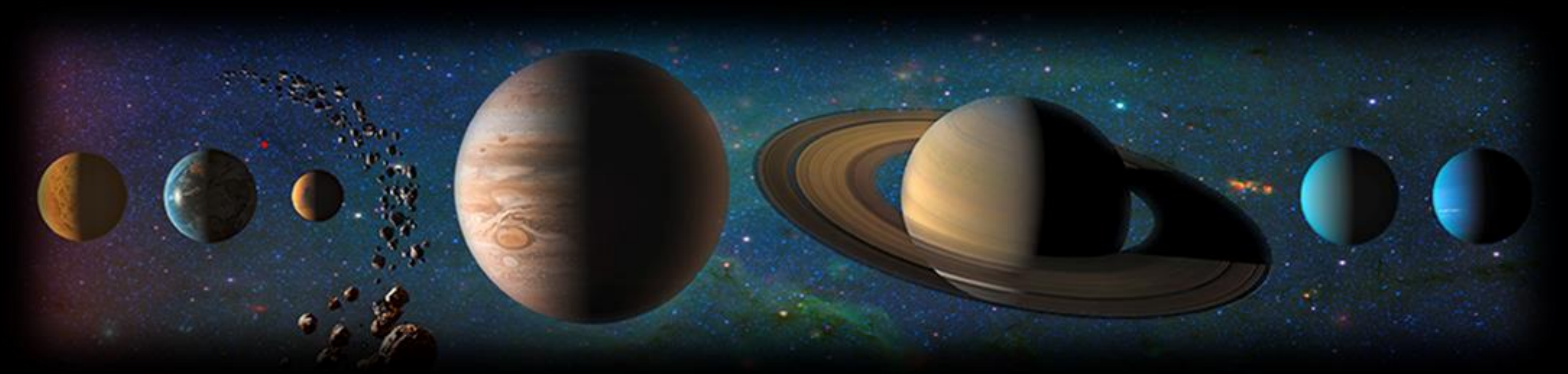
Global Reference Atmospheric Model (GRAM)



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Outline

- GRAM Overview
- Model Data Input and Features of the GRAMs
- GRAM Upgrades
- Upgraded and New GRAM Releases

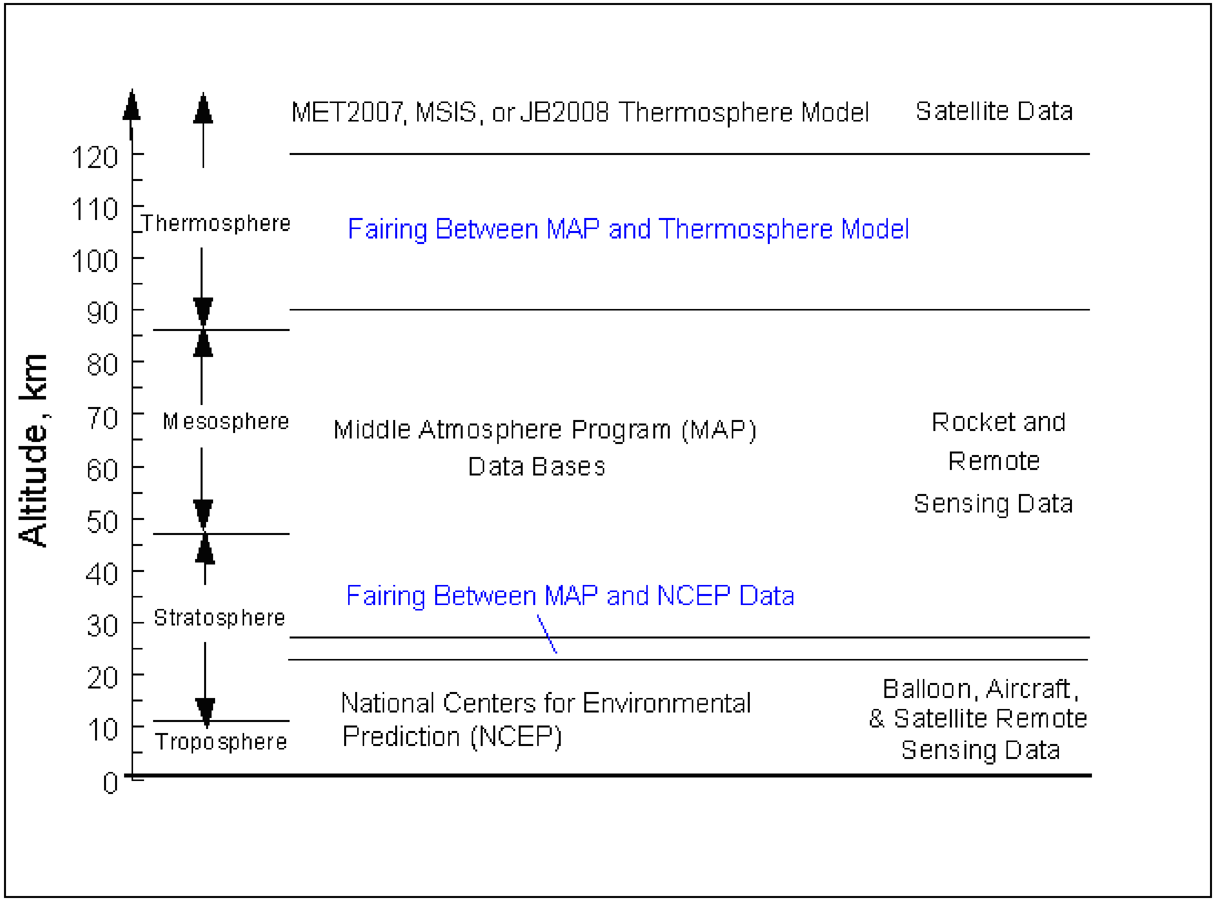
GRAM Overview

- Engineering-oriented atmospheric models that estimate mean values and statistical variations of atmospheric properties for numerous planetary destinations
- Currently available for Earth, Mars, Venus, Titan, and Neptune
- Outputs include atmospheric density, temperature, pressure, chemical composition, radiative fluxes (for Mars-GRAM), and wind components along a user-defined path
  - Includes seasonal, geographic, and altitude variations
- Widely used by the engineering community because of their ability to create realistic atmospheric dispersions
- Can be integrated into high fidelity flight dynamic simulations of launch, entry, descent and landing (EDL), aerobraking and aerocapture

GRAM Overview (Continued)

- Optional trajectory input file consisting of time, height, latitude, and longitude can be used to provide the GRAM trajectory path
- Optional auxiliary profile consisting of height, latitude, longitude, temperature, pressure, density, eastward wind, and northward wind may be used to replace model data in the GRAMs
- Not a forecast model
- Available through the NASA Software Catalog https://software.nasa.gov/

Earth-GRAM Model Data Input



Range Reference Atmosphere (RRA) Option

Auxiliary Profile Input Option

Earth-GRAM Features

- Range Reference Atmosphere (RRA) site specific databases
  - Includes 1983, 2006, and 2013 RRA databases
  - 15 2013 RRA sites developed by MSFC/Natural Environments Branch for the Range Commanders Council – Meteorology Group
  - Climatology built from balloon and rocketsonde measurements for 1983 and 2006 and only balloon measurements for 2013 RRA databases
  - MSFC/Natural Environments Branch recommends use of 2013 RRA database
- Earth-GRAM 2016 Version 2.0 Upgrades:
  - C++ object-oriented code (not in GRAM Suite format)
  - CorrMonte – produces hourly dispersions
  - CorrTraj – produces correlated Ballistic (Up-Down) Atmospheric Profile
  - Includes vertical fairing between 2013 RRA database and the standard Earth-GRAM stratospheric climatology/MAP database

Mars-GRAM Model Data Input

- From surface to 80 km altitude Mars-GRAM is based on NASA Ames Mars General Circulation Model (MGCM) data
- From 80 to 170 km (MapYear = 0) or 240 km (MapYear = 1 and 2) Mars-GRAM is based on University of Michigan Mars Thermospheric General Circulation Model (MTGCM) data
  - Above this point Stewart thermosphere model data is used
- Surface topography from MGS Mars Orbiter Laser Altimeter (MOLA) altitudes referenced to the MOLA constant potential surface (areoid)
- Options for representing the mean atmosphere:
  - MapYear =0, user-controlled dust optical depth and data interpolated from MGCM and MTGCM results driven by selected values of globally-uniform dust optical depth
  - MapYear = 1 and 2, data from MGCM and MTGCM results driven by observed TES dust optical depth during TES year 1 and 2

Mars-GRAM Features

- Input parameters allow standard deviations of Mars-GRAM perturbations to be adjusted:
  - rpscale scales density perturbations up or down
  - rwscale scales wind perturbations
  - wlscale adjusts the wavelengths (spectral range) of the perturbations
- Mars Dust Storm Modeling
  - Can adjust the optical depth of the uniformly mixed background dust level
  - Can add a seasonal dust optical depth
  - Can set the dust particle diameter and density
  - Can provide the starting areocentric longitude of the Sun (Ls), position, duration, intensity, and radius of a dust storm

Venus-GRAM Model Data Input

- Input atmospheric data files are from the Venus International Reference Atmosphere (VIRA)
- Lower atmosphere: 0 -100 km
  - VIRA data depend on height and latitude
- Middle-atmosphere: 100 -150 km
  - VIRA data depend on height and local solar time (LST = 0 or LST = 12 Venus hours)
- Upper-altitude: 150 - 250 km
  - VIRA data depend on height and solar zenith angle
- Insures smooth variation between height regions by averaging values at the two transition heights (100 km and 150 km)

Venus-GRAM Model Data Input (Continued)

- Venus-GRAM thermosphere has been extended to an altitude of 1000 km, by a model based on the following assumptions:
  - VIRA conditions and constituents at 250 km are used as lower boundary values
  - Constant (exospheric) temperature is assumed above 250 km (exospheric temperature = local VIRA temperature at 250 km)
  - Hydrostatic conditions are computed separately for each constituent (diffusive separation)
  - Total pressure is computed from constituent partial pressures
  - Mass density is computed from constituent number densities

Titan-GRAM Model Data Input – Voyager Observations

- ModelType = 1, atmospheric density, temperature, and pressure are characterized by Yelle et al.[1] engineering model profiles based on observations from Voyager radio science, Infrared Interferometer Spectrometer and Radiometer (IRIS), and the Ultraviolet Spectrometer (UVS)
  - Data consist of the average, minimum, and maximum profiles of: total number density, number densities for nitrogen, methane, and argon, mass density, air pressure, air temperature, and a correction factor for the perfect gas law equation
  - Data have been extended from 1,300 km to 2,200 km altitude by utilizing a simple thermosphere model that includes diffusive separation
  - A small amount of argon has been added to the minimum case profile to avoid problems caused by assuming zero argon
  - Includes a basic zonal wind model including latitude variations and perturbations

Titan-GRAM Model Data Input – Titan GCM

- ModelType = 2, Titan GCM data used as input data
- Lower altitude GCM data is from Hourdin et al.[2]
  - Data consist of daily mean temperature and zonal wind for 31 pressure levels from 1,465 mbar to 0.3 mbar at 10° latitude intervals from –90° to 90° at Ls = 0 and Ls = 270
  - Estimates for other seasons are generated by 180° Ls offset and hemispheric reversal
- Upper altitude Titan GCM data is computed using a parameterized fit to Titan exospheric temperatures taken from Mueller-Wodarg et al.[3]
- Nitrogen compressibility factor is accounted for when using the lower altitude GCM data
  - Data for the nitrogen compressibility factors are from J. Hilsenrath et al.[4]

Titan-GRAM Features

- Includes Huygens Atmospheric Structure Instrument (HASI)/Doppler Wind Experiment (DWE) and Cassini Composite Infrared Spectrometer (CIRS) auxiliary profiles produced by a Titan-GRAM Comparison Study by Justh and Justus[5]
- These auxiliary profiles allow Titan-GRAM to better replicate the HASI/DWE and CIRS observational data

Neptune-GRAM Model Data Input

- Atmospheric input data is based on observations from Voyager radio science, Infrared Interferometer Spectrometer and Radiometer (IRIS), and the Ultraviolet Spectrometer (UVS) provided in figures from *Neptune and Triton*[6]
  - Data consist of profiles of average, minimum, and maximum temperature values
  - Additional thermodynamic values have been derived from the data using hydrostatics and the ideal gas law
  - Data have been extended in altitude by utilizing a simple thermospheric model that includes diffusive separation
  - Includes a basic zonal wind model including latitude variations and perturbations

Titan-GRAM and Neptune-GRAM Features

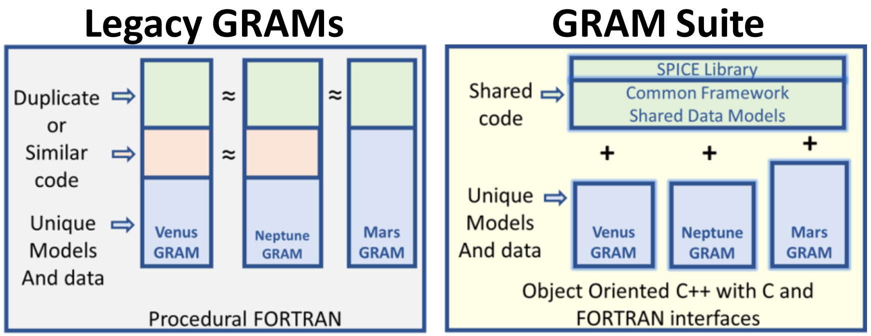
- Titan-GRAM Model Type =1 and Neptune-GRAM do not explicitly compute time-dependent or latitude-dependent atmospheric values of density, temperature, and pressure
- Contain minimum-to-maximum envelope of data containing variations of the mean with respect to latitude, season, and time
- Selecting a value for the input parameter MinMaxFactor generates a mean profile within the minimum-to-maximum envelope
  - MinMaxFactor determines where, within the envelope of minimum-to-maximum conditions, a given atmospheric profile falls
  - MinMaxFactor is any real number between –1 (minimum) and 1 (maximum) with 0 providing the average Titan profile
  - MinMaxFactor values between –1 and 0 are automatically interpolated between minimum and average conditions
  - MinMaxFactor values between 0 and 1 are automatically interpolated between average and maximum conditions

GRAM Upgrades

- NASA Science Mission Directorate (SMD) has provided funding support to upgrade the GRAMs for Fiscal Year 2018 through 2020
- GRAM Upgrade Primary Objectives:
  - Modernize the code
    - Develop a new framework that transitions the original Fortran code to C++
    - Take advantage of the object-oriented capabilities of C++
  - Upgrade atmosphere models
    - Update the atmosphere models in the existing GRAMs
    - Establish a foundation for developing GRAMs for additional destinations (Saturn, Uranus, and Jupiter)
  - Socialize plans and status to improve communication between users, modelers, and developers

Code Modernization – GRAM Suite

- Developed a common C++ framework that simplifies model updates, integration, testing, and maintenance
- Common framework supports all solar system destination models
- Provides a uniform user interface for all planetary GRAMs
- Includes C++ library with C and Fortran interfaces which can be incorporated in a trajectory (or orbit propagation) code



- Release of the rearchitected existing planetary GRAMs will contain the original atmosphere models; new model updates are being developed as part of future GRAM upgrades

Model Upgrades – GRAM Suite

- GRAM ephemeris has been upgraded to the NASA Navigation and Ancillary Information Facility (NAIF) Spacecraft Planet Instrument C-matrix Events (SPICE) toolkit (version N0066)
- GRAM team has distributed funding in Fiscal Year 2020 for two projects that will improve the atmospheric models in the GRAMs
  - Reanalysis of the Venus Express radio occultation observations
    - Sanjay Limaye and Patrick Fry at the University of Wisconsin
    - Produce number density, temperature, and pressure profiles (40-90 km altitude)
  - Development of empirical global models for Venus, Jupiter, Saturn, Uranus, Neptune, and Titan
    - Kunio Sayanagi, Justin Garland, and Ryan McCabe at Hampton University
    - Ongoing work to develop models that will be used in future GRAM updates
    - Will incorporate latest data available for each destination
    - Working with Ralph Lorenz (JHUAPL) and Jared Bell (GSFC) (Titan model development)

Model Upgrades – GRAM Suite
New Mars Model Data

- Received updated MGCM datasets from ARC
  - Low, average, and high dust cases for 12 Ls values in 30 degree increments from 0 to 360
  - Includes new explicit longitudinal and time-of-sol variability
    - Legacy Mars-GRAM MGCM data based on diurnal and semi-diurnal tidal components
    - Currently determining the best method of implementing longitudinal and time-of-sol variability into Mars-GRAM
- Coordinating with Steve Bougher (University of Michigan) to obtain Mars Global Ionosphere-Thermosphere Model (M-GITM) data that will replace the MTGCM data in legacy Mars-GRAM
- M-GITM and updated MGCM data will be incorporated into a future GRAM Suite release

Model Upgrades – GRAM Suite
Improvements in Speed of Sound Calculations

- GRAMs compute speed of sound based on a thermodynamic parameterization using temperature and γ, the ratio of specific heats for a given constituent gas mixture
- GRAM legacy codes use a constant γ, which is physically unrealistic
  - Analyses have shown this formulation to over-estimate speed of sound by as much as 10%
- GRAM Suite uses an improved methodology for computing γ, involving evaluation of Shomate coefficients in run-time for the current constituent combination
- Future development will replace the Shomate coefficients with high-precision specific heat values derived from detailed quantum-mechanical computations

Model Updates - Earth-GRAM Updates

- Supporting the GRAM common core rearchitecture of Earth-GRAM into the GRAM Suite format
- Implementing 2019 RRA database in Earth-GRAM
- Completed comparison study of Earth-GRAM 2016 Version 2.0 data to Modern-Era Retrospective Analysis for Research and Applications, Version 2 (MERRA-2) data
  - MERRA-2 shows good comparison to Earth-GRAM Version 2.0 data sources
  - MERRA-2 appears to be a good data upgrade option to replace NCEP and MAP in Earth-GRAM
- Currently implementing MERRA-2 data into Earth-GRAM

Upgraded GRAM Releases

- GRAM Suite Version 1.0 (Released May 2020) includes:
  - Rearchitected Neptune-GRAM (common GRAM framework and planet–specific code)
  - Makefile and Visual Studio solutions for building the GRAM Suite
  - Neptune-GRAM User Guide (NASA/TM–20205001193)
  - GRAM Programmer's Manual
  - Examples and tests for successful implementation of Neptune-GRAM
- GRAM Suite Version 1.1 (Released September 2020) added:
  - Rearchitected Titan-GRAM (common GRAM framework and planet–specific code)
  - Titan-GRAM User Guide
  - Examples and tests for successful implementation of Titan-GRAM
- Rearchitected Mars, Venus, and Earth-GRAM will be released in future versions of the GRAM Suite

New GRAM Releases

- Uranus-GRAM
  - Based on an individual profile generated by Gary Allen (ARC) from Voyager 2 occultation data
- Jupiter-GRAM
  - Based on individual profile produced from Seiff et al.[7] model
- Saturn-GRAM
  - Based on data from Koskinen and Guerlet[8]
- Uranus, Jupiter, and Saturn-GRAM will be released in future versions of the GRAM Suite

Summary

- GRAMs are a critical tool set that influences mission selection and decisions
- Upgrades of the existing GRAMs and development of new GRAMs are ongoing
  - GRAM Suite Version 1.1 has been released and is available via the NASA Software Catalog https://software.nasa.gov/
  - Future versions of the GRAM Suite will contain the rearchitected and new GRAMs
  - Contact us if you are interested in being a beta tester
- NASA SMD funding has been essential to addressing current limitations and accomplishing GRAM developmental goals

References

1. Yelle, R.V.; Strobell, D.F.; Lellouch, E.; and Gautier, D.: “Engineering Models for Titan’s Atmosphere,” in *Huygens: Science, Payload and Mission*, ESA SP-1177, August 1997.
2. Hourdin, F.; Talagrand, O.; Sadourny, R.; et al.: “Numerical Simulation of the General Circulation of the Atmosphere of Titan,” *Icarus*, Vol. 117, Issue 2, pp. 358–374, doi:10.1006/icar.1995.1162, October 1995.
3. Mueller-Wodarg, I.C.F.: “The Application of General Circulation Models to the Atmospheres of Terrestrial-Type Moons of the Giant Planets,” in *Geophysical Monograph Series*, “Atmospheres in the Solar System,” M. Mendillo, A. Nagy, and J.H. Waite (eds.), American Geophysical Union, January 2002.
4. Hilsenrath, J.: *Tables of Thermodynamic and Transport Properties of Air, Argon, Carbon Dioxide, Carbon Monoxide, Hydrogen, Nitrogen, Oxygen, and Steam*, National Bureau of Standards, Pergamon Press, New York, 478 pp., 1960.
5. Justh, H.L. and Justus, C.G.: “Comparisons of Huygens Entry Data and Titan Remote Sensing Observations with the Titan Global Reference Atmospheric Model (Titan-GRAM),” unpublished data, November 2007.
6. Cruikshank, D.P.: *Neptune and Triton*, University of Arizona Press, Tucson, AZ, 1995.
7. Seiff, A., et al.: “Thermal structure of Jupiter's atmosphere near the edge of a 5-µm hot spot in the north equatorial belt,” *Journal of Geophysical Research*, Vol. 103, No. E10, pp. 22,857-22,889, 1998.
8. Koskinen, T.T. and Guerlet, S.: “Atmospheric structure and helium abundance on Saturn from Cassini/UVIS and CIRS observations,” *Icarus*, Vol. 307, pp. 161-171, June 2018.