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

H.L. Justh
Marshall Space Flight Center, Huntsville, Alabama

A.M. Dwyer Cianciolo
Langley Research Center, Hampton, Virginia

J. Hoffman
Analytical Mechanics Associates, Hampton, Virginia

G.A. Allen, Jr.
Analytical Mechanics Associates, Moffett Field, California

June 2021

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National Aeronautics and
Space Administration

Marshall Space Flight Center • Huntsville, Alabama 35812

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PREFACE

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

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

For technical, programmatic or policy questions, please contact

Hilary Justh
Planetary GRAM Lead
NASA MSFC EV44
Marshall Space Flight Center, AL 35812
Phone: 256-544-3694
Fax: 256-544-3060
E-mail: Hilary.L.Justh@nasa.gov

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LIST OF ACRONYMS

ARC	Ames Research Center
ASCII	American Standard Code for Information Interchange
CSS	Cascading Style Sheets
CSV	comma separated value
ERT	Earth-receive time
GRAM	Global Reference Atmospheric Model
IRIS	Infrared Interferometer Spectrometer and Radiometer
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
Uranus-GRAM	Uranus Global Reference Atmospheric Model
UVS	Ultraviolet Spectrometer

NOMENCLATURE

Ls	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
ρ_0	mean value of atmospheric density
ρ'	perturbed value of atmospheric density

TECHNICAL MEMORANDUM

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

1. INTRODUCTION

1.1 Background and Overview

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

Uranus-GRAM is one option in the GRAM suite that shares a common software core with the other planetary GRAMs while maintaining Uranus specific models. 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 Uranus-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 Uranus-GRAM. Section 3 explains the process to obtain the Uranus-GRAM code, the data files, and how to set up and run the program. Appendices A through E provide additional details regarding the Uranus-GRAM input and output files. Appendix F provides a history of Uranus-GRAM revisions.

1.2 Uranus-GRAM Features

Uranus-GRAM takes advantage of major code modifications made to the GRAMs to improve efficiencies in implementation, run time, and maintenance. Important features include:

(1) The incorporation of NASA's Navigation and Ancillary Information Facility (NAIF) Spacecraft Planet Instrument C-matrix Events (SPICE) library for ephemeris calculations. Uranus ephemeris values, such as longitude of the Sun and solar time, are computed using the NAIF SPICE library for greater accuracy. The use of the NAIF SPICE library requires the Uranus-

GRAM user to download the latest SPICE data before using Uranus-GRAM. Instructions for doing so are provided in section 3.2.

(2) The output is provided in two formats: (1) a comma separated value (CSV) file and (2) a LIST file (LIST.md). The CSV file consolidates all of the column formatted output files 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.

(3) The GRAM Suite contains a library of data models and utilities that includes GRAM atmospheric data for multiple destinations. Refer to the GRAM Programmer's Manual for additional details.

(4) Uranus-GRAM 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. Uranus-GRAM uses an improved methodology for computing γ, involving the evaluation of Shomate coefficients in runtime for the current constituent combination.

2. URANUS-GRAM ATMOSPHERIC DATA

2.1 Uranus-GRAM Atmospheric Data Description

Atmospheric density, temperature, and pressure as a function of height are characterized by the Uranus Atmospheric Model that was developed by the NASA Ames Research Center (ARC).[1,2] The ARC Uranus Atmospheric Model is based on data from three seminal papers[3,4,5] about the Uranus atmosphere regarding observations from the Voyager 2 fly-by of Uranus that occurred on January 24, 1986. Users of this Voyager era-derived model should be mindful that there is evidence for significant seasonal variation in the thermal profiles (to be expected since Uranus' axis-of-rotation is nearly in its orbital plane).[6] The winds on Uranus are currently unknown, as a result this model does not include wind data.

The data contained in this model for the lower atmosphere from –27.5 km to 323.5 km altitude is from Lindal et al.[3] and the upper atmosphere data from 200 to 7,000 km altitude is from Herbert et al.[4] The upper atmosphere data contained in Herbert et al.[4] was soon superseded by data from Bishop et al.[5] which is from 162.6 to 366.1 km altitude. The data in these three papers[3,4,5] is based on Voyager radio science, Infrared Interferometer Spectrometer and Radiometer (IRIS), and the Ultraviolet Spectrometer (UVS). The ARC Uranus Atmospheric Model was created by combining the mole fraction, pressure, and density data from the three papers[3,4,5] which provides the information necessary to define the equilibrium atmospheric state. The Chemical Equilibrium with Applications (CEA) program[7,8] was then used to calculate all of the remaining thermodynamic and transport properties contained in the ARC Uranus Atmospheric Model. The CEA program does have a significant limitation in that its polynomials only provide values for a temperature range from 200° K to 20,000° K and does not model methane phase change. The atmosphere of Uranus can reach temperatures below 50° K which will break CEA's polynomial fits. As a result, CEA was modified with special low temperature routines for atomic hydrogen, molecular hydrogen, and helium. The process of combining the three data sources is shown in figures 1 through 4. There were continuity issues between the Lindal et al.[3] and Bishop et al.[5] data. This was resolved by adding a profile shown in figures 1 through 4 that was produced by utilizing Uranus temperature versus pressure profile data from table 1 of Lindal[9] in a hydrostatic code to compute temperature, pressure, and density versus geometric height (H. L. Justh, private communications, 2011).

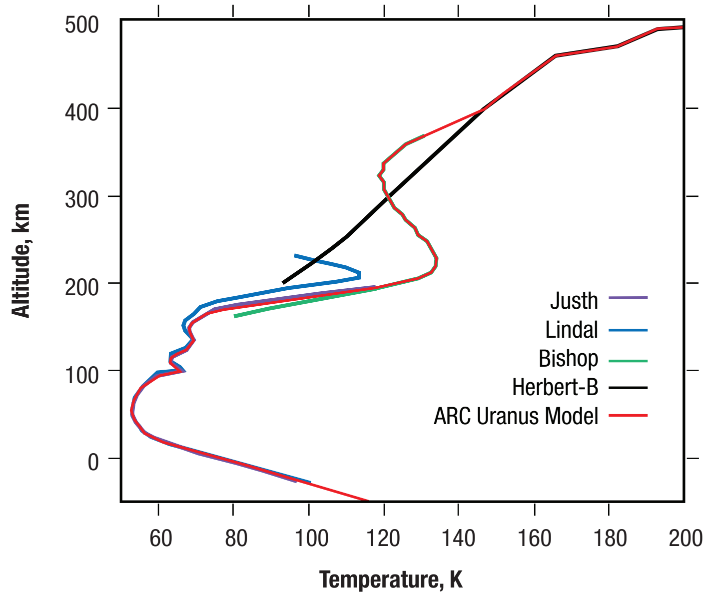

Figure 1. Altitude versus temperature up to 500 km altitude for each data source and the ARC Uranus Atmospheric Model.

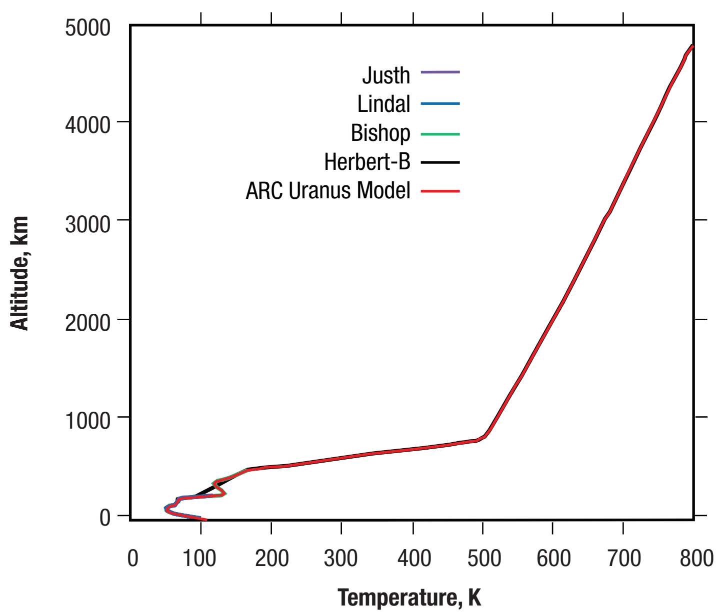

Figure 2. Altitude versus temperature over the full altitude range for each data source and the ARC Uranus Atmospheric Model.

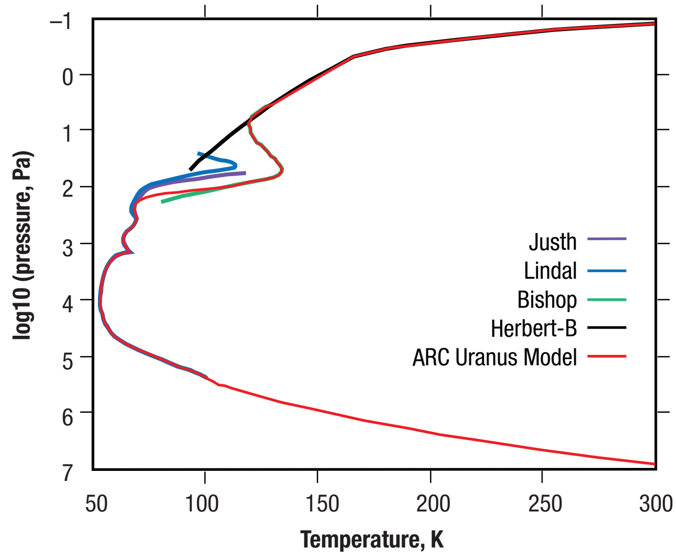

Figure 3. Pressure versus temperature up to 500 km altitude for each data source and the ARC Uranus Atmospheric Model.

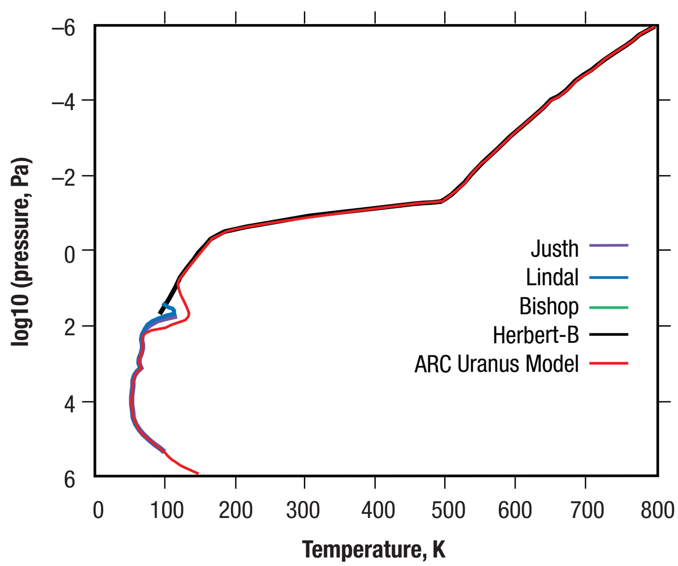

Figure 4. Pressure versus temperature over the full altitude range for each data source and the ARC Uranus Atmospheric Model.

The ARC Uranus Atmospheric model data as incorporated in Uranus-GRAM consist of a profile of the following: total number density, number densities for helium, hydrogen, and methane, mass density, air pressure, and air temperature.

Constituent contributions are shown in figure 5 of this document.

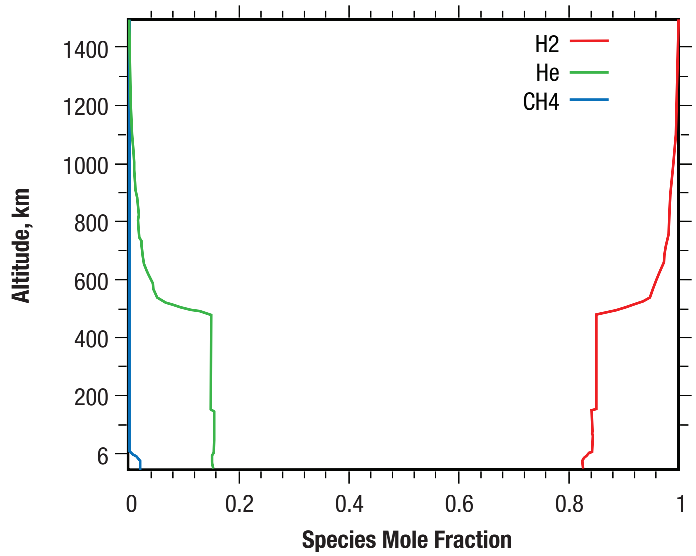

Figure 5. Altitude vs. Uranus atmospheric mole fractions.
Default gas mole fraction: H_2 0.85, He 0.15

Uranus-GRAM density perturbation magnitudes are estimated using

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

and

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

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 (when modeled)
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 ($R' \approx R$). For large relative displacements, the new correlation factor is essentially random ($R' \approx X$).

Table 1 provides the Uranus gravity parameter data from Lindal et al.[3] that was utilized when constructing the ARC Uranus Atmospheric Model. These parameters are utilized in Uranus-GRAM.

Table 1. Uranus gravity parameters.

Uranus	Label	Units	Value
Gravitational Parameter	GM	km^3/s^2	5793964
Mean Equatorial Radius	R_e	km	25559.0
Mean Polar Radius	R_p	km	24973.0
J2 harmonic	J_2	km^5/s^2	0.00334129
Period (retrograde)		s	−62063.71199

2.2 Querying Atmosphere Data

The Uranus-GRAM user-defined path can be generated in multiple ways. The first is to run Uranus-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, Uranus-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, 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 Uranus-GRAM code directly into a user's trajectory code. This version of Uranus-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, Uranus-GRAM writes output to two files: a CSV output file and a LIST output file. These output files are detailed in appendices A and C.

2.3 Monte Carlo Capability

Using the *NumberOfMonteCarloRuns* option in the NAMELIST input file, Uranus-GRAM will generate the user-specified number of trajectories that disperse density and speed of sound. 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.

Utilizing a user-generated trajectory file as described in section 2.5 allows varying trajectory increments to be defined by the user. The Uranus-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 Uranus-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 Uranus-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 with the ability to overwrite the atmosphere model in Uranus-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 Uranus-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 Uranus-GRAM input wind data (currently zeros) 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 Uranus-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 Uranus-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 fairing 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.

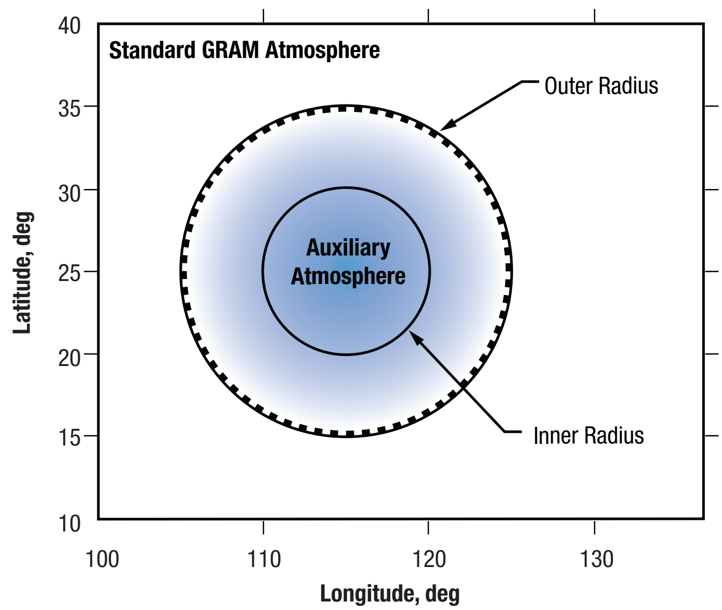

Figure 6. Illustration of two-dimensional auxiliary profile faring implementation with *InnerRadius* = 5° and *OuterRadius* = 10° for a vertical auxiliary profile located at latitude = 25° and longitude = 115°.

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 Uranus-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 URANUS-GRAM

3.1 How to Obtain the Program

Uranus-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 downloaded package.

3.2 Running the Program

The Uranus-GRAM installation includes a set of Windows and Linux 64-bit executable libraries located in the GRAM/Windows and GRAM/Linux folders. The Uranus-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 Uranus-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 Uranus-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 Uranus-GRAM, simply double-click the UranusGRAM.exe file or enter ‘UranusGRAM.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/Uranus/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 Uranus-GRAM command line. The format of this option is ‘UranusGRAM.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

Uranus-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 Uranus-GRAM. All input parameter names are case insensitive. Input parameters whose values are supplied in the input file are given in table 2. (The legacy GRAM input parameters names are still supported and appear in parentheses.)

Table 2. Uranus-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
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). *Note: The current version of Uranus-GRAM has no winds model. This parameter has no effect.	1.0
NSWindPerturbationScale*	Random north/south wind perturbation scale factor (0.0 – 2.0, 1.0 = 3 sigma). *Note: The current version of Uranus-GRAM has no winds model. This parameter has no effect.	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
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

3.4 Program Output

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

Uranus-GRAM gives the user the option to find the date and time for a particular solar longitude (Ls) and Uranus local true solar time (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 of for which Ls and LTST are the user desired values. The SPICE data are required for this capability. The *FindDates* capability is contained within the Uranus-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 Ls and the two dates and times of the target LTST that immediately precede and follow the target Ls 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 Uranus-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 URANUS-GRAM OUTPUT FILE

Uranus-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 wind 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) *** Note: The current version of Uranus-GRAM has no winds model. This value will be zero.**

NSWind_ms*	Mean northward wind component (m/s) *** Note: The current version of Uranus-GRAM has no winds model. This value will be zero.**
EWWindPerturbation_ms*	Eastward wind perturbation (m/s) *** Note: The current version of Uranus-GRAM has no winds model. This value will be zero.**
NSWindPerturbation_ms*	Northward wind perturbation (m/s) *** Note: The current version of Uranus-GRAM has no winds model. This value will be zero.**
PerturbedEWWind_ms*	Total (mean plus perturbed) eastward wind (m/s) *** Note: The current version of Uranus-GRAM has no winds model. This value will be zero.**
PerturbedNSWind_ms*	Total (mean plus perturbed) northward wind (m/s) *** Note: The current version of Uranus-GRAM has no winds model. This value will be zero.**
EWStandardDeviation_ms*	Standard deviation of eastward wind perturbations (m/s) *** Note: The current version of Uranus-GRAM has no winds model. This value will be zero.**
NSStandardDeviation_ms*	Standard deviation of northward wind perturbations (m/s) *** Note: The current version of Uranus-GRAM has no winds model. This value will be zero.**
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))

APPENDIX B — EXAMPLE NAMELIST FORMAT INPUT FILE

The following is an example of the NAMELIST format input file required by Uranus-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            =  'myref_LIST'
   ColumnFileName          =  'myref_OUTPUT'
   EastLongitudePositive   =  0

   TimeFrame   =  1
   TimeScale   =  1
   Month       =  3
   Day         =  25
   Year        =  2020
   Hour        =  12
   Minute      =  30
   Seconds     =  0.0

   InitialRandomSeed          =  1001
   DensityPerturbationScale   =  1.0
   MinimumRelativeStepSize    =  0.0

   TrajectoryFileName   =  'null'
   NumberOfPositions    =  201
   InitialHeight        =  -200.0
   InitialLatitude      =  22.0
   InitialLongitude     =  48.0
   DeltaHeight          =  40.0
   DeltaLatitude        =  0.3
   DeltaLongitude       =  0.5
   DeltaTime            =  500.0

   AuxiliaryAtmosphereFileName  =  'null'
   InnerRadius                  =  0.0
   OuterRadius                  =  0.0

   NumberOfMonteCarloRuns  =  1

   FastModeOn      =  0
   ExtraPrecision  =  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)
   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.

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 Uranus-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)	-200.000	Reference Radius (km)	25474.3
Latitude (deg)	22.000	Local Solar Time (hrs)	18.00
Longitude W (deg)	48.00	Longitude of the Sun (deg)	48.42
Pressure Scale Height (km)	90.698	Orbital Radius (AU)	19.81
Density Scale Height (km)	118.810	One Way Light Time (min)	171.92
Temperature (K)	238.9	Subsolar Latitude (deg)	46.51
Pressure (Pa)	3.959e+06	Subsolar Longitude W (deg)	318.04
Sigma Level	39.593	Solar Zenith Angle (km)	73.18
Pressure Altitude (km)	-333.645	Gravity (m/s^2)	8.874
Surface Pressure (Pa)	1.000e+05	Speed of Sound (m/s)	1064.646
Compressibility Factor (zeta)	1.0336	Specific Gas Constant (J/(kg K))	3291.520
Specific Heat Ratio	1.442	Profile Weight	0.000

Density	Low	Average	High
Density (kg/m^3)	4.9372e+00	5.0360e+00	5.1367e+00
Density Deviation (%)	-2.0	0.0	2.0
Perturbed Density (kg/m^3)	5.0759e+00	Perturbation (%)	0.8
Perturbed Density Deviation (%)	0.79	Perturbed Speed of Sound (m/s)	1060.45

Winds	Mean	Perturbation	Perturbed
Eastward Wind (m/s)	0.0	-0.0	0.0
Northward Wind (m/s)	0.0	-0.0	0.0

Gases	Number Density (#/m^3)	Mass (%)	Mole (%)	Avg Mol Wgt	Cp (J/gK)
Dihydrogen (H2)	9.5995e+26	63.9	82.6	2.02	13.93
Helium (He)	1.7812e+26	23.5	15.3	4.00	5.20
Methane (CH4)	2.3819e+25	12.6	2.0	16.04	2.13
Total	1.1619e+27	100.0	100.0	2.61	10.39

Record #2

Field	Value	Field	Value
Elapsed Time (s)	500.00	Elapsed Time (sols)	0.01
Height Above Ref. Ellipsoid (km)	-160.000	Reference Radius (km)	25472.1
Latitude (deg)	22.300	Local Solar Time (hrs)	18.22
Longitude W (deg)	48.50	Longitude of the Sun (deg)	48.42
Pressure Scale Height (km)	81.355	Orbital Radius (AU)	19.81
Density Scale Height (km)	107.584	One Way Light Time (min)	171.92
Temperature (K)	206.1	Subsolar Latitude (deg)	46.51
Pressure (Pa)	2.468e+06	Subsolar Longitude W (deg)	315.14
Sigma Level	24.681	Solar Zenith Angle (km)	75.14
Pressure Altitude (km)	-260.827	Gravity (m/s^2)	8.847
Surface Pressure (Pa)	1.000e+05	Speed of Sound (m/s)	1010.356
Compressibility Factor (zeta)	1.0684	Specific Gas Constant (J/(kg K))	3402.268
Specific Heat Ratio	1.456	Profile Weight	0.000

Density	Low	Average	High
Density (kg/m^3)	3.4514e+00	3.5204e+00	3.5908e+00
Density Deviation (%)	-2.0	0.0	2.0
Perturbed Density (kg/m^3)	3.5962e+00	Perturbation (%)	2.2
Perturbed Density Deviation (%)	2.15	Perturbed Speed of Sound (m/s)	999.65

Winds	Mean	Perturbation	Perturbed
Eastward Wind (m/s)	0.0	-0.0	0.0
Northward Wind (m/s)	0.0	-0.0	0.0

Gases	Number Density (#/m^3)	Mass (%)	Mole (%)	Avg Mol Wgt	Cp (J/gK)
Dihydrogen (H2)	6.7109e+26	63.9	82.6	2.02	13.58
Helium (He)	1.2452e+26	23.5	15.3	4.00	5.20
Methane (CH4)	1.6651e+25	12.6	2.1	16.04	2.09
Total	8.1226e+26	100.0	100.0	2.61	10.17

(Snipped for brevity)

Record #200

Field	Value	Field	Value
Elapsed Time (s)	99500.00	Elapsed Time (sols)	1.60
Height Above Ref. Ellipsoid (km)	7760.000	Reference Radius (km)	24984.8
Latitude (deg)	81.700	Local Solar Time (hrs)	15.11
Longitude W (deg)	147.50	Longitude of the Sun (deg)	48.44
Pressure Scale Height (km)	590.865	Orbital Radius (AU)	19.81
Density Scale Height (km)	590.758	One Way Light Time (min)	172.00
Temperature (K)	800.0	Subsolar Latitude (deg)	46.52
Pressure (Pa)	3.447e-08	Subsolar Longitude W (deg)	100.92
Sigma Level	0.000	Solar Zenith Angle (km)	37.07
Pressure Altitude (km)	16955.583	Gravity (m/s^2)	5.365
Surface Pressure (Pa)	1.000e+05	Speed of Sound (m/s)	2140.936
Compressibility Factor (zeta)	1.0021	Specific Gas Constant (J/(kg K))	4121.664
Specific Heat Ratio	1.390	Profile Weight	0.000

Density	Low	Average	High
Density (kg/m^3)	9.2097e-15	1.0453e-14	1.1864e-14
Density Deviation (%)	-11.9	0.0	13.5
Perturbed Density (kg/m^3)	1.0915e-14	Perturbation (%)	4.4
Perturbed Density Deviation (%)	4.42	Perturbed Speed of Sound (m/s)	2095.14

Winds	Mean	Perturbation	Perturbed
Eastward Wind (m/s)	0.0	-0.0	0.0
Northward Wind (m/s)	0.0	0.0	0.0

Gases	Number Density (#/m^3)	Mass (%)	Mole (%)	Avg Mol Wgt	Cp (J/gK)
Dihydrogen (H2)	3.1138e+12	99.9	100.0	2.02	14.67
Helium (He)	0.0000e+00	0.0	0.0	4.00	5.20
Methane (CH4)	3.1141e+08	0.1	0.0	16.04	3.92
Total	3.1141e+12	100.0	100.0	2.02	14.66

Record #201

Field	Value	Field	Value
Elapsed Time (s)	100000.00	Elapsed Time (sols)	1.61
Height Above Ref. Ellipsoid (km)	7800.000	Reference Radius (km)	24984.0
Latitude (deg)	82.000	Local Solar Time (hrs)	15.33
Longitude W (deg)	148.00	Longitude of the Sun (deg)	48.44
Pressure Scale Height (km)	590.865	Orbital Radius (AU)	19.81
Density Scale Height (km)	590.758	One Way Light Time (min)	172.00
Temperature (K)	800.0	Subsolar Latitude (deg)	46.52
Pressure (Pa)	3.447e-08	Subsolar Longitude W (deg)	98.02
Sigma Level	0.000	Solar Zenith Angle (km)	37.61
Pressure Altitude (km)	16955.583	Gravity (m/s^2)	5.352
Surface Pressure (Pa)	1.000e+05	Speed of Sound (m/s)	2140.936
Compressibility Factor (zeta)	1.0021	Specific Gas Constant (J/(kg K))	4121.664
Specific Heat Ratio	1.390	Profile Weight	0.000

Density	Low	Average	High
Density (kg/m^3)	9.2097e-15	1.0453e-14	1.1864e-14
Density Deviation (%)	-11.9	0.0	13.5
Perturbed Density (kg/m^3)	1.1222e-14	Perturbation (%)	7.4
Perturbed Density Deviation (%)	7.36	Perturbed Speed of Sound (m/s)	2066.28

Winds	Mean	Perturbation	Perturbed
Eastward Wind (m/s)	0.0	-0.0	0.0
Northward Wind (m/s)	0.0	-0.0	0.0

```
| Gases           | Number Density (#/m^3)  | Mass (%)  | Mole (%)  | Avg Mol Wgt  | Cp (J/gK)   |
|---------------- |---------------------- |--------- |--------- |------------ |-----------
| Dihydrogen (H2) | 3.1138e+12            | 99.9      | 100.0     | 2.02         | 14.67       |
| Helium (He)     | 0.0000e+00            | 0.0       | 0.0       | 4.00         | 5.20        |
| Methane (CH4)   | 3.1141e+08            | 0.1       | 0.0       | 16.04        | 3.92        |
| Total           | 3.1141e+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++' 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)	-200.000	Reference Radius (km)	25474.3
Latitude (deg)	22.000	Local Solar Time (hrs)	18.00
Longitude W (deg)	48.00	Longitude of the Sun (deg)	48.42
Pressure Scale Height (km)	90.698	Orbital Radius (AU)	19.81
Density Scale Height (km)	118.810	One Way Light Time (min)	171.92
Temperature (K)	238.9	Subsolar Latitude (deg)	46.51
Pressure (Pa)	3.959e+06	Subsolar Longitude W (deg)	318.04
Sigma Level	39.593	Solar Zenith Angle (km)	73.18
Pressure Altitude (km)	-333.645	Gravity (m/s^2)	8.874
Surface Pressure (Pa)	1.000e+05	Speed of Sound (m/s)	1064.646
Compressibility Factor (zeta)	1.0336	Specific Gas Constant (J/(kg K))	3291.520
Specific Heat Ratio	1.442	Profile Weight	0.000

Density	Low	Average	High
Density (kg/m^3)	4.9372e+00	5.0360e+00	5.1367e+00
Density Deviation (%)	-2.0	0.0	2.0
Perturbed Density (kg/m^3)	5.0759e+00	Perturbation (%)	0.8
Perturbed Density Deviation (%)	0.79	Perturbed Speed of Sound (m/s)	1060.45

Winds	Mean	Perturbation	Perturbed
Eastward Wind (m/s)	0.0	-0.0	0.0
Northward Wind (m/s)	0.0	-0.0	0.0

Gases	Number Density (#/m^3)	Mass (%)	Mole (%)	Avg Mol Wgt	Cp (J/gK)
Dihydrogen (H2)	9.5995e+26	63.9	82.6	2.02	13.93
Helium (He)	1.7812e+26	23.5	15.3	4.00	5.20
Methane (CH4)	2.3819e+25	12.6	2.0	16.04	2.13
Total	1.1619e+27	100.0	100.0	2.61	10.39

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 URANUS-GRAM

The following are provided with the Uranus-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
- Uranus: 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 URANUS-GRAM

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

To build Uranus-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 URANUS-GRAM VERSION REVISIONS

Table 6. Uranus-GRAM version revisions.

Version	Date	Comments
2021	5/2021	First release of Uranus-GRAM.

REFERENCES

1. Allen Jr., G.A.; Marley, M.S.; and Agrawal, P.: "Uranus Atmospheric Model for Engineering Application", Paper Presented at the 11th International Planetary Probe Workshop, Abstract #8023, Pasadena, CA, June 16-20, 2014.

2. Allen Jr., G.A.; Marley, M.S.; and Agrawal, P.: "Uranus Atmospheric Model for Engineering Application", Paper Presented at the Workshop on the Study of the Ice Giant Planets, Abstract #2001, Laurel, MD, July 28-30, 2014.

3. Lindal, G.F.; Lyons, J.R.; Sweetnam, D.N.; Eshleman, V.R.; Hinson, D.P.; and Tyler, G.L.: "The Atmosphere of Uranus: Results of Radio Occultation Measurements with Voyager 2," *Journal of Geophysical Research*, Vol. 92, No. A13, pp. 14,987-15,001, December 30, 1987.

4. Herbert, F.; Sandel, B.R.; Yelle, R.V.; Holberg, J.B.; Broadfoot, A.L.; Shemansky, D.E.; Atreya, S.K.; and Romani, P.N.: "The Upper Atmosphere of Uranus: EUV Occultations Observed by Voyager 2," *Journal of Geophysical Research*, Vol. 92, No. A13, pp. 15,093- 15,109, December 30, 1987.

5. Bishop, J.; Atreya, S.K.; Herbert, F.; and Romani, P.: "Reanalysis of Voyager 2 UVS Occultations at Uranus: Hydrocarbon Mixing Ratios in the Equatorial Stratosphere," *Icarus*, Vol. 88, pp. 448-464, 1990.

6. Melin, H.; Stallard, T.S.; O'Donoghue, J.; Miller, S.; Geballe, T. R.; Trafton, L. M.; and Blake, J. S. D.: "Post-Equinoctial Observations of the Ionosphere of Uranus," *Icarus*, Volume 223, Issue 2, pp. 741-748, 2013.

7. Gordon, S.; and McBride, B.: "Computer Program for Calculations of Complex Chemical Equilibrium Compositions and Applications I. Analysis," NASA Reference Publication 1311, October 1994.

8. Gordon, S.; and McBride, B.: "Computer Program for Calculations of Complex Chemical Equilibrium Compositions and Applications II. Users Manual and Program Description," NASA Reference Publication 1311, June 1996.

9. Lindal, G.: "The Atmosphere of Neptune: An analysis of radio occultation data acquired with Voyager 2," *The Astronomical Journal*, Vol. 103, No. 3, pp. 967-982.

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14. ABSTRACT
This Technical Memorandum (TM) presents the Uranus Global Reference Atmospheric Model (Uranus-GRAM) and the updated features of the GRAMs. Uranus-GRAM is an engineering-oriented atmospheric model that estimates mean values and statistical variations of atmospheric properties for Uranus. This TM summarizes the atmospheric data model in Uranus-GRAM and provides a guide for the user to obtain, set up, and run the code in various configurations. Additional details regarding the Uranus-GRAM input and output files and how to interpret Uranus-GRAM results are also provided.

15. SUBJECT TERMS
Uranus Global Reference Atmospheric Model, Uranus-GRAM, Uranus, atmospheric density, atmospheric temperature, atmospheric models

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