GLOBAL REFERENCE ATMOSPHERIC MODELS, INCLUDING THERMOSPHERES, FOR MARS, VENUS AND EARTH

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ABSTRACT

Marshall Space Flight Center's Natural Environments Branch has developed Global Reference Atmospheric Models (GRAMs) for Mars, Venus, Earth, and other solar system destinations. Mars-GRAM has been widely used for engineering applications including systems design, performance analysis, and operations planning for aerobraking, entry descent and landing, and aerocapture. Preliminary results are presented, comparing Mars-GRAM with measurements from Mars Reconnaissance Orbiter during its aerobraking in Mars' thermosphere. Venus-GRAM is based on the COSPAR Venus International Reference Atmosphere (VIRA), and is suitable for similar engineering applications in the thermosphere or other altitude regions of the atmosphere of Venus. Until recently, the thermosphere in Earth-GRAM has been represented by the Marshall Engineering Thermosphere (MET) model. Earth-GRAM has recently been revised. In addition to including an updated version of MET, it now includes an option to use the Naval Research Laboratory Mass Spectrometer Incoherent Scatter Radar Extended Model (NRLMSISE-00) as an alternate thermospheric model. Some characteristics and results from Venus-GRAM and Earth-GRAM thermospheres are also presented.

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Marshall Space Flight Center's Natural Environments Branch has developed Global Reference Atmospheric Models (GRAMs) for Mars, Venus, Earth, and other solar system destinations. Mars-GRAM has been widely used for engineering applications including systems design, performance analysis, and operations planning for aerobraking, entry descent and landing, and aerocapture. Preliminary results are presented, comparing Mars-GRAM with measurements from Mars Reconnaissance Orbiter (MRO) during its aerobraking in Mars' thermosphere. Venus-GRAM is based on the Committee on Space Research (COSPAR) Venus International Reference Atmosphere (VIRA), and is suitable for similar engineering applications in the thermosphere or other altitude regions of the atmosphere of Venus. Until recently, the thermosphere in Earth-GRAM has been represented by the Marshall Engineering Thermosphere (MET) model. Earth-GRAM has recently been revised. In addition to including an updated version of MET, it now includes an option to use the Naval Research Laboratory Mass Spectrometer Incoherent Scatter Radar Extended Model (NRLMSISE-00) as an alternate thermospheric model. Some characteristics and results from Venus-GRAM and Earth-GRAM thermospheres are also presented.

I. Introduction

M arshall Space Flight Center's Natural Environments Branch has developed Global Reference Atmospheric Models (GRAMs) for Mars, Venus, Earth, and other Solar system destinations[1-4]. Mars-GRAM has been widely used for engineering applications including systems design, performance analysis, and operations planning for aerobraking, entry descent and landing, and aerocapture. The thermosphere section of Mars-GRAM is based on output data sets from the University of Michigan Mars Thermospheric General Circulation Model (MTGCM)[5]. Venus-GRAM is based on the Committee on Space Research (COSPAR) Venus International Reference Atmosphere (VIRA)[6], and is suitable for similar engineering applications in the thermosphere or other altitude regions of the atmosphere of Venus. For Venus-GRAM, the thermospheric section has been extended to higher altitudes by using a simple constant-temperature, diffusive separation model. Until recently, the thermosphere in Earth-GRAM has been represented by the Marshall Engineering Thermosphere (MET) model[4]. Earth-GRAM has recently been revised. In addition to including an updated version of MET, it now includes an option to use the Naval Research Laboratory Mass Spectrometer Incoherent Scatter (MSIS) Radar Extended Model (NRLMSISE-00)[7] as an alternate thermospheric model.

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As illustrated by Fig. 1, thermospheric densities for Venus, Earth, and Mars are quite similar, compared to thermospheric densities for other planets, exemplified by Titan and Neptune profiles in this figure.

Preliminary results are presented, comparing Mars-GRAM thermospheric densities with accelerometer-measured density from Mars Reconnaissance Orbiter (MRO) during its aerobraking in Mars' thermosphere. Some characteristics and results from Venus-GRAM and Earth-GRAM thermospheres are also presented.

II. Mars-GRAM Thermosphere

A major application for the thermospheric part of Mars-GRAM has been in support of aerobraking planning and operations at Mars. Aerobraking involves multi-orbit passes through the atmosphere, using density-drag to gradually circularize a high-eccentricity (captured) orbit into a more circular operations (science) orbit. This contrasts with aerocapture, which uses a single drag pass through the atmosphere to get into a captured orbit from interplanetary transfer orbit. Typical altitudes and atmospheric densities for aerobraking and aerocapture at Mars, or other destinations, are shown in Fig. 1.

Mars Reconnaissance Orbiter (MRO) is currently performing aerobraking operations at Mars. Figure 2 shows preliminary results comparing Mars-GRAM density with MRO accelerometer-derived density[8]. A height offset of +5 km was used for Mars-GRAM. The range of altitudes and latitudes encountered during this observation period are given in the figure labels. Since MRO is in a Sun-synchronous orbit, each periapsis pass occurs at the same local time, but at a different longitude. The large observed orbit-to-orbit variation in periapsis density (about 21% standard deviation in Fig. 2) is due to longitude-and-altitude-varying waves near periapsis (a possible combination of stationary or traveling
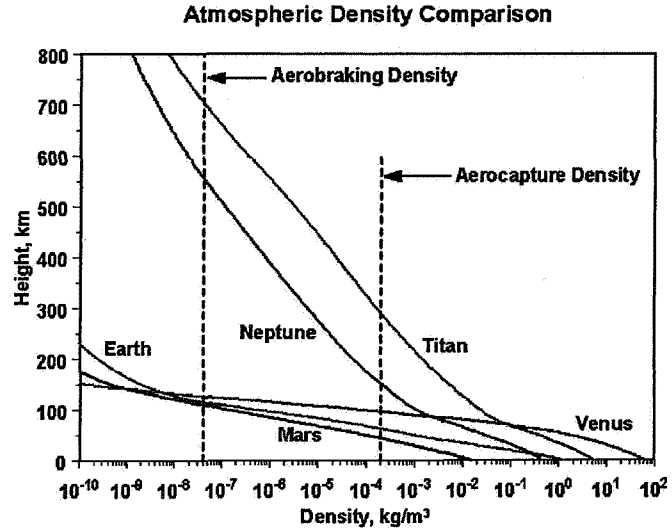

Figure 1. Comparison of typical profiles of atmospheric density for Venus, Earth, Mars and other planets. Typical altitudes and densities for aerocapture or aerobraking are indicated by the vertical dashed lines.
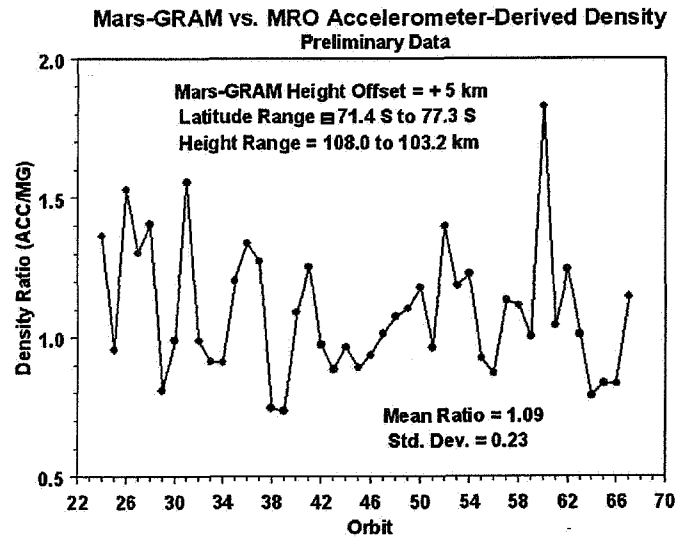

Figure 2. Preliminary data for density ratio (accelerometer/Mars-GRAM) from Mars Reconnaissance Orbiter (MRO) aerobraking operations.

planetary-scale waves plus local, large-scale gravity waves). Mars-GRAM values used for the ratios in Fig. 2 are for the mean atmosphere only (not including wave-perturbation effects).

III. Venus-GRAM Thermosphere

Below 250 km altitude, Venus-GRAM is based on the Venus International Reference Atmosphere (VIRA)[6] model. The 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

Figure 3 shows a plot of typical Venus-GRAM exospheric temperature versus time of day, together with altitude-time contours of Venus-GRAM thermospheric density. As expected, exospheric temperature is highest (about 300 K) for a few hours on either side of solar noon. Normally, hydrostatic conditions mean that densities at high altitudes are larger for higher exospheric temperatures (density increases as the entire atmospheric column expands, because of larger temperatures). However, Fig. 3 shows that, above about 300 km altitude, density is at a relative minimum near solar noon, despite the higher values of exospheric temperature at this time of day. This apparent anomaly can be explained from information in Fig. 4 and Fig. 5, which show (respectively) contours of mean molecular weight (M) and density scale height (H) versus altitude and local time. H is proportional to T / M, where T is temperature. Higher exospheric temperature near noon (Fig. 3) would tend to make H larger near this time of day. However, higher values of M near noon (Fig. 4) would tend to make H smaller near this time of day. For conditions of Fig. 3 - Fig. 5, the M effect dominates, making H smaller near noon (Fig. 5). Since density varies with altitude z as Exp(-z/H), smaller H near noon means that density falls off more rapidly near noon than in morning or afternoon. Hence smaller density values are seen near noon above about 300 km in Fig. 3.

IV. Earth-GRAM Thermosphere

The thermosphere in Earth-GRAM has been represented by the Marshall Engineering Thermosphere (MET) model[4]. For an anticipated release in late 2006, Earth-GRAM has been revised, to including an updated version of MET, plus an option to use the Naval Research
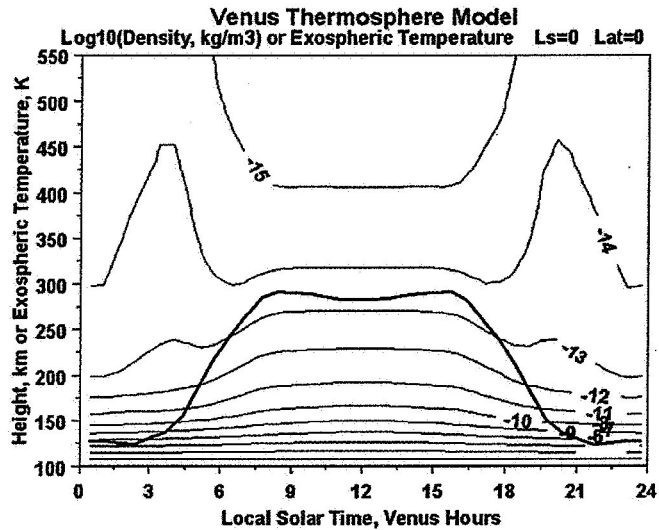
Figure 3. Contours of Venus thermospheric density versus altitude and time of day, and a plot of exospheric temperature (un-numbered line) versus time of day, at Latitude=0, Ls=0 (Spring equinox). Density contours are labeled in units of Log base-10 of density in kg/m^3.
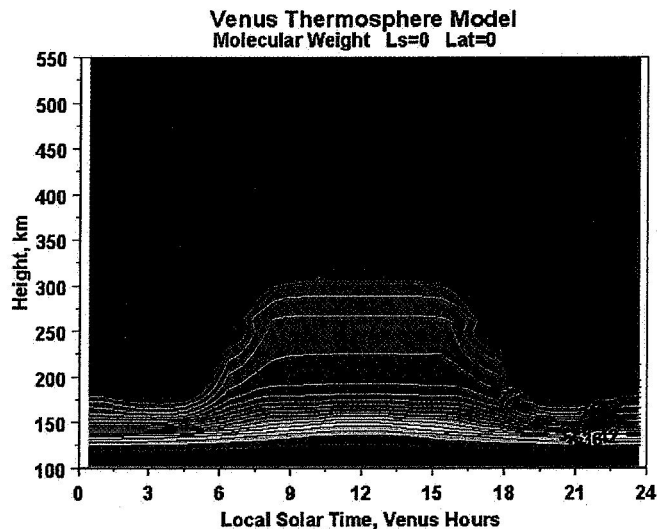
Figure 4. Contours on Venus mean molecular weight (M) versus altitude and time of day, at same conditions as in Figure 3.

Laboratory Mass Spectrometer Incoherent Scatter (MSIS) Radar Extended Model (NRLMSISE-00)[7] as an alternate thermospheric model.

A sample comparison of MET and MSIS density values is given in Fig. 6, which plots contours of MET/MSIS ratio versus altitude and latitude for January at 13 hours local time, for solar activity conditions given in the figure caption. Figure 6 shows MET/MSIS density ratios near 1, except at high northern (winter) latitudes greater than about 60 degrees, and altitudes either above about 600 km or below about 150 km.

Acknowledgments

References

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[2]Justus, C. G., Duvall, A. L., and Keller, V. W., "Atmospheric Models for Mars Aerocapture," *41st AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit*, 11 - 13 July, 2005, Tucson, AZ.

[3]Justus, C. G., Duvall, A. L., and Keller, V. W., "Mars Aerocapture and Validation of Mars Global Reference Atmospheric Model with Thermal Emission Spectrometer Data," *53rd Joint Army-Navy-NASA-Air Force (JANNAF) Propulsion Meeting*, 5 – 8 December, 2005, Monterey, CA.

[4]Justus, C. G., Duvall, A. L., and Keller, V. W., "Trace Constituent Updates in the Marshall Engineering Thermosphere and Global Reference Atmospheric Model," *Advances in Space Research* (to be published).

[5]Bougher, S. W., "Comparative Thermospheres: Venus and Mars," *Advances in Space Research*, Vol. 15, No. 4, 1995, pp. 21-45.

[6]Kliore, A. J., Moroz, V. I., and Keating, G. M. (editors), "The Venus International Reference Atmosphere," *Advances in Space Research*, Vol. 5, No. 11, 1985, pp. 1-304.
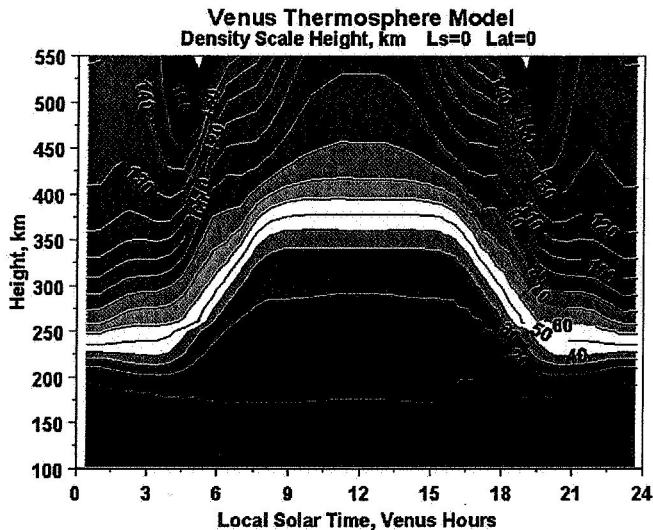

Figure 5. Contours on Venus density scale height (H) versus altitude and time of day, at same conditions as in Figure 3.
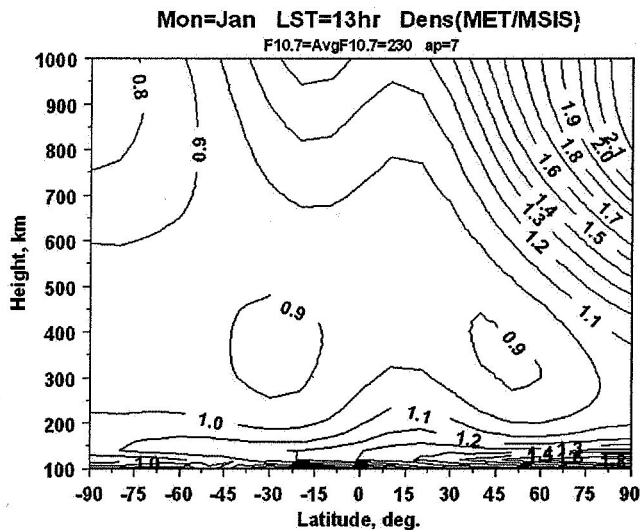

Figure 6. Comparison of Earth-GRAM thermospheric density from Marshall Engineering Thermosphere (MET) model and MSIS model (contours of MET/MSIS ratio) versus altitude and latitude, for January, local time = 13 hours, and solar activity F10.7 = Avg(F10.7) = 230, and ap = 7.

[7]Hedin, A. E., "Extension of the MSIS Thermosphere Model into the Middle and Lower Atmosphere," *Journal of Geophysical Research*, Vol. 96, 1991, p. 1159.

[8]Tolson, R. H., Keating, G. M., Zurek, R. W., Bougher, S. W., and Justus, J., "Application of MGS and MO Aerobraking Accelerometer Data to Atmospheric Modeling," *AIAA/AAS Astrodynamics Specialist Conference & Exhibit*, 21 - 24 August, 2006, Keystone, CO.
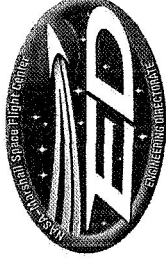
Global Reference Atmospheric Models, Including Thermospheres, for Mars, Venus and Earth

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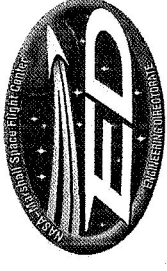[2]Morgan Research Corporation
NASA Marshall Space Flight Center

GRAM Models

- The Global Reference Atmospheric Model (GRAM) series are engineering-oriented planetary atmospheric models

- Marshall Space Flight Center's Natural Environments Branch has developed GRAMs for:
  - Earth
  - Mars
  - Venus
 - Neptune
  - Titan

Aerobraking and Aerocapture

- Aerobraking

  - Involves multi-orbit passes through the atmosphere, using density-drag to gradually circularize a high-eccentricity (captured) orbit into a more circular operations (science) orbit

- Aerocapture

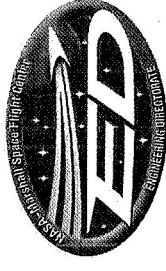 - Uses a single drag pass through the atmosphere to get into a captured orbit from interplanetary transfer orbit

Atmospheric Density Comparison

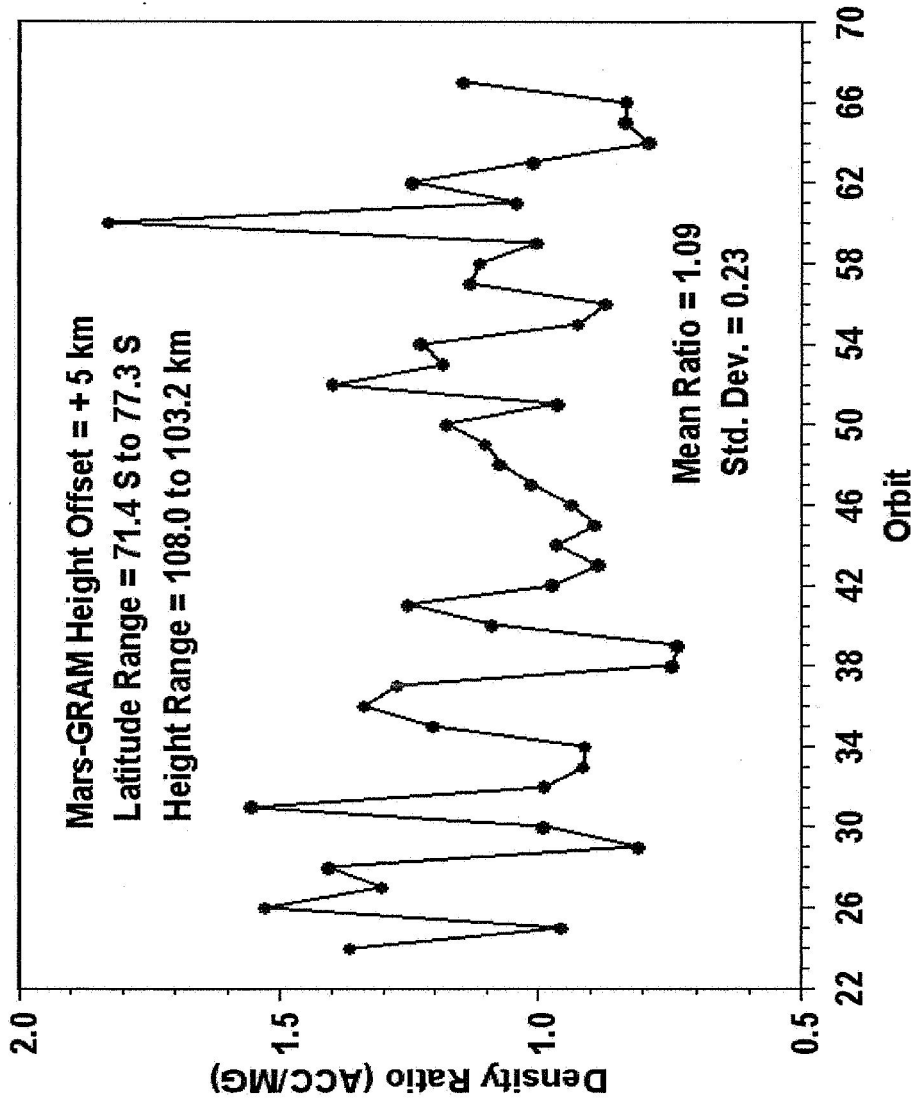Typical altitudes and atmospheric densities for aerobraking and aerocapture
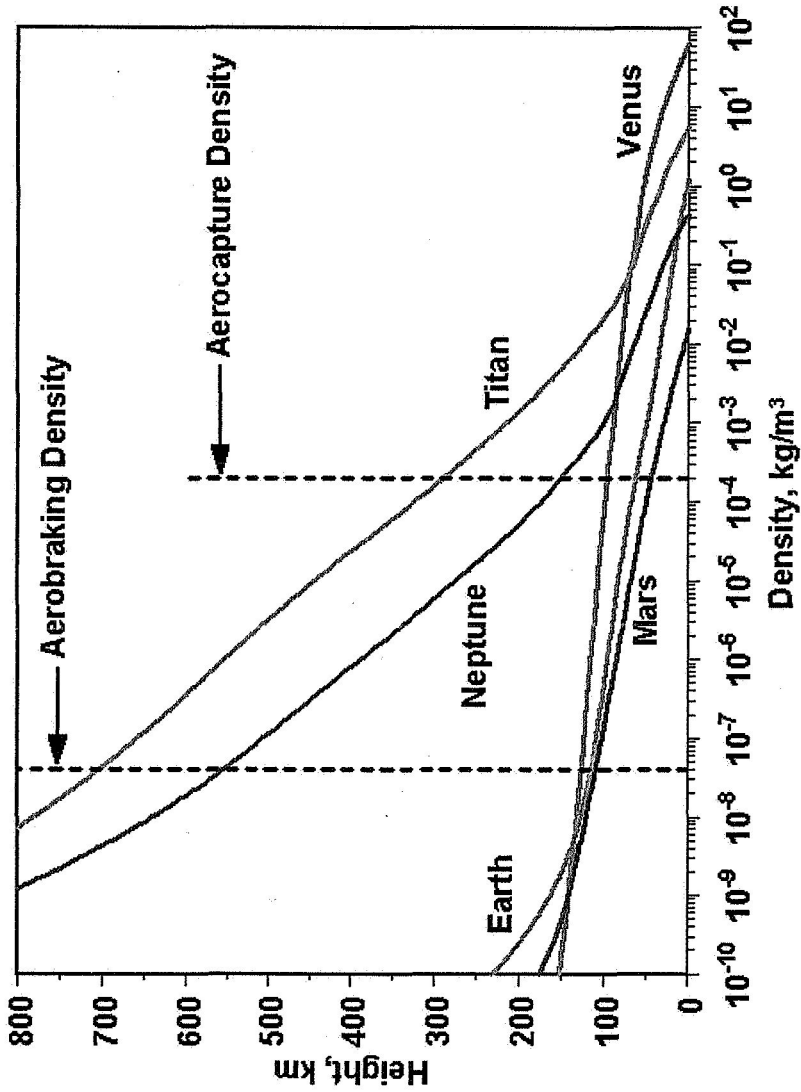
Mars-GRAM 2005

- Mars-GRAM has been been widely used for engineering applications including:
  - Systems design
  - Performance analysis
  - Operations planning for aerobraking, entry descent and landing, and aerocapture

- Thermosphere section of Mars-GRAM is based on output data sets from the University of Michigan Mars Thermospheric General Circulation Model (MTGCM)

Mars-GRAM vs. MRO Accelerometer-Derived Density

Mars-GRAM Height Offset = +5 km
Latitude Range = 71.4 S to 77.3 S
Height Range = 108.0 to 103.2 km

Mean Ratio = 1.09
Std. Dev. = 0.23

Density Ratio (ACC/MG)

Orbit

6

Venus-GRAM Thermosphere

- Below 250 km altitude, Venus-GRAM is based on the Venus International Reference Atmosphere (VIRA) model.

- The Venus-GRAM thermosphere has been 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

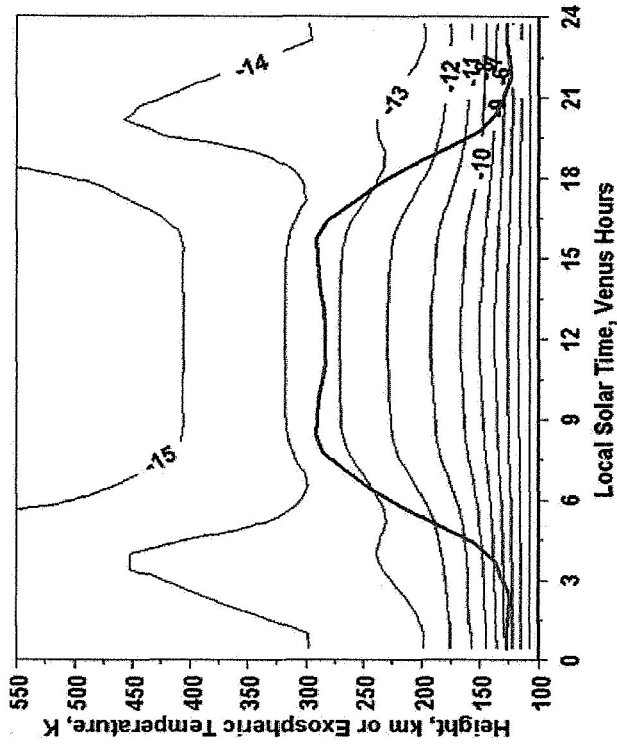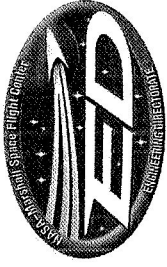 - Mass density is computed from constituent number densities

Venus-GRAM Thermosphere Model

Log10(Density,kg/m³) or Exospheric Temperature
Ls=0 Lat=0

- Exospheric temperature is highest (about 300K) for a few hours on either side of solar noon

- Normally, hydrostatic conditions mean that densities at high altitudes are larger for higher exospheric temperatures
  - density increases as the entire atmospheric column expands, because of larger temperatures

- Above about 300 km altitude, density is at a relative minimum near solar noon, despite the higher values of exospheric temperature at this time of day
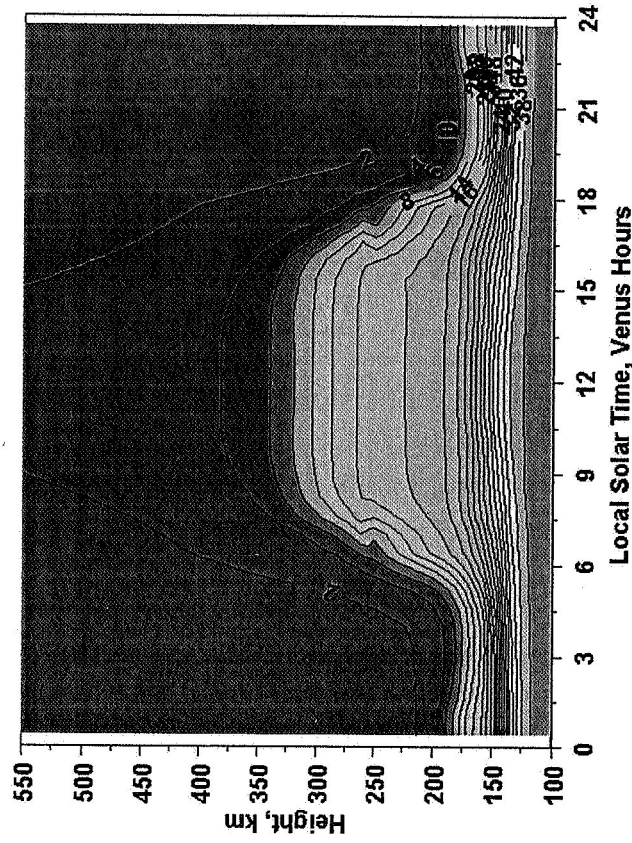
Venus-GRAM Thermosphere Model

Molecular Weight Ls=0 Lat=0

- Anomaly can be explained by examining the relationship between the mean molecular weight (M) and density scale height (H) versus altitude and local time

- H is proportional to T / M, where T is temperature

- Higher exospheric temperature near noon would tend to make H larger near this time of day

- Higher values of M near noon would tend to make H smaller near this time of day

Venus-GRAM Thermosphere Model

- For conditions of Ls=0, Lat=0, the M effect dominates, making H smaller near noon as shown in this slide

- Density varies with altitude z as Exp(-z/H)
  - smaller H near noon means that density falls off more rapidly near noon than in morning or afternoon.

- Thus, above about 300 km altitude, density is at a relative minimum near solar noon as shown in Slide 8

Density Scale Height, km Ls=0 Lat=0

10
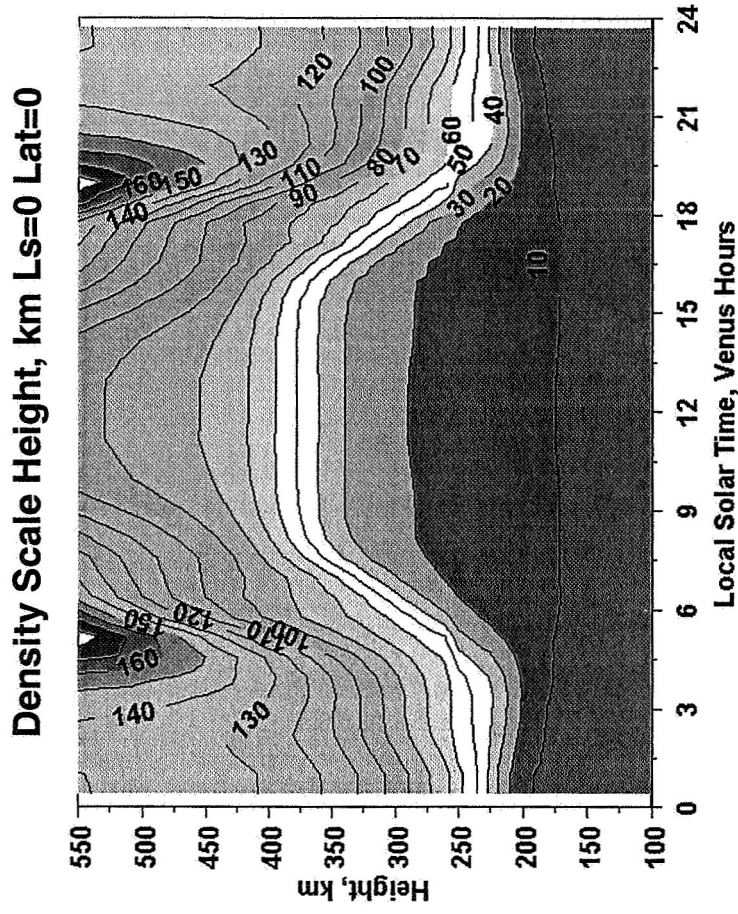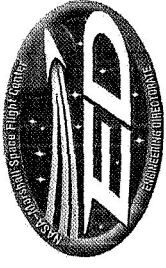
Earth-GRAM 2006

- Thermosphere in past versions of Earth-GRAM has been represented by the Marshall Engineering Thermosphere (MET) model

- Earth-GRAM 2006 has been revised

  – Includes an updated version of MET

  – Option to use the Naval Research Laboratory Mass Spectrometer Incoherent Scatter (MSIS) Radar Extended Model (NRLMSISE-00) as an alternate thermospheric model.

Comparison of MET and MSIS density values

Mon=Jan LST=13hr Dens(MET/MSIS)
F10.7=AvgF10.7=230 ap=7