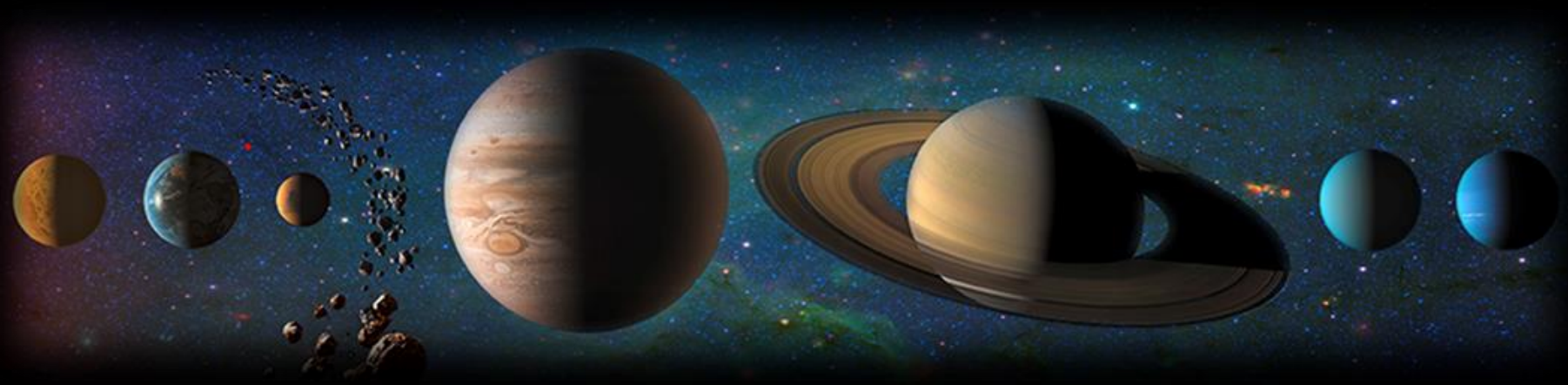
Global Reference Atmospheric Model (GRAM) Suite Overview and Current Status



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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, Neptune, Uranus, and Jupiter
- Outputs include atmospheric density, temperature, pressure, chemical composition, radiative fluxes (for Mars-GRAM), and wind components along a user-defined path
  - Includes seasonal, diurnal, 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)

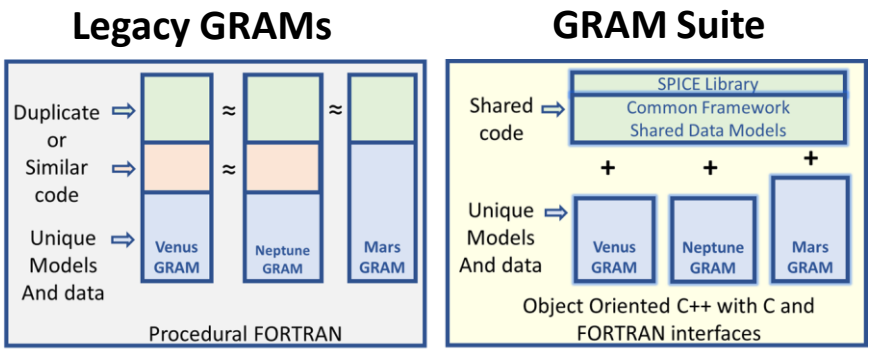
- Optional trajectory input file consisting of time, height, latitude, and longitude can be used to provide the GRAM trajectory path
- Optional auxiliary profile consisting of height, latitude, longitude, temperature, pressure, density, eastward wind, and northward wind may be used to replace model data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

GRAM Upgrades

- NASA Science Mission Directorate (SMD) has provided funding support to upgrade the GRAMs since Fiscal Year 2018
- 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

GRAM Suite

- Common object-oriented C++ framework
- Includes a common GRAM library of data models and utilities
  - Reduces duplicated code
  - Ensures consistent constants across all GRAMs
  - Simplifies bug fixes
  - Streamlines the interface with trajectory codes
- Includes C++ library with C and Fortran interfaces which can be incorporated in a trajectory (or orbit propagation) code



Upgrades contained within the 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) for increased accuracy
  - Requires the GRAM user to download the latest SPICE data before using the GRAM Suite
- Input parameters have been renamed to be more descriptive
  - Legacy input parameter names are still accepted to maintain compatibility with existing NAMELIST input files from prior GRAM versions
- Output files have been reformatted
  - Comma separated value file
    - Consolidates the column formatted output files from the legacy GRAMs into a single file that can easily be loaded into data centric programs
  - LIST file
    - Can be read using a American Standard Code for Information Interchange (ASCII) reader or a Markdown syntax for enhanced rendering in a web browser

GRAM Suite Improvements in Speed of Sound Calculations

- GRAMs compute 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
  - C_v is the specific heat capacity of a gaseous mixture for isochoric processes
- 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 includes 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

GRAM Suite 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 (NASA/TM–20205006805)
  - Examples and tests for successful implementation of Titan-GRAM

GRAM Suite Releases

- GRAM Suite Version 1.2 (Released July 2021) added:
  - New Uranus-GRAM (common GRAM framework and planet–specific code)
    - Uranus-GRAM atmospheric data is from the NASA Ames Research Center (ARC) Uranus Atmospheric Model[1,2]
    - Based on Voyager radio science, Infrared Interferometer Spectrometer and Radiometer (IRIS), and Ultraviolet Spectrometer (UVS) data from the Voyager 2 fly-by of Uranus that occurred on January 24, 1986[3,4,5]
    - Includes atmospheric density, pressure, temperature, and chemical composition (helium, hydrogen, and methane)
    - Does not include wind data
  - Uranus-GRAM User Guide (NASA/TM -20210017250)
  - Examples and tests for successful implementation of Uranus-GRAM

Upgraded GRAM Releases

- GRAM Suite Version 1.3 (Released October 2021) added:
  - New Jupiter-GRAM (common GRAM framework and planet-specific code)
    - Based on Galileo probe Atmospheric Structure Instrument (ASI) data from Seiff et al.[6]
    - Includes atmospheric density, pressure, and temperature
    - Does not include chemical composition or winds
  - Rearchitected Venus-GRAM (common GRAM framework and planet-specific code)
  - Jupiter-GRAM User Guide (NASA/TM-20210022058)
  - Venus-GRAM User Guide (NASA/TM-20210022168)
  - Examples and tests for successful implementation of Jupiter-GRAM and Venus-GRAM

Upgraded GRAM Releases

- GRAM Suite Version 1.4 (Released November 2021) added:
  - Rearchitected and Updated Earth-GRAM (common GRAM framework and planet-specific code)
    - Addition of the 2019 Range Reference Atmosphere database
    - Able to produce correlated atmospheric dispersions from a ballistic (up-down) trajectory
    - Able to correlate atmospheric dispersions originating from multiple atmosphere objects
  - Rearchitected Mars-GRAM (common GRAM framework and planet-specific code)
  - Updated Earth-GRAM User Guide (NASA/TM-20210022157)
  - Updated Mars-GRAM User Guide (NASA/TM-20210023957)
  - Examples and tests for successful implementation of Earth-GRAM and Mars-GRAM

GRAM Upgrade Team Funded Projects

- The GRAM project has established several ongoing contracts to improve atmospheric data in the GRAMs
- Beginning Fiscal Year 2020
  - University of Wisconsin - Sanjay Limaye and Patrick Fry
    - Reanalysis of the Venus Express radio occultation observations
      - Calculating number density, temperature, and pressure profiles (40-90 km altitude)
    - Analysis of Akatsuki thermal imaging data
      - Calculating temperature values at the limb altitudes as a function of solar time
  - Hampton University - Kunio Sayanagi, Justin Garland, and Ryan McCabe
    - Developing global models for Venus, Jupiter, Saturn, Uranus, Neptune, and Titan
- Beginning Fiscal Year 2022
  - Johns Hopkins University Applied Physics Laboratory – Ralph Lorenz
    - Develop Dragonfly atmospheric profile for use in Titan-GRAM upgrade

Fiscal Year 2022 GRAM Suite Upgrade Activities

- Established GRAM Working Groups
  - Focused on discussing potential GRAM upgrades and developing a forward plan
  - Venus-GRAM and Titan-GRAM Working Groups meet once a month
  - Mars-GRAM Working Group will be starting soon
- Earth-GRAM Upgrades to be released by end of FY2022
  - Implement Modern-Era Retrospective analysis for Research and Applications, version 2 (MERRA-2) data
  - Update Earth-GRAM User Guide
- Venus-GRAM Upgrades - Currently Under Discussion
  - Incorporate Magellan datasets to improve thermospheric datasets
  - Improve zonal, meridional, and vertical winds

Summary

- GRAMs are frequently used toolsets and vital in assessing effects of atmospheres on interplanetary spacecraft during the program life cycle process
- Upgrades of the existing GRAMs and development of new GRAMs are continuing
  - Venus-GRAM and Titan-GRAM Working Groups have been established
  - Upgraded Earth-GRAM to be released by end of Fiscal Year 2022
  - Saturn-GRAM currently under initial stages of development
  - Ongoing discussions with modeling groups within NASA and academia regarding status of their models
  - Ongoing discussions with planetary mission teams (VERITAS, DAVINCI, Dragonfly, MAVEN, etc.) to determine potential mission support by the GRAM team, utilization of collected atmospheric data, and needed GRAM upgrades

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