et al.[5] Exospheric temperatures are from Bishop et al.[3] A plot of the data, as it has been incorporated in Neptune-GRAM, is provided in figures 1 and 2 of this document.

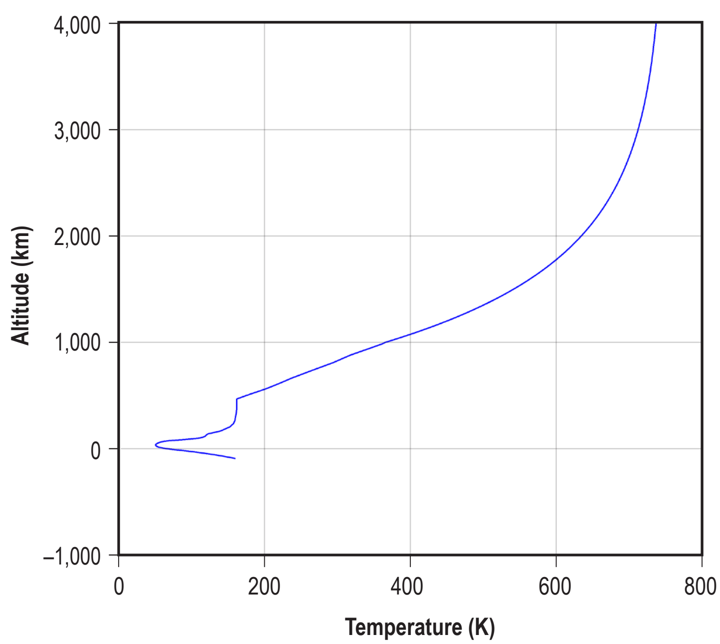

Figure 1. Altitude versus temperature for netavg.txt profile.

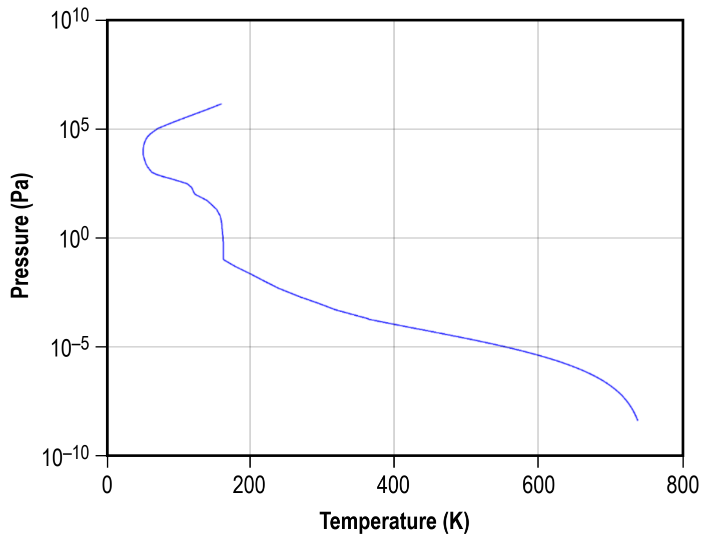

Figure 2. Pressure versus temperature for netavg.txt profile.

Density perturbation magnitudes are estimated using

$$\rho' = \rho_0 \left(1 + R' P_F P_U\right) \tag{1}$$

and

$$R' = e^{-S} R + X\sqrt{1 - e^{-2S}} \quad , \tag{2}$$

where ρ' is the perturbed value of atmospheric density, ρ_0 is the mean value of atmospheric density, R' is the correlation factor for the current time step, P_F is the modeled perturbation factor (typically height dependent), P_U is the user-supplied perturbation multiplier, S is the relative displacement from the last time step using NS, EW, vertical movement, and winds, R is the correlation factor for the previous time step, and the value of X is provided by a random number generator. Note that for small relative displacements, the new correlation factor is close to the previous correlation factor ($R' \approx R$). And, for large relative displacements, the new correlation factor is essentially random ($R' \approx X$).

The basic zonal wind model is from Ingersoll et al.[5] Latitudinal variation of the zonal wind is from the second equation on page 143 of "Huygens Science, Payload and Mission," ESA SP-1177,[6] fit to Neptune data, and figure 26 of Ingersoll et al.[5] Wind perturbation magnitudes are from Ingersoll et al.[5] The wind perturbations in Neptune-GRAM are shown in figures 3 and 4 of this document.

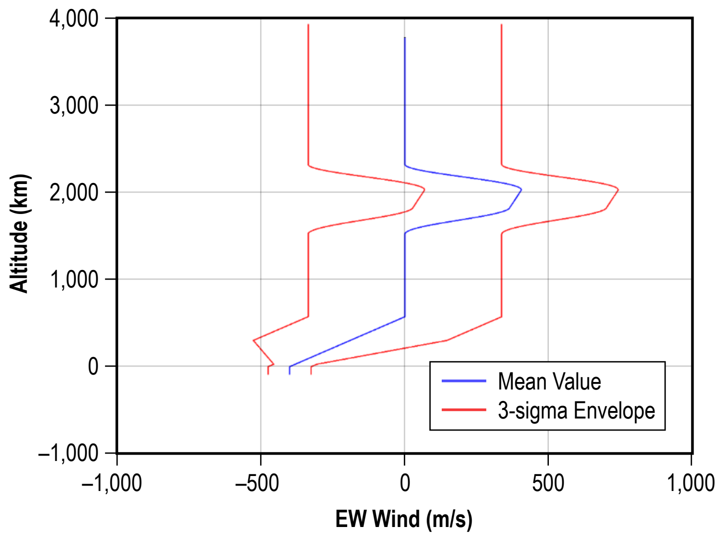

Figure 3. Three-sigma envelope of Neptune-GRAM east (positive)/west (negative) wind.

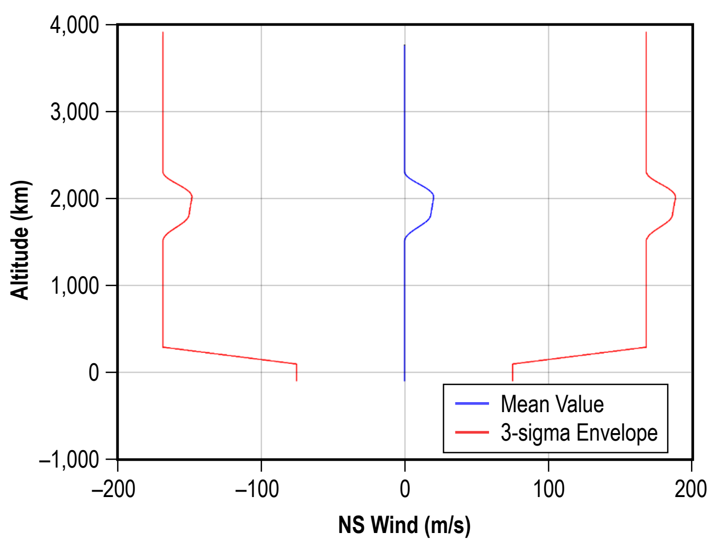

Figure 4. Three-sigma envelope of Neptune-GRAM north (positive)/south (negative) wind.

Latitude gradient estimates of temperature are from figure 11 of Ingersoll et al.[5] Methane model fractions are from information contained in Orton et al.,[7] Yelle et al.,[8] and Bishop et al.[3] Constituent contributions are shown in figure 5 of this document. Planetary constants (radius, gravity, etc.) are from the Planetary Data System "Standard Planetary Information, Formulae and Constants" Web page: http://atmos.nmsu.edu/jsdap/encyclopediawork.html . Table 1 provides the Neptune gravity parameter data that are utilized in Neptune-GRAM.

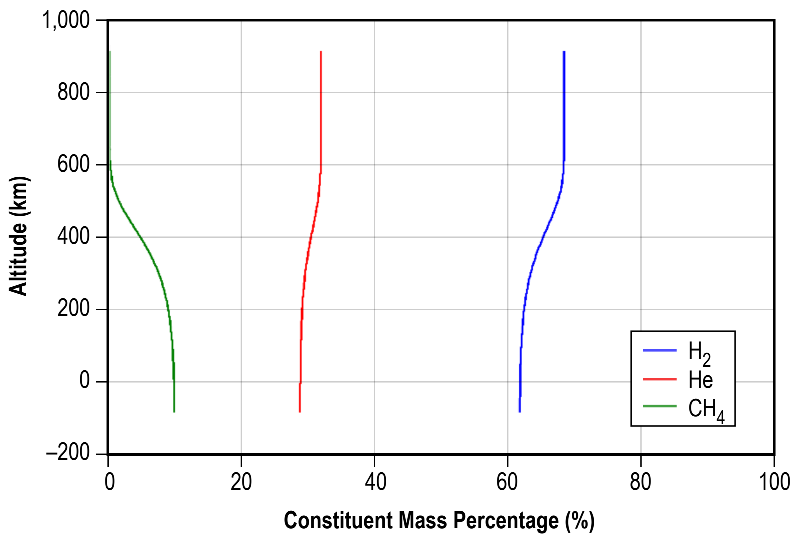

Figure 5. Mean constituent contributions by percent.

Table 1. Neptune gravity parameters.

Neptune	Label	Units	Value
Gravitational parameter	GM	km^3/s^2	6835099.5
Mean equatorial radius	R_e	km	24764.0
Mean polar radius	R_p	km	24341.0
J_2 harmonic	J_2	–	3411e-6
Period	–	s	57996.0

2.1.2 Input Parameter *MinMaxFactor*

Neptune-GRAM does not explicitly compute time-dependent or latitude-dependent atmospheric values. Neptune-GRAM includes a minimum-to-maximum envelope of Neptune data that contains variations of the mean with respect to latitude, season, and time of day. By selecting the appropriate value for the input parameter *MinMaxFactor*, a mean profile can be generated within the minimum-to-maximum envelope.

MinMaxFactor (previously known as *Fminmax*) determines where, within the envelope of minimum-to-maximum conditions, a given atmospheric profile falls. *MinMaxFactor* can be any real number between –1 (minimum) and 1 (maximum). *MinMaxFactor* = 0 gives the nominal Neptune profile. Neptune-GRAM has a built-in routine for generating random high-frequency perturbations about the selected mean profile. The amplitude of the perturbation variations, especially at high altitudes, will extend beyond the range of maximum-to-minimum bounds in the Neptune model envelope. Users wishing to vary mean atmosphere profiles (in a Monte Carlo sense) between Neptune minimum and maximum profiles can do so by randomly selecting values of *MinMaxFactor* between –1 and 1. *MinMaxFactor* values between –1 and 0 are automatically interpolated between minimum and average conditions. Likewise, *MinMaxFactor* values between 0 and 1 are automatically interpolated between average and maximum conditions. Figure 6 illustrates the relationship between *MinMaxFactor* and the computed mean and perturbed density profiles.

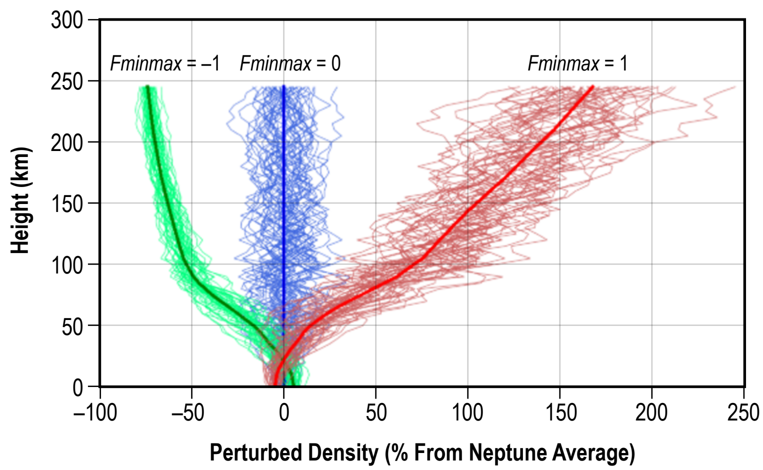

Figure 6. *MinMaxFactor* (*Fminmax*) and Neptune-GRAM computed densities for a sample Monte Carlo output.

Users wishing to more explicitly account for latitudinal, seasonal, and time-of-day effects on locations within the minimum-maximum envelope may be guided by table 2 in selecting values for *MinMaxFactor*. The input parameter *ComputeMinMaxFactor* (alternatively *IFMM*) may be utilized to automatically adjust *MinMaxFactor* for seasonal, latitude, and time-of-day effects. Allowable values for *ComputeMinMaxFactor* are 1 (automatically adjust *MinMaxFactor* for seasonal, latitude, and time of day) and 0 (do not automatically adjust *MinMaxFactor*).

Table 2. Guide for user-selected *MinMaxFactor* values.

Effect	*MinMaxFactor* Negative	*MinMaxFactor* Near 0	*MinMaxFactor* Positive
Latitudinal/seasonal	Winter/polar latitudes	Near-equatorial latitudes Equinox, all latitudes	Summer/polar latitudes
Time of day	Night	Near twilight	Day

2.2 Querying Atmosphere Data

The Neptune-GRAM user-defined path can be generated in multiple ways. The first is to run Neptune-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, Neptune-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 Neptune-GRAM code directly into a user's trajectory code. This version of Neptune-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, Neptune-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, Neptune-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 are described in section 2.2.

Using a user-generated trajectory file, specified using the input parameter *Trajectory-FileName,* that contains a specified time history of altitude, latitude, and longitude, removes the constant increment constraint criteria. The Neptune-GRAM perturbation model uses the time, altitude, latitude, and longitude changes from the previous perturbation update to provide the perturbations and will result in the trajectory evaluation method providing more realistic perturbations than the *NumberOfMonteCarloRuns* option.

Running Neptune-GRAM directly in a trajectory 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 Neptune-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 Option

The auxiliary atmosphere option provides the user with the ability to overwrite the atmosphere model in Neptune-GRAM with a profile of atmosphere quantities versus altitude. This option is controlled by setting input parameters *AuxiliaryAtmosphereFileName*, *profileWeight*, *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 Neptune-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 Neptune-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. The *OuterRadius* is the latitude-longitude radius (degrees) beyond which weight for the auxiliary atmosphere profile is 0.0. Mean conditions are specified by the auxiliary atmospheric profile input file if the desired point is within the *InnerRadius* from the auxiliary profile latitude and longitude location at the given altitude; mean conditions are given by the standard Neptune-GRAM data if the desired point is beyond the *OuterRadius* from the latitude and longitude location of the auxiliary atmosphere profile at the given altitude. An illustration of the fairing occurring between the *InnerRadius* and *OuterRadius* is provided in figure 7. If *InnerRadius* = 0, then the auxiliary atmosphere profile data are not used. The profile weight factor (*profileWeight*) for the auxiliary atmosphere profile also 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). First and second auxiliary atmosphere profile points (and next-to-last and last auxiliary atmosphere profile points) should therefore be selected to be wide 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.

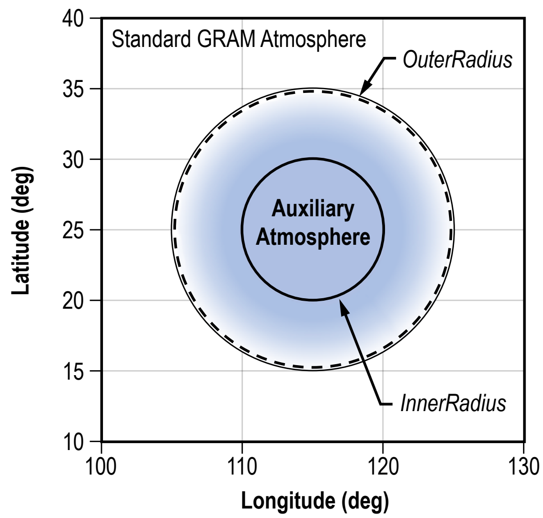

Figure 7. Illustration of auxiliary profile faring implementation with *InnerRadius* = 5° and *OuterRadius* = 10° for a vertical auxiliary profile located at latitude = 25° and longitude = 115°.

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 Neptune-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 NEPTUNE-GRAM

3.1 How to Obtain the Program

Neptune-GRAM is available through the NASA Software Catalog: https://software.nasa.gov. The software is offered free of charge. See appendices D through F for summaries of the program and data files available in the downloadable file.

3.2 Running the Program

The Neptune-GRAM installation includes a set of Windows and Linux 64-bit executable libraries located in the GRAM/Windows and GRAM/Linux folders. The Neptune-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 Neptune-GRAM, the NAIF SPICE data files must be downloaded. These data are available via File Transfer Protocol (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 Neptune-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 Neptune-GRAM, simply double-click the NeptuneGRAM.exe file or enter 'NeptuneGRAM.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/Neptune/sample_inputs folder. On exit, the program will name the output files generated. In this case, they will be myref_LIST.md and myref_OUTPUT.csv. Both files are plain text and can be viewed in a text editor, such as WordPad, with no word wrapping. The myref_OUTPUT.csv file is best viewed using a spreadsheet program such as 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 Neptune-GRAM command line. The format of this option is 'NeptuneGRAM.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

Neptune-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 Neptune-GRAM. All input parameter names are case insensitive. Input parameters whose values are supplied in the input file are as follows (the legacy Neptune-GRAM input parameter names are still supported and appear in parentheses) (see table 3):

Table 3. Neptune-GRAM 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
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>
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

Table 3. Neptune-GRAM input parameters (Continued).

Input Parameter	Description	Default
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
Perturbation Parameters		
InitialRandomSeed (NR1)	The integer seed value for the random number generator. The allowable range is 1 to 29999. To do Monte Carlo simulations with a variety of perturbations, use a different random number seed on each model run. To repeat a given random number sequence on a later model run, use the same random number seed value.	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		
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
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>

Table 3. Neptune-GRAM input parameters (Continued).

Input Parameter	Description	Default
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 Neptune-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 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)	0
Neptune Parameters		
MinMaxFactor (FMINMAX)	This parameter determines where within the envelope of minimum-to-maximum a given profile falls. *MinMaxFactor* can be any real number between -1.0 (minimum) and +1.0 (maximum). *MinMaxFactor* = 0.0 gives the average (nominal) Neptune profile.	0.0
ComputeMinMaxFactor (IFMM)	Set to 1 to automatically adjust input *MinMaxFactor* for seasonal, latitude, and time-of-day effects. Set to 0 to use the input *MinMaxFactor* "as is".	1
DinitrogenMoleFraction (FMOLNITRO)	Mole fraction (0.0 to 0.6) of molecular nitrogen (N_2).	0.0

3.4 Program Output

There are two general types of program output provided by Neptune-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 plaintext 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 Neptune-GRAM distribution includes sample files ref_input.txt and traj_input.txt for application in a reference test run. To verify the Neptune-GRAM build, execute *NeptuneGRAM.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

Neptune-GRAM allows the user to calculate areocentric longitude of the Sun (Ls) and Neptune local true solar time (LTST) for a given date and time. It also computes the Earth date and time of the next closest occurrence to the initial input date and time for which Ls and LTST are any desired values. The SPICE data are required for this capability. The FindDates capability is contained within the Neptune-GRAM program and controlled via the usual NAMELIST inputs. This utility is controlled by the *FindDates* input parameter (see table 4). The utility will return three dates: the date of the target Ls and the two dates of the target LTST that immediately precede and follow the target Ls date.

Table 4. 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 Neptune-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 NEPTUNE-GRAM OUTPUT FILE

Neptune-GRAM produces a CSV output file (see table 5) 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 5. 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

Table 5. OUTPUT.csv (or as prescribed in the *ColumnFileName* input parameter) (Continued).

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, Ls
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.
H2nd_m3	Number density of molecular hydrogen (#/m^3)
H2mass_pct	Molecular hydrogen concentration, percent by mass
H2mole_pct	Mole fraction (%) of molecular hydrogen concentration (or % by volume)
H2amw	Average molecular weight of molecular hydrogen (amu)
H2cp_JgK	Specific heat capacity by constant pressure (J/(g K))
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)
Hecp_JgK	Specific heat capacity by constant pressure (J/(g K))
CH4nd_m3	Number density of methane (#/m^3)
CH4mass_pct	Methane concentration, percent by mass
CH4mole_pct	Mole fraction (%) of methane concentration (or % by volume)
CH4amw	Average molecular weight of methane (amu)
CH4cp_JgK	Specific heat capacity by constant pressure (J/(g K))
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)
N2cp_JgK	Specific heat capacity by constant pressure (J/(g K))
MinMaxFactor	The computed min/max factor

APPENDIX B—EXAMPLE NAMELIST FORMAT INPUT FILE

The following is an example of the NAMELIST format input file required by Neptune-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      = 89
 Hour      = 0
 Minute    = 0
 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        = 20.0
 DeltaLatitude      = 0.3
 DeltaLongitude     = 0.5
 DeltaTime          = 500.0

 AuxiliaryAtmosphereFileName = 'null'
 InnerRadius = 0.0
 OuterRadius = 0.0

 NumberOfMonteCarloRuns = 1

 MinMaxFactor           = 0.0
 ComputeMinMaxFactor    = 1
 DinitrogenMoleFraction = 0.0

 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

 MinMaxFactor           = Factor (-1. to +1. to vary between minimum and
                          maximum allowed mean profiles
 ComputeMinMaxFactor    = 0 to use Fminmax input value "as is"
                          1 to automatically adjust input the factor for
                            seasonal, latitude, and time-of-day effects
 DinitrogenMoleFraction = N2 mole fraction (0.0 to 0.6)
```

```
  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 NeptuneGram
  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     = 89
  Ihr       = 0
  Imin      = 0
  Sec       = 0.0
  NPOS      = 201
  LonEast   = 0
  Fminmax   = 0.0
  IFMM      = 1
  NR1       = 1001
  NVARX     = 1
  NVARY     = 0
  LOGSCALE  = 0
  FLAT      = 22.0
  FLON      = 48.0
  FHGT      = 0.0
  DELHGT    = 20.0
  DELLAT    = 0.3
  DELLON    = 0.5
  DELTIME   = 500.0
  profnear  = 0.0
  proffar   = 0.0
  rpscale   = 1.0
  NMONTE    = 1
  corlmin   = 0.0
  fmolnitro = 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
               Neptune-event time (NET)
 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
 Fminmax   =  Factor (-1. to +1. to vary between min and max allowed
               mean profiles
 IFMM      =  1 to automatically adjust input Fminmax for seasonal,
               latitude, and time-of-day effects, or 0 to use Fminmax
               input value "as is"
 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
 fmolnitro =  N2 mole fraction (0.0 to 0.6)
```

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 are provided in the file ref_LIST.md. This file allows users to complete a test run after compiling Neptune-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	8/25/2021	Density Perturbation Scale	1.00
Start Time	15:45:00.00	EW Wind Perturbation Scale	1.00
Julian Day	2459452.156250	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)	24703.3
Latitude (deg)	22.000	Local Solar Time (hrs)	3.71
Longitude W (deg)	48.00	Longitude of the Sun (deg)	305.67
Pressure Scale Height (km)	23.793	Orbital Radius (AU)	29.92
Density Scale Height (km)	41.949	One Way Light Time (min)	240.92
Temperature (K)	71.1	Subsolar Latitude (deg)	-21.99
Pressure (Pa)	1.000e+05	Subsolar Longitude W (deg)	283.60
Sigma Level	1.000	Solar Zenith Angle (km)	129.03
Pressure Altitude (km)	-0.000	Gravity (m/s^2)	10.985
Surface Pressure (Pa)	1.000e+05	Speed of Sound (m/s)	579.090
Compressibility Factor (zeta)	0.9977	Specific Gas Constant (J/(kg K))	3177.234
Specific Heat Ratio	1.484	Profile Weight	0.000

Density	Low	Average	High
Density (kg/m^3)	4.3386e-01	4.4254e-01	4.5139e-01
Density Deviation (%)	-1.4	0.5	2.5
Perturbed Density (kg/m^3)	4.5003e-01	Perturbation (%)	1.7
Perturbed Density Deviation (%)	2.23	Perturbed Speed of Sound (m/s)	567.65

Winds	Mean	Perturbation	Perturbed
Eastward Wind (m/s)	-310.8	9.2	-301.6
Northward Wind (m/s)	0.0	-6.9	-6.9

Gases	Number Density (#/m^3)	Mass (%)	Mole (%)	Avg Mol Wgt	Cp (J/gK)
Dihydrogen (H2)	8.1373e+25	61.7	79.7	2.02	13.09
Helium (He)	1.9088e+25	28.7	18.7	4.00	5.20
Methane (CH4)	1.6051e+24	9.7	1.6	16.04	2.07
Total	1.0207e+26	100.0	100.0	2.61	9.77

Record #2

Field	Value	Field	Value
Elapsed Time (s)	500.00	Elapsed Time (sols)	0.01
Height Above Ref. Ellipsoid (km)	20.000	Reference Radius (km)	24701.7
Latitude (deg)	22.300	Local Solar Time (hrs)	3.88
Longitude W (deg)	48.50	Longitude of the Sun (deg)	305.67
Pressure Scale Height (km)	16.271	Orbital Radius (AU)	29.92
Density Scale Height (km)	19.244	One Way Light Time (min)	240.92
Temperature (K)	54.8	Subsolar Latitude (deg)	-21.99
Pressure (Pa)	3.249e+04	Subsolar Longitude W (deg)	286.70
Sigma Level	0.325	Solar Zenith Angle (km)	126.74
Pressure Altitude (km)	18.294	Gravity (m/s^2)	10.968
Surface Pressure (Pa)	1.000e+05	Speed of Sound (m/s)	508.259
Compressibility Factor (zeta)	0.9979	Specific Gas Constant (J/(kg K))	3179.012
Specific Heat Ratio	1.484	Profile Weight	0.000

Density	Low	Average	High
Density (kg/m^3)	1.7732e-01	1.8663e-01	1.9642e-01
Density Deviation (%)	-4.9	0.1	5.3
Perturbed Density (kg/m^3)	1.8455e-01	Perturbation (%)	-1.1
Perturbed Density Deviation (%)	-1.04	Perturbed Speed of Sound (m/s)	505.24

Winds	Mean	Perturbation	Perturbed
Eastward Wind (m/s)	-295.1	-11.5	-306.6
Northward Wind (m/s)	0.0	-3.3	-3.3

Gases	Number Density (#/m^3)	Mass (%)	Mole (%)	Avg Mol Wgt	Cp (J/gK)
Dihydrogen (H2)	3.4320e+25	61.7	79.7	2.02	13.09
Helium (He)	8.0504e+24	28.7	18.7	4.00	5.20
Methane (CH4)	6.7448e+23	9.6	1.6	16.04	2.07
Total	4.3045e+25	100.0	100.0	2.61	9.77

(Snipped for brevity)

Record #200

Field	Value	Field	Value
Elapsed Time (s)	99500.00	Elapsed Time (sols)	1.72
Height Above Ref. Ellipsoid (km)	3980.000	Reference Radius (km)	24349.6
Latitude (deg)	81.700	Local Solar Time (hrs)	14.25
Longitude W (deg)	147.50	Longitude of the Sun (deg)	305.69
Pressure Scale Height (km)	403.889	Orbital Radius (AU)	29.92
Density Scale Height (km)	400.356	One Way Light Time (min)	240.87
Temperature (K)	799.1	Subsolar Latitude (deg)	-21.99
Pressure (Pa)	3.095e-08	Subsolar Longitude W (deg)	181.24
Sigma Level	0.000	Solar Zenith Angle (km)	105.95
Pressure Altitude (km)	11633.617	Gravity (m/s^2)	8.445
Surface Pressure (Pa)	1.000e+05	Speed of Sound (m/s)	2138.357
Compressibility Factor (zeta)	1.0000	Specific Gas Constant (J/(kg K))	4115.997
Specific Heat Ratio	1.390	Profile Weight	0.000

Density	Low	Average	High
Density (kg/m^3)	8.2900e-15	9.4091e-15	1.0679e-14
Density Deviation (%)	440.0	512.9	595.6
Perturbed Density (kg/m^3)	1.0310e-14	Perturbation (%)	9.6
Perturbed Density Deviation (%)	571.56	Perturbed Speed of Sound (m/s)	2086.29

Winds	Mean	Perturbation	Perturbed
Eastward Wind (m/s)	405.3	-105.1	300.2
Northward Wind (m/s)	0.0	-8.1	-8.1

Gases	Number Density (#/m^3)	Mass (%)	Mole (%)	Avg Mol Wgt	Cp (J/gK)
Dihydrogen (H2)	2.7937e+12	100.0	100.0	2.02	14.66
Helium (He)	3.9941e+07	0.0	0.0	4.00	5.20

Methane (CH4)	1.0000e-09	0.0	0.0	16.04	3.92
Total	2.7937e+12	100.0	100.0	2.02	14.66

Record #201

Field	Value	Field	Value
Elapsed Time (s)	100000.00	Elapsed Time (sols)	1.72
Height Above Ref. Ellipsoid (km)	4000.000	Reference Radius (km)	24349.0
Latitude (deg)	82.000	Local Solar Time (hrs)	14.42
Longitude W (deg)	148.00	Longitude of the Sun (deg)	305.69
Pressure Scale Height (km)	404.496	Orbital Radius (AU)	29.92
Density Scale Height (km)	401.672	One Way Light Time (min)	240.87
Temperature (K)	799.3	Subsolar Latitude (deg)	-21.99
Pressure (Pa)	2.933e-08	Subsolar Longitude W (deg)	184.34
Sigma Level	0.000	Solar Zenith Angle (km)	106.39
Pressure Altitude (km)	11672.860	Gravity (m/s^2)	8.434
Surface Pressure (Pa)	1.000e+05	Speed of Sound (m/s)	2138.530
Compressibility Factor (zeta)	1.0000	Specific Gas Constant (J/(kg K))	4115.905
Specific Heat Ratio	1.390	Profile Weight	0.000

Density	Low	Average	High
Density (kg/m^3)	7.8543e-15	8.9146e-15	1.0118e-14
Density Deviation (%)	440.0	512.9	595.6
Perturbed Density (kg/m^3)	8.7233e-15	Perturbation (%)	-2.1
Perturbed Density Deviation (%)	499.74	Perturbed Speed of Sound (m/s)	2207.88

Winds	Mean	Perturbation	Perturbed
Eastward Wind (m/s)	401.2	27.8	429.0
Northward Wind (m/s)	0.0	31.9	31.9

Gases	Number Density (#/m^3)	Mass (%)	Mole (%)	Avg Mol Wgt	Cp (J/gK)
Dihydrogen (H2)	2.6468e+12	100.0	100.0	2.02	14.67
Helium (He)	3.5985e+07	0.0	0.0	4.00	5.20
Methane (CH4)	1.0000e-09	0.0	0.0	16.04	3.92
Total	2.6468e+12	100.0	100.0	2.02	14.66

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++’ plug-in 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 Microsoft Word 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	8/25/2021	Density Perturbation Scale	1.00
Start Time	15:45:00.00	EW Wind Perturbation Scale	1.00
Julian Day	2459452.156250	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)	24703.3
Latitude (deg)	22.000	Local Solar Time (hrs)	3.71
Longitude W (deg)	48.00	Longitude of the Sun (deg)	305.67
Pressure Scale Height (km)	23.793	Orbital Radius (AU)	29.92
Density Scale Height (km)	41.949	One Way Light Time (min)	240.92
Temperature (K)	71.1	Subsolar Latitude (deg)	-21.99
Pressure (Pa)	1.000e+05	Subsolar Longitude W (deg)	283.60
Sigma Level	1.000	Solar Zenith Angle (km)	129.03
Pressure Altitude (km)	-0.000	Gravity (m/s^2)	10.985
Surface Pressure (Pa)	1.000e+05	Speed of Sound (m/s)	579.090
Compressibility Factor (zeta)	0.9977	Specific Gas Constant(J/(kg K))	3177.234
Specific Heat Ratio	1.484	Profile Weight	0.000

Density	Low	Average	High
Density (kg/m^3)	4.3386e-01	4.4254e-01	4.5139e-01
Density Deviation (%)	-1.4	0.5	2.5
Perturbed Density (kg/m^3)	4.5003e-01	Perturbation (%)	1.7
Perturbed Density Deviation (%)	2.23	Perturbed Speed of Sound (m/s)	574.25

Winds	Mean	Perturbation	Perturbed
Eastward Wind (m/s)	-310.8	9.2	-301.6
Northward Wind (m/s)	0.0	-6.9	-6.9

Gases	Number Density(#/m^3)	Mass(%)	Mole(%)	Avg MolWgt	Cp(J/gK)
Dihydrogen (H2)	8.1373e+25	61.7	79.7	2.02	13.09
Helium (He)	1.9088e+25	28.7	18.7	4.00	5.20
Methane (CH4)	1.6051e+24	9.7	1.6	16.04	2.07
Total	1.0207e+26	100.0	100.0	2.61	9.77

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 NEPTUNE-GRAM

The following are provided with the Neptune-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 and a Programmer's Manual.
- 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
  - md files: Markdown files used to build the Programmer's Manual
- Neptune: 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
- Doxyfile and DoxygenLayout.html: Configuration files used to generate the Programmer's Manual.

APPENDIX E—BUILDING NEPTUNE-GRAM

The Neptune-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 Neptune-GRAM. Instructions can be found in the first chapter of the GRAM Programmer's Manual.

To build Neptune-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 prebuilt 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 NEPTUNE-GRAM VERSION REVISIONS

Table 6 provides version revisions of Neptune-GRAM.

Table 6. Neptune-GRAM version revisions.

Version	Date	Comments
2002 beta	7/9/2002	First release for Titan/Neptune systems analysis team. Based on model atmospheres developed from figures in *Neptune and Triton.*[2]
2002 beta	12/20/2002	Added new feature to allow repeat of random perturbation sequence in trajectory program (example program dumytraj.f). Also provide new example trajectory program (multtraj.f) that allows atmospheric values and perturbations to be evaluated at multiple positions during one trajectory run.
2003 beta	10/20/2003	Added ephemeris routine and place-holder routine to compute effects on *Fminmax* due to latitude, time-of-day, and Ls. Ephemeris requires Earth date and time input, which can be in Earth-receive time or Neptune-event time, and in UTC or TT. New input option *IFMM* controls whether Lat-TOD-Ls effects are computed or only user input value of *Fminmax* is used. Capability to import externally-computed, high-precision ephemeris values also added. Added optional N_2 concentration (0 to 0.6%). Included compressibility effect (zeta = p / (rho * R/M * T). Used slightly larger Tmax-Tmin range at pressures below 5E-4 mbar (heights above about 500 km), based on recommendations of Darrell Strobel.
2004	7/1/2004	Added option to substitute auxiliary input profile of thermodynamic and/or wind data for Neptune 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 '_N04' 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.
2020		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. Speed of sound computations have been improved with the addition of specific heat capacity computations by temperature for constituent gases.

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