Mars Aerocapture and Validation of Mars-GRAM with TES Data

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Mars Global Reference Atmospheric Model (Mars-GRAM) is a widely-used engineering-level Mars atmospheric model. Applications include systems design, performance analysis, and operations planning for aerobraking, entry descent and landing, and aerocapture. Typical Mars aerocapture periapsis altitudes (for systems with rigid-aeroshell heat shields) are about 50 km. This altitude is above the 0-40 km height range covered by Mars Global Surveyor Thermal Emission Spectrometer (TES) nadir observations. Recently, TES limb sounding data have been made available, spanning more than two Mars years (more than 200,000 data profiles) with altitude coverage up to about 60 km, well within the height range of interest for aerocapture. Results are presented comparing Mars-GRAM atmospheric density with densities from TES nadir and limb sounding observations. A new Mars-GRAM feature is described which allows individual TES nadir or limb profiles to be extracted from the large TES databases, and to be used as an optional replacement for standard Mars-GRAM background (climatology) conditions. For Monte-Carlo applications such as aerocapture guidance and control studies, Mars-GRAM perturbations are available using these TES profile background conditions.

I. Introduction

Mars Global Reference Atmospheric Model (Mars-GRAM) is an engineering-level atmospheric model widely used for diverse mission applications[1-7]. From 0 km to 80 km altitude, Mars-GRAM is based on NASA Ames Mars General Circulation Model (MGCM)[8], while above 80 km it is based on Mars Thermospheric General Circulation Model (MTGCM)[9]. Mars-GRAM and MGCM use surface topography from Mars Global Surveyor Mars Orbiter Laser Altimeter (MOLA)[10], with altitudes referenced to the MOLA areoid, or constant potential surface.

Mars-GRAM 2001, the previous version of Mars-GRAM, has been validated against data from Radio Science (RS) observations[11], and from Thermal Emission Spectrometer (TES) nadir profiles[12]. A newly-released version of Mars-GRAM, named Mars-GRAM 2005, is described here and is validated against RS data, nadir TES data, and TES data from Mars limb soundings[13]. While both the RS and TES nadir data extend up to an altitude of about 40 km, TES limb data reach altitudes of about 60 km or slightly higher. Results from comparison of Mars-GRAM with TES limb data are particularly relevant for aerocapture at Mars, since aerocapture periapsis altitude would typically be in the range of about 40-60 km, i.e., above the height range covered by RS or TES nadir data.

II. New Mars-GRAM Features

Two new features of Mars-GRAM 2005 that are of importance for aerocapture are:

1) Option to use input data sets from MGCM and MTGCM model runs that were designed to closely simulate the 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).
2) Option to read and use any "auxiliary profile" of temperature and density versus altitude.

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In exercising the auxiliary profile Mars-GRAM option, the alternate data (i.e., values from the auxiliary profile) totally replace data from the original MGCM/MTGCM databases. One example of an auxiliary profile would be data from RS or TES (nadir or limb) observations at a particular location and time.

III. Validation of Mars-GRAM 2005

For Mars-GRAM 2001 validation studies (Refs. 2 and 5), 2,480 RS profiles were compared with Mars-GRAM results for the same location and time as each RS profile. Mars-GRAM 2005 climatology has been compared with over 12,000 RS profiles, approximately 5 times as many as for the 2001 comparison. The new, larger RS database provides more complete seasonal (Ls) coverage, over a wide range of latitudes, than represented in the earlier validation comparisons. Figure 1 presents results of average Mars-GRAM minus RS atmospheric density as a function of height and latitude, with all seasons (Ls values) combined. At almost all heights and latitudes, mean Mars-GRAM density differs by less than 10% from mean RS density. These results are slightly better than for the comparison of RS data with Mars-GRAM 2001, where a zone of slightly greater than 10% differences was seen at heights above about 32 km and latitudes poleward of about 50N.

Comparisons of Mars-GRAM 2005 climatology with TES limb data (Conrath et al., 1999) have also been conducted. Figure 2 compares atmospheric density profiles from Mars-GRAM 2005 and TES limb data at representative Phoenix landing conditions (Ls = 78 degrees, latitude = 67.5N, longitude = 223.1E, for limb data from TES Year 1). The TES limb data profile in Fig. 2 is an average of 17 individual limb profiles that are near this location and time. The average TES limb profile, formatted for use as an "auxiliary profile" in Mars-GRAM 2005, is also given in Table 1. Zero wind values in Table 1 indicate that no wind observations are available, so original MGCM wind values are assumed. Figure 2 shows good agreement between Mars-GRAM 2005 and TES limb densities for heights up to about 30 km, and above about 50 km. Mars-GRAM 2005 density becomes about 15% higher than TES limb density near 40 km altitude.

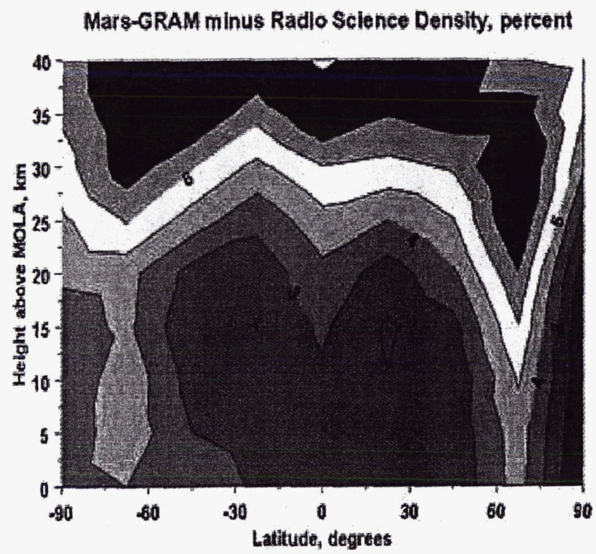

Figure 1. Average Mars-GRAM minus RS atmospheric density as a function of height and latitude.

In contrast to the high latitude case shown in Fig. 2, Fig. 3 compares Mars-GRAM 2005 density at equatorial conditions (for Ls=120) with both TES limb data and TES nadir data. TES limb and nadir data agree quite well with each other, over the full height range for which nadir data are available. Figure 3 shows that Mars-GRAM 2005 density agrees well with both types of TES data, up to a height of about 30 km. However, Mars-GRAM 2005 densities begin to deviate (on the low side) from TES limb data above about 30 km, with Mars-GRAM densities being about 40% lower than TES limb data between about 45 km and 55 km.

Figure 4 shows results from Mars-GRAM versus TES limb data density comparisons, averaged over all seasons (all Ls values), all latitudes, and both TES years 1 and 2. This figure shows average Mars-GRAM minus TES density (as percent of TES density) versus height and latitude. Figure 4 shows that results from Figs. 2 and 3 are not atypical. At high northern latitudes, Fig. 4 indicates that Mars-GRAM agrees closely with TES limb data, with Mars-GRAM being about 10% to 15% larger than TES near 40 km altitude. This behavior is similar to that shown in Fig. 2. In contrast, Fig. 4 shows that, over a broad range of low and middle latitudes, Mars-GRAM densities are significantly lower than TES limb densities for heights of about 40 km and higher, analogous to Fig. 3.

Figure 5 shows mean altitude profiles of Mars-GRAM 2005 versus TES limb density and temperature, averaged over all latitudes and seasons (all Ls values), separately for TES Years 1 and 2. In this figure, differences in both mean density and temperature are given in percent. A large, global-scale dust storm occurred during TES Year 2[14]. Note, however, that average Mars-GRAM versus TES comparisons for density and temperature are actually slightly

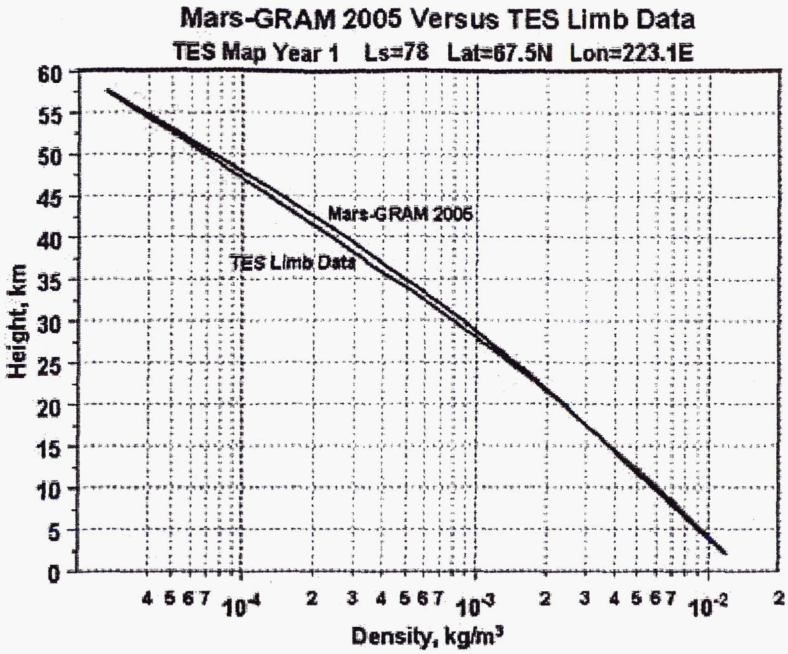

Figure 2. Density profiles from Mars-GRAM 2005 and TES limb data at representative Mars Phoenix landing conditions.

better for TES Year 2 than for TES Year 1. This result would seem to indicate that Mars-GRAM (and MGCM on which it is based) represents dust effects at least as well during dust storm conditions as during non-storm conditions. Figure 5 confirms that the tendency of Mars-GRAM to underestimate density at high altitudes (especially at low-to-middle latitudes) is a feature of both TES Years 1 and 2.

Figure 5 indicates that the tendency of Mars-GRAM to underestimate density at high altitudes (40 to 60 km) results from a "cold bias" in Mars-GRAM temperatures over this upper altitude region. If Mars-GRAM temperatures are colder than observed, over an extended altitude region, then hydrostatics forces Mars-GRAM density to become lower than observed, by an exponentially-increasing

Table 1. Sample Mars-GRAM 2005 auxiliary profile (average of 17 TES limb profiles at Mars Phoenix landing conditions).

Height	Lat	LonE	TempK	PresNm2	Denskgm3	Uwind	Vwind
2.172	67.50	223.10	209.39	4.751E+02	1.187E-02	.00	.00
4.825	67.50	223.10	203.59	3.700E+02	9.509E-03	.00	.00
7.408	67.50	223.10	197.79	2.881E+02	7.622E-03	.00	.00
9.921	67.50	223.10	192.08	2.244E+02	6.113E-03	.00	.00
12.365	67.50	223.10	186.63	1.748E+02	4.900E-03	.00	.00
14.744	67.50	223.10	181.46	1.361E+02	3.925E-03	.00	.00
17.062	67.50	223.10	176.77	1.060E+02	3.138E-03	.00	.00
19.326	67.50	223.10	172.53	8.255E+01	2.504E-03	.00	.00
21.540	67.50	223.10	168.64	6.429E+01	1.995E-03	.00	.00
23.709	67.50	223.10	165.22	5.007E+01	1.586E-03	.00	.00
25.838	67.50	223.10	162.06	3.900E+01	1.259E-03	.00	.00
27.931	67.50	223.10	159.20	3.037E+01	9.982E-04	.00	.00
29.992	67.50	223.10	156.83	2.365E+01	7.891E-04	.00	.00
32.029	67.50	223.10	155.03	1.842E+01	6.218E-04	.00	.00
34.048	67.50	223.10	153.86	1.435E+01	4.881E-04	.00	.00
36.057	67.50	223.10	153.15	1.117E+01	3.822E-04	.00	.00
38.061	67.50	223.10	152.50	8.700E+00	2.991E-04	.00	.00
40.051	67.50	223.10	151.68	6.780E+00	2.344E-04	.00	.00
42.039	67.50	223.10	150.77	5.280E+00	1.837E-04	.00	.00
44.019	67.50	223.10	149.83	4.110E+00	1.439E-04	.00	.00
45.987	67.50	223.10	148.78	3.200E+00	1.129E-04	.00	.00
47.948	67.50	223.10	147.71	2.490E+00	8.851E-05	.00	.00
49.888	67.50	223.10	146.72	1.940E+00	6.946E-05	.00	.00
51.825	67.50	223.10	145.76	1.510E+00	5.446E-05	.00	.00
53.720	67.50	223.10	144.75	1.180E+00	4.289E-05	.00	.00
55.646	67.50	223.10	143.68	9.170E-01	3.360E-05	.00	.00
57.546	67.50	223.10	142.68	7.140E-01	2.636E-05	.00	.00

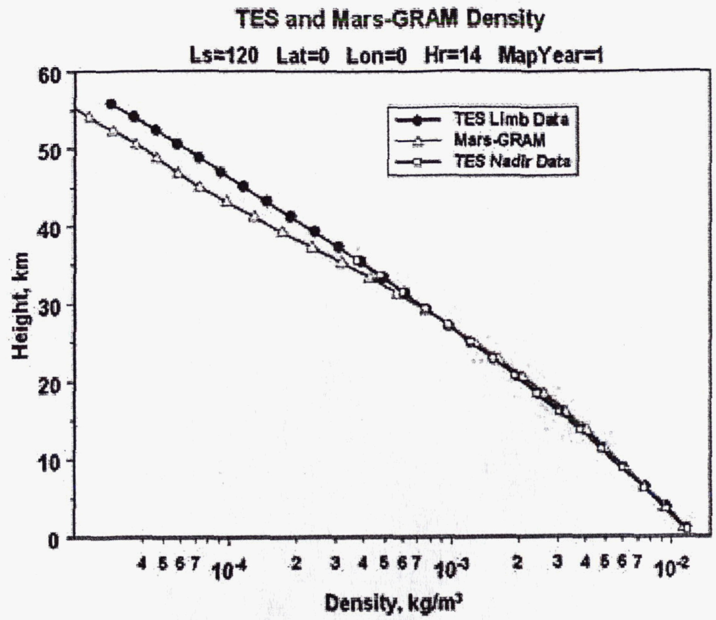

Figure 3. Density profiles from Mars-GRAM 2005, TES nadir data, and TES limb data at equator, for Ls = 120.

amount, as the depth of the cold bias layer increases. A "rule of thumb" approximation to estimate effects of such bias is that if a temperature bias = ± x (in percent) persists over a layer of depth = n scale heights, then the density deviation at the top of the layer will be ± x × n (in percent), assuming density deviation starts at zero at the bottom of the layer. For TES Year-1 data in Fig. 5, we have x averaging about -5% over the layer from about 15 km to about 55 km altitude (roughly 5 scale heights). The rule of thumb thus gives a density deviation = -5% × 5 scale heights = -25% at the top of this layer, is good agreement with observed density deviations at the 55-km layer top.

Preliminary studies by Murphy[§] using various vertical dust profiles suggest that MGCM's tendency to yield a cold bias results from too little dust at upper altitudes in the normal MGCM vertical dust distribution. Mars-GRAM 2005, which is based upon MGCM output, reflects this cold bias. For a given total dust loading (dust optical depth), increasing the relative amount of dust at higher altitudes in MGCM would produce additional heating of the upper altitude layers, thereby reducing or removing the cold bias and the resulting Mars-GRAM tendency toward low densities compared to observations. Until updated MGCM data are available for incorporation in Mars-GRAM, it may be advisable for aerocapture studies to use auxiliary profiles from TES limb data as Mars-GRAM input conditions.

IV. Conclusions

The new Mars-GRAM option to use "auxiliary profiles" derived from TES limb data will be especially useful for aerocapture analyses. For aerocapture maneuvers with periapsis at low-to-middle latitudes, TES limb density data is typically larger than Mars-GRAM density by as much as 40% at periapsis altitudes (40 to 60 km). At high northern and southern latitudes, agreement is better between Mars-GRAM and TES limb densities. However, at high northern latitudes, such as planned for Phoenix entry and landing, Mars-GRAM overestimates

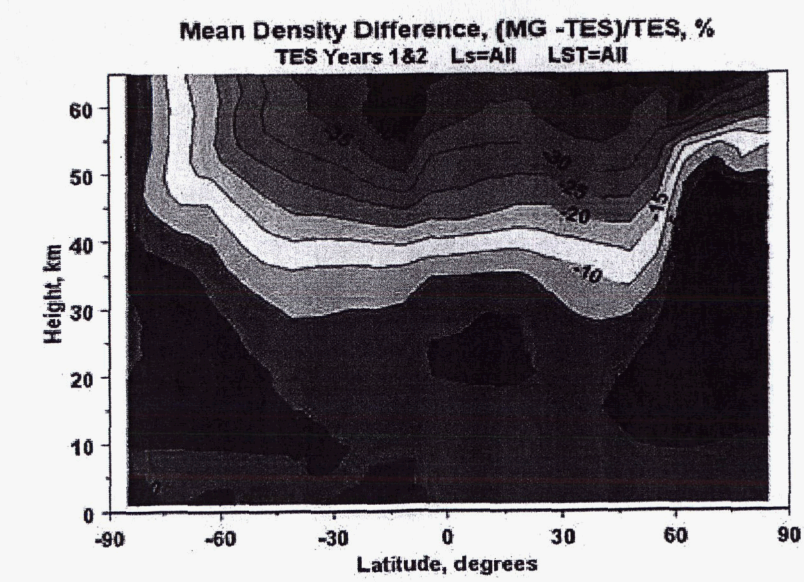

Figure 4. Mean density difference, Mars-GRAM 2005 minus TES limb data, versus height and latitude.

[§] Private communication, 13 Jan. 2005.

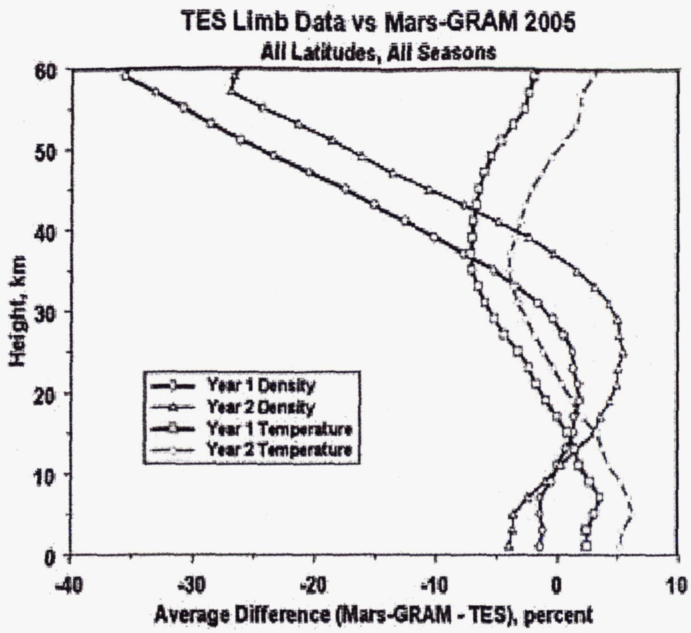

Figure 5. Comparison of Mars-GRAM 2005 density and temperature with TES limb data, for all seasons and latitudes.

density compared to TES limb data by about 10-15% in the 30 to 45-km height range.

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