NASA/TM-20210023957

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

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

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

J. Hoffman
Analytical Mechanics Associates, Hampton, Virginia

November 2021

NASA STI Program Report Series

The NASA STI Program collects, organizes, provides for archiving, and disseminates NASA's STI. The NASA STI program provides access to the NTRS Registered and its public interface, the NASA Technical Reports Server, thus providing one of the largest collections of aeronautical and space science STI in the world. Results are published in both non-NASA channels and by NASA in the NASA STI Report Series, which includes the following report types:

- TECHNICAL PUBLICATION. Reports of completed research or a major significant phase of research that present the results of NASA Programs and include extensive data or theoretical analysis. Includes compilations of significant scientific and technical data and information deemed to be of continuing reference value. NASA counter-part of peer-reviewed formal professional papers but has less stringent limitations on manuscript length and extent of graphic presentations.

- TECHNICAL MEMORANDUM. Scientific and technical findings that are preliminary or of specialized interest, e.g., quick release reports, working papers, and bibliographies that contain minimal annotation. Does not contain extensive analysis.

- CONTRACTOR REPORT. Scientific and technical findings by NASA-sponsored contractors and grantees.

- CONFERENCE PUBLICATION. Collected papers from scientific and technical conferences, symposia, seminars, or other meetings sponsored or co-sponsored by NASA.

- SPECIAL PUBLICATION. Scientific, technical, or historical information from NASA programs, projects, and missions, often concerned with subjects having substantial public interest.

- TECHNICAL TRANSLATION. English-language translations of foreign scientific and technical material pertinent to NASA's mission.

Specialized services also include organizing and publishing research results, distributing specialized research announcements and feeds, providing information desk and personal search support, and enabling data exchange services.

For more information about the NASA STI program, see the following:

- Access the NASA STI program home page at http://www.sti.nasa.gov

- Help desk contact information: https://www.sti.nasa.gov/sti-contact-form/ and select the "General" help request type.

NASA/TM-20210023957

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

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

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

J. Hoffman
Analytical Mechanics Associates, Hampton, Virginia

National Aeronautics and
Space Administration

Marshall Space Flight Center
Huntsville, Alabama 35812

November 2021

Acknowledgments

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

Mars-GRAM was originally developed under the leadership of Dr. Carl Gerald (Jere) Justus. The first release of Mars-GRAM occurred in May of 1988. In 2021, Mars-GRAM was re-released after being converted to the GRAM common framework. A complete history of Mars-GRAM version revisions is contained in appendix F.

Trademarks

Available from:

NASA STI Information Desk
Mail Stop 148
NASA Langley Research Center
Hampton, VA 23681–2199, USA
757–864–9658

This report is also available in electronic form at
<http://www.sti.nasa.gov>

PREFACE

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

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

For technical, programmatic or policy questions, please contact

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

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ACRONYMS

ASCII	American Standard Code for Information Interchange
AU	astronomical unit
COSPAR	Committee on Space Research
CSS	Cascading Style Sheets
CSV	comma separated value
ERT	Earth receive time
FTP	file transfer protocol
GCM	General Circulation Model
GRAM	Global Reference Atmospheric Model
IAU	International Astronomical Union
LDW	longitude-dependent waves
LTST	local true solar time
Mars-GRAM	Mars Global Reference Atmospheric Model
MAVEN	Mars Atmosphere and Volatile Evolution
MGCM	Mars General Circulation Model
MGS	Mars Global Surveyor
MOLA	Mars Orbiter Laser Altimeter
MRO	Mars Reconnaissance Orbiter
MTGCM	Mars Thermospheric General Circulation Model
NAIF	Navigation and Ancillary Information Facility
ODY	Mars Odyssey
PET	planet event time
SMD	Science Mission Directorate
SPICE	Spacecraft Planet Instrument C-matrix Events
TDB	Barycentric Dynamical Time
TDT	Terrestrial Dynamical Time

TES	thermal emission spectrometer
UTC	Coordinated Universal Time

NOMENCLATURE

A_0	diurnal mean value of the given parameter (temperature, pressure, density, and wind components)
A_1	amplitude of the diurnal tide component
A_2	amplitude of the semi-diurnal tide component
B_0	diurnal mean value of longitude-dependent wave
B_1,B_2,B_3	amplitude of the LDW peak for wave-1, wave-2, and wave-3 components
C_p	specific heat capacity of a gaseous mixture for isobaric processes
C_v	specific heat capacity of a gaseous mixture for isochoric processes
d	Julian day at which LDW is evaluated
d_0	Julian day for the primary peak(s) of the LDW traveling component
F10.7	solar flux at 10.7 cm wavelength (10^{-22} W/cm^2 at 1 AU)
F_h	height factor
F(z)	logarithmic height factor
g	gravity (3.712 m/s^2 at the surface of Mars)
H_p	local pressure scale height (km)
H_ρ	local density scale height computed from MGCM data between 80 and 85 km (km)
$H_{\rho d}$	density scale height computed from daily MTGCM data between 80 and 85 km (km)
L_s	solar longitude
m_d	areal dust density (kg/m^2)
n	number of peaks and troughs the wave component has through 360 degrees of longitude
P_F	modeled perturbation factor
P_U	user-supplied perturbation multiplier
p	pressure (Pa)
p_{sfc}	surface pressure (Pa)

q_0	dust mixing ratio, mass of dust per unit mass of air, at the surface
R	gas law constant
R_c	correlation factor for the previous time step
R_c'	correlation factor for the current time step
R_i	Richardson number
S	wave scale parameter
S_r	relative displacement from the last time step using NS, EW, vertical movement, and winds (when modeled)
T	temperature (K)
T_5	temperature at 5 m (K)
T_g	temperature at ground surface (K)
t	local solar time (hours)
u	eastward wind component (m/s)
v	northward wind component (m/s)
X	value provided by a random number generator
ZF	height of the 1.26 nbar pressure level (km)
z	height (km)
Δz_{day}	daily average local height offset value (km)
z_0	surface roughness parameter
Δz_0	input value of constant height offset (km)
γ	ratio of specific heats
λ	longitude (degrees)
ν	vertical dust distribution
ρ	density (kg/m^3)
ρ_{dMGCM}	daily average density from unmodified MGCM data at 80 km (kg/m^3)
ρ_{dMTGCM}	daily average density from unmodified MTGCM data at 80 km (kg/m^3)
ρ_{MGCM}	local density from unmodified MGCM data at 80 km (kg/m^3)

ρ_{MTGCM}	local density from unmodified MTGCM data at 80 km (kg/m^3)
ρ_0	mean value of atmospheric density
ρ'	perturbed value of atmospheric density
τ	dust optical depth
Φ_1, Φ_2, Φ_3	phases (longitude) of the LDW peak for wave-1, wave-2, and wave-3 components
$\Phi_1^{\bullet}$, $\Phi_2^{\bullet}$, $\Phi_3^{\bullet}$	rate of movement of the LDW peak for wave-1, wave-2, and wave-3 components
ϕ_1	phase (local time in hours) of the diurnal tide component
ϕ_2	phase (local time in hours) of the semi-diurnal tide component

TECHNICAL MEMORANDUM

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

1. INTRODUCTION

1.1 Background and Overview

Engineers and mission planners designing vehicles that pass through Mars' atmosphere require an atmospheric model that calculates the mean values and variations of atmospheric properties. The Mars Global Reference Atmospheric Model (Mars-GRAM) is an engineering-oriented model that provides this critical information based on data tables derived from output results from the NASA Ames Mars General Circulation Model (MGCM)[1,2] and the University of Michigan Mars Thermospheric General Circulation Model (MTGCM).[3,4] Mars-GRAM is designed to offer mission planners the flexibility to select input parameters such as time, latitude, longitude, and dust level. Mars-GRAM outputs mean values for atmospheric density, temperature, pressure, winds, and constituents along a user defined path. Mars-GRAM also provides winds and density dispersions.

Mars-GRAM has been used during the aerobraking operations of Mars Global Surveyor (MGS),[5] Mars Odyssey (ODY), Mars Reconnaissance Orbiter (MRO), and the Mars Atmosphere and Volatile Evolution (MAVEN) mission. Mars-GRAM has also been used in the prediction and validation of Mars Pathfinder hypersonic aerodynamics[6] the aerothermodynamic and entry dynamics studies for Mars Polar Lander,[7] the Mars Aerocapture System Study[8], as well as the Aerocapture Technology Assessment Group[9]. Mars-GRAM has been validated against MGS thermal emission spectrometer (TES) Radio Science data[10], and both nadir and limb data from MGS TES.[11]

A Fortran version of Mars-GRAM was originally released in 1988 with many updates through the years[12-18], the latest being Mars-GRAM 2010[19]. Recently the code has been updated and rearchitected in C++ to improve efficiencies in implementation, run time, and maintenance. Mars-GRAM now shares a common software core with other versions of the GRAMs. Additionally, documentation (including this User Guide, a Programmer's Manual, and trajectory code interfaces) has been made available with the software release.

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

1.2 Significant Changes in Mars-GRAM

While the atmosphere model data used in Mars-GRAM has not changed from Mars-GRAM 2010, several major code modifications have been made to improve efficiencies in implementation, run time, and maintenance. The major updates to Mars-GRAM are as follows:

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

(2) The Mars-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 Mars-GRAM versions. Table 4 in section 3.3 provides the new and old input parameter names.

(3) The Navigation and Ancillary Information Facility (NAIF) Spacecraft Planet Instrument C-matrix Events (SPICE) library has been incorporated into the GRAM Suite for ephemeris calculations. Mars 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 Mars-GRAM 2010 ephemeris engine. The use of NAIF SPICE requires the Mars-GRAM user to download the latest SPICE data before using Mars-GRAM. Instructions for doing so are provided in section 3.2.

(4) Due to the increase in computing power and memory since the release of original Mars-GRAM in 1988, the output files have been reformatted. The output is provided in two formats: (1) a comma separated value (CSV) file and (2) a LIST file (formerly LIST.txt, now LIST.md). The CSV file consolidates the column formatted output files from the original release of Mars-GRAM into a single file that can easily be loaded into data centric programs, such as Microsoft Excel or MATLAB®. A detailed list of CSV file parameters and definitions are provided in appendix A. Alternatively, the LIST file can be read using either a standard American Standard Code for Information Interchange (ASCII) reader or a Markdown syntax for enhanced rendering in a web browser. An example of both LIST file formats is provided in appendix C.

(5) The calculation of the speed of sound has been improved in Mars-GRAM. Mars-GRAM computes speed of sound based on a thermodynamic parameterization using density, pressure, and γ, the ratio of specific heats $\frac{C_p}{C_v}$, for a given constituent gas mixture. C_p is the specific heat capacity of a gaseous mixture for isobaric processes and C_v is the specific heat capacity of a gaseous mixture for isochoric processes. Mars-GRAM previously used a constant γ, which is physically unrealistic and over-estimates the speed of sound by as much as 10%. Mars-GRAM now uses an improved methodology for computing γ, involving temperature and pressure dependent tables of C_p and C_v evaluated in run-time for the current constituent combination[20].

2. MARS-GRAM ATMOSPHERIC DATA

From the surface to 80 km altitude, Mars-GRAM is based on the NASA Ames MGCM. Above 80 km, Mars-GRAM is based on the MTGCM. Mars-GRAM and MGCM use surface topography from the MGS Mars Orbiter Laser Altimeter (MOLA), with altitudes referenced to the MOLA constant potential surface (areoid).

There are several Mars-GRAM options for representing the mean atmosphere along entry corridors. These options are specified by the *MapYear* input parameter. Typically, *MapYear* denotes the Mars year for which the data was obtained, with the exception of *MapYear* = 0. *MapYear* = 0 allows a user to control the dust optical depth and utilizes data interpolated from MGCM results that were driven by selected values of globally-uniform dust optical depth (τ) (τ = 0.3, 1.0, and 3.0). For *MapYear* = 1 or 2, the data is from MGCM results driven by the observed TES dust optical depth during MGS TES retrieval years 1 and 2. TES year 1 was from April 1999 through January 2001. TES year 2 was from February 2001 through December 2002. TES year 1 had no global dust storm while TES year 2 had a major, global-scale dust storm that peaked at solar longitude (L_s) = 210. Another option for representing the mean atmosphere is to use the auxiliary profile option that allows the user to input a profile of temperature and density versus altitude. This option is only valid for the *MapYear* = 0 option. Exercising the auxiliary profile Mars-GRAM option replaces the original MGCM database values with the values from the auxiliary profile. Auxiliary profiles, for example, can include data from TES nadir or limb observations or Mars mesoscale model output at a particular location and time.

Mars-GRAM standard inputs are geographic position and time. The user can also adjust the optical depth of the uniformly mixed background dust level, add a seasonal dust optical depth, set the dust particle diameter and density, and provide the starting L_s, position, duration, intensity, and radius of a dust storm. Mars-GRAM outputs include density, temperature, pressure, winds, and selected atmospheric constituents.

Three Mars-GRAM input parameters allow standard deviations of Mars-GRAM perturbations to be adjusted: *DensityPerturbationScale* scales density perturbations up or down, *EWWindPerturbationScale* and *NSWindPerturbationScale* scales wind perturbations, and *PerturbationWaveLengthScale* adjusts wavelengths (spectral range) of the perturbations.

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

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

Table 1. Mars gravity parameters.

Mars	**Label**	**Units**	**Value**
Gravitational Parameter	GM	km^3/s^2	42828.37362069909
Mean Equatorial Radius	R_e	km	3396.2
Mean Polar Radius	R_p	km	3376.2
J2 harmonic	J_2	km^5/s^2	0.00196045
Period		s	88642.44

2.1 MOLA Topography Data

2.1.1 MOLA Areoid

Flying on MGS, the MOLA produced topographic data[21-23] at a variety of high resolutions from 1 by 1 degree to 1/16 by 1/16 degree latitude-longitude grids. MOLA topography is measured relative to the MOLA areoid, which is defined as the gravitational equipotential whose average value at the equator is equal to the mean radius determined by MOLA. Mars-GRAM uses half-degree latitude-longitude resolution data for both MOLA areoid and topography.

Prior to Mars-GRAM 2001, a simple ellipsoid of revolution was used. Previous resolution for Mars-GRAM topography was 7.5 by 9 degrees, a resolution consistent with the evaluation grid of the Ames MGCM. While later versions of Mars-GRAM use MOLA areoid and topography, as defaults, program input options continue to allow users to input and output heights relative to the original Mars-GRAM ellipsoid.

2.1.2 MOLA Topography

MOLA topography height and areoid radius in Mars-GRAM are provided in a binary input file, MOLA_data.bin. This file has been converted from a text file, MOLATOPH.TXT, by running a conversion program that is discussed in appendix F. Each line of the text file corresponds to a latitude-longitude grid point, and contains grid-averaged values of longitude (°E), latitude (°N), planetary radius (m), areoid radius (m), topographic altitude (m), and number of data points in the grid. Planetary radius (radius to the local topographic surface) and areoid radius (radius to the zero-elevation surface) are measured along a planetocentric radius direction from the center of the planet. MOLA latitude data are planetocentric. Topographic altitude is the difference between planetary radius and areoid radius.

Relative to MOLA areoid, the highest point on Mars, the peak of Olympus Mons, is 21.2 km, and lowest, a point in the Hellas Basin, is –7.8 km. For the half-degree resolution MOLA data that is used in Mars-GRAM, the highest and lowest elevations are 21.0 and –7.6 km, respectively.

2.2 Mars General Circulation Model Input Data

2.2.1 Introduction to MGCM and MTGCM Data

Mars-GRAM 2010 utilizes input data tables from the NASA Ames MGCM[1,2] and the University of Michigan MTGCM.[3,4] These tables give the variation of temperature, density, pressure, and wind components with height, latitude, time of day, and L_s. The tables also provide boundary layer data at the topographic surface, as well as 5 and 30 m above the surface as a function of longitude, latitude, time of day, and L_s. MGCM data tables cover altitudes from the surface to 80 km. MTGCM data tables cover altitudes of 80 to 170 km for *MapYear* = 0 and 80 to 240 km for *MapYear* = 1 or 2. A modified latitude-longitude dependent Stewart-type thermospheric model[14] is used for altitudes above 170 km, and includes variation in solar activity at higher altitudes. The Stewart-type thermosphere model starts at a lower boundary condition height of the 1.26 nbar pressure level referred to as height ZF (or ThermosphereBaseHeight_km). Between 80 km and height ZF (typically at about 125 km), MTGCM data are used directly and also for variation in solar activity. MTGCM values are interpolated/extrapolated to any desired solar activity value from MTGCM input data for F10.7 =

70 and 130. F10.7 is the solar flux at 10.7 cm wavelength in units of 10–22 W/cm^2 at 1 astronomical unit (AU). Above 170 km, modified Stewart-type thermosphere model data are used directly. Between height ZF and 170 km, a fairing process is used to smooth transitions from MTGCM values to Stewart-type model values.

Details and formats of MOLA, MGCM, and MTGCM data files are given in appendix F. To facilitate transfer, these files are provided to the user in American Standard Code for Information Interchange (ASCII format). For a shorter Mars-GRAM run time it is best to read the files in binary form, which is also provided. A conversion program discussed in appendix F is provided to convert the ASCII format MGCM and MTGCM data files to binary files on the user's machine.

2.2.2 Evaluation of MGCM and MTGCM Tidal Components

MGCM data tables for *MapYear* = 0 contain L_s value, height, latitude, and tidal coefficients for temperature, pressure, and wind components. Only the A_0 coefficient is given for density. Tidal variations in density are computed from those for pressure and temperature by the perfect gas law relation. MGCM data tables for *MapYear* = 1 and 2 contain L_s value, height, latitude, and tidal coefficients for temperature and density. Only the A_0 coefficient is given for pressure. Tidal variations in pressure are computed from those for density and temperature by the perfect gas law relation. MTGCM data tables contain L_s value, height, latitude, and tidal coefficients for temperature, pressure, density, and wind components. Tidal values for each parameter are computed from the relation:

$$\mathrm{Tide} = A_0 + A_1 \cdot \cos\left[\frac{\pi(t-\phi_1)}{12}\right] + A_2 \cdot \cos\left[\frac{\pi(t-\phi_2)}{6}\right] \qquad (1)$$

where A_0 is diurnal mean value of the given parameter, A_1 is amplitude of the diurnal tide component, t is local solar time in hours, ϕ_1 is phase (local time in hours) of the diurnal component, A_2 is amplitude of the semi-diurnal tide component, and ϕ_2 is phase (local time in hours) of the semidiurnal tide component.

MGCM and MTGCM tidal coefficients are provided at 5 km height increments starting at 0 km relative to the MOLA aeroid and ending at 80 km (MGCM), 170 km (MTGCM *MapYear* =0), or 240 km (MTGCM *MapYear* = 1 or 2) relative to the MOLA aeroid. MGCM coefficient data are provided at 7.5 degrees latitude spacing, while MTGCM data have 5 degrees latitude spacing. Both MGCM and MTGCM data are available at every 30 degrees of L_s angle. For *MapYear* = 0, the MGCM data includes three levels of τ (τ = 0.3, 1, and 3). MGCM tidal coefficients are also provided at the topographic surface and heights 5 and 30 m above local topography. Surface layer MGCM data are at 9 degree longitude spacing (for the same latitudes, L_s values, and dust optical depths as MGCM data above the surface layer).

2.2.3 Interpolation Methods

Equation (1) is used to evaluate each atmospheric parameter at the desired local solar time (t), at 'corners' of a multidimensional 'box' of grid points. This box contains the desired interpolation location, L_s, and τ. Multidimensional interpolation routines are used to evaluate all atmospheric parameters at locations between the MGCM or MTGCM grid points. For data above the surface layer, interpolation is three-dimensional in latitude, L_s, and τ. For surface layer data (topographic surface, and 5 or 30 m above the surface), interpolation is fourdimensional in longitude, latitude, L_s, and τ. Interpolation is logarithmic for τ and linear for all other dimensions.

Interpolation to a desired height in km (z) is done by interpolating between two height levels (z1 and z2) from grid point altitudes just above and below z. Above the surface layer, z1 and z2 are at the 5 km vertical grid spacing of the MGCM or MTGCM data. Near the surface layer (topographic surface or 5 and 30 m above surface height), altitudes z1 and z2 are adjusted as appropriate. Temperature in K, T(z), and wind components in meters per second, u(z), and v(z), are found by linear interpolation on height. Pressure, p(z), is found by first computing local pressure scale height (H_p) in kilometers:

$$H_p = \frac{(z2-z1)}{\ln\left[\frac{p(z1)}{p(z2)}\right]} \tag{2}$$

and evaluating pressure in Pa, p(z), from the hydrostatic relation:

$$p(z) = p(z1) exp\left[\frac{z1 - z}{H}\right] . \tag{3}$$

The specific gas constant (R) is evaluated from pressure, p, density, ρ, and temperature, T, at heights, z1 and z2, by:

$$R(z1) = \frac{p(z1)}{[\rho(z1)T(z1)]} \tag{4}$$

and

$$R(z2) = \frac{p(z2)}{[\rho(z2)T(z2)]} . \tag{5}$$

Density in kg/m^3, $\rho(z)$, at height, z, is then determined by the gas law relation and a linearly-interpolated R value, R(z):

$$\rho(z) = \frac{p(z)}{[R(z)T(z)]} . \tag{6}$$

2.2.4 Interpolation in the Boundary Layer

MGCM data tables used by Mars-GRAM include ground surface temperature. Between the surface and 5 m height, large temperature gradients can exist. There can also be a difference between ground surface temperature and air temperature ‘immediately’ above ground. These features must be represented by a boundary layer model. Following the approach used in the Ames MGCM,[24] Mars-GRAM assumes temperature varies from T_g at ground surface to T_5 at the 5 m level according to the relation:

$$T(z) = T_g + \frac{(T_5-Tg)\left[1+F_h{}^{1/2}F(z)\right]}{\left[1+F_h{}^{1/2}\right]} , \tag{7}$$

where the height factor (F_h) is given by:

$$F_h = (1 - 16R_i)^{1/2} \quad \text{if } R_i < 0\,; \; F_h = \left[1 + \frac{15R_i}{(1+5\,R_i)^{1/2}}\right]^{-1} \text{ if } R_i \geq 0 \tag{8}$$

as a function of Richardson number (R_i) determined from wind and temperature gradients between the ground and 5 m level. Logarithmic height factor, F(z), is given by

$$F(z) = \frac{\ln\left(\frac{z}{z_0}\right)}{\ln\left(\frac{5}{z_0}\right)} \quad , \tag{9}$$

where z_0 is the surface roughness parameter assumed to be 0.01 m, except over surface ice, where z_0 = 0.0001 m is used.[25]

Wind components, eastward (*u*) and northward (*v*), at heights <5 m above the surface are evaluated from a logarithmic boundary layer profile relation:

$$u(\mathrm{z}) = u(5)\mathrm{F(z)} \tag{10}$$

and

$$v(\mathrm{z}) = v(5)\mathrm{F(z)}\ . \tag{11}$$

2.3 Longitude-Dependent (Terrain-Fixed Wave Model)

Tide components evaluated by equation (1) depend only on local solar time. Implicitly, this equation also depends on longitude. At any given instant, solar time varies at a rate of 1 hour for every 15 degrees of longitude. During aerobraking operations, measurements by MGS,[26-29] ODY, and MRO revealed substantial longitude-dependent wave patterns for atmospheric density. Being in Sun synchronous orbits, MGS, ODY and MRO passed through each periapsis at essentially the same latitude and local solar time. Nevertheless, they found substantial variations that tended to repeat as a function of the periapsis longitude. The density variations were of the form of longitude-dependent (i.e., terrain fixed) wave patterns. Mars-GRAM includes an optional model for these longitude-dependent waves (LDW) of the form:

$$\mathrm{LDW} = \mathrm{B_0} + \mathrm{B_1}\cos\left[\pi\left(\lambda - \Phi_1 - \dot{\Phi}_1(\mathrm{d} - \mathrm{d_0})\right)/180\right] + \mathrm{B_2}\cos\left[\pi\left(2\lambda - \Phi_2 - \dot{\Phi}_2(\mathrm{d} - \mathrm{d_0})\right)/180\right] + \mathrm{B_3}\cos\left[\pi\left(3\lambda - \Phi_3 - \dot{\Phi}_3(\mathrm{d} - \mathrm{d_0})\right)/180\right] \ , \tag{12}$$

where λ is longitude (in degrees), B_0 is the diurnal mean value of longitude-dependent wave, B_1, B_2, and B_3 are amplitude, Φ_1, Φ_2, and Φ_3 are phases (longitudes), $\Phi_1^{\bullet}$, $\Phi_2^{\bullet}$, and $\Phi_3^{\bullet}$ are the rate of movement of the LDW peak for wave-1, wave-2, and wave-3 components, d_0 is the Julian day for the primary peak(s) of the LDW traveling component, and d is the Julian day at which LDW is evaluated. The term wave-*n* means the wave component has *n* peaks and troughs through 360 degrees of longitude. LDW perturbations computed by equation (12) are applied as a multiplier to the mean density and pressure computed from MGCM and MTGCM data, as interpolated by methods described in section 2.2.3. Wave model coefficients for equation (12) can be input from the NAMELIST format input file (see appendix B), or from an auxiliary file of time-dependent wave model coefficients named by the input parameter *WaveFile*. Values of LDW coefficients may be determined empirically by accelerometer observations,[26,28] or theoretically, from wave characteristics of Mars General Circulation Models (GCMs).[27,29]

For altitudes above 100 km, LDW perturbations from equation (12) are assumed to be altitude independent. For altitudes below 100 km, LDW perturbations are assumed to diminish in magnitude at an exponential rate, namely,

$$\mathrm{LDW(z)} = 1 + (\mathrm{LDW(100)} - 1)exp[(\mathrm{z} - 100)/\mathrm{S}] \ , \qquad (13)$$

where S is the wave scale parameter, *WaveScale*, from the NAMELIST format input file.

One way of adjusting Mars-GRAM density values up or down (at altitudes below 100 km) is by changing the LDW mean term, B_0 (input parameter *WaveMeanOffset*). For example, if the user wants to adjust Mars-GRAM density values by a factor $W1 = B_0(z1)$ at height $z1$ and $W2 = B_0(z2)$ at height $z2$ (where $z1$ and $z2$ are both <100 km), then use the S value:

$$\mathrm{S} = (\mathrm{z2} - \mathrm{z1})/ln[(\mathrm{W2} - 1)/(\mathrm{W1} - 1)] \ , \qquad (14)$$

which yields a LDW multiplier value at 100 km, $B_0(100)$ given by:

$$\mathrm{B_0(100)} = 1 + (\mathrm{W2} - 1)exp[(100 - \mathrm{z2})/\mathrm{S}] \, . \qquad (15)$$

Once values of S and $B_0(100)$ are input to the program, density at any height (z) (below 100 km) is adjusted by the factor,

$$\mathrm{B_0(z)} = 1 + (\mathrm{B_0(100)} - 1)exp[(\mathrm{z} - 100)/\mathrm{S}] \, . \qquad (16)$$

Note that multipliers may be larger or smaller than 1 (yielding density increase or decrease, respectively).

2.4 Mars-GRAM Climate Factors and Height Adjustment

Below 170 km, Mars-GRAM is based directly on MGCM and MTGCM output and does not need any of the climate factors that were included prior to Mars-GRAM 2001. The only climate adjustment factor that is still included in Mars-GRAM is *ExosphericTemperatureOffset*, which adjusts the exospheric temperature. Mars-GRAM model output can also be affected by the choice of dust optical depth through the input parameter *MGCMConstantDustLevel* (formerly *dusttau*) and by the LDW parameters that were discussed in section 2.3.

Height offsets can be used to control the smoothness of the transition at 80 km altitude between MGCM data and MTGCM data or as another means (besides wave multipliers) to adjust MTGCM data for better agreement with observations, such as those obtained during aerobraking operations. Height offset options are controlled by input parameters *ConstantHeightOffset* and *OffsetModel*. The function of the height offset is very similar to that of the LDW wave parameter B_0 (input parameter *WaveMeanOffset*) that was discussed in section 2.3. B_0 shifts a height versus density plot to the right or left as it increases or decreases density at a given height. The height offset will shift the height-versus-density curve up or down as it increases or decreases the height at which a given density applies. The net result of a positive or negative height offset is to increase or decrease the density at a given height.

The height offset can be specified several ways. If *OffsetModel* = 0 the specific offset value in kilometers provided by the input parameter *ConstantHeightOffset* is used. If *OffsetModel = 1,* Mars-GRAM computes and uses a global height offset that depends on time of year given by L_s. Based on comparisons of MTGCM with density observed during MGS aerobraking,[28] time-of-year dependence of height offset is given as:

$$\text{Height Offset(km)} = \Delta z_0 - 2.5 \sin(\pi L_s/180) \quad , \tag{17}$$

where Δz_0 is an input value of constant height offset given by input parameter *ConstantHeightOffset*. With a default value of Δz_0 = 5 km, height offset values from equation (17) vary seasonally from 2.5 km at L_s = 90 degrees to 7.5 km at L_s = 270 degrees.

If *OffsetModel* = 2, a global average height offset value is utilized. The data utilized for *MapYear* = 0 and *MapYear* = 1 and 2 is shown in tables 2 and 3 and is also provided in the hgtoffst.dat file.

Table 2. Global average height offset (km) required for MTGCM-MGCM matchup, as a function of L_s and dust optical depth for *MapYear* = 0.

L_s (degrees)	Dust Optical Depth		
	0.3	1	3
0	–0.002	–0.001	–0.003
30	–0.001	0.000	0.003
60	0.001	–0.003	–0.002
90	–0.002	–0.002	–0.000
120	0.001	–0.002	–0.001
150	0.004	–0.002	0.011
180	–0.003	–0.004	–0.002
210	–0.002	0.001	–0.001
240	–0.002	–0.001	0.018
270	–0.002	0.004	–0.003
300	–0.001	0.008	–0.002
330	0.033	–0.001	–0.003
360	–0.002	–0.001	–0.003

Table 3. Global average height offset (km) required for MTGCM-MGCM matchup, as a function of L_s and *MapYear* = 1 and 2.

L_s (degrees)	*MapYear*	
	1	2
0	–1.22	–1.25
30	–1.22	-0.38
60	-1.41	–1.78
90	–1.55	–1.57
120	-1.54	–1.46
150	-1.65	-1.51
180	–1.43	–1.25
210	–1.09	2.29

L_s (degrees)	*MapYear*	
	1	2
240	0.49	1.27
270	–0.26	–0.08
300	–1.06	–0.80
330	-1.12	–1.08
360	–1.22	–1.25

If *OffsetModel* = 3, the height offset used is the daily average local height offset value (Δz_{day}) calculated using equation (18):

$$\Delta z_{day} = H_{\rho d} * \ln\left(\frac{\rho_{dMGCM}}{\rho_{dMTGCM}}\right), \quad (18)$$

where $H_{\rho d}$ is the density scale height computed from daily MTGCM data between 80 and 85 km, and densities ρ_{dMGCM} and ρ_{dMTGCM} are daily average densities from unmodified MGCM and MTGCM data at 80 km.

If *OffsetModel* = 4, the height offset used is the local height offset value at the current time (Δz) calculated using equation (19):

$$\Delta z = H_{\rho} * \ln\left(\frac{\rho_{MGCM}}{\rho_{MTGCM}}\right), \quad (19)$$

where H_{ρ} is the local density scale height computed from MGCM data between 80 and 85 km, and densities ρ_{MGCM} and ρ_{MTGCM} are local densities from unmodified MGCM and MTGCM data at 80 km.

Mars-GRAM allows optional regional or global scale dust storms to be activated at any desired L_s. Dust storm simulations are discussed in section 2.5. Based on comparisons between Mars-GRAM and density observed by the MGS accelerometer[26] during the regional Noachis dust storm, an additional height offset of MTGCM data is applied during simulated dust storms. This additional offset amount in kilometers is equal to seven times the value of the dust storm optical depth.

2.5 Quantitative Dust Concentration Model

Background dust optical depth (τ) in a non dust storm case is specified by the input parameter *MGCMConstantDustLevel*. Interpolation routines given in section 2.2.3 interpolate logarithmically between τ values for both MGCM and MTGCM input data. If *MGCMConstantDustLevel* = 0 is input, a prescribed Viking-like seasonal variation of dust optical depth is used, in which case variation of τ with L_s is specified by:

$$\tau = 0.65 - 0.35 \sin(\pi L_s/180) \quad . \quad (20)$$

A model for global or local scale dust storms[13] is retained for *MapYear* = 0. In Mars-GRAM, the input value for dust storm intensity given by input parameter, *StormIntensity*, is equivalent to the peak dust optical depth for the storm. Allowable values for *StormIntensity* range from zero for no dust storm to three for the maximum intensity dust storm. Dust storm intensity is added to background dust optical depth to give total dust optical depth. Mars-GRAM does all necessary interpolations on dust optical depth as it varies with time, L_s, and location for local storms. *StormLatitude* and *StormLongitude* input parameters give the location of the center of the dust storm. The input option, *StormDuration*, allows users to control the duration (in degrees of L_s, where 1 degree of L_s is ~ 2 days) of simulated dust storms. Input parameter *StormMaxRadius* is the maximum radius (kilometers) a dust storm can attain. The radius develops according to the parameterized spatial and temporal profile of buildup and decay in the program. If a value of zero or more than 10,000 km is used for *StormMaxRadius*, the storm is taken to be of global dimensions and uniformly covers Mars, and it builds up and decays in intensity according to the same temporal profile.

Mars-GRAM computes several dust concentration parameters from dust optical depth. Methods used by Haberle et al. in the MGCM are employed.[24,30] Areal dust density (m_d), total column mass of dust per unit ground surface area, is 0.005 times τ. Dust mixing ratio, the mass of dust per unit mass of air, at the surface (q_0) is computed by:

$$q_0 = m_d g/(0.994 exp^{-\nu} p_{sfc}) \ , \qquad (21)$$

where g is gravity, 3.712 m/s^2 at the surface of Mars; ν is input parameter *DustNu*, which controls the vertical dust distribution; and p_{sfc} is surface pressure. Dust mixing ratio at height z is determined by:

$$q(z) = q_0 exp\{\nu[1 - p(z)/p_{sfc}]\} \ , \qquad (22)$$

where *p*(*z*) is pressure at height *z*. Dust mass density, the mass of dust per unit volume of air, is the product of dust mixing ratio and atmospheric density. From the dust mixing ratio, assuming that dust particles are spheres of user specified diameter (*DustDiameter*) and density (*DustDensity)*, Mars-GRAM also computes dust number density, number of dust particles per unit volume of air. Consistent with the MGCM,[30] Mars-GRAM assumes a default particle diameter, 5 µm, and a default particle density, 3,000 kg/m^3.

Dust model output values are written to a CSV output file details of which are discussed in appendix A.

2.6 Solar and Thermal Radiation from Mars-GRAM Output

Auxiliary programs used with Mars-GRAM are described in appendix G. MarsRad.cpp, computes the upwelling and downwelling components of the solar (shortwave) and thermal (longwave) radiation at the surface and the top of the atmosphere. This auxiliary program uses the Mars-GRAM CSV output file, which includes the dust concentration information discussed in section 2.5.

To compute upwelling shortwave radiation at the surface, Mars-GRAM uses surface albedo values from data file MOLA_data.bin that contains the surface albedo at 1 degree latitude-longitude resolution.[31,32]

The auxiliary program MarsRad.cpp produces two output files: Radlist.md and Radout.csv. The computation methods that are used within the program to determine the radiation components contained in the output files are discussed in appendix G. Mars-GRAM output that is used as input to MarsRad.cpp consists of one or more vertical profiles of temperature versus pressure (altitude).

2.7 Slope Wind Model

The slope wind model contained in the Mars-GRAM subroutine slopewind is based on Ye et al.[33] In this model, the slope winds depend on terrain slopes that are determined from MOLA 0.5 degree resolution topography for the MOLA grid containing the latitude-longitude of interest. The method of Ye et al.[33] provides an analytical relationship to compute winds as a function of altitude and terrain slope for daytime, thermally-driven, upslope winds. The slopewind subroutine assumes a diurnal pattern of slope wind variation with time of day. The slope winds apply up to 4.5 km above the surface during the day and up to 2.5 km above the surface at night and are added to background MGCM winds at 7.5 degree latitude × 9 degree longitude resolution. Peak daytime winds are assumed to occur at 15 hours local solar time. Peak nighttime winds, due to downslope drainage flows, are assumed to occur at 3 hours local solar time. Lighter, cross-slope flows occur between these two times. Vertical component slope winds are also computed. These are proportional to the terrain slope, to the horizontal slope winds, and have an assumed variation with altitude, which gives maximum vertical winds near the middle of the slope wind altitude region, and zero vertical winds near the surface and near the top of the slope wind altitude region. The slope winds can also be scaled with the input factor, *BoundaryLayerWindsScale*, with a value of zero suppressing the slope wind output.

2.8 Mars-GRAM Density Perturbations

Mars-GRAM density perturbation magnitudes are estimated using

$$\rho' = \rho_0(1 + R' P_F P_U) \tag{23}$$

and

$$R_c{}' = e^{-S} R_c + X\sqrt{1 - e^{-2S_r}} \tag{24}$$

where ρ' is the perturbed value of atmospheric density, ρ_0 is the mean value of atmospheric density, R_c' is the correlation factor for the current time step, P_F is the modeled perturbation factor (typically height dependent), P_U is the user-supplied perturbation multiplier, S_r is the relative displacement from the last time step using NS, EW, vertical movement, and winds, R_c is the correlation factor for the previous time step, and X is the 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 ($R' \approx X$).

2.9 Mars-GRAM Adjustment Factors

Mars-GRAM includes adjustment factors that are used to alter the daily mean density and pressure values from MGCM and MTGCM data for the *MapYear* = 0 user-controlled dust case.[34] The greatest adjustments are made at large optical depths such as τ >1 (set by input parameter *MGCMConstantDustLevel* (formerly *dusttau*)). The addition of the adjustment factors has led to better correspondence to TES limb data from zero to 60 km altitude as well as better agreement with MGS, ODY, and MRO data at approximately 90 to 130 km altitude. Additional details regarding the adjustment factors including sample results illustrating these improvements can be found in the Mars-GRAM 2010 User Guide.[19]

2.10 Querying Atmosphere Data

The Mars-GRAM user defined path can be generated in multiple ways. The first is to run Mars-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 NAMELIST input file. In standalone mode, Mars-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 2.13. A third method is to incorporate the Mars-GRAM code directly into a user's trajectory code. This version of Mars-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, Mars-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.

2.11 Monte Carlo Capability

Using the *NumberOfMonteCarloRuns* option in the NAMELIST input file, Mars-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 2.10.

A description of a user-generated trajectory file is provided in section 2.13. This feature allows the user to define the trajectory in varied (non-constant) increments. The Mars-GRAM perturbation model uses the time, altitude, latitude, and longitude changes from the previous perturbation step to provide the perturbations to the next step and will result in a trajectory evaluation method that provides more realistic perturbations than the *NumberOfMonteCarloRuns* option.

Running Mars-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 Mars-GRAM into a user's trajectory simulation code are described in the C++, C, and Fortran Interface sections of the GRAM Programmer's Manual.

2.12 Auxiliary Atmosphere Profile Option

The auxiliary atmosphere profile option provides the user the ability to overwrite the atmosphere model in Mars-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 Mars-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 Mars-GRAM input wind data are used if both wind components in the auxiliary atmosphere profile file are set to zero.

A weighting factor for the auxiliary atmosphere profile data (*ProfileWeight*), having values between 0 and 1, is applied between the *InnerRadius* and *OuterRadius*. The *InnerRadius* is the latitude-longitude radius (degrees) within which weight for the auxiliary atmosphere profile is 1.0 (e.g., the data in the auxiliary profile is used as provided). The *OuterRadius* is the latitude-longitude radius (degrees) beyond which the weight for the auxiliary atmosphere profile is 0.0 (e.g., the model uses standard Mars-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 Mars-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 1. If *InnerRadius* = 0, then the auxiliary atmosphere profile data are not used. In addition to faring in latitude and longitude, fairing of the auxiliary atmosphere profile altitude is performed. This only occurs at the beginning and end of the file. The profile weight factor (*ProfileWeight*) for the auxiliary atmosphere profile varies between 0 at the first auxiliary atmosphere profile altitude level and 1 at the second auxiliary atmosphere profile altitude level (and between 1 at the next-to-last auxiliary atmosphere profile altitude level and 0 at the last auxiliary atmosphere profile altitude level). Therefore, care must be taken when selecting the altitude spacing at the beginning and end of the auxiliary atmosphere profile (e.g., selected to be far enough apart in altitude) to ensure that a smooth transition occurs as *ProfileWeight* changes from 0 to 1 near these auxiliary atmosphere profile beginning and end points.

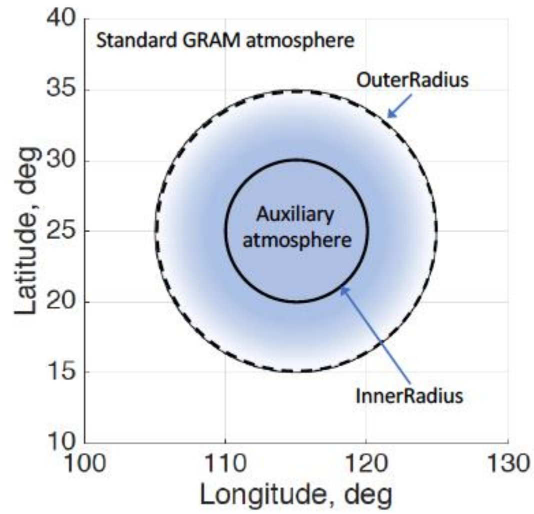

Figure 1. Illustration of two-dimensional auxiliary profile faring implementation with *InnerRadius* = 5° and *OuterRadius* = 10° for a vertical auxiliary profile located at latitude = 25° and longitude = 115°.

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

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

Any additional information included on each line of the trajectory file (e.g. orbit number, measured density, etc.) is ignored. Trajectory increments in these files do not have to be at small or evenly spaced temporal or spatial 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.

2.14 Sample Mars-GRAM Output

The following graphs were produced from outputs of an example Mars-GRAM run. The example is an arbitrary scenario that represents a semi-vertical profile from surface to 600 km altitude in 0.5 km increments, starting at latitude = 18.24 degrees north and longitude = 77.5 degrees east, incrementing longitude +0.01 degree, and incrementing longitude +0.03 degrees, per 0.5 km vertical step. The simulation represents the timeframe with L_s = 270 degrees and local true solar time = 11.53 Mars hours. The simulation used a constant dust optical depth (*MapYear* = 0) with *MGCMConstantDustLevel* = 0.95. Note that the transition between lower-atmosphere and thermosphere datasets occurs at 80 km altitude. Plots of sample Mars-GRAM temperature and pressure output data are provided in figures 2 and 3 of this document.

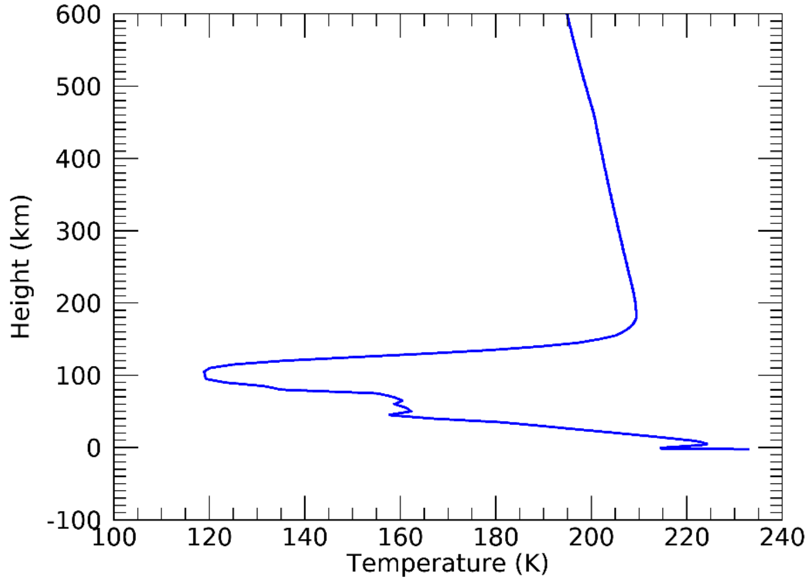

Figure 2. Height versus temperature from a sample Mars-GRAM output.

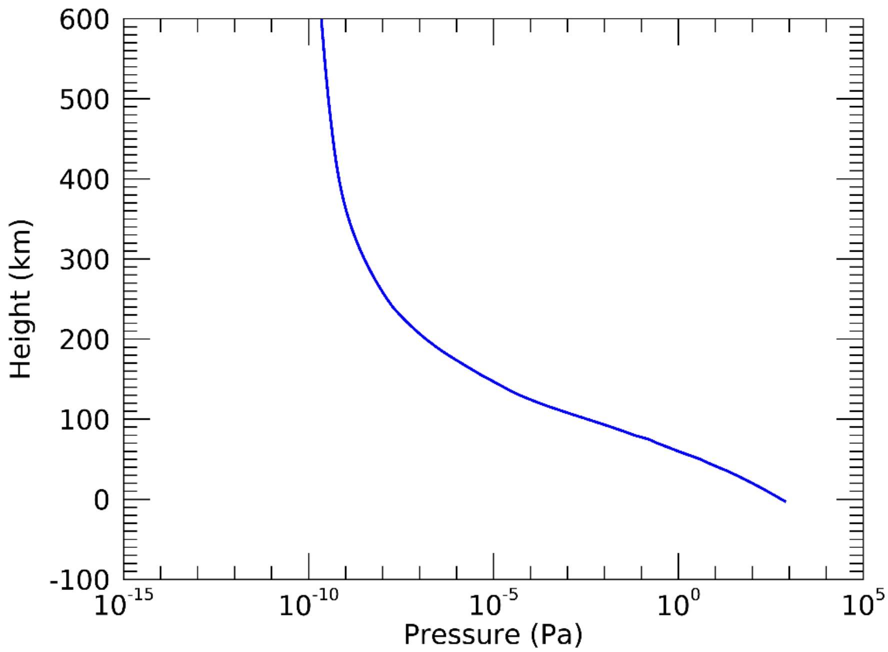

Figure 3. Height versus pressure from a sample Mars-GRAM output.

Sample wind perturbation outputs from Mars-GRAM are shown in figures 4 and 5 of this document.

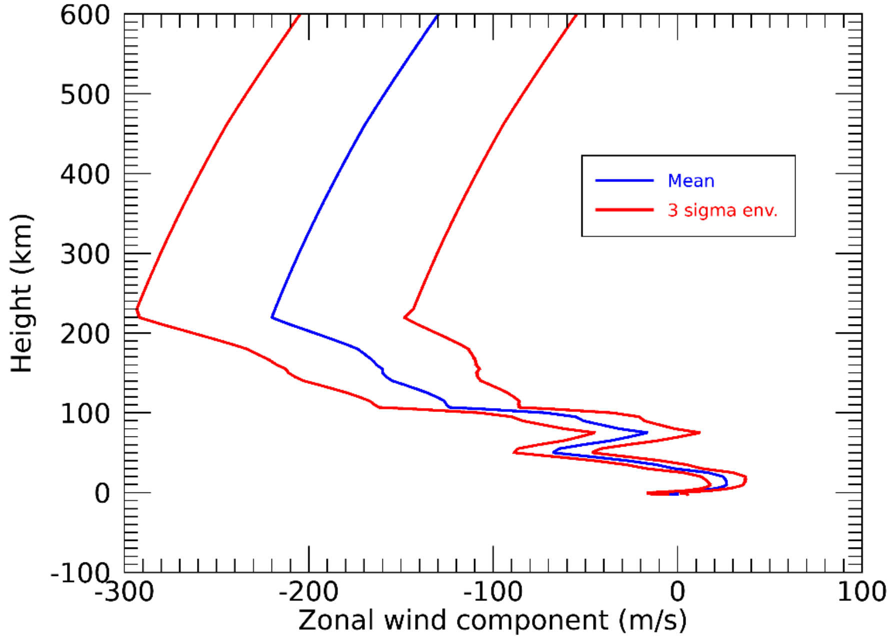

Figure 4. Three-sigma envelope of sample Mars-GRAM east (positive)/west (negative) zonal wind outputs for 32.333° N latitude and -117.8° E longitude.

.

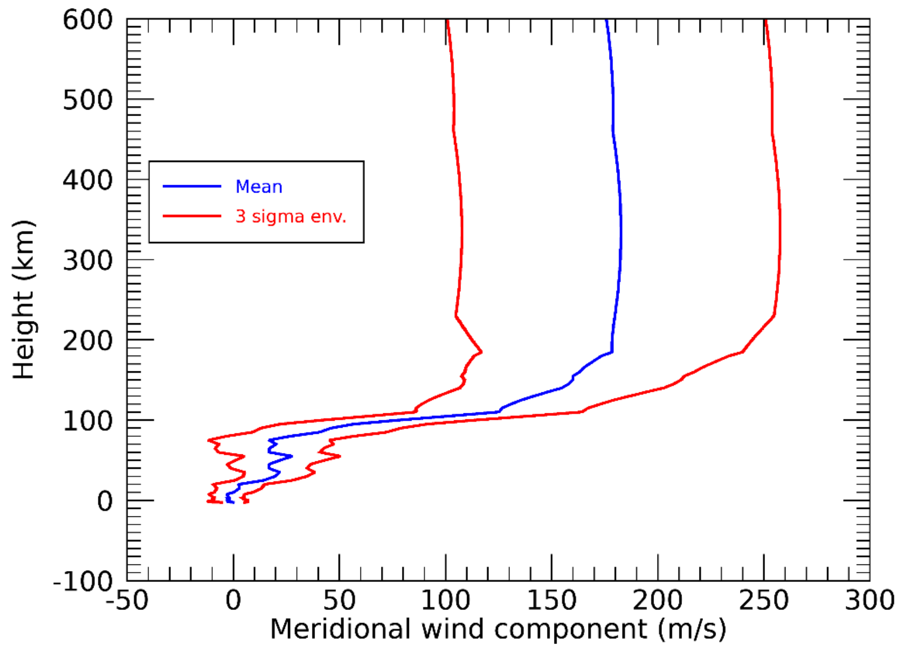

Figure 5. Three-sigma envelope of sample Mars-GRAM north (positive)/south (negative) meridional wind outputs for 32.333° N latitude and -117.8° E longitude.

A sample output of constituent contributions is shown in figure 6 of this document.

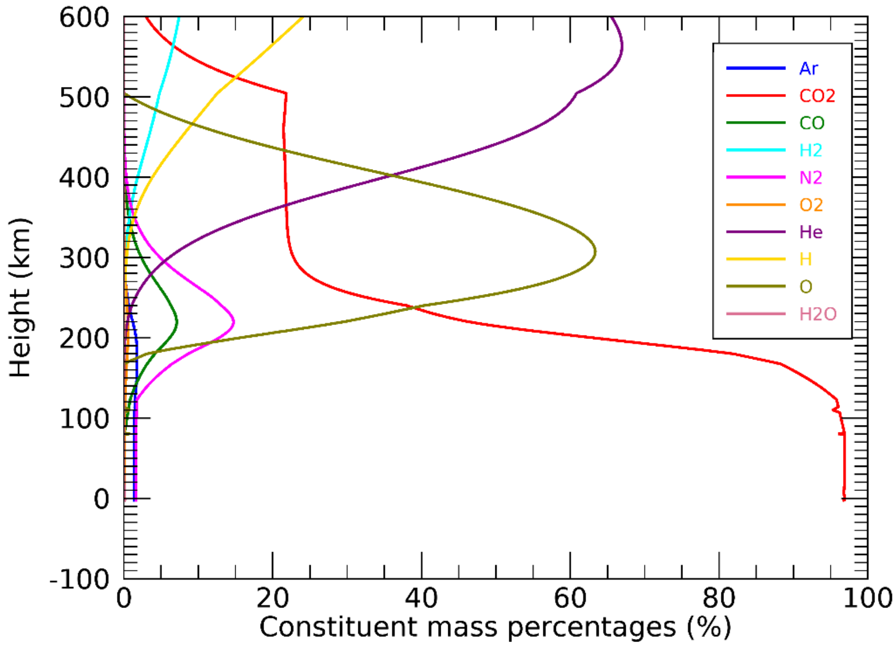

Figure 6. Sample Mars-GRAM mean constituent contributions by percent.

3. HOW TO RUN MARS-GRAM

3.1 How to Obtain the Program

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

3.2 Running the Program

The Mars-GRAM installation includes a set of Windows and Linux 64-bit executable libraries located in the GRAM/Windows and GRAM/Linux folders. The Mars-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 Mars-GRAM, the NAIF SPICE data files must be downloaded. These data are available via file transfer protocol (FTP) from ftp://naif.jpl.nasa.gov/pub/naif/generic_kernels. Information about the SPICE data is available from https://naif.jpl.nasa.gov/naif/data.html and help downloading is available from https://naif.jpl.nasa.gov/naif/download_tip.html. NAIF recommends that the entire collection be downloaded, but these files can be rather large. The files required by Mars-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 Mars-GRAM, simply double-click the MarsGRAM.exe file or enter 'MarsGRAM.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/Mars/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 Mars-GRAM command line. The format of this option is 'MarsGRAM.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

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

Table 4. Mars-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
DataPath (DATADIR)	The location of the binary Mars-GRAM data. This includes MGCM and TES model data, and the MOLA topography and albedo data.	<empty>
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

Input Parameter	Description	Default
Year (MYEAR)	Integer year for the start time. Typically, a 4-digit year. Alternately, years 1970 - 2069 can be input as a 2-digit number.	2000
Month	Integer month (1 through 12) for the start time.	1
Day (MDAY)	Integer day of month for the start time.	1
Hour (IHOUR, IHR)	Integer hour (0 through 23) for the start time in the chosen *TimeScale* and *TimeFrame*.	0
Minute (IMIN)	Integer minute (0 through 59) for the start time in the chosen *TimeScale* and *TimeFrame*.	0
Seconds (SEC)	Real seconds (less than 60.0) for the start time in the chosen *TimeScale* and *TimeFrame*.	0.0
Model Parameters		
MapYear	0 for Mars-GRAM 2001 GCM input data sets 1 or 2 for TES mapping year 1 or 2 GCM input data	0
F107	10.7 cm solar flux at 1 AU.	68.0
HeightAboveSurface (HGTASFCM)	Height above surface in meters.	0.0
IsMolaHeights (MOLAHGTS)	1 for input heights relative to MOLA areoid, 0 for input heights relative to reference ellipsoid	1
ComputeMinMax (IDAYDATA)	1 for daily max/min data output, 0 for none	1
PerturbationWaveLengthScale (WLSCALE)	Scale factor for perturbation wavelengths (0.1-10).	1.0
MeanWindsScale (WMSCALE)	Scale factor for mean winds.	1.0
BoundaryLayerWindsScale (BLWINFAC)	Scale factor for boundary layer slope winds (0 = none).	1.0
OffsetModel (IBOUGHER)	Model selection for height offset term. 0 = no L_s-dependent (Bougher) height offset term 1 = add L_s-dependent term, -A*Sin(Ls) (km) to constant term (*ConstantHeightOffset*) [offset amplitude A = 2.5 for *MapYear*=0 or 0.5 for *MapYear* > 0] 2 = use global mean height offset 3 = use daily average height offset at local position 4 = use height offset at current time and local position. Value of *ConstantHeightOffset* is ignored if *OffsetModel* = 2, 3, or 4.	2
ConstantHeightOffset (ZOFFSET)	Constant height offset (km) for MTGCM data or constant part of L_s-dependent (Bougher) height offset (0.0 means no constant offset). Positive offset increases density, negative offset decreases density.	3.25
ExosphericTemperatureOffset (DELTATEX)	Adjustment for exospheric temperature (K).	0.0
ExosphericTemperatureFactor (STDL)	Adjustment factor for exospheric temperature.	0.0

Input Parameter	Description	Default
EquatorialRadius (REQUA)	Equatorial radius (km) for reference ellipsoid.	3396.2
PolarRadius (RPOLE)	Polar radius (km) for reference ellipsoid.	3376.2
Dust Model Parameters		
DustNu	Parameter for vertical distribution of dust density.	0.003
DustDiameter (DUSTDIAM)	Dust particle diameter (micrometers, assumed monodisperse).	5.0
DustDensity (DUSTDENS)	Dust particle density (kg/m^3).	3000.0
MGCMConstantDustLevel (DUSTTAU)	Optical depth of background dust level (no time-developing dust storm, just uniformly mixed dust), 0.1 to 3.0, or use 0 for assumed seasonal variation of background dust.	0.3
MGCMMinDustLevel (DUSTMIN)	Minimum seasonal dust level if input *MGCMConstantDustLevel*=0 (>=0.1).	0.3
MGCMMaxDustLevel (DUSTMAX)	Maximum seasonal dust level if input *MGCMConstantDustLevel*=0 (<=1.0).	1.0
Dust Storm Parameters		
StormLongitudeSun (ALS0)	Starting L_s value (degrees) for dust storm (0 = none).	0.0
StormDuration (ALSDUR)	Duration (in L_s degrees) for dust storm.	48.0
StormIntensity (INTENS)	Dust storm intensity (0.0 - 3.0).	0.0
StormMaxRadius (RADMAX)	Maxmum radius (km) of dust storm (0 or >10000 = global).	0.0
StormLatitude (DUSTLAT)	Latitude (degrees) for center of dust storm.	0.0
StormLongitude (DUSTLON)	Longitude (degrees) (West positive if *EastLongitudePositive*=0, or East positive if *EastLongitudePositive*=1) for center of dust storm.	0.0
Wave Model Parameters		
WaveFile	(Optional) file for time-dependent wave coefficient data. *WaveFile* contains time (sec) relative to start time, and wave model coefficients from the given time to the next time in the data file. Each line contains: WaveTime, WaveMeanOffset, WaveDate, WaveAmplitude1, WavePhase1, WavePhase1Rate, WaveAmplitude2, WavePhase2, WavePhase2Rate, WaveAmplitude3, WavePhase3, WavePhase3Rate	<empty>
WaveDate	Julian date for (primary) peak(s) of wave (0 for no traveling component).	0.0
WaveMeanOffset (WAVEA0)	Mean term of longitude-dependent wave multiplier for density.	1.0
WaveAmplitude1 (WAVEA1)	Amplitude of wave-1 component of longitude-dependent wave multiplier for density.	0.0
WavePhase1 (WAVEPHI1)	Phase of wave-1 component of longitude-dependent wave multiplier (longitude, with West positive if *EastLongitudePositive* = 0, East positive if *EastLongitudePositive* = 1).	0.0

Input Parameter	Description	Default
WavePhase1Rate (PHI1DOT)	Rate of longitude movement (degrees per day) for wave-1 component (westward positive if *EastLongitudePositive* = 0, eastward positive if *EastLongitudePositive* = 1).	0.0
WaveAmplitude2 (WAVEA2)	Amplitude of wave-2 component of longitude-dependent wave multiplier for density.	0.0
WavePhase2 (WAVEPHI2)	Phase of wave-2 component of longitude-dependent wave multiplier (longitude, with west positive if *EastLongitudePositive* = 0, east positive if *EastLongitudePositive* = 1).	0.0
WavePhase2Rate (PHI2DOT)	Rate of longitude movement (degrees per day) for wave-2 component (westward positive if *EastLongitudePositive* = 0, eastward positive if *EastLongitudePositive* = 1).	0.0
WaveAmplitude3 (WAVEA3)	Amplitude of wave-3 component of longitude-dependent wave multiplier for density.	0.0
WavePhase3 (WAVEPHI3)	Phase of wave-3 component of longitude-dependent wave multiplier (longitude, with West positive if *EastLongitudePositive* = 0, East positive if *EastLongitudePositive* = 1).	0.0
WavePhase3Rate (PHI3DOT)	Rate of longitude movement (degrees per day) for wave-3 component (westward positive if *EastLongitudePositive* = 0, eastward positive if *EastLongitudePositive* = 1).	0.0
WaveScale (WSCALE)	Vertical scale (km) of longitude-dependent wave damping at altitudes below 100 km (10<=*WaveScale*<=10,000 km).	20.0
	Perturbation Parameters	
InitialRandomSeed (NR1)	The integer seed value for the random number generator. The allowable range is 1 to $9*10^8$. 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	0.0

Input Parameter	Description	Default
	MinRelativeStepSize. *MinRelativeStepSize* = 0.0 means always update perturbations.	
Trajectory Parameters		
EastLongitudePositive (LONEAST)	This flag controls the convention for input and output of longitudes. East positive convention if *EastLongitudePositive* = 1. West positive convention if *EastLongitudePositive* = 0.	1
NumberOfPositions (NPOS)	The number of positions to generate and evaluate, if an automatically-generated profile is to be produced. This parameter is ignored if a *TrajectoryFileName* is provided.	21
InitialHeight (FHGT)	Height (km) of the initial position.	0.0
InitialLatitude (FLAT)	Latitude (degrees, north positive) of the initial position.	0.0
InitialLongitude (FLON)	Longitude (degrees) of the initial position. The direction of positive longitudes is determined by the *EastLongitudePositive* parameter.	0.0
DeltaHeight (DELHGT)	Height increment (km) between successive steps in an automatically generated profile (positive upward).	10.0
DeltaLatitude (DELLAT)	Latitude increment (degrees, north positive) between successive steps in an automatically generated profile.	0.0
DeltaLongitude (DELLON)	Longitude increment (degrees) between successive steps in an automatically generated profile. The direction of positive longitudes is determined by the *EastLongitudePositive* parameter.	0.0
DeltaTime (DELTIME)	Time increment (seconds) between steps in an automatically generated profile.	0.0
Monte Carlo Parameters		
NumberOfMonteCarloRuns (NMONTE)	Number of Monte Carlo runs during one execution of the program. New/different starting random numbers are automatically generated for each of the Monte Carlo profiles or trajectories.	1
Auxiliary Atmosphere Parameters		
AuxiliaryAtmosphereFileName (PROFILE)	(Optional) Input file name of the profile data for the auxiliary atmosphere.	<empty>
InnerRadius (PROFNEAR)	(Optional) Latitude-longitude radius (degrees) within which weight for the auxiliary profile is 1.0 (A value of 0.0 implies no auxiliary atmosphere data is present.)	0.0
OuterRadius (PROFFAR)	(Optional) Latitude-longitude radius (degrees) beyond which weight for auxiliary profile is 0.0.	0.0
Output Parameters		
FastModeOn	Controls the speed and accuracy of ephemeris calculations by regulating the frequency of the	0

Input Parameter	Description	Default
	computation of L_S, One-Way Light Time, orbital radius, and solar declination. 0: More accurate, but slower. Computes these values each time. 1: Faster, but less accurate. Computes these values once at the beginning.	
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 Mars-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 Pa) 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

3.4 Program Output

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

Mars-GRAM gives the user the option to find the date and time for a particular L_s and Mars 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 for which L_s and LTST are the user desired values. The SPICE data are required for this capability. The *FindDates* capability is contained within the Mars-GRAM program and controlled by the *FindDates* input parameter (see table 5). The utility will return three dates and times: the date and times of the target L_s and the two dates and times of the target LTST that immediately precede and follow the target L_s date. A sample *FindDates* input file can be found in the sample_inputs file.

Table 5. 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
DataPath (DATADIR)	The location of the binary Mars-GRAM data. This includes MGCM and TES model data, and the MOLA topography and albedo data.	<empty>
FindDates	The parameter flags the use of the FindDates auxiliary capability. Use the FindDates capability if *FindDates* = 1. Use Mars-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 MARS-GRAM OUTPUT FILE

Mars-GRAM produces a CSV output file (see table 6) 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 6. OUTPUT.csv (or as prescribed in the *ColumnFileName* input parameter).

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

EWWind_ms	Mean eastward wind component (m/s)
NSWind_ms	Mean northward wind component (m/s)
EWWindPerturbation_ms	Eastward wind perturbation (m/s)
NSWindPerturbation_ms	Northward wind perturbation (m/s)
VerticalWindPerturbation_ms	Upward wind perturbation (m/s)
PerturbedEWWind_ms	Total (mean plus perturbed) eastward wind (m/s)
PerturbedNSWind_ms	Total (mean plus perturbed) northward wind (m/s)
PerturbedVerticalWind_ms	Total (mean plus perturbed) upward wind (m/s)
EWStandardDeviation_ms	Standard deviation of eastward wind perturbations (m/s)
NSStandardDeviation_ms	Standard deviation of northward wind perturbations (m/s)
VerticalStandardDeviation_ms	Standard deviation of upward wind perturbations (m/s)
LongitudeOfTheSun_deg	The planetocentric longitude of the sun, L_s (degree)
SubsolarLatitude_deg	The latitude of the sub-solar point at the current time (degree)
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* (degree)
LocalSolarTime_hr	The local solar time using 24 “hour” intervals (hour)
SolarZenithAngle_deg	The solar zenith angle (degree)
OneWayLightTime_min	One way light time to/from Earth and the current position (minutes)
OrbitalRadius_AU	The current orbital radius of the planet (AU)
SecondsPerSol	The number of seconds in a local sol (planetary day)
TotalNumberDensity_m3	Number density of the atmosphere (#/m^3)
SpecificGasConstant_JkgK	Specific gas constant (J/(kg K))
SpecificHeatRatio	Specific heat ratio of the gas mixture
AverageMolecularWeight	Average molecular weight at the current position (amu)
CompressibilityFactor	Compressibility factor (or zeta). This quantifies the deviation of a real gas from ideal gas behavior (zeta = 1 for ideal gases).
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 argon (amu)
CO2nd_m3	Number density of carbon dioxide (#/m^3)
CO2mass_pct	Carbon dioxide concentration, percent by mass
CO2mole_pct	Mole fraction (%) of carbon dioxide concentration (or % by volume)
CO2amw	Average molecular weight of carbon dioxide (amu)
COnd_m3	Number density of carbon monoxide (#/m^3)
COmass_pct	Carbon monoxide concentration, percent by mass
COmole_pct	Mole fraction (%) of carbon monoxide concentration (or % by volume)
COamw	Average molecular weight of carbon monoxide (amu)
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)
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)
O2nd_m3	Number density of molecular oxygen (#/m^3)
O2mass_pct	Molecular oxygen concentration, percent by mass
O2mole_pct	Mole fraction (%) of molecular oxygen concentration (or % by volume)
O2amw	Average molecular weight of molecular oxygen (amu)
Hend_m3	Number density of helium (#/m^3)
Hemass_pct	Helium concentration, percent by mass
Hemole_pct	Mole fraction (%) of helium concentration (or % by volume)
Heamw	Average molecular weight of helium (amu)
Hnd_m3	Number density of atomic hydrogen (#/m^3)
Hmass_pct	Atomic hydrogen concentration, percent by mass
Hmole_pct	Mole fraction (%) of atomic hydrogen concentration (or % by volume)
Hamw	Average molecular weight of atomic hydrogen (amu)
Ond_m3	Number density of atomic oxygen (#/m^3)
Omass_pct	Atomic oxygen concentration, percent by mass
Omole_pct	Mole fraction (%) of atomic oxygen concentration (or % by volume)
Oamw	Average molecular weight of atomic oxygen (amu)
H2Ond_m3	Number density of water (#/m^3)
H2Omass_pct	Water concentration, percent by mass
H2Omole_pct	Mole fraction (%) of water concentration (or % by volume)
H2Oamw	Average molecular weight of water (amu)
TemperatureDaily_K	Mean daily temperature (K)
PressureDaily_Pa	Mean daily pressure (Pa)
DensityDaily_kgm3	Mean daily density (kg/m^3)
EWWindDaily_ms	Mean daily east/west winds (m/s)
NSWindDaily_ms	Mean daily north/south winds (m/s)
TemperatureMin_K	Daily minimum temperature (K)
TemperatureMax_K	Daily maximum temperature (K)
DensityMin_kgm3	Daily minimum density (kg/m^3)
DensityMax_kgm3	Daily maximum density (kg/m^3)
PlanetoGraphicHeight_km	Planetographic height (km)
PlanetoGraphicLatitude_deg	Planetographic latitude (degrees)
ReferenceHeight_km	Height relative to the reference ellipsoid (km)
ReferenceRadius_km	Latitude radius relative to the reference ellipsoid (km)
GroundTemperature_K	Temperature at ground level (K)
ThermosphereBaseHeight_km	Height of 1.26 nbar level (km)
ThermosphereBaseTemperature_K	Temperature at the 1.26 nbar level (K)
ExosphericTemperature_K	Temperature of the exosphere (K)
F1PeakHeight_km	Altitude of the peak F1 ionization (km)
Albedo	Surface albedo
HeightOffset_km	Height offset as selected by *OffsetModel* (km)
LocalHeightOffset_km	Local height offset (km)
DustOpticalDepth	Dust optical depth

DustColumnArealDensity_kgm2	Dust column areal density (kg/m^2)
DustMixingRatio	Dust mixing ratio
DustMassDensity_ugm3	Dust mass density (micrograms dust)/m^3)
DustNumberDensity_m3	Dust number density (number of dust particles)/m^3)
IceIsPresent	When true (1), CO_2 ice is present on the polar surface
WavePerturbation_pct	Perturbation factor for traveling or standing waves (%)

APPENDIX B – EXAMPLE NAMELIST FORMAT INPUT FILE

The following is an example of the NAMELIST format input file required by Mars-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
  DataPath              = '..\data\'
  SpicePath             = '\spice'
  ListFileName          = 'ref_LIST'
  ColumnFileName        = 'ref_OUTPUT'
  EastLongitudePositive = 1
  IsPlanetoCentric = 1

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

  MapYear            = 0
  F107               = 68.0
  HeightAboveSurface = 0.0
  IsMolaHeights      = 1
  ComputeMinMax      = 1

  PerturbationWaveLengthScale  = 1.0
  MeanWindsScale               = 1.0
  BoundaryLayerWindsScale      = 1.0

  OffsetModel          = 2
  ConstantHeightOffset = 3.25

  ExosphericTemperatureOffset = 0.0
  ExosphericTemperatureFactor = 0.0
```

```
 MGCMConstantDustLevel = 0.3
 MGCMMinDustLevel      = 0.3
 MGCMMaxDustLevel      = 1.0

 DustNu       = 0.003
 DustDiameter = 5.0
 DustDensity  = 3000.0

 StormLongitudeSun = 0.0
 StormDuration     = 48.0
 StormIntensity    = 0.0
 StormMaxRadius    = 0.0
 StormLatitude     = 0.0
 StormLongitude    = 0.0

 WaveDate        = 0.0
 WaveMeanOffset  = 1.0
 WaveAmplitude1  = 0.0
 WavePhase1      = 0.0
 WavePhase1Rate  = 0.0
 WaveAmplitude2  = 0.0
 WavePhase2      = 0.0
 WavePhase2Rate  = 0.0
 WaveAmplitude3  = 0.0
 WavePhase3      = 0.0
 WavePhase3Rate  = 0.0
 WaveScale       = 20.0

 FastModeOn        = 0
 ExtraPrecision    = 0
 UseLegacyOutputs  = 0
 DensityPrintScale = 0

$END

Explanation of variables:
 DataPath          =  Path to binary data for MGCM and TES models.
 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
 IsPlanetoCentric      =  1 for Planeto-centric latitude and height input,
                          0 for Planeto-graphic latitude and height input

 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 - 2^24 = 16,777,216)
 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

  MapYear            =  1 or 2 for TES mapping year 1 or 2 GCM input data, or 0 for
                        Mars-GRAM 2001 GCM input data sets
  F107               =  10.7 cm solar flux (10**-22 W/cm**2 at 1 AU)
  HeightAboveSurface =  height above surface (0-4500 m); use if InitialHeight <= -10.
km
  IsMolaHeights      =  1 for input heights relative to MOLA areoid,
                        0 for input heights relative to reference ellipsoid
  ComputeMinMax      =  1 for daily max/min data output; 0 for none

  PerturbationWaveLengthScale  =  scale factor for perturbation wavelengths (0.1-10)
  MeanWindsScale               =  scale factor for mean winds
  BoundaryLayerWindsScale      =  scale factor for boundary layer slope winds (0 =
none)

  OffsetModel           =  0 for no Ls-dependent (Bougher) height offset term; 1
                           means add Ls-dependent (Bougher) term, -A*Sin(Ls) (km),
                           to constant term (ConstantHeightOffset) [offset
                           amplitude A = 2.5 for MapYear=0 or 0.5 for MapYear > 0];
                           2 means use global mean height offset; 3 means use
                           daily average height offset at local position; 4 means
                           use height offset at current time and local position.
                           Value of ConstantHeightOffset is ignored if ibougher = 2,
3, or 4.
  ConstantHeightOffset  =  constant height offset (km) for MTGCM data or constant
                           part of Ls-dependent (Bougher) height offset (0.0 means
                           no constant offset).  Positive offset increases density,
                           negative offset decreases density.

  ExosphericTemperatureOffset =  adjustment for exospheric temperature (K)
  ExosphericTemperatureFactor =  adjustment factor for exospheric temperature

  MGCMConstantDustLevel  =  Optical depth of background dust level (no time-developing
                            dust storm, just uniformly mixed dust), 0.1 to 3.0, or use
                            0 for assumed seasonal variation of background dust
  MGCMMinDustLevel  =  Minimum seasonal dust level if input mgcmConstantDustLevel=0
(>=0.1)
  MGCMMaxDustLevel  =  Maximum seasonal dust level if input mgcmConstantDustLevel=0
(<=1.0)
```

```
  DustNu            =  Parameter for vertical distribution of dust density (Haberle
                       et al., J. Geophys. Res., 104, 8957, 1999)
  DustDiameter      =  Dust particle diameter (micrometers, assumed monodisperse)
  DustDensity       =  Dust particle density (kg/m**3)

  StormLongitudeSun =  starting Ls value (degrees) for dust storm (0 = none)
  StormDuration     =  duration (in Ls degrees) for dust storm (default = 48)
  StormIntensity    =  dust storm intensity (0.0 - 3.0)
  StormMaxRadius    =  max. radius (km) of dust storm (0 or >10000 = global)
  StormLatitude     =  Latitude (degrees) for center of dust storm
  StormLongitude    =  Longitude (degrees) (West positive if EastLongitudePositive=0,
or East
                       positive if EastLongitudePositive=1) for center of dust storm

  WaveFile        =  (Optional) file for time-dependent wave coefficient data.
                     WaveFile contains time (sec) relative to start time, and
                     wave model coefficients from the given time to the next time in
the data file.
                     Each line contains: WaveTime, WaveMeanOffset, WaveDate,
WaveAmplitude1,
                     WavePhase1, WavePhase1Rate, WaveAmplitude2, WavePhase2,
WavePhase2Rate,
                     WaveAmplitude3, WavePhase3, WavePhase3Rate
  WaveDate        =  Julian date for (primary) peak(s) of wave (0 for no traveling
component)
  WaveMeanOffset  =  Mean term of longitude-dependent wave multiplier for density
  WaveAmplitude1  =  Amplitude of wave-1 component of longitude-dependent wave
                     multiplier for density
  WavePhase1      =  Phase of wave-1 component of longitude-dependent wave
                     multiplier (longitude, with West positive if
EastLongitudePositive = 0,
                     East positive if EastLongitudePositive = 1)
  WavePhase1Rate  =  Rate of longitude movement (degrees per day) for wave-1
                     component (Westward positive if EastLongitudePositive = 0,
Eastward
                     positive if EastLongitudePositive = 1)
  WaveAmplitude2  =  Amplitude of wave-2 component of longitude-dependent wave
                     multiplier for density
  WavePhase2      =  Phase of wave-2 component of longitude-dependent wave
                     multiplier (longitude, with West positive if
EastLongitudePositive = 0,
                     East positive if EastLongitudePositive = 1)
  WavePhase2Rate  =  Rate of longitude movement (degrees per day) for wave-2
                     component (Westward positive if EastLongitudePositive = 0,
Eastward
                     positive if EastLongitudePositive = 1)
  WaveAmplitude3  =  Amplitude of wave-3 component of longitude-dependent wave
                     multiplier for density
  WavePhase3      =  Phase of wave-3 component of longitude-dependent wave
                     multiplier (longitude, with West positive if
EastLongitudePositive = 0,
                     East positive if EastLongitudePositive = 1)
  WavePhase3Rate  =  Rate of longitude movement (degrees per day) for wave-3
                     component (Westward positive if EastLongitudePositive = 0,
Eastward
                     positive if EastLongitudePositive = 1)
  WaveScale       =  Vertical scale (km) of longitude-dependent wave damping
                     at altitudes below 100 km (10<=WaveScale<=10,000 km)

  FastModeOn        = Flags use of faster ephemeris computations (less accurate)
                      0 Most accurate ephemeris computations are used
                      1 Faster computations with slight loss in accuracy
  ExtraPrecision    = For the new column output format, this parameter
```

```
                      adds precision to all outputs.
  UseLegacyOutputs  = Flags which outputs to generate.
                      0 Use the new output formats.
                      1 Use output formats closely matching those of the
                                     legacy NeptuneGram.
  DensityPrintScale = For legacy outputs only.
                      0 regular SI units
                      1 log-base-10 scale
                      2 percentage deviations from Mean model
                      3 SI units with density in kg/km**3

  EquatorialRadius   =  Equatorial radius (km) for reference ellipsoid
  PolarRadius        =  Polar radius (km) for reference ellipsoid
```

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

```
$INPUT_M10
  SpicePath = '\spice'
  LSTFL    = 'LIST.txt'
  OUTFL    = 'OUTPUT.txt'
  TRAJFL   = 'null'
  profile  = 'null'
  WaveFile = 'null'
  DATADIR  = '..\data\'
  IERT     = 1
  IUTC     = 1
  MONTH    = 3
  MDAY     = 25
  MYEAR    = 2020
  NPOS     = 201
  IHR      = 12
  IMIN     = 30
  SEC      = 0.0
  LonEW    = 1
  Dusttau  = 0.3
  Dustmin  = 0.3
  Dustmax  = 1.0
  Dustnu   = 0.003
  Dustdiam = 5.0
  Dustdens = 3000.0
  ALS0     = 0.0
  ALSDUR   = 48.
  INTENS   = 0.0
  RADMAX   = 0.0
  DUSTLAT  = 0.0
  DUSTLON  = 0.0
  MapYear  = 0
  F107     = 68.0
  STDL     = 0.0
  NR1      = 1001
  LOGSCALE = 0
  FLAT     = 22.0
  FLON     = 48.0
  FHGT     = 0.0
  MOLAhgts = 1
  hgtasfcm = 0.0
  zoffset  = 3.25
  ibougher = 2
  DELHGT   = 2.0
  DELLAT   = 0.3
  DELLON   = 0.5
```

```
 DELTIME  = 500.0
 deltaTEX = 0.0
 profnear = 0.0
 proffar  = 0.0
 rpscale  = 1.0
 rwscale  = 1.0
 wlscale  = 1.0
 wmscale  = 1.0
 blwinfac = 1.0
 NMONTE   = 1
 WaveA0   = 1.0
 WaveDate = 0.0
 WaveA1   = 0.0
 Wavephi1 = 0.0
 phi1dot  = 0.0
 WaveA2   = 0.0
 Wavephi2 = 0.0
 phi2dot  = 0.0
 WaveA3   = 0.0
 Wavephi3 = 0.0
 phi3dot  = 0.0
 iuwave   = 0
 Wscale   = 20.
 corlmin  = 0.0
 ipclat   = 1
 idaydata = 1
$END

Explanation of variables:
LSTFL    =  List file name (CON for console listing)
OUTFL    =  Output file name
TRAJFL   =  (Optional) Trajectory input file. File contains time (sec)
             relative to start time, height (km), latitude (deg),
             longitude (deg W if LonEW=0, deg E if LonEW=1, see below)
profile  =  (Optional) auxiliary profile input file name
WaveFile =  (Optional) file for time-dependent wave coefficient data.
             See file description under parameter iuwave, below.
DATADIR  =  Directory for COSPAR data and topographic height data
GCMDIR   =  Directory for GCM binary data files
IERT     =  1 for time input as Earth-Receive time (ERT) or 0 Mars-event
             time (MET)
IUTC     =  1 for time input as Coordinated Universal Time (UTC), or 0
             for Terrestrial (Dynamical) Time (TT)
MONTH    =  (Integer) month of year
MDAY     =  (Integer) day of month
MYEAR    =  (Integer) year (4-digit; 1970-2069 can be 2-digit)
NPOS     =  max # positions to evaluate (0 = read data from trajectory
             input file)
IHR      =  Hour of day (ERT or MET, 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
LonEW    =  0 for input and output West longitudes positive; 1 for East
             longitudes positive
Dusttau  =  Optical depth of background dust level (no time-developing
             dust storm, just uniformly mixed dust), 0.1 to 3.0, or use
             0 for assumed seasonal variation of background dust
Dustmin  =  Minimum seasonal dust tau if input Dusttau=0 (>=0.1)
Dustmax  =  Maximum seasonal dust tau if input Dusttau=0 (<=1.0)
Dustnu   =  Parameter for vertical distribution of dust density (Haberle
             et al., J. Geophys. Res., 104, 8957, 1999)
Dustdiam =  Dust particle diameter (micrometers, assumed monodisperse)
Dustdens =  Dust particle density (kg/m**3)
```

```
ALS0     =  starting Ls value (degrees) for dust storm (0 = none)
ALSDUR   =  duration (in Ls degrees) for dust storm (default = 48)
INTENS   =  dust storm intensity (0.0 - 3.0)
RADMAX   =  max. radius (km) of dust storm (0 or >10000 = global)
DUSTLAT  =  Latitude (degrees) for center of dust storm
DUSTLON  =  Longitude (degrees) (West positive if LonEW=0, or East
             positive if LonEW = 1) for center of dust storm
MapYear  =  1 or 2 for TES mapping year 1 or 2 GCM input data, or 0 for
             Mars-GRAM 2001 GCM input data sets
F107     =  10.7 cm solar flux (10**-22 W/cm**2 at 1 AU)
STDL     =  std. dev. for thermosphere variation (-3.0 to +3.0)
NR1      =  starting random number (0 < NR1 < 30000)
NVARX    =  x-code for plotable output (1=hgt above MOLA areoid).
             See file xycodes.txt
NVARY    =  y-code for 3-D plotable output (0 for 2-D plots)
LOGSCALE =  0=regular SI units, 1=log-base-10 scale, 2=percentage
             deviations from COSPAR model, 3=SI units, with density
             in kg/km**3 (suitable for high altitudes)
FLAT     =  initial latitude (N positive), degrees
FLON     =  initial longitude (West positive if LowEW = 0 or East
             positive if LonEW = 1), degrees
FHGT     =  initial height (km); <=-10 means evaluate at surface height;
             > 3000 km means planeto-centric radius
MOLAhgts =  1 for input heights relative to MOLA areoid, otherwise
            input heights are relative to reference ellipsoid
hgtasfcm =  height above surface (0-4500 m); use if FHGT <= -10. km
zoffset  =  constant height offset (km) for MTGCM data or constant
            part of Ls-dependent (Bougher) height offset (0.0 means
            no constant offset).  Positive offset increases density,
            negative offset decreases density.
ibougher =  0 for no Ls-dependent (Bougher) height offset term; 1
            means add Ls-dependent (Bougher) term, -A*Sin(Ls) (km),
            to constant term (zoffset) [offset amplitude A = 2.5 for
            MapYear=0 or 0.5 for MapYear > 0]; 2 means use global mean
            height offset from data file hgtoffst.dat; 3 means use
            daily average height offset at local position; 4 means
            use height offset at current time and local position.
            Value of zoffset is ignored if ibougher = 2, 3, or 4.
DELHGT   =  height increment (km) between steps
DELLAT   =  Latitude increment (deg) between steps (Northward positive)
DELLON   =  Longitude increment (deg) between steps (Westward positive
             if LonEW = 0, Eastward positive if LonEW = 1)
DELTIME  =  time increment (sec) between steps
deltaTEX =  adjustment for exospheric temperature (K)
profnear =  Lat-lon radius (degrees) within which weight for auxiliary
              profile is 1.0 (Use profnear = 0.0 for no profile input)
proffar  =  Lat-lon radius (degrees) beyond which weight for auxiliary
              profile is 0.0
rpscale  =  random density perturbation scale factor (0-2)
rwscale  =  random wind perturbation scale factor (>=0)
wlscale  =  scale factor for perturbation wavelengths (0.1-10)
wmscale  =  scale factor for mean winds
blwinfac =  scale factor for boundary layer slope winds (0 = none)
NMONTE   =  number of Monte Carlo runs
iup      =  0 for no LIST and graphics output, or unit number for output
WaveA0   =  Mean term of longitude-dependent wave multiplier for density
WaveDate =  Julian date for (primary) peak(s) of wave (0 for no traveling
             component)
WaveA1   =  Amplitude of wave-1 component of longitude-dependent wave
             multiplier for density
Wavephi1 =  Phase of wave-1 component of longitude-dependent wave
             multiplier (longitude, with West positive if LonEW = 0,
             East positive if LonEW = 1)
phi1dot  =  Rate of longitude movement (degrees per day) for wave-1
```

```
             component (Westward positive if LonEW = 0, Eastward
             positive if LonEW = 1)
WaveA2   =  Amplitude of wave-2 component of longitude-dependent wave
             multiplier for density
Wavephi2 =  Phase of wave-2 component of longitude-dependent wave
             multiplier (longitude, with West positive if LonEW = 0,
             East positive if LonEW = 1)
phi2dot  =  Rate of longitude movement (degrees per day) for wave-2
             component (Westward positive if LonEW = 0, Eastward
             positive if LonEW = 1)
WaveA3   =  Amplitude of wave-3 component of longitude-dependent wave
             multiplier for density
Wavephi3 =  Phase of wave-3 component of longitude-dependent wave
             multiplier (longitude, with West positive if LonEW = 0,
             East positive if LonEW = 1)
phi3dot  =  Rate of longitude movement (degrees per day) for wave-3
             component (Westward positive if LonEW = 0, Eastward
             positive if LonEW = 1)
iuwave   =  Unit number for (Optional) time-dependent wave coefficient
             data file "WaveFile" (or 0 for none).
             WaveFile contains time (sec) relative to start time, and
             wave model coefficients (WaveA0 thru Wavephi3) from the
             given time to the next time in the data file.
Wscale   =  Vertical scale (km) of longitude-dependent wave damping
             at altitudes below 100 km (10<=Wscale<=10,000 km)
corlmin  =  minimum relative step size for perturbation updates
             (0.0-1.0); 0.0 means always update perturbations, x.x
             means only update perturbations when corlim > x.x
ipclat   =  1 for Planeto-centric latitude and height input,
            0 for Planeto-graphic latitude and height input
requa    =  Equatorial radius (km) for reference ellipsoid
rpole    =  Polar radius (km) for reference ellipsoid
idaydata =  1 for daily max/min data output; 0 for none
```

APPENDIX C – SAMPLE OUTPUT LIST FILE

Following is a portion of the LIST file output produced by the standard input parameters given in appendix B. The output data given below is provided in the file ref_LIST.md. This file allows users to complete a test run after compiling Mars-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
Input Heights	Planetocentric	Ref Ellips Equat Rad (km)	3396.20
Relative to	MOLA areoid	Ref Ellips Polar Rad (km)	3376.20
Dust Nu	0.0030	Pert Wave Length Scale	1.00
Dust Diameter (m)	5.00e+00	Mean Winds Scale	1.00
Dust Den (kg/m^3)	3000.0	Boundary Layer Winds Scale	1.00
F10.7 Flux 1 AU	68.0	F10.7 Flux at Mars	30.9

Field	Value	Field	Value
Dust Storm LS (deg)	0.00	Storm Duration (deg)	48.00
Storm Intensity	0.00	Storm MaxRadius (km)	0.00
Storm Latitude (deg)	0.00	Storm Longitude (deg)	0.00
Wave 1 (A, P, R)	0.000, 0.000, 0.000	Wave Date	0.00
Wave 2 (A, P, R)	0.000, 0.000, 0.000	Wave Mean Offset	1.00
Wave 3 (A, P, R)	0.000, 0.000, 0.000	Wave Scale	20.00

Record #1

Field	Value	Field	Value
Elapsed Time (s)	0.00	Elapsed Time (sols)	0.00
Height Above MOLA Areoid (km)	0.000	MOLA Areoid Radius (km)	3393.8
Latitude (deg)	22.000	Local Solar Time (hrs)	2.26
Longitude E (deg)	48.00	Longitude of the Sun (deg)	172.16
Pressure Scale Height (km)	10.458	Orbital Radius (AU)	1.48
Density Scale Height (km)	10.458	One Way Light Time (min)	12.58
Temperature (K)	171.3	Subsolar Latitude (deg)	3.29
Pressure (Pa)	5.387e+02	Subsolar Longitude E (deg)	194.11
Sigma Level	1.039	Solar Zenith Angle (km)	138.17
Pressure Altitude (km)	-0.398	Gravity (m/s^2)	3.710
Surface Pressure (Pa)	5.186e+02	Speed of Sound (m/s)	210.813
Compressibility Factor (zeta)	0.9865	Specific Gas Constant (J/(kg K))	188.976
Specific Heat Ratio	1.373	Profile Weight	0.000
Height Above MOLA Surface (km)	-0.398	Topographic Height (km)	0.398
Height Above Ref. Ellipsoid (km)	0.394	Reference Ellipsoid Radius (km)	3393.4
Planetographic Height (km)	0.394	Planetographic Latitude (deg)	22.236
Ground Temperature (K)	166.3	Height Offset (km)	-0.001
Surface Albedo	0.274	Local Height Offset (km)	0.000

Field	Value	Field	Value
Daily Mean Temperature (K)	210.03	Daily Mean Density (kg/m^3)	1.3114e-02
Min Daily Temperature (K)	169.66	Min Daily Density (kg/m^3)	8.9169e-03
Max Daily Temperature (K)	272.98	Max Daily Density (kg/m^3)	1.8011e-02
Daily Mean Pressure (Pa)	5.205e+02	Ice Is Present	0

Field	Value	Field	Value
Dust Optical Depth	0.300	Dust Column Areal Density(kg/m^2)	1.500e-03
Dust Mass Density (ug/m^2)	1.802e+02	Dust Mixing Ratio (dust/air)	1.083e-05
Dust Number Density (#/m^3)	9.179e+05	cos(Solar Zenith Angle)	-0.7451

Density	Low	Average	High

Density (kg/m^3)	1.6315e-02	1.6641e-02	1.6974e-02
Density Deviation (%)	5.3	7.4	9.5
Perturbed Density (kg/m^3)	1.6773e-02	Perturbation (%)	0.8
Perturbed Density Deviation (%)	8.21	Perturbed Speed of Sound (m/s)	209.98

Winds	Mean	Perturbation	Perturbed
Eastward Wind (m/s)	0.0	-1.6	-1.6
Northward Wind (m/s)	0.0	-0.3	-0.3

Gases	Number Density (#/m^3)	Mass (%)	Mole (%)	Avg Mol Wgt
Argon (Ar)	4.2861e+21	1.7	1.9	39.96
Carbon Dioxide (CO2)	2.1886e+23	96.1	94.8	44.01
Carbon Monoxide (CO)	2.5977e+20	0.1	0.1	28.01
Dihydrogen (H2)	0.0000e+00	0.0	0.0	2.02
Dinitrogen (N2)	7.1436e+21	2.0	3.1	28.02
Dioxygen (O2)	3.3770e+20	0.1	0.1	32.00
Helium (He)	0.0000e+00	0.0	0.0	4.00
Hydrogen (H)	0.0000e+00	0.0	0.0	1.01
Oxygen (O)	0.0000e+00	0.0	0.0	16.00
Water (H2O)	7.9376e+16	0.0	0.0	18.02
Total	2.3089e+23	100.0	100.0	43.40

Record #2

Field	Value	Field	Value
Elapsed Time (s)	500.00	Elapsed Time (sols)	0.01
Height Above MOLA Areoid (km)	2.000	MOLA Areoid Radius (km)	3393.7
Latitude (deg)	22.300	Local Solar Time (hrs)	2.43
Longitude E (deg)	48.50	Longitude of the Sun (deg)	172.16
Pressure Scale Height (km)	10.452	Orbital Radius (AU)	1.48
Density Scale Height (km)	7.831	One Way Light Time (min)	12.58
Temperature (K)	197.7	Subsolar Latitude (deg)	3.29
Pressure (Pa)	4.448e+02	Subsolar Longitude E (deg)	192.08
Sigma Level	0.858	Solar Zenith Angle (km)	136.04
Pressure Altitude (km)	1.604	Gravity (m/s^2)	3.706
Surface Pressure (Pa)	5.186e+02	Speed of Sound (m/s)	224.759
Compressibility Factor (zeta)	0.9865	Specific Gas Constant (J/(kg K))	188.975
Specific Heat Ratio	1.352	Profile Weight	0.000
Height Above MOLA Surface (km)	1.604	Topographic Height (km)	0.396
Height Above Ref. Ellipsoid (km)	2.406	Reference Ellipsoid Radius (km)	3393.3
Planetographic Height (km)	2.406	Planetographic Latitude (deg)	22.538
Ground Temperature (K)	165.6	Height Offset (km)	-0.001
Surface Albedo	0.272	Local Height Offset (km)	0.000

Field	Value	Field	Value
Daily Mean Temperature (K)	214.48	Daily Mean Density (kg/m^3)	1.0786e-02
Min Daily Temperature (K)	195.41	Min Daily Density (kg/m^3)	9.5155e-03
Max Daily Temperature (K)	238.05	Max Daily Density (kg/m^3)	1.2153e-02
Daily Mean Pressure (Pa)	4.372e+02	Ice Is Present	99

Field	Value	Field	Value
Dust Optical Depth	0.300	Dust Column Areal Density(kg/m^2)	1.500e-03
Dust Mass Density (ug/m^2)	1.287e+02	Dust Mixing Ratio (dust/air)	1.081e-05
Dust Number Density (#/m^3)	6.555e+05	cos(Solar Zenith Angle)	-0.7198

Density	Low	Average	High
Density (kg/m^3)	1.1672e-02	1.1905e-02	1.2143e-02
Density Deviation (%)	-10.2	-8.4	-6.6
Perturbed Density (kg/m^3)	1.1997e-02	Perturbation (%)	0.8
Perturbed Density Deviation (%)	-7.72	Perturbed Speed of Sound (m/s)	223.90

Winds	Mean	Perturbation	Perturbed
Eastward Wind (m/s)	3.0	-4.5	-1.5
Northward Wind (m/s)	3.9	-1.4	2.5

Gases	Number Density (#/m^3)	Mass (%)	Mole (%)	Avg Mol Wgt
Argon (Ar)	3.0665e+21	1.7	1.9	39.96
Carbon Dioxide (CO2)	1.5657e+23	96.1	94.8	44.01
Carbon Monoxide (CO)	1.8585e+20	0.1	0.1	28.01
Dihydrogen (H2)	0.0000e+00	0.0	0.0	2.02
Dinitrogen (N2)	5.1108e+21	2.0	3.1	28.02
Dioxygen (O2)	2.4160e+20	0.1	0.1	32.00
Helium (He)	0.0000e+00	0.0	0.0	4.00

Hydrogen (H)	0.0000e+00	0.0	0.0	1.01	
Oxygen (O)	0.0000e+00	0.0	0.0	16.00	
Water (H2O)	8.2851e+18	0.0	0.0	18.02	
Total	1.6519e+23	100.0	100.0	43.40	

(Snipped for brevity)

Record #200

Field	Value	Field	Value
Elapsed Time (s)	99500.00	Elapsed Time (sols)	1.12
Height Above MOLA Areoid (km)	398.000	MOLA Areoid Radius (km)	3378.5
Latitude (deg)	81.700	Local Solar Time (hrs)	11.80
Longitude E (deg)	147.50	Longitude of the Sun (deg)	172.79
Pressure Scale Height (km)	145.645	Orbital Radius (AU)	1.48
Density Scale Height (km)	71.970	One Way Light Time (min)	12.50
Temperature (K)	175.2	Subsolar Latitude (deg)	3.03
Pressure (Pa)	1.571e-09	Subsolar Longitude E (deg)	150.57
Sigma Level	0.000	Solar Zenith Angle (km)	78.75
Pressure Altitude (km)	3927.624	Gravity (m/s^2)	2.989
Surface Pressure (Pa)	8.087e+02	Speed of Sound (m/s)	990.565
Compressibility Factor (zeta)	1.3744	Specific Gas Constant (J/(kg K))	245.225
Specific Heat Ratio	1.640	Profile Weight	0.000
Height Above MOLA Surface (km)	402.480	Topographic Height (km)	-4.480
Height Above Ref. Ellipsoid (km)	399.900	Reference Ellipsoid Radius (km)	3376.6
Planetographic Height (km)	399.899	Planetographic Latitude (deg)	81.786
Ground Temperature (K)	163.1	Height Offset (km)	-0.001
Surface Albedo	0.181	Local Height Offset (km)	-0.001
F1 Peak Height (km)	129.1	Thermosphere Base Height (km)	118.445
Exospheric Temperature (K)	175.2	Thermosphere Base Temperature (K)	136.5

Field	Value	Field	Value
Daily Mean Temperature (K)	0.00	Daily Mean Density (kg/m^3)	0.0000e+00
Min Daily Temperature (K)	0.00	Min Daily Density (kg/m^3)	0.0000e+00
Max Daily Temperature (K)	0.00	Max Daily Density (kg/m^3)	0.0000e+00
Daily Mean Pressure (Pa)	0.000e+00	Ice Is Present	99

Field	Value	Field	Value
Dust Optical Depth	0.300	Dust Column Areal Density(kg/m^2)	1.500e-03
Dust Mass Density (ug/m^2)	0.000e+00	Dust Mixing Ratio (dust/air)	0.000e+00
Dust Number Density (#/m^3)	0.000e+00	cos(Solar Zenith Angle)	0.1951

Density	Low	Average	High
Density (kg/m^3)	1.8106e-15	2.6253e-15	3.8067e-15
Density Deviation (%)	-99.9	-99.9	-99.9
Perturbed Density (kg/m^3)	2.1595e-15	Perturbation (%)	-17.7
Perturbed Density Deviation (%)	-99.90	Perturbed Speed of Sound (m/s)	1092.20

Winds	Mean	Perturbation	Perturbed
Eastward Wind (m/s)	57.9	16.1	74.0
Northward Wind (m/s)	146.1	-6.5	139.6

Gases	Number Density (#/m^3)	Mass (%)	Mole (%)	Avg Mol Wgt
Argon (Ar)	1.2815e+04	0.0	0.0	39.96
Carbon Dioxide (CO2)	0.0000e+00	0.0	0.0	44.01
Carbon Monoxide (CO)	1.8619e+07	0.0	0.0	28.01
Dihydrogen (H2)	3.2336e+10	4.1	6.8	2.02
Dinitrogen (N2)	3.8482e+07	0.1	0.0	28.02
Dioxygen (O2)	2.3536e+05	0.0	0.0	32.00
Helium (He)	2.2448e+11	56.8	47.5	4.00
Hydrogen (H)	1.8910e+11	12.1	40.0	1.01
Oxygen (O)	2.6558e+10	26.9	5.6	16.00
Water (H2O)	0.0000e+00	0.0	0.0	18.02
Total	4.7253e+11	100.0	100.0	3.35

Record #201

Field	Value	Field	Value
Elapsed Time (s)	100000.00	Elapsed Time (sols)	1.13
Height Above MOLA Areoid (km)	400.000	MOLA Areoid Radius (km)	3378.5
Latitude (deg)	82.000	Local Solar Time (hrs)	11.96
Longitude E (deg)	148.00	Longitude of the Sun (deg)	172.80
Pressure Scale Height (km)	147.555	Orbital Radius (AU)	1.48

```
| Density Scale Height (km)          | 73.288     | One Way Light Time (min)           | 12.50      |
| Temperature (K)                    | 175.4      | Subsolar Latitude (deg)            | 3.02       |
| Pressure (Pa)                      | 1.550e-09  | Subsolar Longitude E (deg)         | 148.55     |
| Sigma Level                        | 0.000      | Solar Zenith Angle (km)            | 79.03      |
| Pressure Altitude (km)             | 3980.526   | Gravity (m/s^2)                    | 2.986      |
| Surface Pressure (Pa)              | 8.056e+02  | Speed of Sound (m/s)               | 995.128    |
| Compressibility Factor (zeta)      | 1.3704     | Specific Gas Constant (J/(kg K))   | 245.225    |
| Specific Heat Ratio                | 1.640      | Profile Weight                     | 0.000      |
| Height Above MOLA Surface (km)     | 404.447    | Topographic Height (km)            | -4.447     |
| Height Above Ref. Ellipsoid (km)   | 401.901    | Reference Ellipsoid Radius (km)    | 3376.6     |
| Planetographic Height (km)         | 401.901    | Planetographic Latitude (deg)      | 82.083     |
| Ground Temperature (K)             | 162.3      | Height Offset (km)                 | -0.001     |
| Surface Albedo                     | 0.193      | Local Height Offset (km)           | -0.001     |
| F1 Peak Height (km)                | 129.2      | Thermosphere Base Height (km)      | 118.429    |
| Exospheric Temperature (K)         | 175.4      | Thermosphere Base Temperature (K)  | 136.7      |

| Field                              | Value      | Field                              | Value      |
|------------------------------------|------------|------------------------------------|------------|
| Daily Mean Temperature (K)         | 0.00       | Daily Mean Density (kg/m^3)        | 0.0000e+00 |
| Min Daily Temperature (K)          | 0.00       | Min Daily Density (kg/m^3)         | 0.0000e+00 |
| Max Daily Temperature (K)          | 0.00       | Max Daily Density (kg/m^3)         | 0.0000e+00 |
| Daily Mean Pressure (Pa)           | 0.000e+00  | Ice Is Present                     | 99         |

| Field                              | Value      | Field                              | Value      |
|------------------------------------|------------|------------------------------------|------------|
| Dust Optical Depth                 | 0.300      | Dust Column Areal Density(kg/m^2)  | 1.500e-03  |
| Dust Mass Density (ug/m^2)         | 0.000e+00  | Dust Mixing Ratio (dust/air)       | 0.000e+00  |
| Dust Number Density (#/m^3)        | 0.000e+00  | cos(Solar Zenith Angle)            | 0.1902     |

| Density                            | Low        | Average                            | High       |
|------------------------------------|------------|------------------------------------|------------|
| Density (kg/m^3)                   | 1.7706e-15 | 2.5673e-15                         | 3.7226e-15 |
| Density Deviation (%)              | -99.9      | -99.9                              | -99.9      |
| Perturbed Density (kg/m^3)         | 3.1171e-15 | Perturbation (%)                   | 21.4       |
| Perturbed Density Deviation (%)    | -99.90     | Perturbed Speed of Sound (m/s)     | 903.12     |

| Winds                              | Mean          | Perturbation  | Perturbed     |
|------------------------------------|---------------|---------------|---------------|
| Eastward Wind  (m/s)               | 64.3          | 4.7           | 69.0          |
| Northward Wind  (m/s)              | 142.9         | 34.6          | 177.5         |

| Gases                 | Number Density (#/m^3) | Mass (%) | Mole (%) | Avg Mol Wgt |
|-----------------------|------------------------|----------|----------|-------------|
| Argon (Ar)            | 1.1185e+04             | 0.0      | 0.0      | 39.96       |
| Carbon Dioxide (CO2)  | 0.0000e+00             | 0.0      | 0.0      | 44.01       |
| Carbon Monoxide (CO)  | 1.6925e+07             | 0.0      | 0.0      | 28.01       |
| Dihydrogen (H2)       | 3.2110e+10             | 4.2      | 6.9      | 2.02        |
| Dinitrogen (N2)       | 3.4980e+07             | 0.1      | 0.0      | 28.02       |
| Dioxygen (O2)         | 2.1106e+05             | 0.0      | 0.0      | 32.00       |
| Helium (He)           | 2.2168e+11             | 57.4     | 47.5     | 4.00        |
| Hydrogen (H)          | 1.8809e+11             | 12.3     | 40.3     | 1.01        |
| Oxygen (O)            | 2.5177e+10             | 26.1     | 5.4      | 16.00       |
| Water (H2O)           | 0.0000e+00             | 0.0      | 0.0      | 18.02       |
| Total                 | 4.6711e+11             | 100.0    | 100.0    | 3.31        |

--------------------
## 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.

MarsGRAM 2021 :: GRAMLib 2021b :: GRAM Suite 1.4

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
Input Heights	Planetocentric	Ref Ellips Equat Rad (km)	3396.20
Relative to	MOLA areoid	Ref Ellips Polar Rad (km)	3376.20
Dust Nu	0.0030	Pert Wave Length Scale	1.00
Dust Diameter (m)	5.00e+00	Mean Winds Scale	1.00
Dust Den (kg/m^3)	3000.0	Boundary Layer Winds Scale	1.00
F10.7 Flux 1 AU	68.0	F10.7 Flux at Mars	30.9

Field	Value	Field	Value
Dust Storm LS (deg)	0.00	Storm Duration (deg)	48.00
Storm Intensity	0.00	Storm MaxRadius (km)	0.00
Storm Latitude (deg)	0.00	Storm Longitude (deg)	0.00
Wave 1 (A, P, R)	0.000, 0.000, 0.000	Wave Date	0.00
Wave 2 (A, P, R)	0.000, 0.000, 0.000	Wave Mean Offset	1.00
Wave 3 (A, P, R)	0.000, 0.000, 0.000	Wave Scale	20.00

Record #1

Field	Value	Field	Value
Elapsed Time (s)	0.00	Elapsed Time (sols)	0.00
Height Above MOLA Areoid (km)	0.000	MOLA Areoid Radius (km)	3393.8
Latitude (deg)	22.000	Local Solar Time (hrs)	2.26
Longitude E (deg)	48.00	Longitude of the Sun (deg)	172.16
Pressure Scale Height (km)	10.458	Orbital Radius (AU)	1.48
Density Scale Height (km)	10.458	One Way Light Time (min)	12.58
Temperature (K)	171.3	Subsolar Latitude (deg)	3.29
Pressure (Pa)	5.387e+02	Subsolar Longitude E (deg)	194.11
Sigma Level	1.039	Solar Zenith Angle (km)	138.17
Pressure Altitude (km)	-0.398	Gravity (m/s^2)	3.710
Surface Pressure (Pa)	5.186e+02	Speed of Sound (m/s)	210.813
Compressibility Factor (zeta)	0.9865	Specific Gas Constant (J/(kg K))	188.976
Specific Heat Ratio	1.373	Profile Weight	0.000
Height Above MOLA Surface (km)	-0.398	Topographic Height (km)	0.398
Height Above Ref. Ellipsoid (km)	0.394	Reference Ellipsoid Radius (km)	3393.4
Planetographic Height (km)	0.394	Planetographic Latitude (deg)	22.236
Ground Temperature (K)	166.3	Height Offset (km)	-0.001
Surface Albedo	0.274	Local Height Offset (km)	0.000

Field	Value	Field	Value
Daily Mean Temperature (K)	210.03	Daily Mean Density (kg/m^3)	1.3114e-02
Min Daily Temperature (K)	169.66	Min Daily Density (kg/m^3)	8.9169e-03
Max Daily Temperature (K)	272.98	Max Daily Density (kg/m^3)	1.8011e-02
Daily Mean Pressure (Pa)	5.205e+02	Ice Is Present	0

Field	Value	Field	Value
Dust Optical Depth	0.300	Dust Column Areal Density(kg/m^2)	1.500e-03
Dust Mass Density (ug/m^2)	1.802e+02	Dust Mixing Ratio (dust/air)	1.083e-05

Dust Number Density (#/m^3)	9.179e+05	cos(Solar Zenith Angle)	-0.7451

Density	**Low**	**Average**	**High**
Density (kg/m^3)	1.6315e-02	1.6641e-02	1.6974e-02
Density Deviation (%)	5.3	7.4	9.5
Perturbed Density (kg/m^3)	1.6773e-02	Perturbation (%)	0.8
Perturbed Density Deviation (%)	8.21	Perturbed Speed of Sound (m/s)	209.98

Winds	**Mean**	**Perturbation**	**Perturbed**
Eastward Wind (m/s)	0.0	-1.6	-1.6
Northward Wind (m/s)	0.0	-0.3	-0.3

Gases	**Number Density (#/m^3)**	**Mass (%)**	**Mole (%)**	**Avg Mol Wgt**
Argon (Ar)	4.2861e+21	1.7	1.9	39.96
Carbon Dioxide (CO2)	2.1886e+23	96.1	94.8	44.01
Carbon Monoxide (CO)	2.5977e+20	0.1	0.1	28.01
Dihydrogen (H2)	0.0000e+00	0.0	0.0	2.02
Dinitrogen (N2)	7.1436e+21	2.0	3.1	28.02
Dioxygen (O2)	3.3770e+20	0.1	0.1	32.00
Helium (He)	0.0000e+00	0.0	0.0	4.00
Hydrogen (H)	0.0000e+00	0.0	0.0	1.01
Oxygen (O)	0.0000e+00	0.0	0.0	16.00
Water (H2O)	7.9376e+16	0.0	0.0	18.02
Total	2.3089e+23	100.0	100.0	43.40

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 MARS-GRAM

The following are provided with the Mars-GRAM distribution:

- Build: A makefile system for building the GRAM Suite.
- MSVS: A Visual Studio solution for building the GRAM Suite (no Fortran).
- Documentation: A User Guide, a Programmer's Manual, a report detailing the updated methodology to compute the speed of sound in the GRAM Suite, a GRAM Suite change log, and a subfolder of additional Mars-GRAM documentation.
- 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
- Mars: 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 MARS-GRAM

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

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

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

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

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

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

APPENDIX F – DETAILS OF MGCM, MTGCM, AND MOLA DATA FILES

Time-of-Day Variation of MGCM and MTGCM Data

ASCII format MGCM and MTGCM data files are provided, each having values for amplitudes and phases of diurnal and semi-diurnal components. The diurnal period is 24 Mars hours and the semi-diurnal period is 12 Mars hours. Generically, the amplitudes and phases are as follows:

A_0 = Diurnal mean value of the given parameter
A_1 = Amplitude of the diurnal tide component
ϕ_1 = Phase (local time in Mars hours) of the diurnal component
A_2 = Amplitude of the semi-diurnal tide component
ϕ_2 = Phase (local time in Mars hours) of the semi-diurnal component

For temperature, wind components, and height of 1.26 nbar level (ZF), data files give amplitudes in the same units as those of the parameter, K for temperature, m/s for wind, or km for ZF. For pressure and density, data files give amplitudes in units of percent of the mean value A_0. A_0 units for pressure are Pa, while density A_0 units are kg/m^3.

Three slightly different functions for tidal variation versus time of day are used. For MGCM and MTGCM temperatures and winds and MTGCM ZF heights, function TideX is used, where

$$\text{TideX} = A_0 + A1 * \cos((\pi/12) * (t - \phi_1)) + A2 * \cos((\pi/6) * (t - \phi_2))$$

and t is the local solar time in Mars hours. Note that units for A_1 and A_2 are same as those for A_0 in this function form. For MGCM and MTGCM pressure and density data which have A_1 and A_2 in units of percent of A_0, function TideY is used, where

$$\text{TideY} = A_0 * (1 + 0.01 * A_1 * \cos((\pi/12) * (t - \phi_1)) + 0.01 * A2 * \cos((\pi/6) * (t - \phi_2)))$$

TES MTGCM data used for *MapYear = 1 or 2* extend to higher altitude, 240 km versus 170 km for Mars-GRAM MTGCM data used for *MapYear = 0*. Consequently, tidal amplitudes for density and pressure for the new data grow to larger values than for the Mars-GRAM MapYear=0 data. To accommodate this situation, an alternate model is adopted for pressure and density variation with time of day, whereby it is the log of pressure and density that are assumed to vary as cosine of time of day. Namely TES mapping year 1 and 2 MTGCM pressure and density tides are computed by

$$\text{tTideY} = A_0 * ((1.0d0 + 0.01d0 * A1) ** c1) * ((1.0d0 + 0.01d0 * A_2) ** c2)$$

where exponents c1 and c2 are given by

$$c1 = \cos((\pi/12) * (t - \phi_1))$$

$$c2 = \cos((\pi/6) * (t - \phi_2)$$

Near-Surface MGCM Data

Near-surface MGCM data files are provided as follows in ASCII format:

sfc00xxy.txt	MGCM temperature data at topographic surface
sfc05xxy.txt	MGCM temperature and wind data at 5 m height above the surface
sfc30xxy.txt	MGCM temperature and wind data at 30 m height above the surface

Naming convention for these files is:

xx = 03, 10, 30 for Mars-GRAM *MapYear* = 0 data at globally-uniform dust optical depths of 0.3, 1.0, and 3.0

xx = y1, y2 for data at time-and space-variable dust optical depth as observed during TES mapping years 1 and 2

y = version number

Each record of these files contains L_s value, latitude, longitude, and tidal coefficients (A_0, A_1, ϕ_1, A_2, ϕ_2) for temperature, and for eastward and northward wind components, except for ground surface data files, which contain only temperature information.

MGCM Data Up to 80.0 km Altitude

Files of zonally-averaged MGCM data up to 80.0 km altitude above the MOLA areoid are provided as follows in ASCII format:

tpdloxxy.txt	MGCM temperature, pressure, and density data
uvloxxy.txt	MGCM eastward and northward wind data

Naming convention for these files is:

xx = 03, 10, 30 for Mars-GRAM *MapYear* = 0 data at globally-uniform dust optical depths of 0.3, 1.0, and 3.0. These data are at 5.0 km intervals from 0.0 km to 80.0 km above MOLA

xx = y1, y2 for data at time-and space-variable dust optical depths as observed during TES mapping years 1 and 2. These data are at 1.0 km interval from -5.0 km to +10.0 km above MOLA, and 5.0 km interval from 10.0 km to 80.0 km above MOLA

y = version number

For the MGCM data sets, each record of the tpdloxx.txt files contains L_s value, height, latitude, and tidal coefficients for temperature and pressure. Only the A_0 coefficient is given for density. Tidal variations in density are computed from those for pressure and temperature by the perfect gas law relation. For the TES mapping year 1 and 2 data, each record of the tpdloxx.txt files contains L_s value, height, latitude, and tidal coefficients for temperature and density. Only the A_0 coefficient is given for pressure. Tidal variations in pressure are computed from those for density and temperature by the perfect gas law relation.

For both MGCM and TES mapping year 1 and 2 data, each record of the uvloxx.txt files contains L_s value, height, latitude, and tidal coefficients for the eastward and northward wind components.

MTGCM Data Up to 170.0 or 240.0 km Altitude

Zonally-averaged MTGCM data are provided in ASCII format at 5.0 km height resolution for the altitude range of 80.0 to 170.0 km for Mars-GRAM data and 80.0 to 240.0 km for TES mapping year 1 and 2 data. Data sets are provided for different levels of solar activity as characterized by 10.7 cm solar flux, F10.7, as measured at 1.0 AU.

tpdlsxxy.txt	MTGCM temperature, pressure, and density data for low solar activity (F10.7 = 70)
tpdmsxxy.txt	MTGCM temperature, pressure, and density data for moderate solar activity (F10.7 = 130)
tpdhsxxy.txt	MTGCM temperature, pressure, and density data for high solar activity (F10.7 = 200; available for TES mapping years 1 and 2 only)
uvlsxxy.txt	MTGCM eastward and northward wind data for F10.7 = 70
uvmsxxy.txt	MTGCM eastward and northward wind data for F10.7 = 130
uvhsxxy.txt	MTGCM eastward and northward wind data for F10.7 = 200 (available for TES mapping years 1 and 2 only)

Naming convention for these files is:

xx = 03, 10, 30 for Mars-GRAM *MapYear* = 0 data at globally-uniform dust optical depths of 0.3, 1.0, and 3.0.

xx = y1, y2 for data at time-and space-variable dust optical depths as observed during TES mapping years 1 and 2.

y = version number

Each record of the tpdlsxxy.txt, tpdmsxxy.txt and tpdhsxxy.txt files contains L_s value, height, latitude, and tidal coefficients for temperature, pressure, and density. Because of height variations in molecular weight, tidal coefficients are retained for all three of these thermodynamic components. Each record of the uvlsxxy.txt, uvmsxxy.txt and uvhsxxy.txt files contains L_s value, height, latitude, and tidal coefficients for the eastward and northward wind components.

Files zfhtlsy.txt, and zfhtmsy.txt for Mars-GRAM *MapYear* = 0 data, F10.7 = 70 or 130 and zfTESlsy.txt, zfTESmsy.txt, and zfTEShsy.txt for TES mapping years 1 and 2, F10.7 = 70, 130, or 200 provide tidal coefficient information for altitude ZF, the height of the 1.26 nbar level. Each record of the ZF files contains dust optical depth or TES mapping year, L_s, latitude, and tidal coefficient values. The mean ZF value and tidal amplitudes are given in km.

MOLA Areoid and Topography Data

MOLA areoid and topography data at 1/2 by 1/2 degree latitude-longitude resolution is provided in ASCII file MOLATOPH.TXT. Each line of this file contains East longitude and latitude at the center of the 1/2 by 1/2 degree grid box, grid-box-average radius in meters to the topographic surface, areoid radius in meters which is the radius to reference constant potential surface, evaluated at the center of the grid box, topography which is the grid-box-average difference in meters between the local planetary radius and areoid; this is analogous to the local terrain height above sea level for Earth, and Num which equals the number of laser shots averaged over the grid box. MOLA latitudes are planetocentric. Longitudes in the MOLA input file are with respect to the International Astronomical Union (IAU) 1991 prime meridian. A shift of about 0.24 degrees is made automatically within Mars-GRAM, in order to convert to longitudes relative to the IAU 2000 prime meridian.

Surface Albedo Data

Global surface albedo at 1 by 1 degree latitude-longitude resolution is given in file albedo1.txt. Each line of this file contains latitude, and West longitude at the center of the 1 by 1 degree grid box, and grid-box-average surface albedo which is the ratio of the surface-reflected solar flux to that incident on the surface.

Global Mean MGCM-MTGCM Height Offset Data

Height offsets can be used to control the smoothness of the transition at 80 km altitude between MGCM data and MTGCM data. Height offset options are controlled by input parameters *ConstantHeightOffset* and *OffsetModel*. Option *OffsetModel* = 2 causes the height offsets to be evaluated from global average height offset data given in the file hgtoffst.dat. In the first part of this file, global-average offsets in km are given for Mars-GRAM *MapYear* = 0 data as a function of L_s and dust optical depth of 0.3, 1.0, and 3.0. In the second part of this file, global-average offsets are given versus L_s for TES mapping years 1 and 2, y1 or y2.

TES Dust Optical Depth Data

Observed average dust optical depth from TES mapping years 1 and 2 are provided in the file TESdust1.txt. TES mapping year 1 was from April 1999 through January 2001. TES mapping year 2 was from February 2001 through December 2002. In terms of L_s, TES mapping years 1 and 2 cover from L_s = 115, through L_s = 360/0, and back to L_s = 115 the following Mars year. A conventional Mars year runs from L_s = 0 to L_s = 360. There were no global-scale dust storms during TES mapping year 1. However, a very intense, global-scale dust storm began near the end of June 2001, during TES mapping year 2. Each line of file TESdust1.txt contains TES mapping year (1 or 2), L_s, latitude, West longitude, and the average TES optical depth expressed as visible-wavelength optical depth, approximately twice the optical depth values measured by TES at its 9 micron observing wavelength. Data in this file are at a resolution of 5.0 degrees in L_s, 7.5 degrees in latitude, and 9.0 degrees in longitude.

COSPAR Reference Data

Committee on Space Research (COSPAR) Northern hemisphere mean reference data, as given in Pitts et al[35], are provided in file COSPAR2.DAT. Each line of this file contains height (km), temperature (K), pressure (mbar), and density (g/cm^3).

Conversion of ASCII Data to Binary

Source code is provided for programs called makeMGCMbin.cpp and makeTESbin.cpp that reads the ASCII format MGCM and MTGCM data files and the TES dust optical depth data file and writes them out in binary format. After this ASCII-to-binary conversion is completed once, subsequent reading of the binary format files significantly shortens the time required to initialize Mars-GRAM on each run. The program makeMGCMbin.cpp will also convert the MOLA topography data and the albedo data files. ZF data files, height offset file, and COSPAR reference data file are sufficiently small that they have been embedded within Mars-GRAM.

Note: For PC/Linux users, all necessary binary version data files are supplied and the ASCII-to-binary conversion programs do not have to be run. The conversion is only necessary if the architecture of the target machine uses a different endianness.

To run Mars-GRAM, the binary-version data files must be in the directory whose pathname is given by the input parameter *DataPath* in the NAMELIST input file. In this distribution of Mars-GRAM, the binary data is located in the *data* subfolder of the *Mars* folder. The text data can be found in the *ASCII* subfolder of the *data* folder.

APPENDIX G – AUXILIARY PROGRAM FOR USE WITH MARS-GRAM

Program MarsRad

Program MarsRad.cpp uses the Mars-GRAM CSV output file containing height profile information to compute various solar (shortwave) and thermal (longwave) fluxes at the surface and the top of the atmosphere. These profiles must start at the surface, should usually extend upward to a height of from 10.0 to 30.0 km, and may be at any desired height resolution with a limit of 1,000 points per profile.

Program MarsRad runs interactively, with the only user input required being the name of the Mars-GRAM CSV output file and a heat rate option. The MarsRad program computes various solar (shortwave) and thermal (longwave) fluxes at the surface and the top of the atmosphere. Two MarsRad output files are produced. Output file Radlist.md contains an annotated set of radiation fluxes, equivalent black-body temperatures, and albedos in markdown format. Output file Radout.csv, suitable for input to a plot program, contains fluxes and other information in one line for each set of output. The output file Radout.csv can be used to plot solar and thermal radiation data as a map latitude-longitude cross section, or as latitude-time or longitude-time cross sections.

Longwave radiative fluxes are computed by a broad-band (emissivity) method, patterned after Savijarvi[36]. Dust optical depth tau is for the shortwave (solar) spectrum. For longwave calculations, infrared emissivity versus shortwave solar optical depth curves are used, adapted from Haberle et al.[30]. Infrared emissivities for CO_2 and water vapor are functions of pressure-scaled optical path lengths with emissivities from Staley and Jurica[37]. Shortwave fluxes are computed from total dust optical depth adjusted for small amount of clear-sky optical depth by a delta-Eddington method[38]. Both longwave and shortwave effects of water vapor are included, with relative humidity assumed constant at 20%[36]. Dust optical properties assumed are 0.7 for asymmetry parameter, and 0.9 for single-scatter albedo. Other reasonable values may be found in Table 1 of Murphy et al.[39]. Values of asymmetry parameter and single-scatter albedo as well as assumed relative humidity can be changed in data statements near the beginning of the MarsRad program.

Output parameters given in Radlist.csv output file in addition to position variables are:

tau	Total vertical dust optical depth
MarsAU	Mars orbital radius (AU)
mu0	Cosine of solar zenith angle
ice	0 for no ice on the surface, 1 for ice on the surface (affects surface albedo)

Longwave (LW) fluxes F (W/m^2):

Fdown(sfc)	Downwelling LW flux at surface
Fup(sfc)	Upwelling LW flux at surface (related to Tsfc)

Fup(toa)	Upwelling LW flux at top-of-atmosphere
Femit(atmos)	LW flux emitted by atmosphere [Fup(toa) - net LW at sfc]

Radiative (equivalent black-body) temperatures (K):

Tsky(sfc)	Equivalent sky temperature [related to Fdown(sfc)]
Tsfc	Ground surface temperature [related to Fup(sfc)]
Teff(toa)	Effective black-body temperature at top-of-atmosphere

Shortwave (SW) fluxes E (W/m^2):

Edown(sfc)	Downwelling SW flux at surface
Eup(sfc)	Upwelling SW flux at surface [albedo times Edown(sfc)]
Eup(toa)	Upwelling SW flux at top-of-atmosphere
Eabsorb(atmos)	Net SW flux absorbed by atmosphere
Edown(toa)	Solar flux at toa = mu0*(solar constant)/$MarsAU^2$

Surface albedo	Surface albedo interpolated from file albedo1.txt
Planetary albedo	Ratio Eup(toa)/Edown(toa)

SW+LW Fluxes (W/m^2):

Absorbed(sfc)	SW+LW flux absorbed at the surface Emitted(toa)
Upwelling	SW+LW flux at top-of-atmosphere

Controlled by heat rate input option, MarsRad also outputs optical path lengths for water vapor (H_2O), CO_2, and dust. H_2O and CO_2 optical path lengths are scaled by pressure to the 0.75 power. With the option set to 1, the program also outputs various fluxes (W/m^2) and heating rates (K/day) as a function of pressure level. These optional outputs are:

Pres	Pressure (mb)
uH2O	Pressure-scaled H_2O optical path (precipitable micrometers)
uCO2	Pressure-scaled CO_2 optical path (atmosphere-centimeters)
udust	Dust optical depth from surface to given pressure level
LWFup	Upwelling LW flux at pressure level
LWFdn	Downwelling LW flux at pressure level
LWFnet	Net (up - down) LW flux at pressure level

LWdTdt LW heating rate at pressure level

SWdTdt SW heating rate at pressure level

TotdTdt Total (LW+SW) heating rate at pressure level

Parameters given in Radout.txt output file in addition to plot variables, Var_X and, optionally, Var_Y are:

albsfc	Surface albedo (interpolated from file albedo1.txt)
tau	Total vertical dust optical depth (for solar wavelengths)
RadAU	Mars orbital radius (AU)
mu0	Cosine of solar zenith angle
ice	0 for no ice on the surface, 1 for ice on the surface
Tsfc	Ground surface temperature (K)
Fusfc	Upwelling LW flux at surface (W/m^2)
Tsky	Equivalent sky temperature (K)
Fdsfc	Downwelling LW flux at surface (W/m^2)
Teff	Effective black-body temperature at top-of atmosphere (K)
Futoa	Upwelling LW flux at top-of-atmosphere (W/m^2)
Edsfc	Downwelling SW flux at surface (W/m^2)
Eusfc	Upwelling SW flux at surface (W/m^2)
Edtoa	Solar flux at toa = mu0*(solar constant)/$RadAU^2$ (W/m^2)
Eutoa	Upwelling SW flux at top-of-atmosphere (W/m^2)
Planalb	Planetary albedo = ratio Eutoa/Edtoa
thet	Solar zenith angle (degrees)
Tdif	Diffuse transmittance for diffuse irradiance
Tdir	Diffuse transmittance for beam irradiance
Tbeam	Beam transmittance

APPENDIX F – HISTORY OF MARS-GRAM VERSION REVISIONS

Table 7. Mars-GRAM version revisions.

Version	Date	Comments
1.00	5/20/1988	Preliminary version with earlier Stewart thermosphere model and no realistic latitude-longitude variation. Documented in ED44-5-20-88 preliminary report.
2.00	7/1/1989	Version documented in July 1989 technical report. Has newer Stewart thermosphere model and realistic latitude-longitude variability.
2.10	9/2/1989	Adds version numbers to main and all subroutines. Corrects formats 790 and 795 in DATASTEP subroutine.
2.11	10/2/1989	Corrects "ATIO" to "RATIO" and "FH" to "PFH" in THERMOS subroutine. Corrects MARSGRAM, ATMOS2, DATASTEP, PRESSURE, PSURFACE, STEWART2, STRATOS, TEMPS, and TSURFACE to have lines <= 72 characters in length.
2.20	10/7/1989	Corrects illegal log call in THERMOS by adding ES factors to ZF in ATMOS2. Adds EScalc subroutine in STEWART2. Changes name of terrain height file to HEIGHTS.DAT.
2.21	10/8/1989	Removes character data from COMMON DATA and puts it in new COMMON FILENAME.
2.22	11/16/1989	Adds REAL J2 to RELLIPS, and REAL nmals to PSURFACE. Changes Julian date by -0.5 to be consistent with astronomical convention of day starting at Greenwich noon. ORBIT adds back 0.5 to Julian day for consistency with derivation of coefficients.
3.0	10/14/1991	Adds option for local-scale dust storm, and Zurek wave perturbation model. Allows heights to go "below" local terrain height and return "realistic" pressure, density and temperature, not the surface values. Both Interactive and Batch versions available. Batch version uses NAMELIST input, and is completely modular, so that the main driver program can easily be replaced by any calling program, such as a trajectory simulation program.
3.1	12/17/1992	Change comments and code for DENSRP output to be perturbations in %; change DENSLO output file to DENSRM, containing random perturbation magnitude in %; change DENSHI output file to DENSWA, containing wave perturbation in %; add DENSWA to the OUTPUT file. Modify DENSHI and DENSLO to include the wave perturbation amplitude. Delete several unused variables from declaration statements in the MAIN routine and in subroutines SETUP, ATMOS2, PSURFACE, STEWART2, DZDUST, THERMOS, and STRATOS.
3.1	3/14/1994	Transferred version 3.1 to MSFC UNIX environment and tested
3.2	11/28/1994	Corrected DENSHI, DENSLO initial value problem. Added parameter value output to Datastep. Modified DZDUST to use same dust storm start time and intensity as for lower altitude. Changed output file units to iu0 for messages (normally screen) and iup for LIST output (iup = 0 also suppresses LIST and other output in batch version). Corrected error in calculation of time-step correlations. Added line number codes in columns 73-80. Sorted MARSSUBS

Version	Date	Comments
		into alphabetical order by line number codes. Renamed Commons RAND to RANDCOM and DATA to DATACOM. Modified E-format in LIST output to have a leading digit. Made code consistent for indentation of If..Then..Else segments and Do..Continue loops. Moved the NAMELIST read into SETUP for the batch version and removed the commons from the batch main (to simplify the use of SETUP and DATASTEP as subroutines in other driver programs). Deleted additional unused variables in ATMOS2 and ORBIT. Defined pi180 in DATASTEP and corrected NVAR to NVARX. Corrected slight inconsistency in pressure interpolation in subroutine STRATOS. Added time (rel. to initial time) in sols to standard LIST file. Added time and solar longitude to the OUTPUT list.
3.3	2/7/1995	Simplified vertical interpolation method in subroutine STRATOS. Added DENSLO and DENSHI output files back ("1 sigma" density envelopes). Corrected erroneous comments associated with file open statements in the batch version code. Added maxfiles option to suppress output of TMAX, TMIN and TAVG files for systems that cannot have more than 16 files open at one time (i.e. set maxfiles = 16 in the Block Data routine).
3.31	3/28/1995	Added check for density perturbations not to exceed value set by wave instability (i.e. maximum perturbation magnitude consistent with d-theta/dz > 0). Insured that wave amplitudes are zero if wave perturbation model is not selected. Added output of F10.7 at 1AU and at Mars orbit.
3.32	4/11/1995	Added COSPAR NH mean atmosphere and output of density deviations from COSPAR values (also new option logscale = 2). Suppress output of NSWIND and EWWIND if maxfiles = 16.
3.33	8/9/1995	Takes polar cap radius from Alb function and makes it a separate function, polecap. Uses new regressions for Tavg versus Absorb (the daily average surface-absorbed solar flux). Uses new regression for diurnal temperature amplitude (Tamp) versus Qa [the diurnal range (midnight-noon difference) in surface-absorbed solar flux]. These changes in temperature regressions are all in the Tsurface subroutine.
3.34	11/1/1995	Added comments for JPL Programmer's Guide. Corrected logic error in density to OUTPUT file (added format 810). Corrected problem with crlat and polar in Tsurface. Corrected semi-diurnal term in dusty-case wave model. Corrected term in maximum mountain-wave perturbation model.
3.4	4/1/1996	Added climate factors for temperature profile (CF0-CF75), adjustment factors for base height of thermosphere (deltaZF), temperature at base of thermosphere (deltaTF) and exospheric temperature (deltaTEX). Included new subroutine Thermpar to compute thermospheric parameters based on parameterizations from the Bougher Mars Thermospheric Global Circulation Model (MTGCM), including new variations with latitude and local solar time. Adjusted wind coefficient in thermospheres to better agree with MTGCM winds. Revised the calculation of solar longitude in the ORBIT subroutine, using 687-day and 777-day period terms. Added default values for batch version input, so that only non-reference

Version	Date	Comments
		parameter values need be in the INPUT NAMELIST file. Added a recheck of the final density perturbation values so that the stability limits will not be exceeded. Added output of the solar latitude and the orbital radius to the LIST file. Changed xycode output to local solar time in hours (from hour angle in degrees). Added output to LIST file of local exospheric temperature, temperature, and height of base of thermosphere, for output altitudes above 75 km.
3.5	7/1996	Changed temperature renormalization to be at 25 km above reference ellipsoid datum, not 25 km above local terrain height. Removed terms producing large gradient in surface pressure poleward of 55 deg. Added option (ipopt) to do hydrostatic interpolation from 75 km to 1.26 nbar. Added climate adjustment factor for surface pressure (CFp). Added calculation of density scale height [H(rho), retaining pressure scale height H(p)]. Added plot output files for density scale height [file=HGTrho, unit=35, files(18)], temperature of 1.26 nbar level [file=Tbase, unit=36, files(19)], and height of 1.26 nbar level [file=Zbase, unit=37, files(20)]. Added option for plot output versus pressure level (NVARX or NVARY = 9). Increased minimum and maximum allowed random perturbation magnitudes (by about a factor of 2) and added input of random perturbation scale factor (rpscale), with allowable values 0-3. Changed lapse rates 30 - 50 km and 50 - 75 km (to 1.19 K/km and 0.44 K/km, respectively). Corrected problem with computing position displacements (DELHGT, DELLAT and DELLON) in mode when trajectory file (TRAJDATA) is read in.
3.6	11/1996	Added Monte Carlo feature in Batch version and created new dummy trajectory-computing version (marstraj). Optional NAMELIST format INPUT now includes NMONTE = number on Monte Carlo runs and iup [0 to suppress LIST and graphics output files; iup not equal to zero causes output of LIST and graphics files (default)]. Added random seed (NR1) and NMONTE to argument list of SETUP subroutine. Rewind trajectory input data file (TRAJDATA) when end-of-file is encountered. Apply random perturbation scaling factor (rpscale) to SIGD, DENSHI, and DENSLO. Include new subroutine Randinit to re-initialize the random number seed (NR1) for each Monte Carlo run. NOTE THAT NO INTERACTIVE VERSION 3.6 IS PROVIDED. Batch (and dummy trajectory) version 3.6 and interactive version 3.5 should give the same output if identical input parameters are used [including NMONTE = 1 (the default case)].
3.7	6/1997	Added time- or latitude-dependent climate factors (CFs) on trajectory input data. CFs include (CF0, CF5, CF15, CF30, CF50, CF75, CFp, deltaZF, deltaTF, and deltaTEX). To use CFs from the INPUT file, use CFs of 0.0 on the trajectory input file. Non-zero CFs on the trajectory input file will supersede those on the INPUT file. Two auxiliary programs are provided for adding CFs to trajectory files: Program bldmgt.f will generate a "trajectory" consisting of user-defined steps in height, latitude, longitude, and time. Program rdmgt.f will read a previously generated trajectory data file (TRAJDATA, containing time, height, latitude, and longitude) and will add CFs. Both bldmgt and rdmgt programs interpolate CFs from an

Version	Date	Comments
		auxiliary CF data file (cfinfo.txt, see description in bldmgt.f or rdmgt.f source code).
3.8	11/1998	Code line numbers (in parentheses) give approximate starting line(s) where changes appear in code. Changed former batch version code line numbers from MARB to MGRM (MGRM 1). Reduced number of graphics output files; included more variables in each file (SETU 36, SETU 90, DSTP 280); See file "headers.txt". Changed to NASA Ames low resolution topography (SETU 15), using average terrain height at poles for all longitudes. Decreased temperature gradient at polar cap edge (ALBL 26, TSRF 53a). Revised procedure whereby input heights <= -5 km are treated as being at the terrain surface (ATM2 54b, ATM2 82, DSTF 14). Revised lapse rate at surface for surface temperature calculation (ATM2 67, ATM2 99). Revised perturbation magnitudes versus height (ATM2 217b, DSTP 50a, DSTP 199b). New iterative procedure for finding ZF (height of 1.26 nbar level) for hydrostatic interpolation option (ATM2 2144a). Pressure scale height added to DATASTEP output (DSTP 2a). Added corlim factor (ratio of trajectory step size to minimum size for assured perturbation accuracy) with warning messages if corlim < 1 (DSTP 80). Added gradient wind (curvature) correction to winds (DSTP 160g). Added check to limit wind components to less than sound speed divided by square root of two (DSTP 151a, DSTP 160h). Delete low latitude wind model based on second derivatives. Treat "surface" winds as being at 10 cm, rather than Viking level of 1.6 m (DSTP 165). Added new wind perturbation model, including tidal winds (DSTP 229, DSTP 244c, WAVE 91, MGRM 88). Included computation of F1 ionization peak altitude and molecular weight; added to output files (DSTP 246i, DSTP 290, DSTP 254d, STRA 47a). Added climate factors to LIST output (DSTP 256a). Convert surface pressure latitude variation to cosine terms, to insure diurnal amplitude goes to zero at the poles (PSRF 61). Changed to new values of reference ellipsoid radii, gravity term, and rotation rate (consistent with current JPL values) (RLPS 9a, RLPS 18a). Added centrifugal term to gravity (RLPS 22). Use molecular scale temperature in stratospheric interpolation to account for height variation of molecular weight (STRA 16, STRA 47h). Remove ES(8) and ES(9) terms from calculation of ZF, but not TF; make perturbation standard deviations more consistent in thermosphere (STW2 37d). Include effect of height change of molecular weight in computation of density scale height (STW2 61a, THRM 133b). Add Pathfinder landing site to set of locations that have terrain height specified (TERN 12a). Apply climate factors to minimum, maximum and average surface temperatures (TMPS 138e). Include Cos(LAT)/Cos(75) factor in wave perturbations, to insure zero amplitude at the poles (WAVE 77a). Allow variable climate factors to be passed from trajectory program to Mars-GRAM subroutines (CFIN 1, MART 58b). Allow optional high resolution solar positions to be passed from trajectory program to Mars-GRAM subroutines (DUMT 35a, MGRM 72, DSTP 35). Add subroutine SublTchk to assure that temperatures do not go below CO2 sublimation

Version	Date	Comments
		temperature (ATM2 72d, ATM2 106b, PRES 29a, STCK 1, STRA 47k, THRM 132b).
Mars-GRAM 2000(ver 1)	3/2000	All parameterizations for temperature versus height, latitude, longitude, time of day, and L_s and for surface pressure versus latitude, longitude, time of day, and L_s have been replaced by input data tables. These tables give variation of temperature, density, pressure and wind components with height, latitude, time of day, and L_s. The tables also provide boundary layer data at 5m and 30m above the surface as a function of longitude. The tables are from the NASA Ames Mars Global Circulation Model (MGCM), for the surface through 80 km altitude, and from the University of Arizona Mars Thermospheric Global Circulation Model (MTGCM) for 80 - 170 km altitude. The modified Stewart thermospheric model is still used for higher altitudes, and for dependence on solar activity. With this direct input of MGCM and MTGCM data, there is no longer a need to input "climate factors" (CF0 through CF75, CFp, deltaTF and deltzZF). Adjustment of exospheric temperature by the parameter *deltaTEX* is still an option. Consistent with observations from Mars Global Surveyor, a new longitude-dependent wave model is included, with user-input amplitudes and phases for waves 1 through 3 (1 - 3 wavelengths around the planet). Wave model coefficients can be input from the NAMELIST format input file, or from an auxiliary file of time-dependent wave model coefficients. A simplified version of the mountain wave perturbation model has been substituted for the earlier one. The simplified model does not require evaluation of surface density and temperature gradients (to get Brunt Vaisala frequency). With MGCM and MTGCM data input for several dust optical depths (tau), the global value of tau can be provided as an input, or if tau = 0 is input, a prescribed Viking-like seasonal variation of dust optical depth is used. The global or local dust storm model is retained, with the program doing all necessary interpolations on dust optical depth as it varies with time (L_s, and with space, for local storms). A switch (*LonEW*) allows users to select to use East Longitude positive, rather than the USGS map standard of West Longitude positive. Default (*LonEW* = 0) is still West Longitude positive. The *LonEW* switch also determines if the longitude wave model phases are in West or East Longitude. Options are now provided whereby the user can specify the name of the NAMELIST format input file, the name of the (optional) trajectory input file, and the path names to the directories where the MGCM, MTGCM and other input data reside.
Mars-GRAM 2001 (ver 1)	5/2001	Revised to use Mars Orbiter Laser Altimeter (MOLA) topography at 1/2 x 1/2 degree resolution. Altitude is defined as height above the MOLA areoid (equipotential surface). Optionally, input height information can be given as height above old reference ellipsoid, then converted to height above MOLA areoid within the program. Revised MGCM data, based on MOLA topography, are used for 0 - 80 km. MTGCM data are the same as for Mars-GRAM 2000 at moderate solar activity (F10.7 = 130), with an added MTGCM data set at low solar activity (F10.7 = 70). MTGCM dependence on solar activity is interpolated/extrapolated logarithmically on F10.7. Fairing

Version	Date	Comments
		between MTGCM data and Stewart model thermosphere is now done over the interval 155 - 170 km (instead of ZF to 170 km, as in Mars-GRAM 2000). Height adjustment (with new parameter *zoffset*) of the MTGCM data is now an option. A new file, hgtoffst.dat, gives the height offsets required to get best match between the MOLA-based MGCM data and the Mars-GRAM 2000 MTGCM data, on a global basis. Optionally, local height offset required for MGCM-MTGCM matchup can be computed and used, or a L_s-dependent height offset can be applied. Height offset due to a dust storm is also computed and added to any input offset. Duration of dust storm (in degrees of L_s angle) is also controlled by a new input parameter *ALSDUR*. *LOGSCALE* = 3 now allows output of densities in units of kg/km**3 (appropriate for high altitudes). A new set of MGCM temperature data at the surface allows more realistic boundary layer temperature gradients, using a logarithmic profile. A boundary layer model is used to estimate difference between ground temperature and air temperature immediately above the ground. New parameter *hgtasfcm* allows easy evaluation of atmospheric variables at any fixed height above the surface (0 - 4500 m). For easier comparison with General Circulation Model data, two new output parameters are introduced: sigma level = local pressure divided by surface pressure, and pressure height = -Log(sigma). Daily output data now includes local daily minimum temperature and density, and local daily maximum temperature and density. Longitude dependent wave perturbations now applied to daily density as well as density at local place and time. Height above the old reference ellipsoid is also an available output parameter. A new output file, MarsRad.txt, contains (along with other output files) necessary information for input to a new auxiliary program (marsrad.f) that computes solar and thermal radiation fluxes at the surface and top-of-atmosphere. File MarsRad.txt contains quantitative dust loading parameters, column mass per unit area, local dust mixing ratio, and dust mass and number of particles per unit volume. Surface albedo, interpolated from new albedo input file, is also output on file MarsRad.txt.
Mars-GRAM 2005 (beta ver 0)	9/2003	More precise ephemeris for solar angles and positions; uses IAU rotation coordinates, computes one-way light time, and allows input time to be Earth-receive time or Mars-event time and Terrestrial Dynamical time or UTC. User input for equatorial and polar radii of reference ellipsoid, and option for input height and latitude to be planeto-centric or planeto-graphic (with respect to ellipsoid) or planeto-centric with respect to MOLA (GSFC) areoid. Output height can also still be planeto-centric with respect to MOLA topographic surface. Perturbation model modified to allow more control of how often to update perturbations (or to update mean conditions without updating perturbations). New feature to allow repeat of random perturbation sequence in trajectory program (example program dumytraj.f). Also provide new example trajectory program (multtraj.f) that allows atmospheric values and perturbations to be evaluated at multiple positions during one trajectory run. Vertical wind perturbation model added. New input parameters allow separate scaling for density and wind perturbations, and multiplier factor for

Version	Date	Comments
		perturbation scale lengths, as well as scaling factor for mean winds. Minimum and maximum dust tau values for seasonal variation in dust optical depth (input *Dusttau* = 0) can be input. New slope wind model (based on Ye, Segal, and Pielke, 1990) computes MOLA slope effects on winds from 0 - 4.5 km above the surface (day) or 0 - 2.5 km (night). Slope winds can also be scaled with an input factor (with 0 factor to suppress slope wind output). Option for traveling component of longitude-dependent waves 1 - 3 now included.
Mars-GRAM 2005 (beta ver 0)	12/2003	Added vertical component for slope winds, also scaled with slope wind factor. Vertical slope winds are computed from terrain slope times total horizontal wind (mean horizontal wind plus horizontal slope wind). Vertical slope winds are computed over height range 0 - 4.5km above the surface (day) or 0 - 2.5 km (night), and are added to vertical perturbed winds, with the combined vertical wind output as "VertWind" in the LIST file and "VWpert" in the winds.txt file. Modified maximum magnitudes for random density and wind perturbations, using revised wave saturation condition. Total variance at aerobraking altitudes now accounted for only by combination of variance from small-scale random perturbations plus stationary or travelling long waves. Added species concentration output. Dispensed with fairing between MTGCM and Stewart models above 155 km, in favor of adjustment of the Stewart model to agree with MTGCM values at the top of the altitude range for which they are available. Adjustment to the Stewart model continues upward from the last available MTGCM level to all higher altitudes.
Mars-GRAM 2005 (D.P. beta ver 1)		At request of GN&C customers concerned about interface with double-precision trajectory codes, converted all calculations to double precision. Added new MGCM and MTGCM data sets for TES mapping years 1 and 2 and new subroutines in file TESsubs.f. Option to use previous (Mars-GRAM 2001 MGCM and MTGCM) data or new TES mapping year 1 and 2 data is controlled by new input option MapYear (= 0 to use previous data). New data sets were produced from MGCM and MTGCM models using TES-observed global distributions of dust optical depth. These used new techniques for better matchup of MGCM and MTGCM data near 80 km. Required height offsets for best MGCM/MTGCM matchup are now much smaller (although not zero). Added output of height offset values on LIST.txt and Density.txt files. Added option to substitute auxiliary input profile of thermodynamic and/or wind data for MGCM/MTGCM climatology, within user-specified region. Use of this option controlled by (optional) input profile file name and parameters *profnear* and *proffar*. For TES mapping year > 0, switch-over from MTGCM to Stewart thermosphere values extending upward to 240 km. Converted to option for long file names for LIST, OUTPUT, TRAJECTORY files, etc. (up to character*60). Added option to suppress daily max/min data calculations, to increase run speed. 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 '_M05' was appended to all these names. No suffix was appended in

Version	Date	Comments
		source code for auxiliary programs (e.g. marsrad.f). Modified routine to automatically generate random seed numbers.
Mars-GRAM 2005 (D.P. ver 1)		Replaced bogus Map Year 2 MTGCM data (replicated Year 1 data) with correct Year 2 MTGCM data. Deleted unused variable maxfiles from Common DATACOM. Fixed problem with perturbation correlation terms RHOd, RHOu, and RHOv in wrapper routine. Simplified input/output of variables in wrapper routine. Corrected problem with water vapor concentrations at high near-surface temperatures. Corrected problem with dust mass density if LOGSCALE = 3. Added option to interpret input height values > 3000 km as planeto-centric radius (in km). Corrected comments in topoareo subroutine and README files to correctly indicate original MOLA data is in IAU 1991 (not IAU 1997) rotation coordinates [This is a correction in comments only; topoareo code is not affected].
Mars-GRAM 2005 (Ver 1.1)	10/2005	Patch to fix problem of unnecessary calls to random number generator when perturbation updates are not being done. Revisions to subroutine ProfTerp to allow dual-valued auxiliary profiles (e.g. inbound and outbound legs of an aerocapture trajectory). Add transmittance output to MarsRad program; make heatrate option user-input controlled.
Mars-GRAM 2005 (Ver 1.2 Sep 06)	9/2006	Changed 3-D and 4-D interpolation/extrapolation routines to work in logarithmic scale for density and pressure (still linear scale for temperature and winds). Logarithmic extrapolation for dust optical depth is important, because of certain high-altitude cases where MGCM data are so sensitive to dust loading that linear extrapolation to optical depths as low as 0.1 (from data at tau = 0.3 and 1.0) can yield negative density or pressure. Added "Save" commands insure necessary variables are treated as "static", for compilers which do not default to this option. Other changes (which have no effect on output): (1) insure a default value is assigned to input parameter blwinfac, and (2) delete unnecessary reassignment of various perturbation scale parameters.
Mars-GRAM 2005 (Ver 1.2 Dec 06)	12/2006	Patch to correct Densmax and P1max interpolation error for case when idaydata = 0.
Mars-GRAM 2005 (Ver 1.2 Feb 07)	2/2007	Patch to correct for missing rwscale effect on part of SIGW from near-surface altitudes.
Mars-GRAM 2005 (Ver 1.2 Jul 07)	7/2007	Patch to add effect of wave perturbations to auxiliary profile pressure and density input data, and correct effect of wave perturbations on Stewart thermosphere output.
Mars-GRAM 2005 (Ver 1.3 Sep 09)	9/2009	Patch to adjust input values of MGCM Map Year 0 pressure and density for dust optical depths 0.3, 1.0, and 3, to achieve better match with Map Years 1 and 2 MGCM output at comparable dust loading. Patch to allow L_s-dependent dust storms to start as early as L_s = 120.

Version	Date	Comments
Mars-GRAM 2010 (Ver 1.0 Beta Sep 2010)	9/2010	Fortran 90 Mars-GRAM version. Uses more standard PC binary form input data files. Applies empirical adjustment factors to MGCM and MTGCM input data, to achieve better comparison with TES Limb data in the 0 - 60 km height range, and MRO and Odyssey aerobraking data above about 95 km. Adjustment factors depend on L_s, latitude, and altitude. Most significant adjustments are for large dust optical depths (> 1.0). NAMELIST input files must now have identifier $INPUT_M10 in 1st line, instead of $INPUT.
Mars-GRAM 2010 (Ver 1.0 Nov 10)	11/2010	Revised empirical adjustment factors for MTGCM data, derived by comparison with MGS, Odyssey, and MRO aerobraking observations. Forces agreement between (revised) Map Year 0 MGCM at 80 km and (revised) Map Year 0 MTGCM at 80 km. Revised standard deviations of the perturbation model, based on comparisons with MGS, ODY, and MRO aerobraking observations. Eliminated parameter *STDL* from the NAMELIST input (*STDL* is now superseded by the revised perturbation standard deviations).
Mars-GRAM 2021	9/2021	The ephemeris engine has been replaced with the NAIF SPICE library. Code has been converted to a C++ framework. LIST and OUTPUT file formats have been updated. Input parameter names have been updated to be more descriptive. Planetary constants have been updated. Mars-GRAM now computes speed of sound based on a thermodynamic parameterization using density, pressure, and γ, the ratio of specific heats, for a given constituent gas mixture. Mars-GRAM previously used a constant γ, which is physically unrealistic and overestimates the speed of sound by as much as 10%. Mars-GRAM now uses an improved methodology for computing γ, involving temperature and pressure dependent tables of C_V and C_P evaluated in run-time for the current constituent combination.

REFERENCES

1. Haberle, R.M.; Pollack, J.B.; Barnes, J.R.; et al.: "Mars Atmospheric Dynamics as Simulated by the NASA Ames General Circulation Model 1. The Zonal-Mean Circulation," *Journal of Geophysical Research*, Vol. 98, No. E2, pp. 3093–3123, 1993.

2. Barnes, J.R.; Pollack, J.B.; Haberle, R.M.; et al.: "Mars Atmospheric Dynamics as Simulated by the NASA Ames General Circulation Model 2. Transient Baroclinic Eddies," *Journal of Geophysical Research*, Vol. 98, No. E2, pp. 3125–3148, 1993.

3. Bougher, S.W.; Roble, R.G.; Ridley, E.C.; et al.: "The Mars Thermosphere: 2. General Circulation with Coupled Dynamics and Composition," *Journal of Geophysical Research*, Vol. 95, No. B9, pp. 14811–14827, 1990.

4. Bougher, S.W.; Engel, S.; Roble, R.G.; and Foster, B.: "Comparative Terrestrial Planet Thermospheres. 2. Solar Cycle Variation of Global Structure and Winds at Equinox," *Journal of Geophysical Research*, Vol. 104, No. E7, pp. 16,591–16,611, 1999.

5. Lyons, D.T.; Beerer, J.G.; Esposito, P.; and Johnson, M.D.: "Mars Global Surveyor: Aerobraking Overview," *Journal of Spacecraft and Rockets*, Vol. 36, No. 3, pp. 307–313, 1999.

6. Gnoffo, P.A.; Braun, R.D.; Weilmuenster, K.J.; et al.: "Prediction and Validation of Mars Pathfinder Hypersonic Aerodynamic Database," *Journal of Spacecraft and Rockets,* Vol. 36, No. 3, pp. 367–373, 1999.

7. Queen, E.M.; Cheatwood, F.M.; Powell, R.W.; and Braun, R.D.: "Mars Polar Lander Aerothermodynamic and Entry Dispersion Analysis," *Journal of Spacecraft and Rockets*, Vol. 36, No. 3, pp. 421–428, 1999.

8. Wright, H.S.; Oh, D.Y.; Westhelle, C.H.; Fisher, J.L.; Dyke, R.E.; Edquist, K.T.; Brown, J.L.; Justh, H.L.; Munk, M.M.: "Mars Aerocapture Systems Study," NASA/TM-2006-214522, Marshall Space Flight Center, AL, November 2006.

9. Justh, H.L.; and Justus, C.G.: "Global Reference Atmospheric Models (GRAMs) and Aerocapture," *Aerocapture Technology Expo*, September 7, 2006.

10. Justus C.G.; Duvall, A.; and Keller, V.W.: "Mars Aerocapture and Validation of Mars-GRAM with TES Data," *53rd Joint Army-Navy-NASA-Air Force (JANNAF) Propulsion Meeting*, December 5–8, 2005.

11. Smith M.D.: "Interannual Variability in TES Atmosphere Observations of Mars during 1999- 2003," *Icarus*, Vol. 167, pp. 148–165, 2004.

12. Justus, C.G.: "Mars Global Reference Atmospheric Model for Mission Planning and Analysis," *Journal of Spacecraft and Rockets*, Vol. 28, No. 2, pp. 216–221, 1991.

13. Justus, C.G.; James, B.F.; and Johnson, D.L.: "Mars Global Reference Atmospheric Model (Mars-GRAM 3.34): Programmer's Guide," NASA Technical Memorandum 108509, Marshall Space Flight Center, AL, 1996.

14. Justus, C.G.; Johnson, D.L.; and James, B.F.: "A Revised Thermosphere for the Mars Global Reference Atmospheric Model (Mars-GRAM Version 3.4)," NASA Technical Memorandum 108513, Marshall Space Flight Center, AL, 1996.

15. Justus, C.G.; James, B.F.; and Johnson, D.L.: "Recent and Planned Improvements in the Mars Global Reference Atmospheric Model (Mars-GRAM)," *Advances in Space Research*, Vol. 19, No. 8, pp. 1223–1231, 1997.

16. Justus, C.G.; and James, B.F.: "Mars Global Reference Atmospheric Model (Mars-GRAM) Version 3.8: Users Guide," NASA/TM—1999–209629, Marshall Space Flight Center, May 1999.

17. Justus, C.G.; and James, B.F.: "Mars Global Reference Atmospheric Model 2000 Version (Mars-GRAM 2000): Users Guide," NASA/TM—2000–210279, Marshall Space Flight Center, March 2000.

18. Justus, C.G.; and Johnson, D.L.: "Mars Global Reference Atmospheric Model 2001 Version (Mars-GRAM 2001): Users Guide," NASA/TM-2001-210961, Marshall Space Flight Center, April 2001.

19. Justh, H.L.: "Mars Global Reference Atmospheric Model 2010 Version: Users Guide," NASA/TM-2014-217499, Marshall Space Flight Center, February 2014.

20. Burns, L.: "Methodology for Creating Thermodynamic Tables for Application to Computation of Speed of Sound by the Global Reference Atmospheric Model (GRAM) Suite," JPID-FY21-001252, August 2021.

21. Smith, D.E.; and Zuber, M.T.: "The Relationship Between MOLA Northern Hemisphere Topography and the 6.1-mbar Atmospheric Pressure Surface of Mars." *Geophysical Research Letters*, Vol. 25, No. 24, pp. 4397–4400, 1998.

22. Zuber, M.T.; Smith, D.E.; Phillips, R.J.; et al.: "Shape of the Northern Hemisphere of Mars from the Mars Orbiter Laser Altimeter," *Geophysical Research Letters*, Vol. 25, No. 24, pp. 4393–4396, 1998.

23. Smith, D.E.; Zuber, M.T.; Solomon, S.C.; et al.: "The Global Topography of Mars and Implications for Surface Evolution," *Science*, Vol. 284, pp. 1495–1503, 1999.

24. Haberle, R.M.; Joshi, M.M.; Murphy, J.R.; et al.: "General Circulation Model Simulations of the Mars Pathfinder Atmospheric Structure Investigation/Meteorology Data," *Journal of Geophysical Research,* Vol. 104, No. E4, pp. 8957–8974, 1999.

25. Haberle, R.M.; Hourbin, H.C.; Hertenstein, R.; and Herdtle, T.: "A Boundary-layer Model for Mars: Comparisons with Viking Lander and Entry Data," *Journal of Atmospheric Sciences,* Vol. 50, No. 11, pp. 1544–1559, 1993.

26. Keating, G.M.; et al.: "The Structure of the Upper Atmosphere of Mars: In Situ Accelerometer Measurements from Mars Global Surveyor," *Science*, Vol. 279, No. 5357, pp. 1672–1676, 1998.

27. Bridger, A.F.C.: "Stationary Wave Activity Simulated by the NASA Ames MGCM Incorporating New MOLA Topography Data," *Fifth International Conference on Mars*, Pasadena, CA, July 18–23, 1999.

28. Bougher, S.; Keating, G.; Zurek, R.; et al.: "Mars Global Surveyor Aerobraking: Atmospheric Trends and Model Interpretation," *Advanced Space Research*, Vol. 23, No. 11, pp. 1887–1897, 1999.

29. Joshi, M.M.; Hollingsworth, J.L.; Haberle, R.M.; and Bridger, A.F.C.: "An Interpretation of Martian Thermospheric Waves Based on Analysis of a General Circulation Model," *Geophysical Research Letters,* Vol. 27, No. 5, pp. 613–616, 2000.

30. Haberle, R.M.; Leovy, C.B.; and Pollack, J.B.: "Some Effects of Global Dust Storms on the Atmospheric Circulation of Mars," *Icarus*, Vol. 50, pp. 322–367, 1982.

31. Kieffer, H.H.; Martin, T.Z.; Peterfreund, A.R.; et al.: "Thermal and Albedo Mapping of Mars During the Viking Primary Mission," *Journal of Geophysical Research*, Vol. 82, No. 28, pp. 4249–4281, 1977.

32. Paige, D.A.; Bachman, J.E.; and Keegan, K.D.: "Thermal and Albedo Mapping of the Polar Regions of Mars Using Viking Thermal Mapper Observations," *Journal of Geophysical Research,* Vol. 99, No. E12, pp. 25959–25991, 1994.

33. Ye, Z.J.; Segal, M.; and Pielke, R.A.: "A comparative study of daytime thermally induced upslope flow on Mars and Earth," *Journal of the Atmospheric Sciences,* Vol. 47, No. 5, pp. 612–628, 1990.

34. Justh, H.L.; Justus, C.G.; and Ramey, H.S.: "Mars-GRAM 2010: Improving the Precision of Mars-GRAM," *Fourth International Workshop on the Mars Atmosphere: Modeling and Observations*, Paris, France, February 8–11, 2011.

35. Pitts, D.E., Tillman; J.E.; Johnson, N.C.; et al.: "The Mars Atmosphere: Observations and Model Profiles for Mars Missions," NASA JSC-24455, NASA Johnson Space Center, TX, 1991.

36. Savijarvi, H.: "Radiative Fluxes on a Dustfree Mars," *Contributions to Atmospheric Physics*, Vol. 64, No. 2, pp. 103–112, 1991.

37. Staley, D.O.; and Jurica, G.M.: "Flux Emissivity Tables for Water Vapor, Carbon Dioxide and Ozone," *Journal of Applied Meteorology*, Vol. 9, pp. 365–372, 1970.

38. Joseph, J.H.; Wiscombe, W.J.; and Weinman, J.A.: "The Delta-Eddington Approximation for Radiative Flux Transfer," *Journal of Atmospheric Sciences*, Vol. 33, No. 12, pp. 2452–2459, 1976.

39. Murphy, J.R. et al., *Journal of Geophysical Research*, Vol. 98, No. E2, pp. 3197–3220, February 25, 1993.