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

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August 2020

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Space Administration

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

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PREFACE

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

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

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LIST OF ACRONYMS

ASCII	American Standard Code for Information Interchange
CIRS	Cassini Composite Infrared Spectrometer
CSS	Cascading Style Sheets
CSV	comma separated value
DWE	Doppler Wind Experiment
ERT	Earth-receive time
GCM	General Circulation Model
GRAM	Global Reference Atmospheric Model
HASI	Huygens Atmospheric Structure Instrument
IRIS	Infrared Interferometer Spectrometer and Radiometer
Ls	longitude of the Sun
LTST	local true solar time
MSFC	Marshall Space Flight Center
NAIF	Navigation and Ancillary Information Facility
SMD	Science Mission Directorate
SPICE	Spacecraft Planet Instrument C-matrix Events
TET	Titan-event time
Titan-GRAM	Titan Global Reference Atmospheric Model
UVS	Ultraviolet Spectrometer

TECHNICAL MEMORANDUM

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

1. INTRODUCTION

1.1 Background and Overview

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

A Fortran version of Titan-GRAM was originally released in 2004. Recently, the code has been updated and rearchitected in C++ to improve efficiencies in implementation, run time, and maintenance. Titan-GRAM now shares a common software core with other versions of the GRAMs. Additionally, documentation including this User Guide, a Programmer's Manual, and trajectory code interfaces has been made available with the software release.

This Technical Memorandum summarizes the atmospheric data model in Titan-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 Titan-GRAM. Section 3 explains the process to obtain the Titan-GRAM code and data files and how to set up and run the program. Appendices A through E provide additional details regarding the Titan-GRAM input and output files. Appendix F provides a history of Titan-GRAM revisions.

1.2 Significant Changes in Titan-GRAM

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

(1) The Titan-GRAM input parameters have been renamed to be more descriptive. The legacy input parameter names are still accepted to maintain compatibility with existing NAMELIST input files from prior Titan-GRAM versions. Table 3 in section 3.3 provides the new and old input parameter names.

(2) The code has incorporated NASA's Navigation and Ancillary Information Facility (NAIF) Spacecraft Planet Instrument C-matrix Events (SPICE) library for ephemeris calculations. Titan ephemeris values, such as longitude of the Sun and solar time, are now computed using the NAIF SPICE library for greater accuracy. The values generated by SPICE are slightly different from those generated in the original custom Titan-GRAM 2004 ephemeris engine. While the values produced by the new and legacy Titan-GRAMs will compare favorably, slight differences in the *MinMaxFactor* are observed as a result of this change. Details of the *MinMaxFactor* are discussed in section 2.1.2. Additionally, the use of NAIF SPICE requires the Titan-GRAM user to download the latest SPICE data before using Titan-GRAM. Instructions for doing so are provided in section 3.2.

(3) Due to the increase in computing power and memory since the original release of Titan-GRAM in 2004, the output files have been reformatted. The output is provided in two formats: (1) a comma separated value (CSV) file and (2) a LIST file (formerly LIST.txt, now LIST.md). The CSV file consolidates all of the column formatted output files from the original release of Titan-GRAM into a single file that can easily be loaded into data centric programs, such as Microsoft Excel or MATLAB®. A detailed list of CSV file parameters and definitions are provided in appendix A. Alternatively, the LIST file can be read using either a standard American Standard Code for Information Interchange (ASCII) reader or a Markdown syntax for enhanced rendering in a web browser. An example of both LIST file formats is provided in appendix C.

(4) The primary changes in this version of Titan-GRAM involve a rearchitecture from Fortran to a common object-oriented C++ framework. The new architecture creates a common GRAM library of data models and utilities. Additionally, upon release of all the rearchitected GRAMs, the user will be able to compile the GRAMs into a single library containing GRAM atmospheric data for multiple destinations. The common C++ framework reduces duplicated code, ensures consistent constants across all GRAMs, simplifies bug fixes, and streamlines the interface with trajectory codes. Users should refer to the GRAM Programmer's Manual for additional details.

(5) The calculation of the speed of sound has been improved in Titan-GRAM. Titan-GRAM computes speed of sound based on a thermodynamic parameterization using temperature and γ, the ratio of specific heats for a given constituent gas mixture. Titan-GRAM previously used a constant γ, which is physically unrealistic and overestimates the speed of sound by as much as 10%. Titan-GRAM now uses an improved methodology for computing γ, involving the evaluation of Shomate coefficients in run time for the current constituent combination.

2. TITAN-GRAM ATMOSPHERIC DATA

2.1 Titan-GRAM Input Data

2.1.1 Overview of Titan-GRAM Data

When input parameter *ModelType* = 1, atmospheric density, temperature, and pressure as a function of height are characterized by engineering model profile envelopes from Yelle et al.[2] representing expected minimum, average, and maximum conditions. The Yelle models are based on observations from Voyager radio science, Infrared Interferometer Spectrometer and Radiometer (IRIS), and the Ultraviolet Spectrometer (UVS). The model profiles provide an adequate fit to all three sources of variations and uncertainties: (1) Uncertainties in the analysis of the Voyager data, (2) estimated range of latitudinal variations in atmospheric structure, and (3) temporal changes in the atmosphere due to seasonal and diurnal variations.

The Yelle data consist of the average, minimum, and maximum profiles of the following: total number density, number densities for nitrogen, methane, and argon, mass density, air pressure, air temperature, and a correction factor for the perfect gas law equation. Data in these three files have been extended above 1,300 km altitude by utilizing a simple thermosphere model that includes diffusive separation. A small amount of argon has been added to the minimum case profile to avoid problems caused by assuming zero argon. A plot of the Yelle data as it has been incorporated in Titan-GRAM is provided in figures 1 and 2.

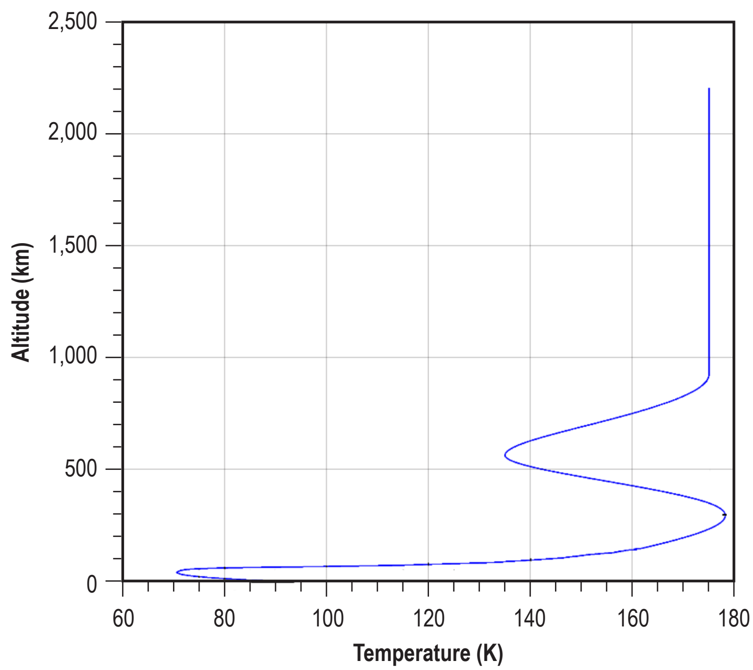

Figure 1. Altitude versus temperature for titanavg.txt profile.

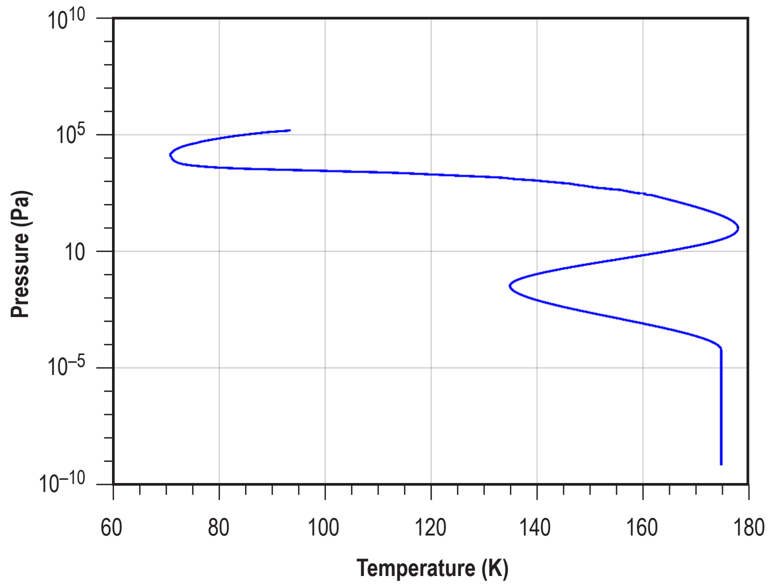

Figure 2. Pressure versus temperature for titanavg.txt profile.

Density perturbation magnitudes are estimated using

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

and

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

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
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 ($R' \approx X$).

The basic zonal wind model is from Bird et al.[3] and Flasar et al.[4] Latitude variation of the zonal wind is from equation (2) of Lebreton et al.[5] Standard deviation for wind perturbations is estimated from Lebreton et al., p. 292.[5] The wind perturbations in Titan-GRAM are shown in figures 3 and 4.

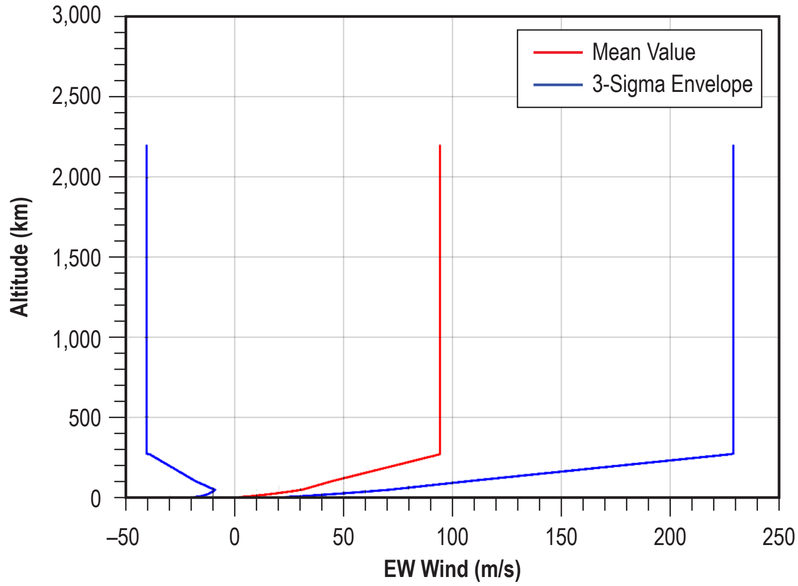

Figure 3. Three-sigma envelope of Titan-GRAM east (positive)/ west (negative) wind.

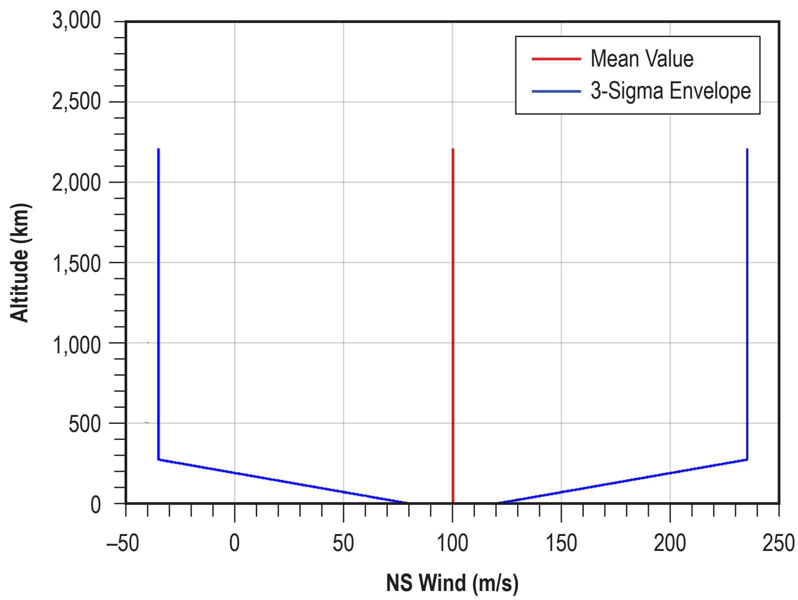

Figure 4. Three-sigma envelope of Titan-GRAM north (positive)/ south (negative) wind.

Latitude gradient effect estimates for temperature and composition are from Coustenis and Bézard,[6] Dire,[7] Bird et al.,[3] and Gautier.[8] Constituent information is from Lebreton et al.[5] Constituent contributions are shown in figure 5.

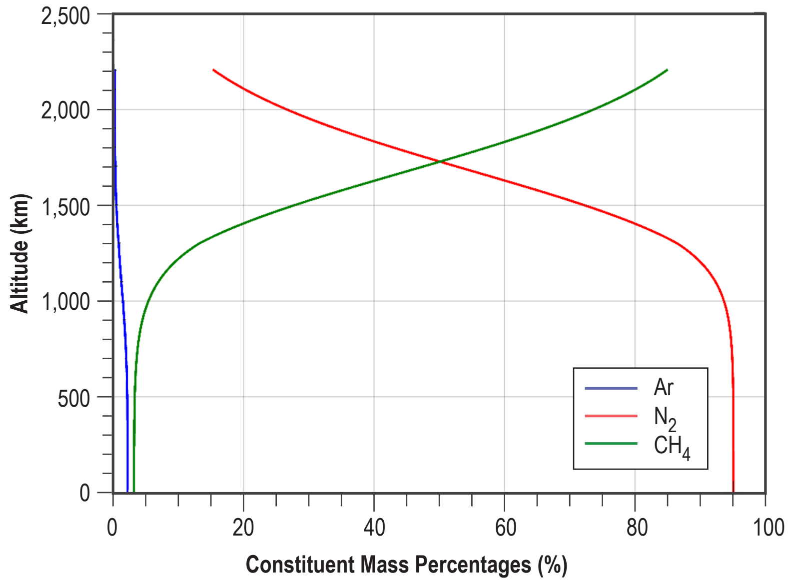

Figure 5. Mean constituent contributions by percent.

The input parameter *MethaneMoleFraction* (previously *fmolmeth*) can be utilized by the user to set the methane mole fraction to a value between 1.0% and 5.0%. If *MethaneMoleFraction* = 0.0, the original Yelle methane mole fraction is used. When *MethaneMoleFraction* = 1.0 to 5.0, this percentage value is used in place of the Yelle value, resulting in the rebalancing of the other constituent mole fractions while preserving the mean molecular weight. This will, of course, also change the number densities and mass fractions for the other Titan-GRAM atmospheric constituents.

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

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

Table 1. Titan gravity parameters.

Titan	Label	Units	Value
Gravitational parameter	GM	km^3/s^2	8978030.0
Mean equatorial radius	R_e	km	2575.5
Mean polar radius	R_p	km	2575.5
J_2 harmonic	J_2		3.15e-5
Period		s	1377684.0

Information on seasons of Titan is from Lorenz et al.[9] Other considerations about atmosphere and dynamics for Titan are from Flasar.[10]

If input parameter *ModelType* = 2, Titan GCM data will be used as the input data for Titan-GRAM. The Titan GCM data used for lower altitudes is from the model of Hourdin et al.[11] and consists of daily mean temperature and zonal wind at 31 pressure levels from 1,465 mbar to 0.3 mbar, at 10° latitude intervals from –90° to 90° at areocentric longitude of the Sun (Ls) = 0 and Ls = 270. Estimates for other seasons are generated by 180° Ls offset and hemispheric reversal. The Titan GCM data used for the upper altitudes are computed using a parameterized fit to Titan exospheric temperatures taken from Mueller-Wodarg et al.[12] The nitrogen compressibility factor is accounted for when using the lower altitude GCM data. Data for the nitrogen compressibility factors are from J. Hilsenrath et al.[13]

2.1.2 Input Parameter *MinMaxFactor*

When *ModelType* = 1, the input parameter *MinMaxFactor* (previously known as *Fminmax*) is utilized and Titan-GRAM does not explicitly compute time-dependent or latitude-dependent atmospheric values. In this case, Titan-GRAM includes a minimum-to-maximum envelope of Titan data that contains variations of the mean with respect to latitude, season, and time of day. By selecting the appropriate value for the input parameter *MinMaxFactor*, a mean profile can be generated within the minimum-to-maximum envelope.

MinMaxFactor determines where, within the envelope of minimum-to-maximum conditions, a given atmospheric profile falls. *MinMaxFactor* can be any real number between –1 (minimum) and 1 (maximum). *MinMaxFactor* = 0.0 gives the average Titan profile. Titan-GRAM has a built-in routine for generating random high-frequency perturbations about the selected mean profile. The amplitude of the perturbation variations, especially at high altitudes, will extend beyond the range of maximum-to-minimum bounds in the Titan model envelope. Users wishing to vary mean atmosphere profiles (in a Monte Carlo sense) between Titan minimum and maximum profiles can do so by randomly selecting values of *MinMaxFactor* between –1 and 1. *MinMaxFactor* values between –1 and 0 are automatically interpolated between minimum and average conditions. Likewise, *MinMaxFactor* values between 0 and 1 are automatically interpolated between average and maximum conditions. Figure 6 illustrates the relationship between *MinMaxFactor* and the computed mean and perturbed density profiles.

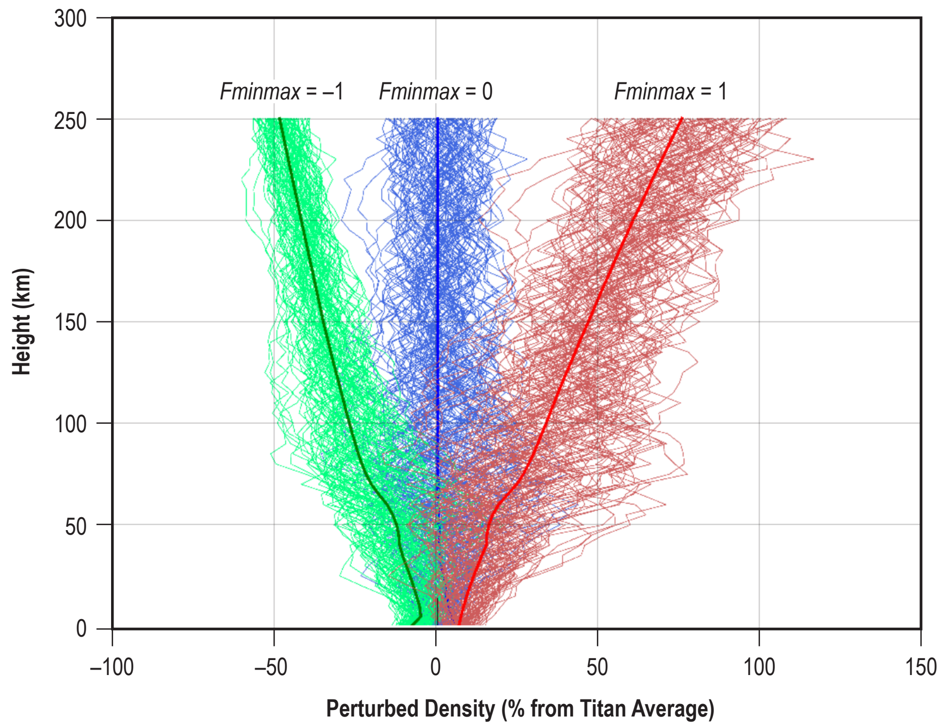

Figure 6. *MinMaxFactor* (*Fminmax*) and Titan-GRAM computed densities for a sample Monte Carlo output. Bold lines represent mean values.

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

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

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

2.2 Querying Atmosphere Data

The Titan-GRAM user-defined path can be generated in multiple ways. The first is to run Titan-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, Titan-GRAM steps automatically in user-defined increments of altitude, latitude, longitude, and time to generate a constantly incremented profile. Each point in the profile will have a corresponding atmospheric value for density, temperature, pressure, winds, and constituents. A second path generation option is to run the model in trajectory evaluation mode where the user provides a trajectory file, specified using *TrajectoryFileName.* The trajectory file contains a specified time history of altitude, latitude, and longitude and removes the constant increment constraint criteria of the previous option. Additional information about trajectory file input can be found in section 2.5. A third method is to incorporate the Titan-GRAM code directly into a user's trajectory code. This version of Titan-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, Titan-GRAM writes output to two files: a CSV output file and a LIST file output. These output files are detailed in appendices A and C.

2.3 Monte Carlo Capability

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

Using a user-generated trajectory file, specified using the input parameter *TrajectoryFileName,* that contains a specified time history of altitude, latitude, and longitude, removes the constant increment constraint criteria. The Titan-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 Titan-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 Titan-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 Titan-GRAM with a profile of atmosphere quantities versus altitude. 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 Titan-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 Titan-GRAM input wind data are used if both wind components in the auxiliary atmosphere profile file are set to zero.

A weighting factor for the auxiliary atmosphere profile data (*ProfileWeight*), having values between 0 and 1, is applied between the *InnerRadius* and *OuterRadius*. The *InnerRadius* is the latitude-longitude radius (degrees) within which weight for the auxiliary atmosphere profile is 1.0. The *OuterRadius* is the latitude-longitude radius (degrees) beyond which the weight for the auxiliary atmosphere profile is 0.0. Mean conditions are specified by the auxiliary atmospheric profile input file if the desired point is within the *InnerRadius*; mean conditions are given by the standard Titan-GRAM data if the desired point is beyond the *OuterRadius*. 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 7. If *InnerRadius* = 0, then the auxiliary atmosphere profile data are not used. In addition to fairing in latitude and longitude, fairing of the 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 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.

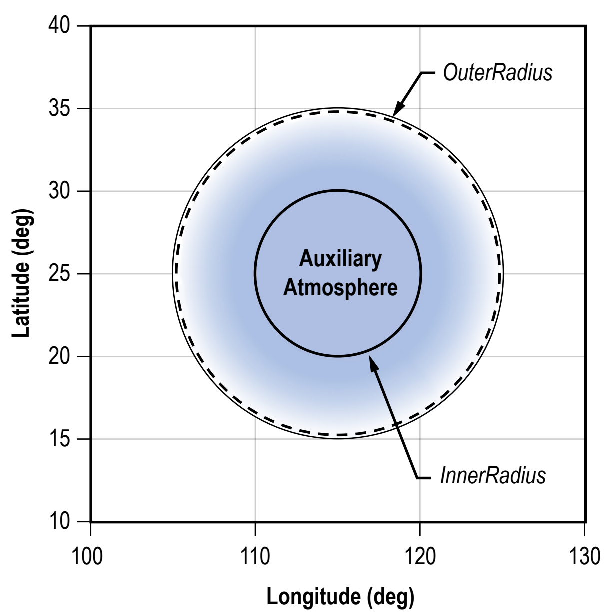

Figure 7. Illustration of two-dimensional auxiliary profile fairing implementation with *InnerRadius* = 5° and *OuterRadius* = 10° for a vertical auxiliary profile located at latitude = 25° and longitude = 115°.

Included in the Titan-GRAM distribution are the Huygens Atmospheric Structure Instrument (HASI)/Doppler Wind Experiment (DWE) and Cassini Composite Infrared Spectrometer (CIRS) auxiliary profiles produced by a Titan-GRAM Comparison Study by Justh and Justus (H.L. Justh and C.G. Justus, "Comparisons of Huygens Entry Data and Titan Remote Sensing Observations with the Titan Global Reference Atmospheric Model (Titan-GRAM)," unpublished data, November 2007). These auxiliary profiles allow Titan-GRAM to better replicate the HASI/DWE and CIRS observational data.

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 Titan-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 *East LongitudePositive*).

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 TITAN-GRAM

3.1 How to Obtain the Program

Titan-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 Titan-GRAM installation includes a set of Windows and Linux 64-bit executable libraries located in the GRAM/Windows and GRAM/Linux folders. The Titan-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 Titan-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 Titan-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 Titan-GRAM, simply double-click the TitanGRAM.exe file or enter 'TitanGRAM.exe' from a command prompt. The program will prompt for the path to an input parameter file in NAMELIST format (see sec. 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/Titan/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 Titan-GRAM command line. The format of this option is 'TitanGRAM.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

Titan-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 Titan-GRAM. All input parameter names are case insensitive. Input parameters whose values are supplied in the input file are given in table 3. (The legacy Titan-GRAM input parameters names are still supported and appear in parentheses.)

Table 3. Titan-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

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

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

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

Input Parameter	Description	Default
Auxiliary Atmosphere Parameters		
AuxiliaryAtmosphereFile-Name (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 are present.)	0.0
OuterRadius (PROFFAR)	(Optional) Latitude-longitude radius (degrees) beyond which weight for the auxiliary profile is 0.0.	0.0
Output Parameters		
FastModeOn	Controls the speed and accuracy of ephemeris calculations. 0: More accurate, but slower. 1: Faster, but less accurate.	0
ExtraPrecision	For the new column output format, this parameter adds precision to all outputs.	0
UseLegacyOutputs	Flags which outputs to generate. 0: Use the new output formats. 1: Use output formats closely matching those of the Legacy Titan-GRAM.	0
DensityPrintScale (LOGSCALE)	Parameter to control units of output values of density and pressure to the legacy output files. This parameter has no effect if *UseLegacyOutputs* is 0. 0: use regular density and pressure units (kg/m^3 and N/m^2) 1: use logarithm (base-10) of the regular units 2: use percent deviation from mean model values of density and pressure 3: use SI units, with density in kg/km^3 (suitable for high altitudes)	0
Titan Parameters		
ModelType	Selects either the Yelle97 model or the GCM95 model. 1: use the Yelle97 model 2: use the GCM95 model	1
MinMaxFactor (FMINMAX)	This parameter determines where within the envelope of minimum-to-maximum a given profile falls. *MinMaxFactor* can be any real number between –1.0 (minimum) and +1.0 (maximum). *MinMaxFactor* = 0.0 gives the average (nominal) Titan profile.	0.0
ComputeMinMaxFactor (IFMM)	Set to 1 to automatically adjust input *MinMaxFactor* for seasonal, latitude, and time-of-day effects. Set to 0 to use the input *MinMaxFactor* “as is”. (For legacy support) Set to 2 to use the GCM95 model.	1
MethaneMoleFraction (fmolmeth)	User-defined methane mole fraction value that overrides Yelle value. Can be set to 1.0 to 5.0 (%). If *MethaneMoleFraction* = 0.0, original Yelle values will be used.	0.0

3.4 Program Output

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

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

Table 4. FindDates input parameters.

Input Parameter	Description	Default
SpicePath or SpiceDir	The location of the NAIF SPICE data files. Absolute paths are recommended. Relative paths are acceptable.	/spice
FindDates	The parameter flags the use of the FindDates auxiliary capability. Use the FindDates capability if *FindDates* = 1. Use Titan-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 TITAN-GRAM OUTPUT FILE

Titan-GRAM produces a CSV output file (see table 5) suitable for passing to a data-centric program for plotting and further analysis. The field names purposely lack any special characters other than an underscore separating the units. Thus, for some fields, such as Gravity_ms2, the precise units must be inferred, as in m/s^2.

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

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

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

HighDensityDeviation_pct	Percent deviation of the high density from the reference density
PerturbedDensityDeviation_pct	Percent deviation of the perturbed density from the reference density
EWWind_ms	Mean eastward wind component (m/s)
NSWind_ms	Mean northward wind component (m/s)
EWWindPerturbation_ms	Eastward wind perturbation (m/s)
NSWindPerturbation_ms	Northward wind perturbation (m/s)
PerturbedEWWind_ms	Total (mean plus perturbed) eastward wind (m/s)
PerturbedNSWind_ms	Total (mean plus perturbed) northward wind (m/s)
EWStandardDeviation_ms	Standard deviation of eastward wind perturbations (m/s)
NSStandardDeviation_ms	Standard deviation of northward wind perturbations (m/s)
LongitudeOfTheSun_deg	The planetocentric longitude of the sun, 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.
Arnd_m3	Number density of argon (#/m^3)
Armass_pct	Argon concentration, percent by mass
Armole_pct	Mole fraction (%) of argon concentration (or % by volume)
Aramw	Average molecular weight of argon (amu)
Arcp_JgK	Specific heat capacity by constant pressure (J/(g K))
CH4nd_m3	Number density of methane (#/m^3)
CH4mass_pct	Methane concentration, percent by mass
CH4mole_pct	Mole fraction (%) of methane concentration (or % by volume)
CH4amw	Average molecular weight of methane (amu)
CH4cp_JgK	Specific heat capacity by constant pressure (J/(g K))
N2nd_m3	Number density of molecular nitrogen (#/m^3)
N2mass_pct	Molecular nitrogen concentration, percent by mass
N2mole_pct	Mole fraction (%) of molecular nitrogen concentration (or % by volume)
N2amw	Average molecular weight of molecular nitrogen (amu)
N2cp_JgK	Specific heat capacity by constant pressure (J/(g K))
MinMaxFactor	The computed min/max factor

APPENDIX B—EXAMPLE NAMELIST FORMAT INPUT FILE

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

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

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

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

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

 AuxiliaryAtmosphereFileName = 'null'
 InnerRadius = 0.0
 OuterRadius = 0.0

 NumberOfMonteCarloRuns = 1

 ModelType              = 1
 MinMaxFactor           = 0.0
 ComputeMinMaxFactor    = 1
 MethaneMoleFraction    = 0.0

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

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

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

 TimeScale = 0 for Terrestrial (Dynamical) Time (TDT)
             1 for time input as Coordinated Universal Time (UTC)
             2 for Barycentric Dynamical Time (TDB)
 Month     = month of year
 Day       = day of month
 Year      = year (4-digit, or 1970-2069 can be 2-digit)
 Hour      = hour of day (meaning controlled by TimeFrame and TimeScale)
 Minute    = minute of hour (meaning controlled by TimeFrame and TimeScale)
 Seconds   = seconds of minute (meaning controlled by TimeFrame and TimeScale)

 InitialRandomSeed        = starting random number (0 - 30000)

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

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


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

 NumberOfMonteCarloRuns = the number of Monte Carlo runs

 ModelType              = 1 to use the Yelle Min/Max data model
                          2 to use the Titan GCM model
 MinMaxFactor           = Factor (-1. to +1. to vary between minimum and
                          maximum allowed mean profiles
 ComputeMinMaxFactor    = 0 to use MinMaxFactor input value "as is"
                          1 to automatically adjust input factor for
                          seasonal, latitude, and time-of-day effects
 MethaneMoleFraction    = Methane mole fraction override (percent) 1.0 to 5.0.
                          Input = 0.0 (default) means use modelled values.
```

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

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

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

 Explanation of variables:
  LSTFL     =  List file name (CON for console listing)
```

```
OUTFL     =  Output file name
TRAJFL    =  (Optional) Trajectory input file name
profile   =  (Optional) auxiliary profile input file name
IERT      =  1 for time input as Earth-receive time (ERT), or 0
              Titan-event time (TET)
IUTC      =  1 for time input as Coordinated Universal Time (UTC),
              or 0 for Terrestrial (Dynamical) Time (TT)
MONTH     =  month of year
MDAY      =  day of month
MYEAR     =  year (4-digit, or 1970-2069 can be 2-digit)
IHR       =  Hour of day (ERT or NET, controlled by IERT
              and UTC or TT, controlled by IUTC)
IMIN      =  minute of hour (meaning controlled by IERT and IUTC)
SEC       =  seconds of minute (meaning controlled by IERT and
              IUTC).  IHR:IMIN:SEC is time for initial position to
              be evaluated
NPOS      =  max # positions to evaluate (0 = read data from
              trajectory input file)
LonEast   =  0 for input and output West longitudes positive; 1 for
              East longitudes positive
Fminmax   =  Factor (-1. to +1. to vary between min and max allowed
              mean profiles
IFMM      =  2 to use Hourdin GCM data input and Mueller-Wodarg
              exospheric temperature model instead of Fminmax
              envelope approach, or 1 to automatically adjust input
              Fminmax for seasonal, latitude, and time-of-day
              effects, or 0 to use Fminmax input value "as is"
NR1       =  starting random number (0 < NR1 < 30000)
LOGSCALE  =  0=regular SI units, 1=log-base-10 scale, 2=percentage
              deviations from Mean model, 3=SI units with density in
              kg/km**3
FLAT      =  initial latitude (N positive), degrees
FLON      =  initial longitude (West positive if LonEast=0 or East
              positive if LonEast = 1), degrees
FHGT      =  initial height (km)
DELHGT    =  height increment (km) between steps
DELLAT    =  latitude increment (deg) between steps
DELLON    =  longitude increment (deg) between steps (West positive
              if LonEast = 0, East positive if LonEast = 1)
DELTIME   =  time increment (seconds) between steps.  Time increment
              is in ERT or NET, as controlled by input parameter
              IERT, and UTC or TT, as controlled by input parameter
              IUTC
profnear  =  Lat-lon radius within which weight for auxiliary profile
              is 1.0 (Use profnear = 0.0 for no profile input)
proffar   =  Lat-lon radius beyond which weight for auxiliary profile
              is 0.0
rpscale   =  random perturbation scale factor (0-2)
NMONTE    =  number of Monte Carlo runs
corlmin   =  Minimum relative step size for perturbations
              (0.0 - 1.0); 0.0 means always update perturbations,
              x.x means only update perturbations when corlim > x.x
fmolmeth  =  Methane mole fraction (percent) 1.0 to 5.0.  Input = 0.0
              means use original Yelle values
```

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 Titan-GRAM on their own computer and to electronically check their output by a file-compare process (e.g., the 'diff' command in UNIX or the 'fc' command from a Windows Command Prompt). Please note that, due to machine-dependent or compiler-dependent rounding differences, some output values may differ slightly from those shown here. These differences are usually no more than one unit in the last significant digit displayed.

Field	Value	Field	Value
Time Frame	Earth Receive Time (ERT)	Initial Random Seed	1001
Time Scale	Coordinated Universal Time (UTC)	Minimum Relative Step Size	0.000
Start Date	8/25/2021	Density Perturbation Scale	1.00
Start Time	15:45:00.00	EW Wind Perturbation Scale	1.00
Julian Day	2459452.156250	NS Wind Perturbation Scale	1.00

Record #1

Field	Value	Field	Value
Elapsed Time (s)	0.00	Elapsed Time (sols)	0.00
Height Above Ref. Ellipsoid (km)	0.000	Reference Radius (km)	2575.5
Latitude (deg)	22.000	Local Solar Time (hrs)	18.08
Longitude W (deg)	48.00	Longitude of the Sun (deg)	137.02
Pressure Scale Height (km)	19.903	Orbital Radius (AU)	9.94
Density Scale Height (km)	28.098	One Way Light Time (min)	74.92
Temperature (K)	93.9	Subsolar Latitude (deg)	17.73
Pressure (Pa)	1.481e+05	Subsolar Longitude W (deg)	139.18
Sigma Level	1.000	Solar Zenith Angle (km)	0.00
Pressure Altitude (km)	-0.000	Gravity (m/s^2)	1.353
Surface Pressure (Pa)	1.481e+05	Speed of Sound (m/s)	194.701
Compressibility Factor (zeta)	0.9657	Specific Gas Constant (J/(kg K))	287.974
Specific Heat Ratio	1.402	Profile Weight	0.000

Density	Low	Average	High
Density (kg/m^3)	5.3153e+00	5.4747e+00	5.6390e+00
Density Deviation (%)	-2.2	0.7	3.8
Perturbed Density (kg/m^3)	5.6156e+00	Perturbation (%)	2.6
Perturbed Density Deviation (%)	3.32	Perturbed Speed of Sound (m/s)	192.24

Winds	Mean	Perturbation	Perturbed
Eastward Wind (m/s)	0.4	10.5	10.9
Northward Wind (m/s)	0.0	-7.3	-7.3

Gases	Number Density (#/m^3)	Mass (%)	Mole (%)	Avg Mol Wgt	Cp (J/gK)
Argon (Ar)	2.8359e+24	3.2	2.4	36.40	0.57
Dinitrogen (N2)	1.1142e+26	95.3	94.9	28.00	1.04
Methane (CH4)	3.1295e+24	1.5	2.7	16.00	2.08
Total	1.1738e+26	100.0	100.0	27.88	1.04

Record #2

Field	Value	Field	Value
Elapsed Time (s)	500.00	Elapsed Time (sols)	0.00

Height Above Ref. Ellipsoid (km)	2.000	Reference Radius (km)	2575.5
Latitude (deg)	22.300	Local Solar Time (hrs)	18.05
Longitude W (deg)	48.50	Longitude of the Sun (deg)	137.02
Pressure Scale Height (km)	19.495	Orbital Radius (AU)	9.94
Density Scale Height (km)	27.215	One Way Light Time (min)	74.92
Temperature (K)	91.2	Subsolar Latitude (deg)	17.73
Pressure (Pa)	1.338e+05	Subsolar Longitude W (deg)	139.31
Sigma Level	0.903	Solar Zenith Angle (km)	0.00
Pressure Altitude (km)	1.979	Gravity (m/s^2)	1.351
Surface Pressure (Pa)	1.481e+05	Speed of Sound (m/s)	191.909
Compressibility Factor (zeta)	0.9664	Specific Gas Constant (J/(kg K))	288.157
Specific Heat Ratio	1.402	Profile Weight	0.000

Density	Low	Average	High
Density (kg/m^3)	4.9252e+00	5.0927e+00	5.2658e+00
Density Deviation (%)	-2.5	0.8	4.2
Perturbed Density (kg/m^3)	5.1750e+00	Perturbation (%)	1.6
Perturbed Density Deviation (%)	2.41	Perturbed Speed of Sound (m/s)	190.38

Winds	Mean	Perturbation	Perturbed
Eastward Wind (m/s)	3.6	6.5	10.1
Northward Wind (m/s)	0.0	-6.5	-6.5

Gases	Number Density (#/m^3)	Mass (%)	Mole (%)	Avg Mol Wgt	Cp (J/gK)
Argon (Ar)	2.6497e+24	3.2	2.4	36.40	0.57
Dinitrogen (N2)	1.0361e+26	95.3	94.9	28.00	1.04
Methane (CH4)	2.9018e+24	1.5	2.7	16.00	2.08
Total	1.0916e+26	100.0	100.0	27.88	1.04

(Snipped for brevity)

Record #200

Field	Value	Field	Value
Elapsed Time (s)	99500.00	Elapsed Time (sols)	0.07
Height Above Ref. Ellipsoid (km)	398.000	Reference Radius (km)	2575.5
Latitude (deg)	81.700	Local Solar Time (hrs)	13.18
Longitude W (deg)	147.50	Longitude of the Sun (deg)	137.06
Pressure Scale Height (km)	52.511	Orbital Radius (AU)	9.94
Density Scale Height (km)	55.958	One Way Light Time (min)	74.98
Temperature (K)	181.0	Subsolar Latitude (deg)	17.72
Pressure (Pa)	1.987e+00	Subsolar Longitude W (deg)	165.16
Sigma Level	0.000	Solar Zenith Angle (km)	0.00
Pressure Altitude (km)	591.045	Gravity (m/s^2)	1.015
Surface Pressure (Pa)	1.536e+05	Speed of Sound (m/s)	273.638
Compressibility Factor (zeta)	0.9969	Specific Gas Constant (J/(kg K))	294.314
Specific Heat Ratio	1.406	Profile Weight	0.000

Density	Low	Average	High
Density (kg/m^3)	3.3908e-05	3.7298e-05	4.1028e-05
Density Deviation (%)	40.3	54.3	69.8
Perturbed Density (kg/m^3)	4.1348e-05	Perturbation (%)	10.9
Perturbed Density Deviation (%)	71.09	Perturbed Speed of Sound (m/s)	259.89

Winds	Mean	Perturbation	Perturbed
Eastward Wind (m/s)	52.1	-96.6	-44.4
Northward Wind (m/s)	0.0	-26.6	-26.6

Gases	Number Density (#/m^3)	Mass (%)	Mole (%)	Avg Mol Wgt	Cp (J/gK)
Argon (Ar)	3.4987e+19	5.8	4.5	36.40	0.57
Dinitrogen (N2)	7.2927e+20	93.2	93.7	28.00	1.04
Methane (CH4)	1.3959e+19	1.0	1.8	16.00	2.08
Total	7.7822e+20	100.0	100.0	28.16	1.02

```
--------------------
## Record #201
--------------------

| Field                              | Value      | Field                              | Value      |
|------------------------------------|------------|------------------------------------|------------|
| Elapsed Time (s)                   | 100000.00  | Elapsed Time (sols)                | 0.07       |
| Height Above Ref. Ellipsoid (km)   | 400.000    | Reference Radius (km)              | 2575.5     |
| Latitude (deg)                     | 82.000     | Local Solar Time (hrs)             | 13.15      |
| Longitude W (deg)                  | 148.00     | Longitude of the Sun (deg)         | 137.06     |
| Pressure Scale Height (km)         | 52.516     | Orbital Radius (AU)                | 9.94       |
| Density Scale Height (km)          | 55.963     | One Way Light Time (min)           | 74.98      |
| Temperature (K)                    | 180.6      | Subsolar Latitude (deg)            | 17.72      |
| Pressure (Pa)                      | 1.914e+00  | Subsolar Longitude W (deg)         | 165.29     |
| Sigma Level                        | 0.000      | Solar Zenith Angle (km)            | 0.00       |
| Pressure Altitude (km)             | 593.066    | Gravity (m/s^2)                    | 1.014      |
| Surface Pressure (Pa)              | 1.536e+05  | Speed of Sound (m/s)               | 273.328    |
| Compressibility Factor (zeta)      | 0.9969     | Specific Gas Constant (J/(kg K))   | 294.311    |
| Specific Heat Ratio                | 1.406      | Profile Weight                     | 0.000      |

| Density                            | Low        | Average                            | High       |
|------------------------------------|------------|------------------------------------|------------|
| Density (kg/m^3)                   | 3.2735e-05 | 3.6008e-05                         | 3.9609e-05 |
| Density Deviation (%)              | 40.7       | 54.8                               | 70.3       |
| Perturbed Density (kg/m^3)         | 3.8346e-05 | Perturbation (%)                   | 6.5        |
| Perturbed Density Deviation (%)    | 64.84      | Perturbed Speed of Sound (m/s)     | 264.87     |

| Winds                              | Mean           | Perturbation   | Perturbed      |
|------------------------------------|----------------|----------------|----------------|
| Eastward Wind  (m/s)               | 51.2           | -67.3          | -16.1          |
| Northward Wind  (m/s)              | 0.0            | -8.0           | -8.0           |

| Gases                | Number Density (#/m^3) | Mass (%) | Mole (%) | Avg Mol Wgt | Cp (J/gK)   |
|----------------------|------------------------|----------|----------|-------------|-------------|
| Argon (Ar)           | 3.3801e+19             | 5.8      | 4.5      | 36.40       | 0.57        |
| Dinitrogen (N2)      | 7.0400e+20             | 93.2     | 93.7     | 28.00       | 1.04        |
| Methane (CH4)        | 1.3471e+19             | 1.0      | 1.8      | 16.00       | 2.08        |
| Total                | 7.5127e+20             | 100.0    | 100.0    | 28.16       | 1.02        |

--------------------
## 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	8/25/2021	Density Perturbation Scale	1.00
Start Time	15:45:00.00	EW Wind Perturbation Scale	1.00
Julian Day	2459452.156250	NS Wind Perturbation Scale	1.00

Record #1

Field	Value	Field	Value
Elapsed Time (s)	0.00	Elapsed Time (sols)	0.00
Height Above Ref. Ellipsoid (km)	0.000	Reference Radius (km)	2575.5
Latitude (deg)	22.000	Local Solar Time (hrs)	18.08
Longitude W (deg)	48.00	Longitude of the Sun (deg)	137.02
Pressure Scale Height (km)	19.903	Orbital Radius (AU)	9.94
Density Scale Height (km)	28.098	One Way Light Time (min)	74.92
Temperature (K)	93.9	Subsolar Latitude (deg)	17.73
Pressure (Pa)	1.481e+05	Subsolar Longitude W (deg)	139.18
Sigma Level	1.000	Solar Zenith Angle (km)	0.00
Pressure Altitude (km)	–0.000	Gravity (m/s^2)	1.353
Surface Pressure (Pa)	1.481e+05	Speed of Sound (m/s)	194.701
Compressibility Factor (zeta)	0.9657	Specific Gas Constant (J/(kg K))	287.974
Specific Heat Ratio	1.402	Profile Weight	0.000

Density	Low	Average	High
Density (kg/m^3)	5.3153e+00	5.4747e+00	5.6390e+00
Density Deviation (%)	–2.2	0.7	3.8
Perturbed Density (kg/m^3)	5.6156e+00	Perturbation (%)	2.6
Perturbed Density Deviation (%)	3.32	Perturbed Speed of Sound (m/s)	192.24

Winds	Mean	Perturbation	Perturbed
Eastward Wind (m/s)	0.4	10.5	10.9
Northward Wind (m/s)	0.0	–7.3	–7.3

Gases	Number Density (#/m^3)	Mass (%)	Mole (%)	Avg Mol Wgt	Cp (J/gK)
Argon (Ar)	2.8359e+24	3.2	2.4	36.40	0.57
Dinitrogen (N2)	1.1142e+26	95.3	94.9	28.00	1.04
Methane (CH4)	3.1295e+24	1.5	2.7	16.00	2.08
Total	1.1738e+26	100.0	100.0	27.88	1.04

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 TITAN-GRAM

The following are provided with the Titan-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
- Titan: 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 TITAN-GRAM

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

To build Titan-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 follows:

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

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

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

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

APPENDIX F—HISTORY OF TITAN-GRAM VERSION REVISIONS

Table 6 gives the history of version revisions.

Table 6. Titan-GRAM version revisions.

Version	Date	Comments
2002 beta	5/1/2002	First release for Titan/Neptune systems analysis team. Based on Yelle et al.[2]
2002 beta	5/1/2002	Added molar (volume) concentrations to output from datastep and TitanTraj subroutines, and to TPresHgt.txt and LIST.txt output files.
2002 beta	5/10/2002	Added new NAMELIST input parameter *corlmin* to control updating of perturbations. If *corlmin* = 0.0, perturbations are always updated; If *corlmin* = x.x, perturbations are not updated (same value returned) until total relative step size accumulates to x.x (0.0 <= *corlmin* <= 1.0). Step size is relative to a step which would produce "totally accurate" perturbation sigma (correlation over one step <= 0.995). Also adds new input parameter *iupdate* as input AND output parameter for wrapper routine TitanTraj. Input value *iupdate* >= 0 means update total step for perturbations; *iupdate* input as <0 means do not update total step for perturbations. Output value of *iupdate* is 1 if perturbations were updated, 0 if perturbations were not updated but step distance was updated, and -1 if neither perturbations nor total step distance was updated.
2002 beta	7/31/2002	Revised perturbation model with smaller standard deviations Beta and larger correlation scales. Bypasses calls to random number routine if perturbations not being updated.
2002 beta	9/5/2002	Added new input option *fmolmeth*, to select methane mole fraction (1-5%). If *fmolmeth* = 0.0 is input, original Yelle methane mole fraction is used.
2002 beta	9/26/2002	Added new feature to allow repeat of random perturbation sequence in trajectory program (example program dumytraj.f). Also provided new example trajectory program (multtraj.f) that allows atmospheric values and perturbations to be evaluated at multiple positions during one trajectory run.
2003 beta	9/15/2003	Added ephemeris routine and place-holder routine to compute effects on *Fminmax* due to latitude, time-of-day, and Ls. Ephemeris requires Earth date and time input, which can be in Earth-receive time or Titan-event time, and in UTC or Terrestrial (Dynamical) Time (TT). New input option *IFMM* controls whether Lat-TOD-Ls effects are computed or only user input value of *Fminmax* is used. Capability to import externally-computed, high-precision ephemeris values also added.
2003 beta	11/15/2003	Added *IFFM*=2 option to compute atmosphere with Titan GCM data from model of Hourdin et al.[11] and Titan exospheric temperature, computed by Jacchia function, with parameters fit to exospheric temperature graphs in Mueller-Wodarg[12].
2004	9/4/2004	Added option to substitute auxiliary input profile of thermodynamic and/or wind data for Titan climatology, within user-specified region. Use of this option is controlled by (optional) input profile file name and input parameters *profnear* and *proffar*. Converted to option for long file names for LIST, OUTPUT, TRAJECTORY files, etc. (up to character*60). In order for users implementing multiple atmospheric models into one trajectory code to avoid duplication of names for source code files, subroutines, functions, and common blocks, suffix '_T04' was appended to all these names. No suffix was appended in source code for auxiliary programs (e.g.finddate.f). Modified routine to automatically generate random seed numbers. Added time effect on perturbation model correlation.
2004	11/1/2007	HASI/DWE and CIRS auxiliary profiles produced from the Titan-GRAM comparison study (Justh and Justus) allow Titan-GRAM to better replicate the Huygens/Cassini observational data. The HASI data profile has been combined with Huygens DWE winds and formatted into an auxiliary profile. CIRS instrument data from the Cassini flybys of Titan for three latitudes (75S, 10S, and 75N) have also been formatted into Titan-GRAM auxiliary profiles.
2020		The ephemeris engine has been replaced with the NAIF SPICE library. Code has been converted to a C++ framework. LIST and OUTPUT file formats have been updated. Input parameter names have been updated to be more descriptive. Planetary constants have been updated. Speed of sound computations have been improved with the addition of specific heat capacity computations by temperature for constituent gases.

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14. ABSTRACT

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

15. SUBJECT TERMS

Titan Global Reference Atmospheric Model, Titan-GRAM, Titan, atmospheric density, atmospheric temperature, atmospheric models, winds

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