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Uranus Global Reference Atmospheric Model (Uranus-GRAM) 2024: User Guide

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August 2024

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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.

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LIST OF ACRONYMS

ARC	Ames Research Center
ASCII	American Standard Code for Information Interchange
BV	Brunt–Vaisala
CEA	Chemical Equilibrium with Applications
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
TDB	Barycentric Dynamical Time
TDT	Terrestrial Dynamical Time
UTC	Coordinated Universal Time
UVS	Ultraviolet Spectrometer

NOMENCLATURE

C_p	specific heat capacity of a gaseous mixture for isobaric processes
C_v	specific heat capacity of a gaseous mixture for isochoric processes
g	gravity
H	altitude
N	BV frequency
P_F	modeled perturbation factor
Ls	solar longitude
P_o	reference pressure at the bottom of the thermosphere
P_U	user-supplied perturbation multiplier
p_o	pressure at zero altitude (100000 Pa)
p	pressure at altitude
R_c	correlation factor for the previous time step
R_c'	correlation factor for the current time step
R	specific gas constant
S	relative displacement from the last time step using NS, EW, vertical movement, and winds (when modeled)
T_o	the corresponding bottom temperature to p_o
T	temperature
X	value provided by a random number generator
z	altitude
θ	potential temperature
Γ	constant lapse rate connecting the bottom temperature to the upper thermospheric temperature
γ	ratio of specific heats
ρ_0	mean value of atmospheric density
ρ'	perturbed value of atmospheric density

TECHNICAL MEMORANDUM

URANUS GLOBAL REFERENCE ATMOSPHERIC MODEL (URANUS-GRAM) 2024: 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, pressure, and zonal wind along a user defined path. Uranus-GRAM also provides dispersions of density and zonal wind.

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

2. URANUS-GRAM ATMOSPHERIC DATA

2.1 Uranus-GRAM Default Atmospheric Data Description

Atmospheric density, temperature, and pressure as a function of altitude are characterized by the updated Uranus Atmospheric Model that was developed by the NASA GRAM team[2,3]. The new model improves upon the previous atmospheric reference, the Ames Research Center (ARC) Uranus Atmospheric Model[4,5] (see Section 2.2), by including modern reanalyses of Voyager flyby measurements as well as more modern observations. The new model also includes zonal wind speeds with an estimated vertical shear. Users of this 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] While the thermospheric model "family" does cover the full range of observed temperature changes, sufficient data is not available to construct a true seasonal trend in Uranus' temperatures and zonal wind structure. Uranus-GRAM's atmospheric reference basis is a 3-segment atmospheric model that consists of "families" of profiles covering the full range of uncertainty in Uranus' atmospheric properties.

For distinction within the Uranus-GRAM program input and output parameters, the legacy ARC Uranus Atmospheric Model will be referred to as the "Voyager" model. And the updated Uranus Atmospheric Model will be referred to as the "Vger" model.

2.1.1 Temperature Structure

At the top of the atmosphere, above 1 Pa, the temperature model consists of a "family" of profiles covering the full range of observed and modelled temperatures since the Voyager era. Specifically, the model adopts the error range of the original Voyager flyby estimates from Teanby et al.[7] at the top (approximately 400-800 K) and bottom (approximately 175-500K) of the thermosphere. This range is represented in numerous contemporary studies[8, 9, 10]. During a Monte Carlo run, atmospheric profiles are generated by connecting evenly spaced points at the top and bottom of the thermosphere with stable temperature profiles. These profiles follow the hydrostatic equation for a constant lapse rate atmosphere:

$$p(z) = P_o \left(\frac{T(z)}{T_o} \right)^{\frac{g}{R\Gamma}} \tag{1}$$

where

$p(z)$ = pressure at altitude z
P_o = a reference pressure at the bottom of the thermosphere
$T(z)$ = temperature at altitude z
T_o = the corresponding bottom temperature to p_o
g = local gravity at z
R = specific gas constant
Γ = constant lapse rate connecting the bottom temperature to the upper thermospheric

temperature.

An example thermospheric model “family” may be seen in Figure 1.

The middle atmosphere between 1-100000 Pa adopts the best-fit tropospheric profile of Orton et al. 2014[10], based on a Voyager 2 reanalysis and new measurements from the Spitzer Space Telescope. It smooths high-altitude oscillations present in the previous Uranus-GRAM model thought to be the result of vertically propagating waves or haze layers. The Orton et al. results have been interpolated to a common, logarithmic grid and are used to set he pressure bounds for the deep and upper atmosphere. The tropospheric model is blended with the calculated thermospheric model via a tanh-based smoothing function to ensure no discontinuities exist in the final 1D profile.

The deep atmosphere model below 100000 Pa adopts the temperature range of Sayanagi et al. 2019[8] by assuming a range of estimated Brunt–Vaisala (BV) frequencies. The BV frequency is one measure of a fluid's static stability. It is the frequency at which a vertically displaced parcel will oscillate and must be real in a stable atmosphere. It is given by the equation:

$$N = \sqrt{\frac{g}{\theta}\frac{d\theta}{dz}} \tag{2}$$

where

N = BV frequency
g = local gravity,
θ = potential temperature
z = altitude.

When rewritten in terms of the actual temperature and pressure, assuming a higher BV frequency approximates the effect of moist air. The warmest deep profile follows the dry adiabatic lapse rate while the coolest profile assumes a constant BV frequency of 0.004 s^{-1}, the highest BV frequency that is not discontinuous with the tropospheric profile. Temperatures are propagated down to 1e7 Pa, the bottom of the temperature model.

All permutations of these three segments are included to form the full model ensemble, as shown in Figure 1. The “mean” default profile is the closest to the mean Voyager profile as shown in Teanby et al. 2022[7]. The lower bound includes the latest thermospheric results of Melin et al. 2019[11], which continues the observed cooling trend of Uranus’ thermospheric temperatures. A Uranus-GRAM-based Monte Carlo analysis using the entire temperature profile ensemble will allow the full range of known atmospheric uncertainty to be explored.

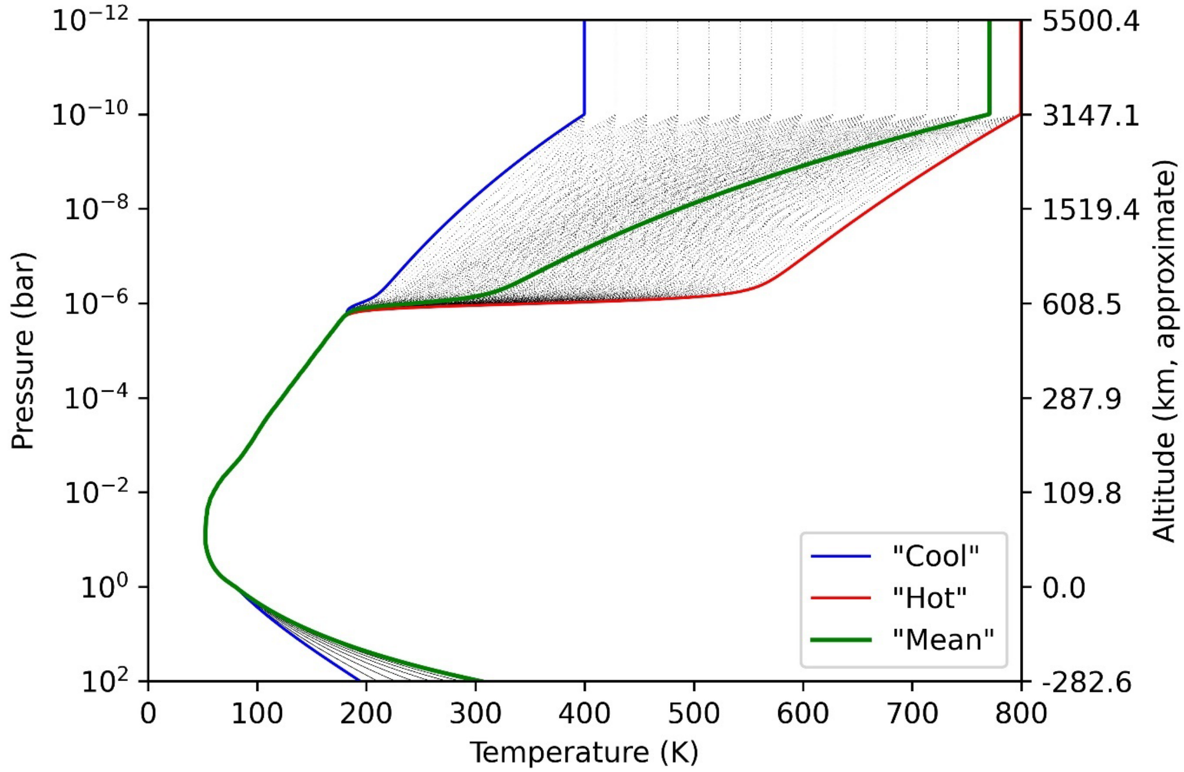

Figure 1. Temperature versus altitude and pressure over the full range of the Uranus-GRAM atmospheric model. The modelled "family" of thermospheric profiles between 15 temperature steps is shown as dotted black lines. The deep atmospheric temperature spread over 10 estimated BV frequency steps is also shown.

2.1.2 Density Conversion

Densities are calculated for each profile using the ideal gas law with an altitudinally-dependent mean molecular mass taken from the legacy Uranus-GRAM atmospheric model (see Section 2.2 and Figure 5). Uranus-GRAM density perturbation magnitudes are estimated using the equations:

$$\rho' = \rho_0(1 + R_c' P_F P_U) \tag{3}$$

and

$$R_c' = e^{-S} R_c + X\sqrt{1 - e^{-2S}} \tag{4}$$

where

ρ' = perturbed value of atmospheric density

ρ_0 = mean value of atmospheric density
$R_c{}'$ = 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 modelled)
R_c = 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 ($R' \approx X$).

2.1.3 Altitude Calculation

The generated temperature-pressure profiles are used to calculate corresponding altitudes using the barometric equation:

$$p = p_o \exp\left[-\int_0^z \frac{dz}{H}\right] = p_o \exp\left[-\int_0^z \frac{g(z)}{R(z)T(z)}dz\right] \tag{5}$$

where

p = pressure
p_o = pressure at zero altitude (100000 Pa)
H = altitude
$g(z)$ = altitudinally-dependent gravity
$R(z)$ = altitudinally-dependent specific gas constant
$T(z)$ = altitudinally-dependent temperature

The local gravity at a particular radius is calculated for a rotating, oblate planet. Table 1 provides the Uranus gravity parameter data from Lindal et al.[12] that was utilized when constructing the Uranus Atmospheric Model. These parameters are utilized throughout 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

2.1.4 Zonal Wind Structure

Uranus-GRAM's zonal wind structure adopts the cloud-top zonal wind profile of Sromovsky et al. 2015[13], which utilized Keck and Gemini AO observations of Uranus combined with a reanalysis of Voyager 2 images by Karkoschka 2015[14]. This zonally-averaged, cloud-top wind profile may be seen in Figure 2. Note that the asymmetric feature observed in the southern jet (around -70 degrees) is thought to be a seasonal effect[13]; however, there is insufficient data to determine the magnitude or periodicity of this potential seasonality.

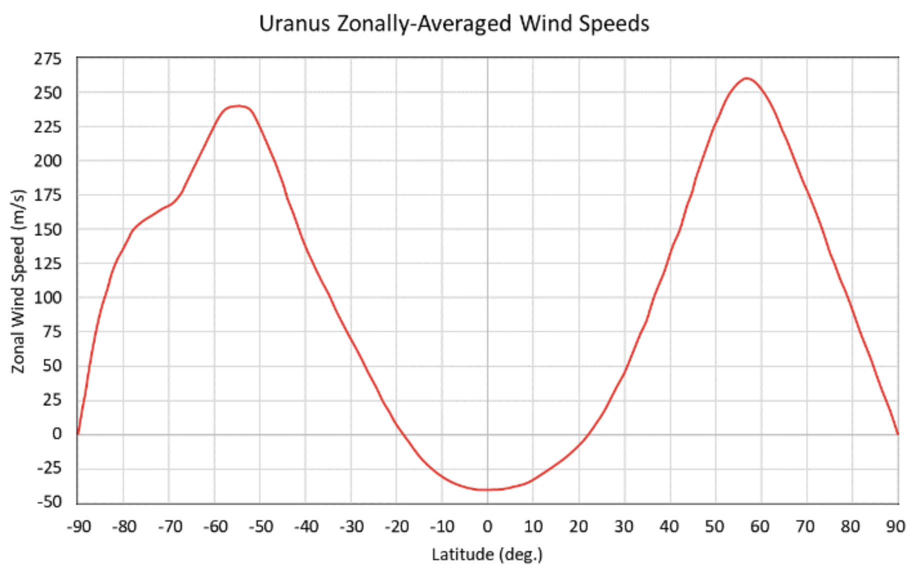

Figure 2. Latitude versus wind speed for the cloud top zonal wind profile adopted by Uranus-GRAM. From Sromovsky et al. 2015[13]

While estimates of Uranus' vertical wind shear remain uncertain, we estimate the change in the cloud-top zonal winds with altitude by adopting the only in-situ measurement of wind shear on a giant planet: the Galileo Probe Doppler Wind Experiment at Jupiter. The measured vertical wind shear of Atkinson et al. 1998[15] has been applied to decay the observed Uranus zonal winds above the clouds. Below cloud level, the winds are held to the cloud-top speeds.

2.2 Legacy Atmospheric Model

Previous versions of Uranus-GRAM[16] utilized the Uranus Atmospheric Model developed by the NASA ARC.[4,5] The ARC Uranus Atmospheric Model was based on data from three contemporary papers[12, 17, 18] regarding observations from the Voyager 2 fly-by of Uranus that occurred on January 24, 1986. The last 40 years of studies have superseded and improved upon the original Voyager results, outdating the original Uranus-GRAM atmospheric model. The current atmospheric model only utilizes the ARC model's number density data; the updated temperature, density, and wind data was developed independently by the GRAM team. In this

Uranus-GRAM release, the ARC Uranus Atmospheric Model has been made available as a legacy option to enable comparisons of studies utilizing older versions of Uranus-GRAM to the current version.

The data contained in the ARC model for the lower atmosphere from –27.5 km to 323.5 km altitude is from Lindal et al.[12] and the upper atmosphere data from 200 to 7,000 km altitude is from Herbert et al.[17] The upper atmosphere data contained in Herbert et al.[17] was soon superseded by data from Bishop et al.[18] which is from 162.6 to 366.1 km altitude. The data in these three papers[12, 17, 18] 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 which provides the information necessary to define the equilibrium atmospheric state. The Chemical Equilibrium with Applications (CEA) program[19,20] was then used to calculate all remaining thermodynamic and transport properties. 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. Continuity issues between the Lindal et al.[12] and Bishop et al.[18] data were resolved by adding a profile shown in Figure 3 that was produced by utilizing Uranus temperature versus pressure profile data from Table 1 of Lindal[21] in a hydrostatic code to compute temperature, pressure, and density versus geometric height (H. L. Justh, private communications, 2011). Constituent gas species are hydrogen, helium, and methane, whose contributions are shown in Figure 4 of this document.

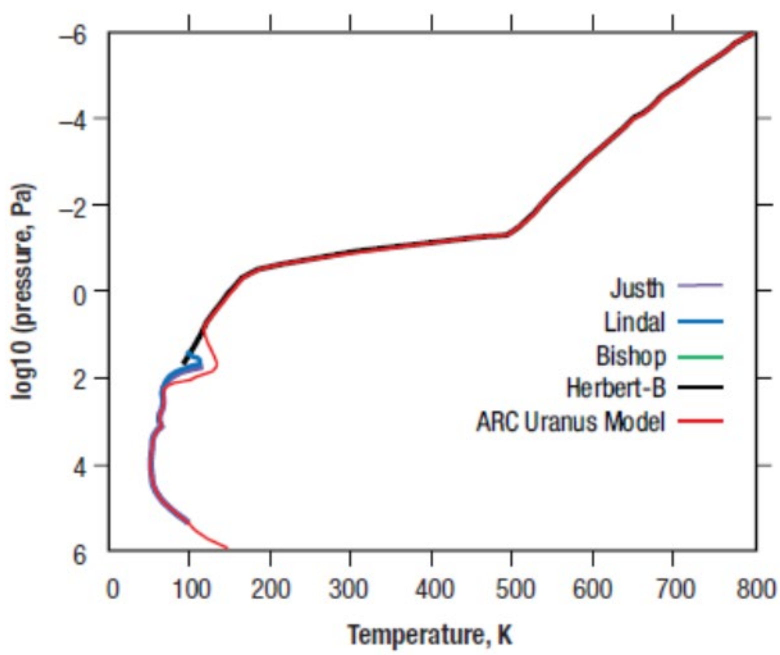

Figure 3. Pressure versus temperature over the full altitude range for each data source and the ARC Uranus Atmospheric Model.

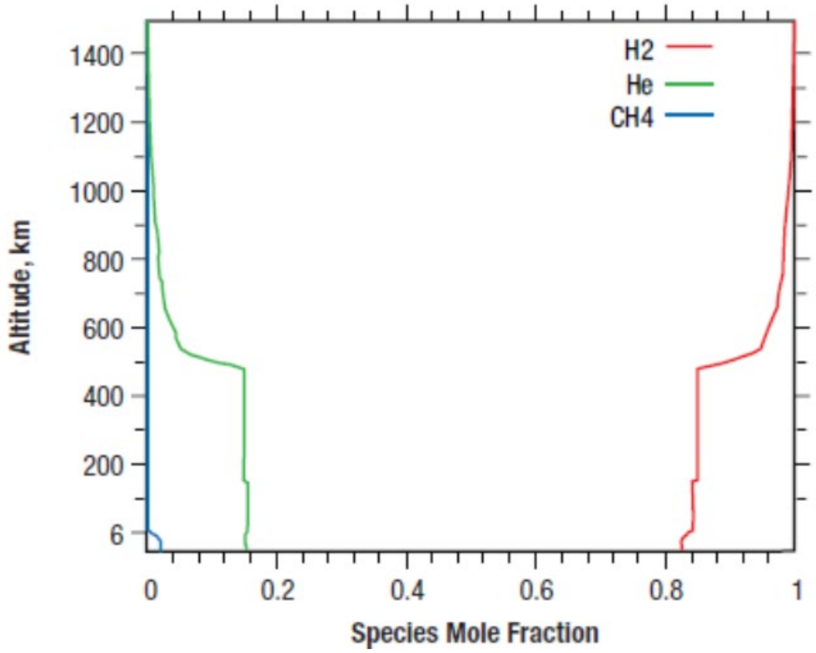

Figure 4. Altitude vs. Uranus atmospheric mole fractions. Default gas mole fraction: H_2 0.85, He 0.15

2.3 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.

2.4 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.

2.5 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.

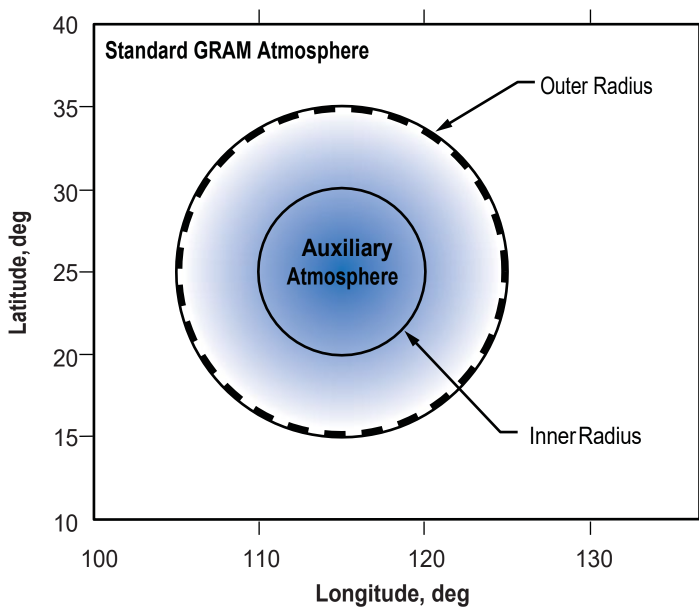

Figure 5. Illustration of two-dimensional auxiliary profile faring implementation with *InnerRadius* = 5° and *OuterRadius* = 10° for a vertical auxiliary profile located at latitude = 25° and longitude = 115°.

2.6 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 beingnegative).
(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 distributed in the GRAM Suite that is available through the NASA Software Catalog: https://software.nasa.gov/software/MFS-33888-1 . 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 present. 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
└──────**/lsk**
        └──────**/naif0012.tls** (time data, **all GRAMs**)
└──────**/pck**
        └──────**/pck00010.tpc** (planetary size/shape data, **all GRAMs**)
└──────**/spk**
        └──────**/planets**
                └──────**/de440_GRAM.bsp** (Earth-GRAM, Venus-GRAM)
        └──────**/satellites**
                └──────/jup365_GRAM.bsp (Jupiter-GRAM)
                └──────/mar097_GRAM.bsp (Mars-GRAM)
                └──────/nep101_GRAM.bsp (Neptune-GRAM)
                └──────/sat441_GRAM.bsp (Saturn-GRAM, Titan-GRAM)
                └──────**/ura116_GRAM.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.

It is now possible to override the default SPICE kernels using NAMELIST file entries. These can be specified in the NAMELIST file, or per the SPICE folder in a file named "spice.txt". All overrides are paths relative to the specified *SpicePath*:

- *SpicePath* = Path to NAIF SPICE data.
- *SpiceLsk* = Optional override of the SPICE leapseconds LSK file.
- *SpicePck* = Optional override of the SPICE planetary constants PCK file.
- *SpiceVenus* = Optional override of the SPICE Venus kernel.
- *SpiceEarth* = Optional override of the SPICE Earth kernel.
- *SpiceMars* = Optional override of the SPICE Mars kernel.
- *SpiceJupiter* = Optional override of the SPICE Jupiter kernel.
- *SpiceSaturn* = Optional override of the SPICE Saturn kernel.
- *SpiceUranus* = Optional override of the SPICE Uranus kernel.
- *SpiceNeptune* = Optional override of the SPICE Neptune kernel.
- *SpiceTitan* = Optional override of the SPICE Saturn kernel (used for Titan).

The GRAM Suite distribution contains a folder named SPICE that contains ephemeris data for the NAIF SPICE library that is utilized within the GRAM Suite. This SPICE kernels "starter pack" enables a user to quickly set up and run the GRAM Suite.

The SPICE kernel starter pack provided with the GRAM Suite originated from the NAIF SPICE website. The planetary kernels were reduced in size using the "spkmerge" tool from the cspice toolkit. The data for moons was stripped from the original files and the time frames were reduced. These kernels are restricted to the dates below.

- BEGIN_TIME = 1 JAN 2000 00:00:00.000
- END_TIME = 1 JAN 2100 00:00:00.000

The default file names for the SPICE kernel starters are as shown below. The original NAIF SPICE file name is contained within each file name.

- *SpiceLsk* = /lsk/naif0012.tls
- *SpicePck* = /pck/pck00011.tpc
- *SpiceVenus* = /spk/planets/de440_GRAM.bsp
- *SpiceEarth* = /spk/planets/de440_GRAM.bsp
- *SpiceMars* = /spk/satellites/mar097_GRAM.bsp
- *SpiceJupiter* = /spk/satellites/jup365_GRAM.bsp
- *SpiceSaturn* = /spk/satellites/sat441_GRAM.bsp
- *SpiceUranus* = /spk/satellites/ura116_GRAM.bsp
- *SpiceNeptune* = /spk/satellites/nep101_GRAM.bsp
- *SpiceTitan* = /spk/satellites/sat441_GRAM.bsp

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
Model Parameters		
ModelType	1 for the Vger model. 2 for the Voyager model (the legacy ARC model). Any other value will select the Vger model.	1
SPICE Parameters		
SpiceLsk	Optional override of the relative (to SpicePath) path to the Spice leapseconds LSK file.	/lsk/naif0012.tls
SpicePck	Optional override of the relative (to SpicePath) path to the Spice planetary constants PCK file.	/pck/pck00011.tpc
SpiceUranus	Optional override of the relative (to SpicePath) path to the Spice Uranus kernel.	/spk/satellites/ura116_GRAM.bsp
SpiceEarth	Optional override of the relative (to SpicePath) path to the Spice Earth kernel. This is used in one way light time computations.	/spk/planets/de440_GRAM.bsp
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 (PRO-FILE)	(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 (%)
DensityStandardDeviation_pct	Standard deviation of the density (%). *** Note: Not modelled. This value will be zero.**
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 *** Note: Not modelled. This value will be zero.**
HighDensityDeviation_pct	Percent deviation of the high density from the reference density *** Note: Not modelled. This value will be zero.**
PerturbedDensityDeviation_pct	Percent deviation of the perturbed density from the reference density
EWWind_ms*	Mean eastward wind component (m/s) *** Note: Vger model only. This value will be zero for the Voyager model.**

NSWind_ms*	Mean northward wind component (m/s) *** Note: NS winds are not modelled. This value will be zero.**
EWWindPerturbation_ms*	Eastward wind perturbation (m/s) *** Note: Vger model only. This value will be zero for the Voyager model.**
NSWindPerturbation_ms*	Northward wind perturbation (m/s) *** Note: NS winds are not modelled. This value will be zero.**
PerturbedEWWind_ms*	Total (mean plus perturbed) eastward wind (m/s) *** Note: Vger model only. This value will be zero for the Voyager model.**
PerturbedNSWind_ms*	Total (mean plus perturbed) northward wind (m/s) *** Note: NS winds are not modelled. This value will be zero.**
EWStandardDeviation_ms*	Standard deviation of eastward wind perturbations (m/s) *** Note: Vger model only. This value will be zero for the Voyager model.**
NSStandardDeviation_ms*	Standard deviation of northward wind perturbations (m/s) *** Note: NS winds are not modelled. 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)
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)
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)
PerturbedTemperature_K	Temperature including large scale perturbation (K)
TemperaturePerturbation_pct	Temperature large scale perturbation (%)
PerturbedPressure_Pa	Pressure including large scale perturbation (Pa)
PressurePerturbation_pct	Pressure large scale perturbation (%)
PerturbedDensityLarge_kgm3	Density including large scale perturbation (kg/m^3)
DensPertSmall_pct	Density small scale perturbation (%)

DensPertLarge_pct	Density large scale perturbation (%)

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
   ModelType             =  1

   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
   ModelType            =  1 for the New Vger model
                           2 for the legacy Voyager model

   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 2022 using the solution /GRAM/MSVS/GRAMs.sln. To rebuild these binaries:

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

Depending on your installations, you may need to set the Platform Toolset of some of the projects. The resulting binaries will be found in /GRAM/MSVS/x64/Release.

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++17 standard.
- C_FLAGS
  – Must be set to use the C11 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 N0067). 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.
2024	7/2024	Updated Uranus Atmosphere model developed by the GRAM Team (Vger model) has been added. The previous ARC model is retained and referred to in the Uranus-GRAM code as the Voyager model.

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