

MARS-GRAM 2010: IMPROVING THE PRECISION OF MARS-GRAM

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Introduction: It has been discovered during the Mars Science Laboratory (MSL) site selection process that the Mars Global Reference Atmospheric Model (Mars-GRAM) when used for sensitivity studies for Thermal Emission Spectrometer (TES) MapYear=0 and large optical depth values, such as $\tau=3$, is less than realistic. 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]. Mars-GRAM 2005 has been validated [2] against Radio Science data, and both nadir and limb data from TES [3].

Traditional Mars-GRAM options for representing the mean atmosphere along entry corridors include: (1) TES mapping year 0, with user-controlled dust optical depth and Mars-GRAM data interpolated from NASA Ames Mars General Circulation Model (MGCM) [4] results driven by selected values of globally-uniform dust optical depth, or (2) TES mapping years 1 and 2, with Mars-GRAM data coming from MGCM results driven by observed TES dust optical depth. From the surface to 80 km altitude, Mars-GRAM is based on NASA Ames MGCM. Above 80 km, Mars-GRAM is based on the University of Michigan Mars Thermospheric General Circulation Model (MTGCM) [5].

MGCM results that were used for Mars-GRAM with MapYear=0 were from a MGCM run with a fixed value of $\tau=3$ for the entire year at all locations. This choice of data has led to discrepancies that have become apparent during recent sensitivity studies for MapYear=0 and large optical depths. Unrealistic energy absorption by time-invariant atmospheric dust leads to an unrealistic thermal energy balance on the polar caps. The outcome is an inaccurate cycle of condensation/sublimation of the polar caps and, as a consequence, an inaccurate cycle of total atmospheric mass and global-average surface pressure. Under an assumption of unchanged temperature profile and hydrostatic equilibrium, a given percentage change in surface pressure would produce a corresponding percentage change in density at all altitudes. Consequently, the final result of a change in surface pressure is an imprecise atmospheric density at all altitudes.

Mars-GRAM 2010 Adjustment Factors: In determining a possible solution to this discrepancy Mars-GRAM was evaluated at locations and times of TES limb observations, and adjustment factors (ratio of observed TES density to Mars-GRAM density) were determined. These adjustment factors $[F(z, \text{Lat}, L_s)]$ were expressed as a function height (z), Latitude (Lat) and areocentric solar longitude (L_s).

For altitudes above 80 km, Mars-GRAM (MTGCM) densities were compared to aerobraking densities measured by Mars Global Surveyor (MGS), Mars Odyssey (ODY), and Mars Reconnaissance Orbiter (MRO). For Mars-GRAM 2010, MGCM and MTGCM data values are modified by these adjustment factors.

Adjustment Factor Requirements The adjustment factors generated by this process had to satisfy the gas law: $p = \rho RT$ as well as the hydrostatic relation: $dp/dz = -\rho g$. If T is assumed to be unchanged and both p and ρ are adjusted by a common factor, F , both relations are preserved. This adjustment factor, F , is applied to the daily mean MGCM density and pressure (0-80 km) and MTGCM density and pressure (above 80 km) The pressure scale height (RT/g) is unchanged by this process. However, since the pressure has been changed by the adjustment factor, the height of the 1.26 nbar pressure level, referred to as ZF in Mars-GRAM, has also been changed.

The daily mean MGCM or MTGCM density, DTA0, and the daily mean MGCM or MTGCM pressure, PTA0, depend on height (z), latitude (Lat), solar longitude (L_s), dust amount (τ), and solar activity parameter (F_{10}). The adjusted values of DTA0' and PTA0' are computed from the adjustment factors F using the following equations:

$$\text{DTA0}' = \text{DTA0} * F(z, \text{Lat}, L_s)$$

$$\text{PTA0}' = \text{PTA0} * F(z, \text{Lat}, L_s)$$

where the adjustment factor F has been determined as described above.

Adjustment factors F are also used to adjust ZF by the relation:

$$\text{ZF}' = \text{ZF} + H \ln(F)$$

where H is local pressure scale height.

Development of MTGCM Factors The Mars-GRAM density and pressure need to be consistent at 80 km, where the transition from MGCM to MTGCM data occurs. Thus, the assumption was made that $F(80, \text{Lat}, L_s)$ for the MTGCM data had to be the same as the adjustment factor at 80 km for the MGCM data. After adjustment factors $F(80, \text{Lat}, L_s)$ were determined from the MGCM analysis, they were used to determine MTGCM adjustment factors by use of the following equation:

$$F(z, \text{Lat}, L_s) = F(80, \text{Lat}, L_s) * (1 + A\zeta + B\zeta^2)$$

where the height parameter $\zeta = (z - 80)$ and the coefficients A and B depend on Lat and L_s .

Final adjustment factors $F(z, \text{Lat}, L_s)$ for MTGCM data were implemented into Mars-GRAM and a validation run comparing Mars-GRAM vs. MGS, ODY, and MRO aerobraking data was completed. Any residual variation of aerobraking density about mean values that became apparent during

this process was used to update the height dependence of Mars-GRAM perturbation standard deviations.

Improvement of Mars-GRAM 2010 at Lower Altitudes: Application of adjustment factors for the MGCM data yields improved comparisons between Mars-GRAM and TES limb data, as shown by density ratios (Mars-GRAM/ TES Limb) given in Figure 1. Prior to adjustment these density ratios were as low as 0.65 near 60 km altitude

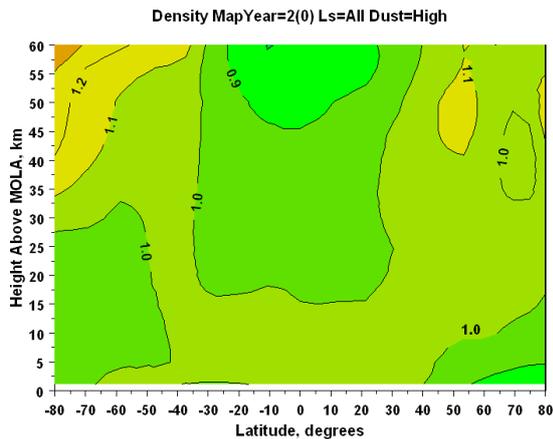


Figure 1. Latitude-height contours of ratio (Mars-GRAM/ TES Limb) after application of MGCM adjustment factors

Improvement of Mars-GRAM 2010 at Aerobraking Altitudes: Application of the adjustment factor $F(z, Lat, L_s)$ to the MTGCM data has resulted in the Mars-GRAM (MG) output being closer on average to the accelerometer (ACC) data from the aerobraking phases of MGS, ODY, and MRO. As shown in Figure 2., the average linear coefficient of ACC/MG without the adjustment is 2.352 ± 1.440 and with the adjustment is 1.001 ± 0.264 .

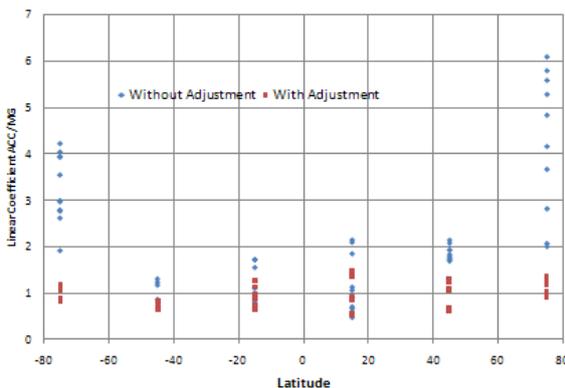


Figure 2. Linear Coefficient of the ratio of ACC data from MGS, ODY and MRO to Mars-GRAM 2010 output versus Latitude

This improvement in Mars-GRAM results can also be seen in the change in the slope of ACC versus MG graphs as shown in Figures 3 and 4. The slope changes dramatically from a maximum of approx-

imately 11 near 70N latitude to a slope that averages around 1 when the adjustment factors are added.

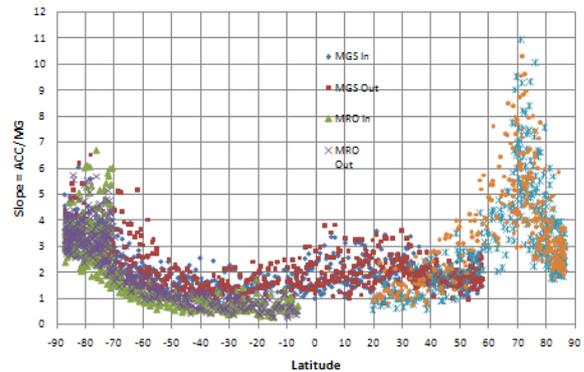


Figure 3. Slope of ACC versus MG as a function of latitude without Adjustment Factors

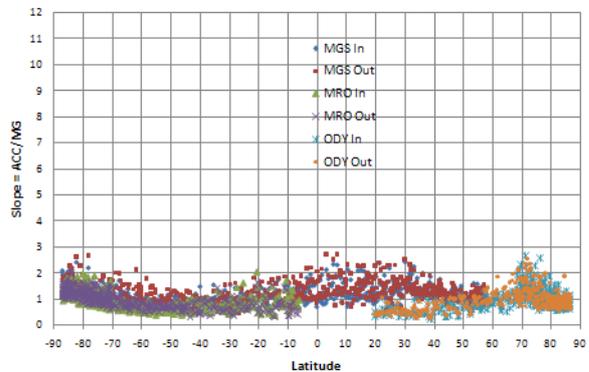


Figure 4. Slope of ACC versus MG as a function of latitude with Adjustment Factors

The addition of adjustment factors has improved Mars-GRAM 2010 results throughout the altitude range of 0 – 130 km. Examples of this improvement in results for various locations, times and dust conditions on Mars will be presented at the conference session.

Conclusions: Mars-GRAM 2010 has been developed, validated and is ready for distribution. Mars-GRAM in the past has been export controlled (EAR-99), but is now classified as publically available. This change in distribution classification has increased the availability of Mars-GRAM 2010 to users. Mars-GRAM 2010 has been updated to Fortran 90/95. Mars-GRAM 2010 now includes adjustment factors that are used to alter the input data from MGCM and MTGCM for the Mapping year 0 (user-controlled dust) case. The greatest adjustment occurs at large optical depths such as $\tau > 1$. The addition of the adjustment factors has led to better correspondence to TES Limb data from 0-60 km as well as better agreement with MGS, Odyssey and MRO data at approximately 90-130 km.

References: [1] Striepe S. A. et al. (2002), *AIAA Atmospheric Flight Mechanics Conference and Exhibit*, Abstract # 2002-4412. [2] Justus C. G. et al. (2005) "Mars Aerocapture and Validation of Mars-GRAM with TES Data", *53rd JANNAP Propulsion*

Meeting. [3] Smith M. D. (2004) *Icarus*, 167, 148-165. [4] Haberle, R. M., Pollack, J. B., Barnes, J. R., et al. (1993) "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. [5] Bougher, S.W., et al. (1990) "The Mars Thermosphere: 2. General Circulation with Coupled Dynamics and Composition", *Journal of Geophysical Research*, Vol. 95, No. B9, pp. 14,811-14,827.

Mars-GRAM 2010: Improving the Precision of Mars-GRAM



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Background

It has been discovered during the Mars Science Laboratory (MSL) landing site selection process that the Mars Global Reference Atmospheric Model (Mars-GRAM) when used for sensitivity studies for Thermal Emission Spectrometer (TES) MapYear = 0 and large optical depth values such as tau = 3 is less than realistic.

Mars-GRAM is an 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
- Mars-GRAM 2005 has been validated² against Radio Science data and both nadir and limb data from the Thermal Emission Spectrometer (TES)³
- Traditional Mars-GRAM options for representing the mean atmosphere along entry corridors include:
 - TES Mapping Year 0, with user-controlled dust optical depth and Mars-GRAM data interpolated from NASA Ames Mars General Circulation Model (MGCM)⁴ model results driven by selected values of globally-uniform dust optical depth
 - TES Mapping Years 1 and 2, with Mars-GRAM data coming from MGCM model results driven by observed TES dust optical depth
- 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 University of Michigan Mars Thermospheric General Circulation Model (MTGCM)⁵.

Reasons for Sensitivity Study Inaccuracies at Large Optical Depths

MGCM results for Mars-GRAM with MapYear = 0 were from MGCM runs with fixed background dust optical depth (tau) values of (0.3, 1.0, and 3.0) for the entire year at all locations.

For the tau = 3.0 case, it has been determined that:

- Unrealistic energy absorption by uniform atmospheric dust leads to an unrealistic thermal energy balance on the polar caps
- Outcome is an inaccurate cycle of condensation/sublimation of the polar caps and, as a consequence, an inaccurate cycle of total atmospheric mass and global-average surface pressure.
- Under an assumption of unchanged temperature profile and hydrostatic equilibrium, a given percentage change in surface pressure would produce a corresponding percentage change in density at all altitudes
- Consequently, for tau = 3.0, the final result is an imprecise atmospheric density at all altitudes

Mars-GRAM 2010 Adjustment Factors

Mars-GRAM was evaluated at locations and times of TES limb observations, and adjustment factors (ratio of observed TES density to Mars-GRAM density) were determined.

- Adjustment factors [F(z, Lat, Ls)] were expressed as a function of height (z), Latitude (Lat) and areocentric solar longitude (Ls).
- For altitudes above 80 km, Mars-GRAM MTGCM densities were compared to aerobraking densities measured by Mars Global Surveyor (MGS), Mars Odyssey (ODY), and Mars Reconnaissance Orbiter (MRO).

References

- ¹Striepke S. A. et al. (2002) AIAA Atmospheric Flight Mechanics Conference and Exhibit, Abstract # 2002-4412.
²Justus C. G. et al. (2005) "Mars Aerocapture and Validation of Mars-GRAM with TES Data", 53rd JANNAF Propulsion Meeting.
³Smith M. D. (2004) Icarus, 167, 148-165.
⁴Haberle, R. M., Pollack, J. B., Barnes, J. R., et al. (1993) "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.
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Background Image of Mars Courtesy NASA

Adjustment Factor Requirements

The adjustment factors generated by this process had to satisfy the gas law: $p = \rho RT$ as well as the hydrostatic relation: $dp/dz = -\rho g$.

- T is assumed to be unchanged and both p and rho are adjusted by a common factor, F, preserving both relations
- Adjustment factor, F, is applied to the daily mean MGCM density and pressure (0-80 km) and MTGCM density and pressure (above 80 km)
- Pressure scale height (RT/g) is unchanged by this process
- Pressure has been changed by the adjustment factor, thus the height of the 1.26 nbar pressure level, referred to as ZF in Mars-GRAM, has changed.

The daily mean MGCM or MTGCM density, DTA0, and the daily mean MGCM or MTGCM pressure, PTA0, depend on z, Lat, Ls, tau, and solar activity parameter (F10).

- The adjusted values of DTA0' and PTA0' are computed from the adjustment factors F using the following equations:

$$DTA0' = DTA0 * F(z, Lat, Ls)$$

$$PTA0' = PTA0 * F(z, Lat, Ls)$$

where the adjustment factor F has been determined as described above.

- Adjustment factors F are also used to adjust ZF by the relation:

$$ZF' = ZF + H \ln(F)$$

where H is local pressure scale height.

Development of MTGCM Factors

Mars-GRAM density and pressure need to be consistent at 80 km, where the transition from MGCM to MTGCM data occurs.

- Assumption was made that F(80, Lat, Ls) for the MTGCM data had to be the same as the adjustment factor at 80 km for the MGCM data.
- After adjustment factors F(80, Lat, Ls) were determined from the MGCM analysis, they were used to determine MTGCM adjustment factors by use of the following equation:

$$F(z, Lat, Ls) = F(80, Lat, Ls) * (1 + A\zeta + B\zeta^2)$$

where the height parameter $\zeta = (z - 80)$ and the coefficients A and B depend on Lat and Ls.

- Final adjustment factors F(z, Lat, Ls) for MTGCM data were implemented into Mars-GRAM and a validation run comparing Mars-GRAM vs. MGS, ODY, and MRO aerobraking data was completed.
- Any residual variation of aerobraking density about mean values that became apparent during this process was used to update the height dependence of Mars-GRAM perturbation standard deviations.

Improvement of Mars-GRAM 2010 at Lower Altitudes

Application of adjustment factors for the MGCM data yields improved comparisons between Mars-GRAM and TES limb data, as shown by density ratios (Mars-GRAM/ TES Limb) given in Figure 1.

- Prior to adjustment these density ratios were as low as 0.65 near 60 km altitude

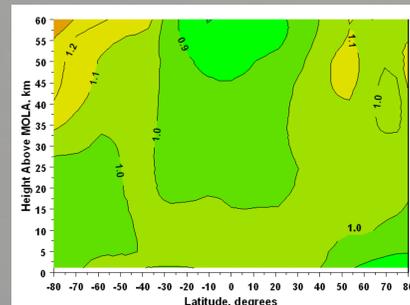


Figure 1. Latitude-height contours of density ratio (Mars-GRAM/ TES Limb) after application of MGCM adjustment factors. These values are averages over all Ls values which have high dust (Ls = 180-270).

Improvement of Mars-GRAM 2010 at Aerobraking Altitudes

As shown in Figures 2 and 3, application of the adjustment factor F(z, Lat, Ls) to the MTGCM data has resulted in the Mars-GRAM (MG) output being closer on average to the accelerometer (ACC) data from the aerobraking phases of MGS, ODY, and MRO.

- When the adjustment factors are added, the slope changes dramatically from a maximum of approximately 11 near 70° N latitude to a slope that averages around 1.

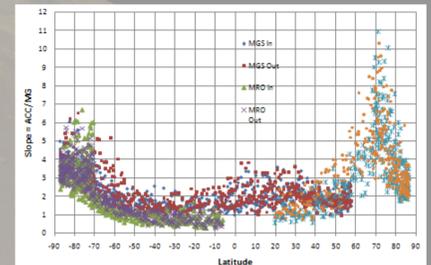


Figure 2. Slope of ACC versus MG as a function of latitude without adjustment factors

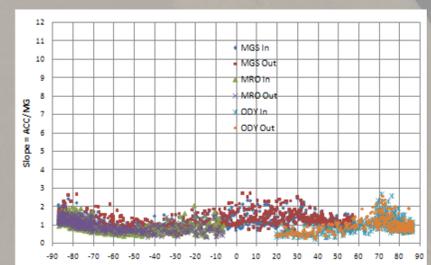


Figure 3. Slope of ACC versus MG as a function of latitude with adjustment factors

Comparison of Mars-GRAM Results with TES data

Mars-GRAM 2005 and Mars-GRAM 2010 MapYear = 0 results have been compared for three locations at LTST 2 and 14.

- Location 1 (L1) = 22.5° S, 180° E, Ls = 90, tau = .11
 - Location 2 (L2) = 22.5° S, 180° E, Ls = 75, tau = .12
 - Location 3 (L3) = 2.5° N, 180° E, Ls = 210, tau = 2.65
- *Location 3 is a Dust Storm case*

As Figure 5 shows, the application of the adjustment factor results in ratios of approximately 1 at lower altitudes.

At the higher altitudes, Mars-GRAM 2010 results have corrected the effect of the underestimated dust aloft in the MGCM. At location 3, the Mars-GRAM 2010 density ratio has shifted closer to 1. This demonstrates that the addition of adjustment factors to Mars-GRAM 2010 has improved the results for the MapYear = 0 cases for large tau values.

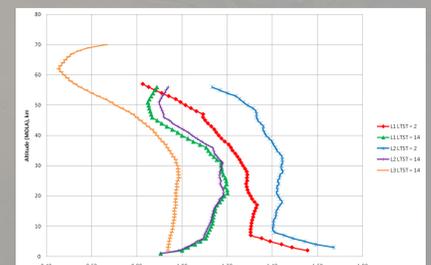


Figure 4. Density Ratio (Mars-GRAM/ TES) for Mars-GRAM 2005

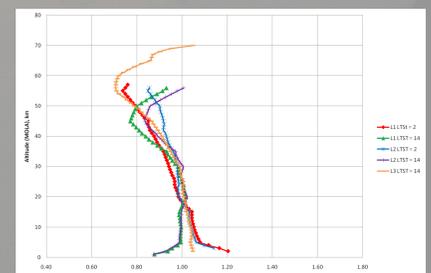


Figure 5. Density Ratio (Mars-GRAM/ TES) for Mars-GRAM 2010

Conclusions

Mars-GRAM 2010 has been developed, validated and is ready for distribution.

- Mars-GRAM is now classified as publically available
- Mars-GRAM 2010 has been updated to Fortran 90/95
- Mars-GRAM 2010 now includes adjustment factors that are used to alter the input data from MGCM and MTGCM for the Mapping Year 0 (user-controlled dust) case
- Greatest adjustment occurs at large optical depths (tau > 1)
- Adjustment factors have led to better correspondence to TES Limb data (0-60 km) as well as MGS, Odyssey and MRO data at approximately 90-130 km