

Mars Global Reference Atmospheric Model (Mars-GRAM 2005) Applications for Mars Science Laboratory Mission Site Selection Processes

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Mars Global Reference Atmospheric Model (Mars-GRAM)

- Engineering-level atmospheric model used for diverse mission applications
- Mars-GRAM's perturbative modeling capability is currently used in a Mars-GCM mode to perform high fidelity engineering and mission simulations for entry, descent, and landing (EDL)
- Traditional Mars-GCM systems for representing the mean atmosphere using entry conditions include:
 - TES Mapping Years 1 and 2 with Mars Global Data using from MGS/MA
 - TES Mapping Year 3 with Mars Global Data using from MGS/MA
 - Global mean Mars atmosphere TES data used
- From the surface to 50 km altitude, Mars-GRAM is based on NASA Ames Mars General Circulation Model (MGS/MA). Mars-GRAM and MGS/MA use input mappings from Mars Global Surveyor Mars Climate Orbiter (MCO) and Mars Global Surveyor Mars Climate Orbiter (MCO) or Mars Global Surveyor Mars Climate Orbiter (MCO) or Mars Global Surveyor Mars Climate Orbiter (MCO).
- Mars-GRAM 2005 has been widely used by various Mars Science data and both near and back area from the Thermal Environment Spectrometer (TES).

New Features of Mars-GRAM 2005

- Option to use input data sets from MGS/MA model runs that were used to create simulation conditions observed during the first two years of TES observations at Mars:
 - TES Year 1: April 1998 through January 2001
 - TES Year 2: February 2001 through December 2002
- Option to read and use an auxiliary profile of temperature and density values (MGS/MA) by using the auxiliary profile Mars-GRAM option. The values from the auxiliary profile replace data from the original MGS/MA databases.
 - Examples of auxiliary profiles:
 - Can use TES lower level wind observations
 - Can use MGS/MA model results as a reference model and use
- The Mars-GRAM parameters allow standard deviations of Mars-GRAM perturbations to be included:
 - specfile can be used to scale density perturbations up or down
 - specfile can be used to scale wind perturbations

Applications for Mars Science Laboratory Mission Site Selection:

- In order to assess Mars Science Laboratory (MSL) landing capabilities, three of the candidate sites that represent a wide range of atmospheric conditions were selected for initial study:
 - Terby Crater
 - Mesa Chasma
 - Gale Crater
- Two mesoscale models were run for the expected MSL landing season and time of day:
 - Mars Regional Atmospheric Modeling System (MRAAMS) of Southwest Research Institute
 - Mars Mesoscale Model number 5 (MMS5) of Oregon State University



New Mars Science Laboratory with Power Source and Extranet Ant. with Concept for Entry, Descent, and Landing

Mars-GRAM Auxiliary Profiles

- Mars-GRAM auxiliary profiles provide vertical profiles of the actual entry conditions used generated by interpolation from the mesoscale model output data.
- Table 1 shows an example Mars-GRAM auxiliary profile from MRAAMS model output at the Terby landing site.
- These Mars-GRAM auxiliary profiles can be used in Mars-GRAM to provide details of MSL entry dynamics simulations.

Table 1 - Example Mars-GRAM Auxiliary Profile

| Altitude (km) | Pressure (hPa) | Temperature (K) | Density (kg/m³) | Wind Speed (m/s) | Wind Direction (deg) |
|---------------|----------------|-----------------|-----------------|------------------|----------------------|
| 50 | 0.012 | 210 | 0.0001 | 0 | 0 |
| 40 | 0.025 | 220 | 0.0002 | 0 | 0 |
| 30 | 0.050 | 230 | 0.0004 | 0 | 0 |
| 20 | 0.100 | 240 | 0.0008 | 0 | 0 |
| 10 | 0.200 | 250 | 0.0016 | 0 | 0 |
| 0 | 1.013 | 288 | 0.0012 | 0 | 0 |

Other Sources of Mars Atmospheric Data

- To assess entry uncertainty in atmospheric representation at these candidate sites, five other sources of atmospheric data were also analyzed:
 - A global Thermal Environment Spectrometer (TES) database containing averages and standard deviations of temperature, density, and thermal wind components, averaged over 5 day's integration latitude bins and 15 degree LxL bins, for each of three Mars years of TES raw data.
 - A global set of TES raw sounding data, which can be queried over any desired range of altitude-longitude and LxL, to estimate averages and standard deviations of temperature and density.
 - Output of means and standard deviations of temperature, density, and winds from Version 4.0 of the European Mars Climate Database (MCO2).

Characteristics of TES Nadir Database

- Three TES Mapping Years:
 - Y1 - 1998-2001
 - Y2 - 2001-1992
 - Y3 - 1992-1998
- Global TES Nadir Data Sets: Means and Standard Deviations for temperature, density, and thermal wind components by:
 - 5 day integration bins
 - 15 degree LxL bins
 - 10 degree LxL bins
 - 10 to 20 Pressure levels, automatically converted to Geometric height by Mars Climate Orbiter
 - Geographic location: input at TES pressure levels or interpolated to 10 degree pressure
 - Output automatically formatted for Mars-GRAM input as Auxiliary Profile

Characteristics of TES Limb Database

- Data for TES Mapping Years 1 and 2 and -10 of TES Mapping Year 3
- Query Program Allows Users to Select Latitude and Latitude Bin and:
 - Input desired LxL and select LxL bin width
 - Choose Y1, Y2, or Y3 from Yearly
- Query Program outputs all individual profiles that match criteria, plus average and standard deviation of temperature and density of all total profiles:
 - Up to 20 Pressure levels, automatically converted to geometric altitude
 - Output at pressure levels, or interpolated to 10 degree pressure
 - Output automatically formatted for Mars-GRAM input as Auxiliary Profile

Mean Density Comparisons

- Study for entry purposes, density is a key parameter in determining the trajectory of the vehicle.
- A global TES limb profile of about 100 km altitude, TES data are used to compare the density profiles of the Mars-GRAM model output with the limb data from the nadir results.
- Below 10 km, differences between MGS/MA and MMS5 results are small.
- Mean density data in Figures 1 and 2 are used to compare the Mars-GRAM model output with the limb data from the nadir results.
- Mars-GRAM results are averaged over TES mapping years 1 and 2 and show good agreement with the limb data, with differences of less than 1% at all altitudes which were quite comparable.

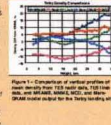


Figure 1 - Comparison of vertical profiles of mean density from TES limb data and Mars-GRAM model output for the Terby landing site.

Zonal Wind Comparison

- Figure 2 compares vertical profiles of zonal wind from MRAAMS, MMS5, MCO, and Mars-GRAM model output.
- Wind results from MRAAMS and MMS5 are more consistent than the density results between these two models (Figure 1).
- Mars-GRAM wind results for TES mapping years 1 and 2 and for the Terby site are compared with the limb data from the nadir results for each other and are plotted separately in this figure.

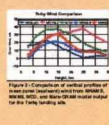


Figure 2 - Comparison of zonal profiles of zonal wind from MRAAMS, MMS5, MCO, and Mars-GRAM model output for the Terby landing site.

Wind Perturbation Comparisons

- Figure 3 compares wind perturbations from MRAAMS and MMS5 models with those from Mars-GRAM perturbation model output at the Terby site.
- Mesoscale modeled standard deviations are slightly larger than TES limb data at 10 to 20 km altitude.
- An increase in all of about 1.2 would better replicate wind standard deviations from MRAAMS or MMS5 simulations at the Gale, Terby, or Mesa sites.

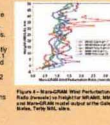


Figure 3 - Comparison of wind perturbations from MRAAMS, MMS5, and Mars-GRAM model output for the Terby landing site.

Density Standard Deviation Comparison

- Observed and mesoscale modeled data by standard deviations are compared with those from Mars-GRAM density perturbation model output at the Terby site.
- Figure 4 includes data with standard deviations from MRAAMS, MMS5, and Mars-GRAM perturbations would be conservative.
- To better represent TES and standard deviation perturbations, specfile values at the entry conditions should be used.

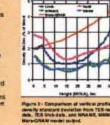


Figure 4 - Comparison of density standard deviations from MRAAMS, MMS5, and Mars-GRAM model output for the Terby landing site.

Density Comparison of Mesoscale Models and TES Limb data

- Figure 5 compares density profiles from TES limb data and mesoscale modeled data for the Terby site.
- The MRAAMS and the MMS5 models differ significantly from each other throughout the atmosphere.
- The mesoscale model data shows the greatest deviation for the MRAAMS model density - 12.5% at -30 km and for the MMS5 model - 10% at -30 km.

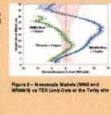


Figure 5 - Comparison of density profiles from TES limb data and mesoscale modeled data for the Terby site.

Conclusions

- The new Mars-GRAM auxiliary profile capability, using data from TES observations, a mesoscale model output, or other sources, allows an auxiliary higher fidelity representation of the atmosphere, and a more accurate way of representing present uncertainty in atmospheric density and winds.
- Figure 3 indicates that, with respect to temperature, Mars-GRAM perturbations would tend to overestimate observed mesoscale modeled variability. To better represent TES and mesoscale model density perturbations, specfile values as low as about 0.4 would be appropriate.
- Some data entry representation of Mars-GRAM allow the user to dynamically change model and relative values with a specfile (Figure 4) that an input value of about 1.2 would better replicate and standard deviations from MRAAMS or MMS5 simulations at the Gale, Terby, or Mesa sites.
- By adjusting the relative and relative values in Mars-GRAM using the specfile as in Figure 4, we can provide more accurate entry and simulation results for EDL at the candidate MSL landing sites.

Acknowledgments

The authors gratefully acknowledge:

- Mike Smith, John Pearl, and other members of the TES team for providing us with their global nadir and limb data.
- Scott Reikin (Southwest Research Institute) for providing MRAAMS output data.
- Jeff Barnes and Dan Tyler (Oregon State University) for providing MMS5 output data.
- Francois Forget (University of Paris) for providing Version 4.0 of the European Mars Climate Database.

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Mars Global Reference Atmospheric Model (Mars-GRAM)

- Engineering-level atmospheric model widely used for diverse mission applications
- Mars-GRAM's perturbation modeling capability is commonly used, in a Monte-Carlo mode, to perform high fidelity engineering end-to-end simulations for entry, descent, and landing (EDL)¹.
- Traditional Mars-GRAM options for representing the mean atmosphere along entry corridors include:
 - TES Mapping Years 1 and 2, with Mars-GRAM data coming from MGCM model results driven by observed TES dust optical depth
 - TES Mapping Year 0, with user-controlled dust optical depth and Mars-GRAM data interpolated from MGCM model results driven by selected values of globally-uniform dust optical depth.
- From the surface to 80 km altitude, Mars-GRAM is based on NASA Ames Mars General Circulation Model (MGCM). Mars-GRAM and MGCM use surface topography from Mars Global Surveyor Mars Orbiter Laser Altimeter (MOLA), with altitudes referenced to the MOLA areoid, or constant potential surface.
- Mars-GRAM 2005 has been validated² against Radio Science data, and both nadir and limb data from the Thermal Emission Spectrometer (TES)³.

New Features of Mars-GRAM 2005

- Option to use input data sets from MGCM model runs that were designed to closely simulate conditions observed during the first two years of TES observations at Mars
 - TES Year 1 = April 1999 through January 2001
 - TES Year 2 = February 2001 through December 2002
- Option to read and use any auxiliary profile of temperature and density versus altitude. In exercising the auxiliary profile Mars-GRAM option, the values from the auxiliary profile replace data from the original MGCM databases
 - Examples of auxiliary profiles:
 - Data from TES (nadir or limb) observations
 - Mars mesoscale model output at a particular location and time
- Two Mars-GRAM parameters allow standard deviations of Mars-GRAM perturbations to be adjusted
 - rpscale can be used to scale density perturbations up or down
 - rwscale can be used to scale wind perturbations

Applications for Mars Science Laboratory Mission Site Selection:

- In order to assess Mars Science Laboratory (MSL) landing capabilities, three of the candidate sites that represent a wide range of atmospheric conditions were selected for initial study:
 - Terby Crater
 - Melas Chasma
 - Gale Crater.
- Two mesoscale models were run for the expected MSL landing season and time of day.
 - Mars Regional Atmospheric Modeling System (MRAMS) of Southwest Research Institute⁴
 - Mars Mesoscale Model number 5 (MMS5) of Oregon State University⁵.



Mars Science Laboratory with Power Source and Extended Arm, Artist's Concept (Courtesy NASA/JPL-Caltech)

Mars-GRAM Auxiliary Profiles

- Mars-GRAM auxiliary profiles (either vertical or along the actual entry corridor) were generated by interpolation from the mesoscale model output data.
- Table 1 shows an example Mars-GRAM auxiliary profile from MRAMS model output at the Terby landing site.
- These Mars-GRAM auxiliary profiles are then used in Mars-GRAM to provide detailed MSL entry dynamics simulations

Table 1 – Example Mars-GRAM Auxiliary Profile – Mean Values from Terby MRAMS Simulation

| Altitude (km) | Temp (K) | Density (kg/m ³) | Pressure (Pa) | WV (m/s) | WZ (m/s) | WY (m/s) | Wx (m/s) | Wy (m/s) | Wz (m/s) |
|---------------|----------|------------------------------|---------------|----------|----------|----------|----------|----------|----------|
| 100.000 | 216.000 | 1.17E-06 | 1.17E-06 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| 90.000 | 216.000 | 1.17E-06 | 1.17E-06 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| 80.000 | 216.000 | 1.17E-06 | 1.17E-06 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| 70.000 | 216.000 | 1.17E-06 | 1.17E-06 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| 60.000 | 216.000 | 1.17E-06 | 1.17E-06 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| 50.000 | 216.000 | 1.17E-06 | 1.17E-06 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| 40.000 | 216.000 | 1.17E-06 | 1.17E-06 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| 30.000 | 216.000 | 1.17E-06 | 1.17E-06 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| 20.000 | 216.000 | 1.17E-06 | 1.17E-06 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| 10.000 | 216.000 | 1.17E-06 | 1.17E-06 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| 0.000 | 216.000 | 1.17E-06 | 1.17E-06 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |

Other Sources of Mars Atmospheric Data

- To assess likely uncertainty in atmospheric representation at these candidate sites, three other sources of atmospheric data were also analyzed:
 - A global Thermal Emission Spectrometer (TES) database containing averages and standard deviations of temperature, density, and thermal wind components, averaged over 5-by-5 degree latitude bins and 15 degree Ls bins, for each of three Mars years of TES nadir data
 - A global set of TES limb sounding data, which can be queried over any desired range of latitude-longitude and Ls, to estimate averages and standard deviations of temperature and density
 - Output of means and standard deviations of temperature, density, and winds from Version 4 of the European Mars Climate Database (MCD)⁶

Characteristics of TES Nadir Database

- Three TES Mapping Years
 - Yr 1 = 4/99 – 2/01
 - Yr 2 = 2/01 – 1/03
 - Yr 3 = 1/03 – 11/04
- Global TES Nadir Data Set - Means and Standard Deviations for temperature, density, and thermal wind components :
 - 5-by-5 degree Lat-Lon bins
 - 15 degree Ls bins
 - Local Solar Time = 2 or 14 hours
 - Up to 21 Pressure Levels, automatically converted to Geometric Height by Database Query Program
 - Query program gives output at TES pressure levels or interpolated to 1-km altitude intervals
 - Output automatically formatted for Mars-GRAM input as Auxiliary Profile

Characteristics of TES Limb Database

- Data for TES Mapping Years 1 and 2 and ~1/2 of TES Mapping Year 3
- Query Program Allows User to Select Lat-Lon, and Ls Bins and Local True Solar Time
 - Input desired Lat-Lon and select Lat-Lon Bin widths
 - Input desired Ls and select Ls Bin width
 - Choose LTST = 2 or 14 hours (or both)
- Query Program outputs all individual profiles that match criteria, plus average and standard deviation of temperature and density of all output profiles
 - Up to 38 Pressure levels, automatically converted to geometric altitude
 - Output at pressure levels, or interpolated to 1-km altitude intervals
 - Output automatically formatted for Mars-GRAM input as Auxiliary Profile

Mean Density Comparisons

- Strictly for reference purposes, density values are represented as percentage difference from MMM5 values.
- A significant bias difference of about 15% is noted between TES nadir and TES limb data, with all of the models tending to agree closer with the limb data than the nadir results.
- Above ~20 km, differences greater than 10% are noted between MRAMS and MMM5 results.
- Nadir and Limb data in Figure 1 were averaged over three years of Mars observations.
- Mars-GRAM results are averages from TES mapping years 1 and 2 and Map year 0 with dust visible optical depth $\tau = 0.1$, all three of which were quite comparable.

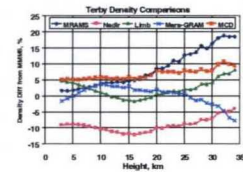


Figure 1 – Comparison of vertical profiles of mean density from TES nadir data, TES limb data, and MRAMS, MMM5, MCD, and Mars-GRAM model output for the Terby landing site.

Zonal Wind Comparison

- Figure 2 compares vertical profiles of mean zonal wind from MRAMS, MMM5, MCD, and Mars-GRAM model output
- Wind results from MRAMS and MMM5 are more consistent than the density results between these two models (Figure 1)
- Mars-GRAM wind results for TES mapping years 1 and 2 and for dust $\tau = 0.1$ are significantly different from each other and are plotted separately in this figure

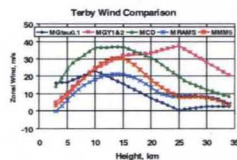


Figure 2 - Comparison of vertical profiles of mean zonal (eastward) wind from MRAMS, MMM5, MCD, and Mars-GRAM model output for the Terby landing site.

Density Standard Deviation Comparison

- Observed and mesoscale-modeled density standard deviations are generally less than Mars-GRAM density standard deviations, an exception being TES nadir values below about 6 km altitude.
- Figure 3 indicates that, with nominal value $rpscale=1$, Mars-GRAM perturbations would be conservative.
- To better represent TES and mesoscale model density perturbations, $rpscale$ values as low as about 0.4 could be used.

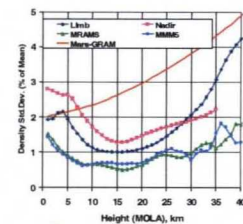


Figure 3 - Comparison of vertical profiles of density standard deviation from TES nadir data, TES limb data, and MRAMS, MMM5, and Mars-GRAM model output.

Wind Perturbation Comparisons

- Figure 4 compares wind perturbations from MRAMS and MMM5 models with those from nominal Mars-GRAM perturbation model values at the three candidate MSL sites.
- Mesoscale-modeled wind standard deviations are slightly larger (by about a factor of 1.1 to 1.2) than Mars-GRAM wind standard deviations.
- An *nwscale* value of about 1.2 would better replicate wind standard deviations from MRAMS or MMM5 simulations at the Gale, Terby, or Melas sites.

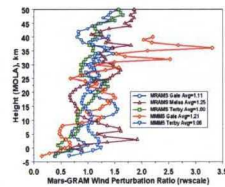


Figure 4 – Mars-GRAM Wind Perturbation Ratio (*nwscale*) vs Height for MRAMS, MMM5, and Mars-GRAM model output at the Gale, Melas, Terby MSL sites.

Density Comparison of Mesoscale Models and TES Limb data

- Figure 5 Compares density profiles from TES limb database and Mars mesoscale models MRAMS and MMM5 at the Terby site.
- The MMM5 Model and the MRAMS model differ significantly from each other throughout the atmosphere
- The mesoscale models also differ from the TES limb data with the greatest deviation for the MRAMS model being ~12.5% at ~30 km and for the MMM5 model ~ -10% at ~35 km

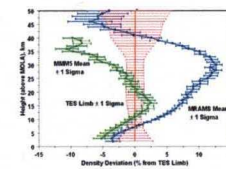


Figure 5 – Mesoscale Models (MMM5 and MRAMS) vs TES Limb Data at the Terby site

Conclusions

- The new Mars-GRAM auxiliary profile capability, using data from TES observations, mesoscale model output, or other sources, allows a potentially higher fidelity representation of the atmosphere, and a more accurate way of estimating inherent uncertainty in atmospheric density and winds.
- Figure 3 indicates that, with nominal value *rpscale*=1, Mars-GRAM perturbations would tend to overestimate observed or mesoscale-modeled variability. To better represent TES and mesoscale model density perturbations, *rpscale* values as low as about 0.4 could be used.
- Some trajectory model implementations of Mars-GRAM allow the user to dynamically change *rpscale* and *nwscale* values with altitude. Figure 4 shows that an *nwscale* value of about 1.2 would better replicate wind standard deviations from MRAMS or MMM5 simulations at the Gale, Terby, or Melas sites.
- By adjusting the *rpscale* and *nwscale* values in Mars-GRAM based on figures such as Figure 3 and 4, we can provide more accurate end-to-end simulations for EDL at the candidate MSL landing sites

Acknowledgments

The authors gratefully acknowledge:

- Mike Smith, John Pearl, and other members of the TES team for providing us with their global nadir and limb data
- Scot Rafkin (Southwest Research Institute) for providing MRAMS output data
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