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Atmosphere Variability at Mars Reconnaissance Orbiter Science Orbit Altitudes Based on Mars Express Reconstructions

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This paper describes the orbit reconstruction of Mars Express (MEX) with the specific goal of estimating the atmospheric density near periapsis and evaluating its variability and predictability. The desired outcome is to validate the covariance analysis assumption of atmospheric variability for the 2005 NASA Mars Reconnaissance Orbiter (MRO), as well as evaluate the accuracy of the density estimates output from the atmosphere model used by MRO. Topics covered include the MRO atmosphere model, MEX orbit determination and post-fit Doppler residuals, and atmosphere trending statistics gleaned from the orbit reconstructions.

INTRODUCTION

Mars atmospheric variability is assumed to be the largest error source for ephemeris prediction during the science phase of the NASA Mars Reconnaissance Orbiter (MRO), slated for launch in August 2005. The MRO science orbit will be 255 x 320 km, with periapsis frozen over the south pole. This altitude regime is contained in an atmospheric region referred to as the exosphere, the lower portion of which has been only sparsely sampled by previous missions as they entered and exited aerobraking. The lack of periapsis tracking data between 255 and 320 km creates a corresponding lack in quantifiable measurements of exospheric density and its variability for the MRO science orbit.

On 25 December 2003, the ESA Mars Express (MEX) spacecraft arrived at the Red Planet and subsequently established a periapsis altitude of approximately 265 km. Fig. 1 shows the altitude versus latitude relationship for the MEX arcs during Feb. 2004 and May-July 2004, along with the MRO frozen science orbit. The close proximity of the

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MEX periapsis altitude to the lower portion of the MRO science orbit allows for a virtually direct comparison of the atmosphere through that region.

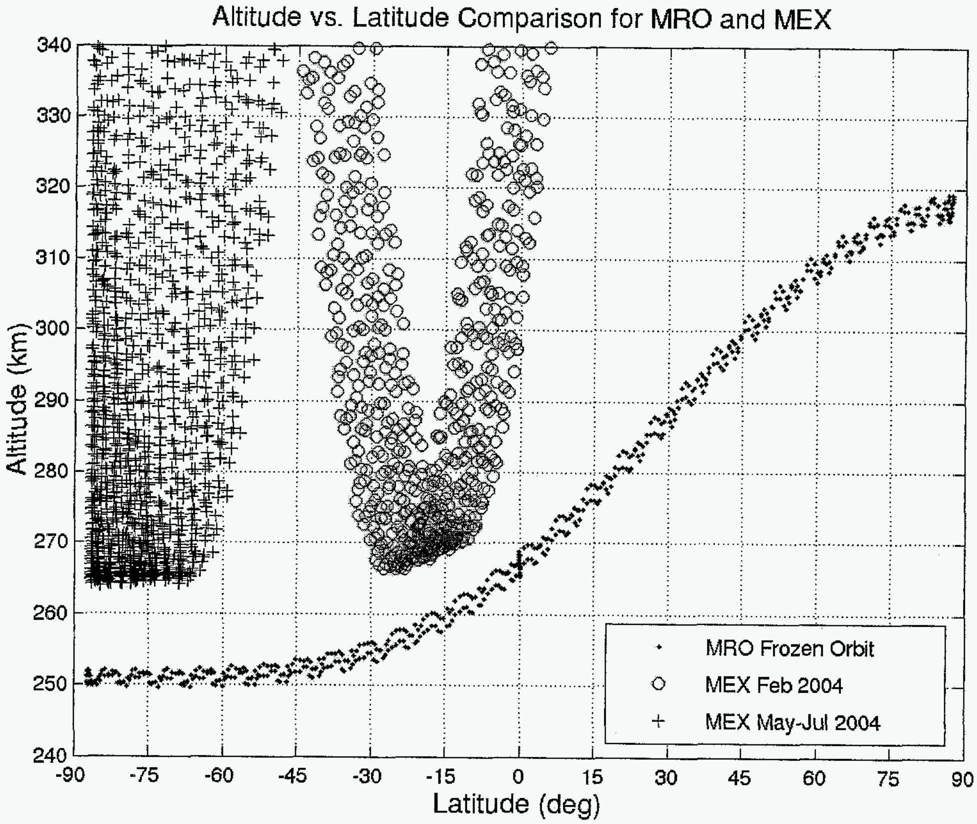

Figure 1. Altitude vs. latitude comparison between MRO frozen primary science orbit and fit spans of MEX precessing orbit. The MEX apoapsis altitude was 11,570 km in February 2004, then 10,110 km in May-July 2004.

The goal of this analysis is to characterize the atmospheric model currently used in the MRO covariance analyses. At issue is the assumption of 35% 1σ uncertainty in density, as well as the overall mean density through the MRO altitude regime. Examination of the MEX flight data provides insight to the validity and accuracy of the MRO assumptions.

Estimates of atmospheric density can be obtained by reconstructing the MEX orbit, assuming that the spacecraft experiences a measurable amount of drag through periapsis. The orbit determination (OD) filter can then estimate a scale factor for each periapsis passage that adjusts the modelled density value to match the observed drag acceleration. The equation for drag acceleration is

$$a_D = -\frac{1}{2}\rho V^2 \frac{C_D A}{m} \tag{1}$$

where ρ is density, V is spacecraft velocity relative to the atmosphere, C_D is drag coefficient, A is effective drag area, and m is spacecraft mass. By scaling ρ in Eqn. 1 to match the drag inferred by MEX tracking data, one must assume that the other parameters on the right hand side are well known. Given that, scale factor estimates become a measure of the variability of the density and, to the point, the atmospheric model.

MARS ATMOSPHERE MODEL

The basic model currently in use by MRO is the Mars Global Reference Atmosphere Model (MarsGRAM), developed by Dr. Jere Justus at the Marshall Space Flight Center [1]. The latest version of MarsGRAM (version 2001) uses as its inputs tables of various atmospheric parameters output by the NASA Ames Mars General Circulation Model (MGCM) and the University of Arizona Mars Thermospheric General Circulation Model (MTGCM). These models are physically based and cover the entire planet. MGCM provides data tables below 80 km altitude; MTGCM provides the tables between 80 and 170 km altitude. Above 170 km, MarsGRAM 2001 uses information from a modified Stewart thermospheric model. The code interpolates between the models to make a smooth transition between MTGCM and the Stewart models between 155 and 170 km.

Since the Stewart model is based on data from the Viking missions in the mid-1970s, it was thought that the use of MarsGRAM 2001 for the MRO science orbit altitudes might not provide the most accurate representation of the density. MTGCM uses more recent data, but is only valid below 170 km, and its structure is not easily adaptable for the purposes of obtaining densities along the path of an orbiting spacecraft. For this reason, Justus and Dr. Stephen Bougher, who developed MTGCM, have collaborated to provide an update to MarsGRAM 2001, dubbed the MRO "Special Edition" (SE), specifically for MRO use. The SE version suppresses the fairing between MTGCM and the Stewart model between 155 and 170 km so that MTGCM data is used all the way up to 170 km. MarsGRAM 2001 SE also applies height-dependent multiplier factors to adjust Stewart model values above 170 km to agree better with special MTGCM data sets covering the altitude range 160 - 250 km. Additional modifications include the application of a density and pressure floor, which prevents those values from being less than 0.1 times daily mean density or pressure, and changes to the reference ellipsoid parameters to reflect the MRO accepted constants. Thus, the SE version gives identical results to the standard MarsGRAM below 155 km, but different values above. It is the MRO SE version that is used in the MEX orbit reconstructions.

MEX ORBIT RECONSTRUCTION: FEBRUARY 2004 ARCS

MEX tracking data and corresponding modelling inputs were obtained as a result of the relationship established between the European Space Operations Center (ESOC) Flight Dynamics and the NASA Jet Propulsion Laboratory (JPL) Navigation teams for MEX interplanetary cruise [2,3]. ESOC provided JPL with auxiliary files and science orbit tracking data from New Norcia through the interface previously defined for cruise. Additional tracking data from JPL Deep Space Network (DSN) sites was also available.

Fit Span & Characteristics

Orbit reconstructions were performed on arcs of tracking data between 1-29 February 2004. Only quiescent periods—periods of no thrusting—were fit, resulting in 14 separate arcs of approximately 2 days each. The two-day arcs avoided momentum wheel off-loading (WOL) maneuvers that were not tracked by the ground. Attempting to fit density/drag estimates and maneuvers in the same arc reduces the confidence in the drag estimates due to aliasing by maneuver mismodelling. In fact, the periapsis passes before and after the WOL, which often occurred near apoapsis, usually could not be estimated due to the lack of tracking data in between to separate them. Therefore, the orbit reconstructions are limited to within the spans of tracking data between WOLs.

Dynamic Models

Accurate dynamic models are paramount to determining the orbit well enough to observe a force as small as drag at orbital (as opposed to aerobraking) altitudes. To that end, the primary models used in this analysis include:

- 85x85 MGS85H2 gravity field, which accounts for tracking data from the NASA Mars Odyssey 200x500 km transition orbit and for Mars nutation [4].
- Third-body perturbations with respect to the Sun, planets, and moons.
- Solar radiation pressure, using the MEX spacecraft model tuned during cruise [3].
- Spacecraft attitude quaternions from telemetry, including body-relative solar panel pointing.
- MarsGRAM 2001 MRO SE.
- Spacecraft component self-shadowing compensation along the drag direction.

With regard to the last item, it was mentioned in Sect. 1 that the other parameters in the drag equation (Eqn. 1) must be well known. In order to accurately model the effective drag area in a free-stream flow, shadowing of one spacecraft component from another must be considered. It is especially important for MEX because the spacecraft attitude around periapsis is not always the same. Some are science passes with the instruments pointed towards the planet, and others are Earth-comm passes with the body-fixed high gain antenna (HGA) pointed to Earth.

Graphical depictions of the spacecraft component self-shadowing computation are shown in Figs. 2 and 3. Fig. 2 illustrates four attitudes of a science pass near the periapsis on 1 February 2004 14:38:06 ET, at latitude –12.186 deg. Fig. 3 shows the same for an Earth-comm pass near the periapsis on 2 February 2004 20:56:35 ET, at latitude –12.922 deg. The view is along the drag direction and filled-in areas indicate blockage.

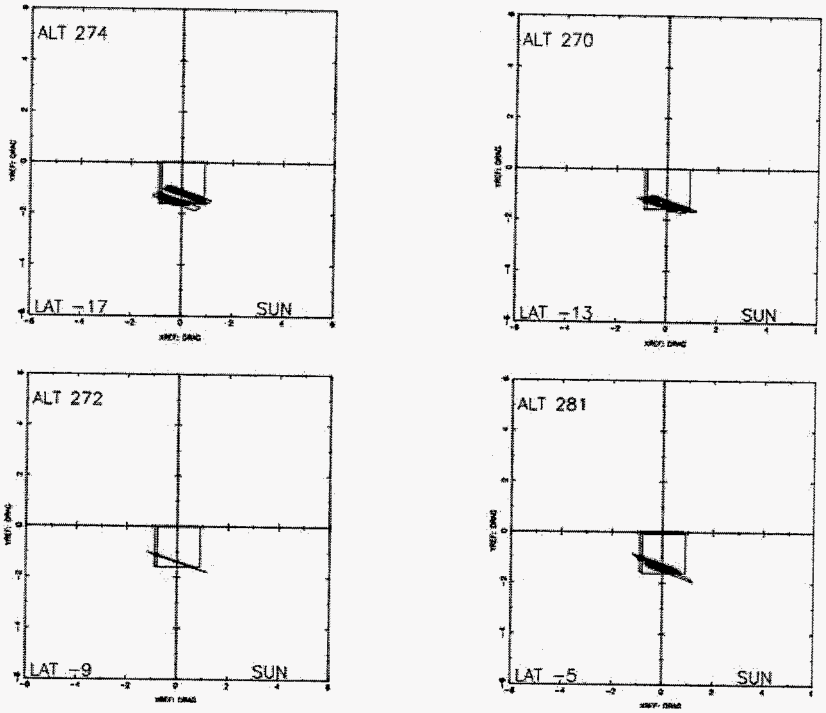

Figure 2. Graphical output from shadow program for a MEX science (non-tracked) pass. View is along the drag direction with shadowed components shaded. Altitude is indicated in km, latitude in deg N. "SUN" indicates that the spacecraft is in full Sun.

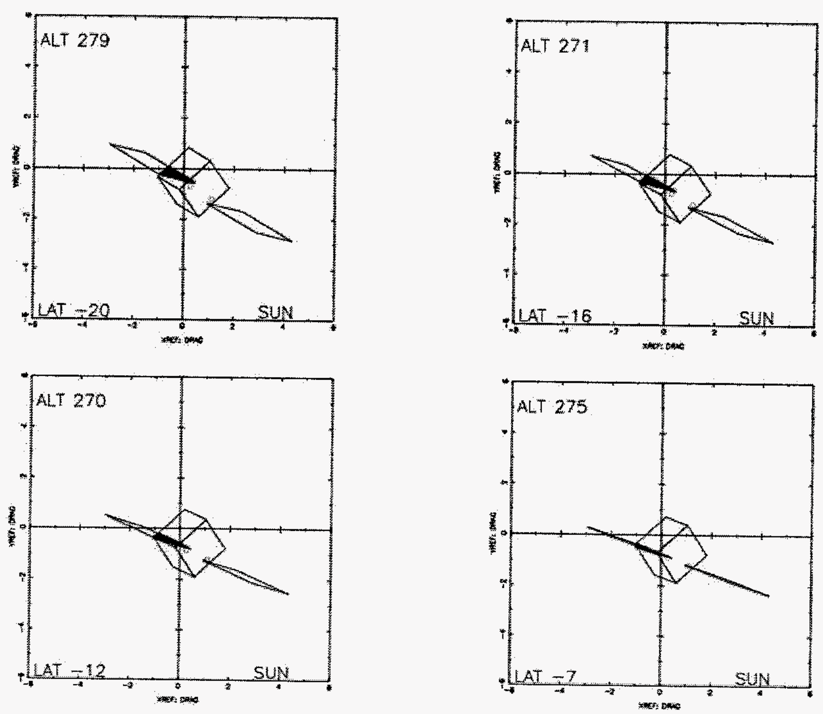

Figure 3. Graphical output from shadow program for a MEX Earth-comm (tracked) pass.

Comparing the figures indicates that there is shadowing in both cases, though relatively small due to the edge-on orientation of the solar panels. Thus, the self-shadowing compensation produces a slight overall decrease in the effective drag area, resulting in a slight overall increase in density scale factor estimates.

Estimated Quantities

Given that only quiescent arcs were reconstructed, the estimated quantities were limited to the spacecraft state, solar radiation pressure (SRP) coefficient, and density scale factors for each periapsis pass during the arc. The initial state was obtained from the reference trajectory, with an essentially infinite a priori uncertainty of 1,000 km in position and 10 m/s in velocity. The SRP coefficient had a nominal value of 1.0 with a 10% 1σ uncertainty. The density scale factors also had a nominal value of 1.0, but with the 35% 1σ uncertainty assumed for the MRO analysis. A constant density scale factor was estimated between each apoapsis. This provided a constant multiplier for the structure of the atmosphere around each periapsis, under the assumption that, by far, the majority of the drag was experienced in the region immediately around periapsis (see Fig. 1).

Results

Only two-way X-band Doppler tracking was used for the orbit reconstructions. The data weight for DSN stations was 0.0056 Hz (0.10 mm/s, one-way), while NNO was weighted at 0.0084 Hz (0.15 mm/s, one-way). A ground station elevation mask of 15 deg was used to eliminate the noisy low elevation measurements. This shortened the NNO passes more so than the DSN (Madrid and Goldstone, i.e., northern hemisphere) passes because of the high declination of Mars during February 2004.

Fig. 4 shows the post-fit residuals for all 14 arcs. The overall noise is 0.029 mm/s, with a DSN/NNO split of 0.021/0.038 mm/s. The fits include all Doppler points but extreme outliers. A zoom in to particular passes would show that some still exhibit subtle signatures, possibly due to gravity mismodelling; however, the achieved residual noise is very good considering that only state, SRP coefficient, and density scale factors are estimated. Adding range data to the fit does not alter the filter solution because the Doppler signal is so strong.

For the estimated state, the 1σ formal uncertainties in epoch position and velocity for the 14 arcs averaged 29 m and 3.3 mm/s, respectively. The SRP coefficients converged from the a priori 0.10 to an average of 0.01 formal uncertainty, with all values between 0.96 and 1.05. The formal uncertainty for the 63 estimated density scale factors reduced from 0.35 to an average of 0.20, with the mean of the estimates being 0.70. Fig. 5 shows the scaled density resulting from the estimated scale factors, along with the density output from the MarsGRAM 2001 MRO SE model at each estimated periapsis point. Clearly, the estimated densities are much noisier than the model. The following section discusses the scale factor estimates and the search for correlations and predictability.

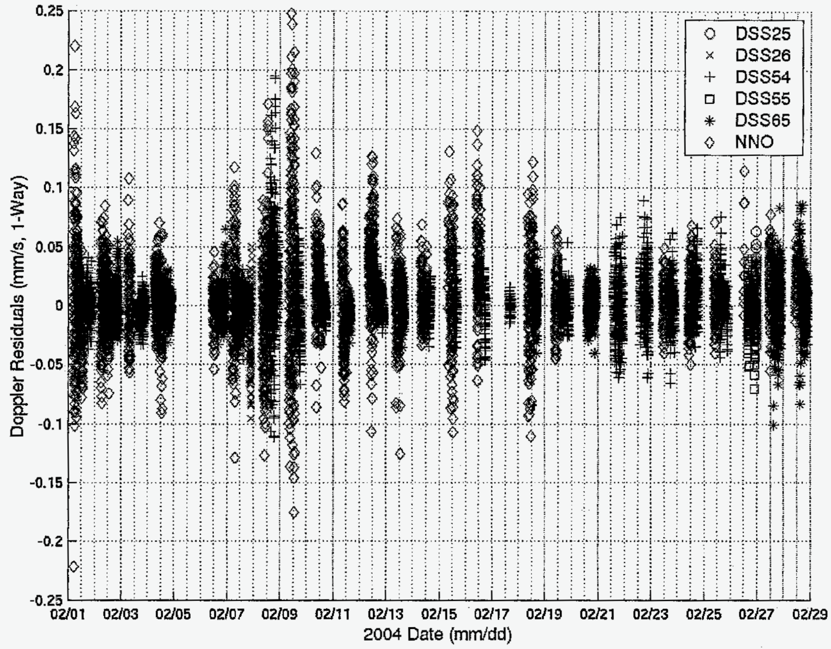

Figure 4. Post-fit 2-way X-band Doppler residuals for MEX orbit reconstruction. 1σ noise is 0.029 mm/s, one-way (0.0016 Hz).

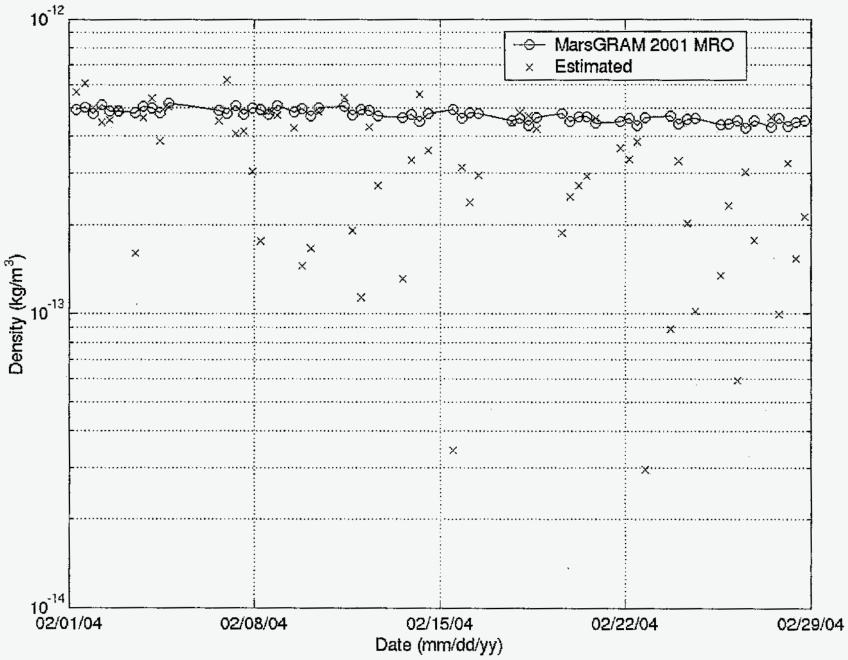

Figure 5. Reconstructed periapsis density versus density modelled by MarsGRAM 2001 MRO at periapsis.

SCALE FACTOR TRENDS

Correlation

Figs. 6-9 show plots of the estimated density scale factor versus time, altitude, latitude, and longitude. The plots against altitude and latitude look similar to the plot with time, but in the opposite direction, because both altitude and latitude are decreasing with time. A line fit to either of those three plots would not make sense hydrostatically because the mean density is decreasing with decreasing altitude. There is probably some other phenomenon occurring, perhaps due to seasonal variation or global dust levels.

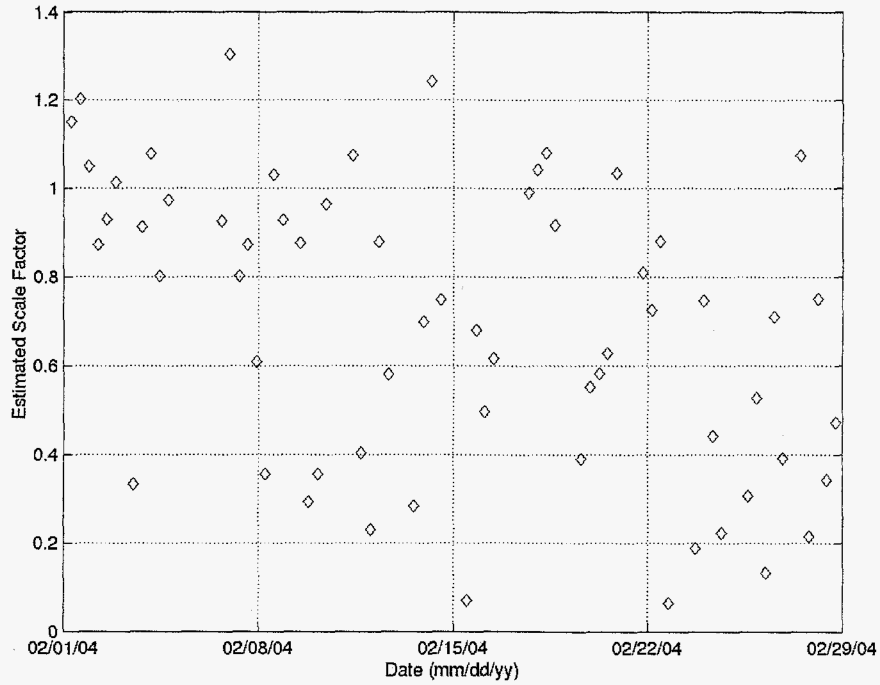

Figure 6. Estimated scale factor vs. time.

The longitude plot in Fig. 9 clearly shows the repeated longitudes of the MEX ground track, but no correlation is obvious. There may be a peak near 200 deg, but it is dubious because there are only three points and all the other longitudes are noisy.

Given the large variability with respect to the model, shown in Fig. 5, searching for a signal in the noise may be fruitless. If there were a seasonal-type variation, a longer data set would be needed to identify it. Also, temporal correlations with longitude, for example, may not be visible with the infrequent re-visits—approximately once every four days. The MEX orbit does not provide visibility into very short-term variations due to the 7.5-hour orbit period and corresponding three periapsis passes per day. By contrast, MRO will be in a 112 min period with 12-13 orbits per day, with the entire orbit within the sensible atmosphere.

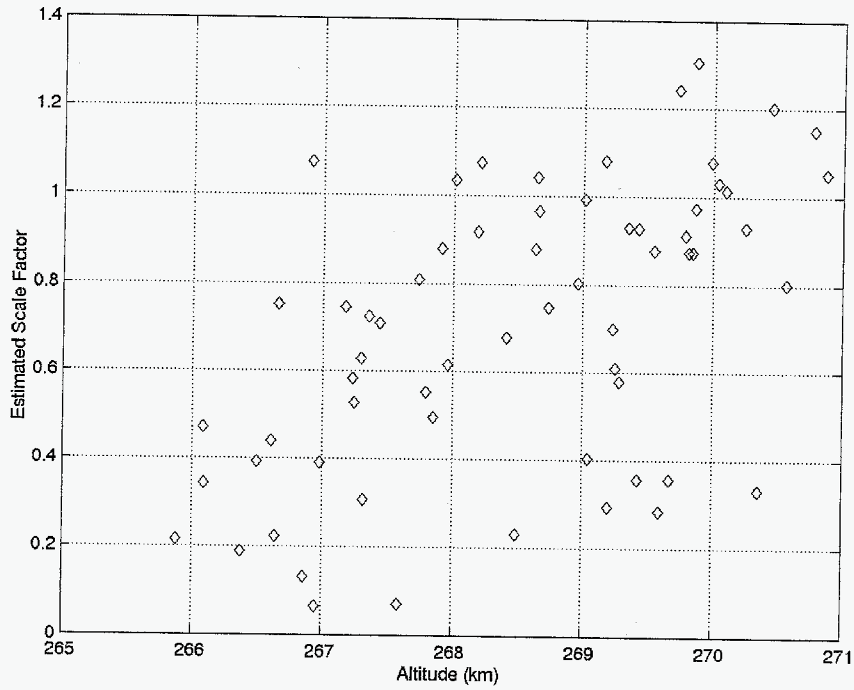

Figure 7. Estimated scale factor vs. altitude of periapsis.

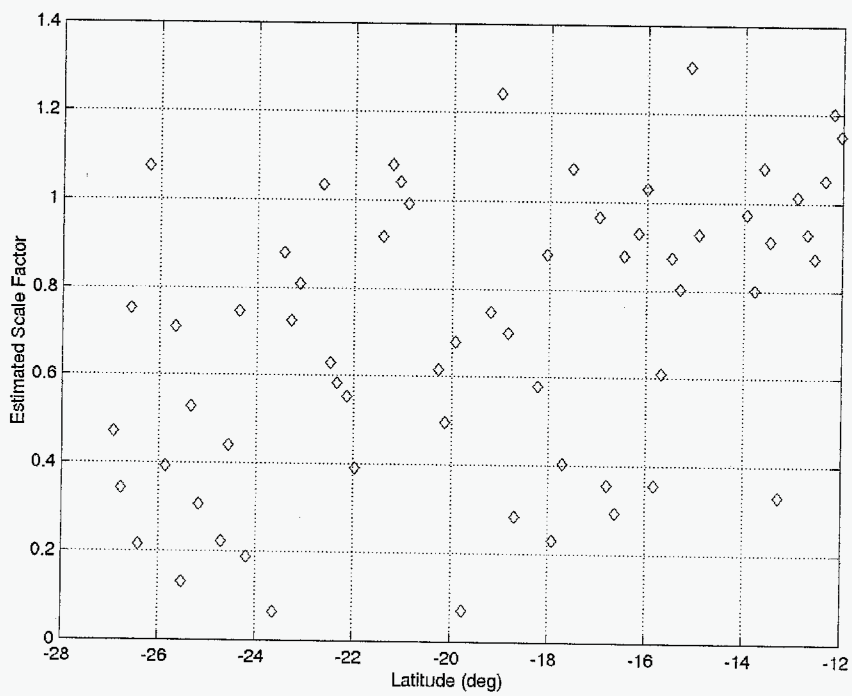

Figure 8. Estimated scale factor vs. latitude of periapsis.

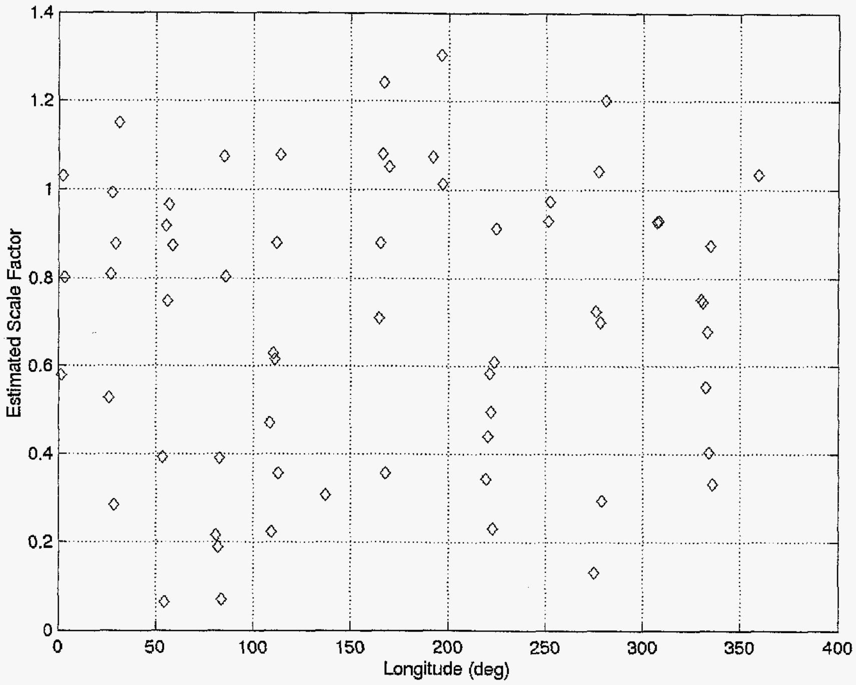

Figure 9. Estimated scale factor vs. longitude of periapsis. Note the repeated longitudes.

Prediction

Given no obvious correlations with these parameters, an attempt is made to fit simple polynomials to the estimates. The goal is to fit a portion of the 1-29 Feb arc, and then use that fit to predict the remainder of the span. Figs. 10-12 show polynomial fits of order 0, 1, and 2, respectively. The top panel shows the estimated scale factor, a fit over 14 days, then a prediction of the next 14 days using that fit. The bottom panel shows the detrended scale factor over the first 14 days, and the scale factor resulting from the originally estimated versus the predicted-from-fit values. Note that the scale factor mean and standard deviation values indicated on the plot are slightly misleading as the predicted scale factors get further from 1.0. It might be a more accurate measure of the fit to examine the standard deviation scaled by the mean.

In any case, the polynomial fits over two weeks do not seems to help the prediction. In each case the variability is at least 35%, which is consistent with the MRO assumption. The best prediction technique for this data set may be to simply estimate a bias for short-term predictions and revert to the nominal model for the long term.

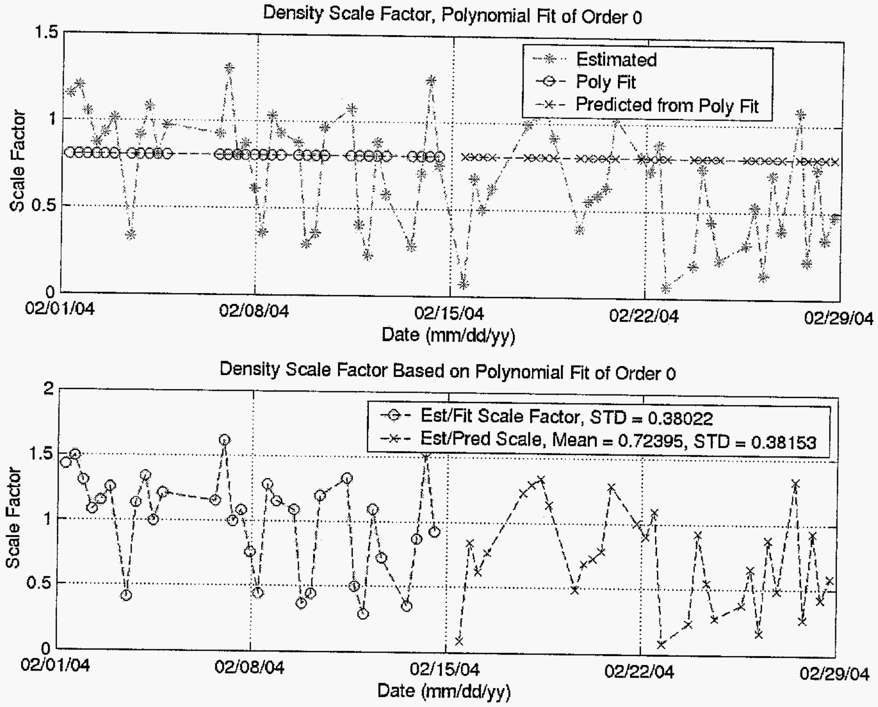

Figure 10. Test density scale factor prediction from zeroth order polynomial fit to first 14 days of arc.

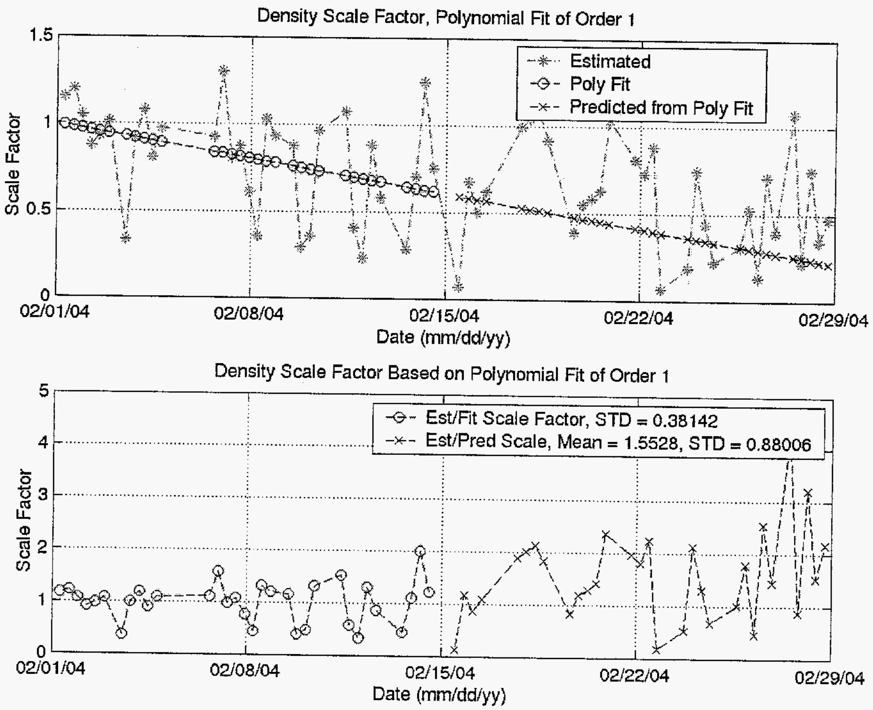

Figure 11. Test density scale factor prediction from first order polynomial fit to first 14 days of arc.

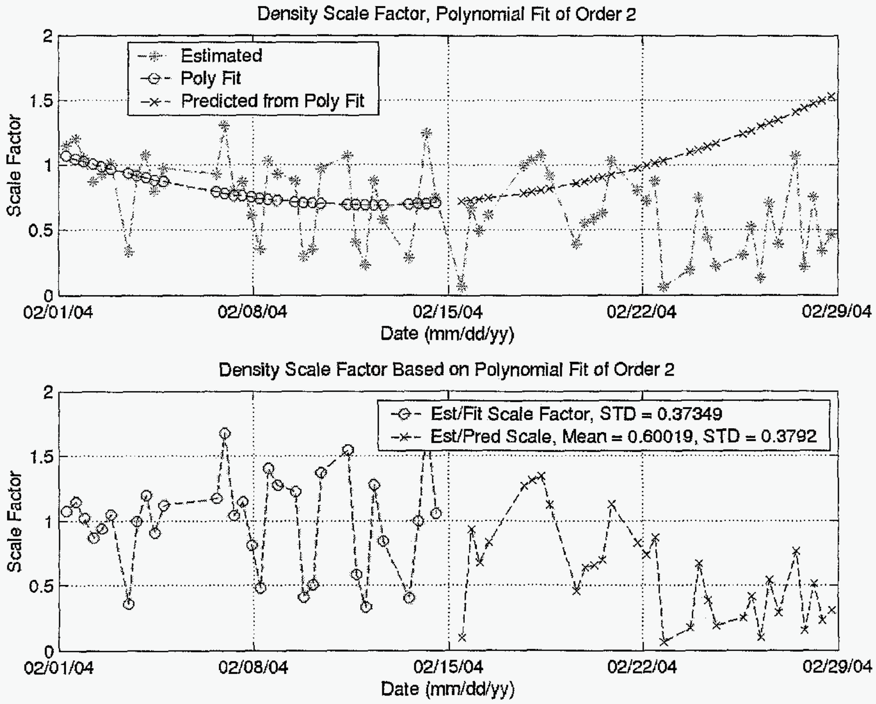

Figure 12. Test density scale factor prediction from second order polynomial fit to first 14 days of arc.

MEX ORBIT RECONSTRUCTION: MAY-JULY 2004 ARCS

Fit Span and Characteristics

Figure 1 shows that during the May to July 2004 arc, the MEX periapsis traverses near the South Pole, where the MRO periapsis will be frozen. In addition to the different periapsis location, the MEX apoapsis altitude is lower than in February by approximately 1,460 km, resulting in an orbit period of 6 hr 40 min. The reconstruction arc spans 15 May to 25 July 2004. As with the previous span, the reconstructions were performed only on periods of no thrusting. This span includes momentum wheel desaturation maneuvers approximately once per day (either every third or fourth apoapsis), resulting in 72 separate arcs.

Dynamic Models

The dynamic models used for this arc are the same, with the exception of no compensation for spacecraft self-shadowing along the drag direction. Every periapsis pass is now nadir pointed, where the solar panels are virtually edge-on to the drag direction (see Figure 2). Given that, and the expected large variability of the estimated density, the self-shadowing compensation would at most make a few percent difference in the overall mean—well within the expected noise.

Estimated Quantities

Spacecraft epoch state, SRP coefficient, and a density scale factor are estimated for each of the 72 arcs, with the same a priori uncertainties as before. However, in this case, the density scale factor is a constant for each arc (over three or four revs), instead of being estimated separately for each periapsis passage. This provides a measure of the daily bias that is less dependent on the amount of tracking between one apoapsis and the next. In other words, two tracking passes per day, independent of their timing relative to the orbit geometry, should provide enough information to the filter to solve for a daily mean bias. Also, the longitudes at the high southern latitudes of periapsis are much closer together, potentially resulting in more uniform measurements of overall bias.

Looking forward to MRO, the primary goal of these reconstructions is to evaluate the daily density bias over the south polar region, where MRO will experience its most significant drag. Does this atmosphere in this region behave differently than the equatorial region analyzed previously? Is it more or less variable, or is it more or less biased with respect to the expected MarsGRAM model values?

Results

Tracking data included both two-way Doppler and range at X-band. The Doppler noise for this time period was equivalent for the DSN and NNO, so they were both weighted at 0.0056 Hz (0.10 mm/s, one-way). Though the range data type only subtly influenced the solution, it was included to add additional insight into residual behavior. Ranging from New Norcia is noisier than DSN ranging, which were consequently weighted at 4 m and 2 m, respectively. An elevation angle cutoff of 10 deg was used at all stations.

Figure 13 shows the post-fit Doppler residuals for all 72 arcs. The overall noise is 0.058 mm/s one-way, with a DSN/NNO split of 0.057/0.058 mm/s. The range residuals are not shown, but the 1σ noise was 0.72 m, with a DSN/NNO split of 0.37/1.1 m. The Doppler noise is twice as large as the residual noise from the February fits (Figure 4). A number of arcs required deletion of significant portions of a tracking pass because of an apparent maneuver during the tracking outage around certain periapses. These changes in Doppler were too large to be reasonably attributed to drag; and some were opposite the drag direction. However, these arcs do not include thrusting by the spacecraft, so the source of the jump in the Doppler (and corresponding slope change in range) must be some other dynamic mismodelling, possibly local gravity.

The epoch states of the 72 one-day arcs converged to an average 1σ formal uncertainty in position and velocity of 157 m and 8.2 mm/s, respectively. The SRP coefficient converged from the a priori 10% uncertainty to an average of 2.3%, with a wider range of estimated values than the February arcs: 0.82 to 1.08 with a mean of 0.96. The formal uncertainty for the 72 estimated density scale factors converged from the a priori value of 0.35 to an average of 0.22, with the mean of the estimates being 0.49. Three of the arcs did not reduce the formal sigma to less than 0.349, so they were eliminated from the plots that show the scale factor (or density) estimates.

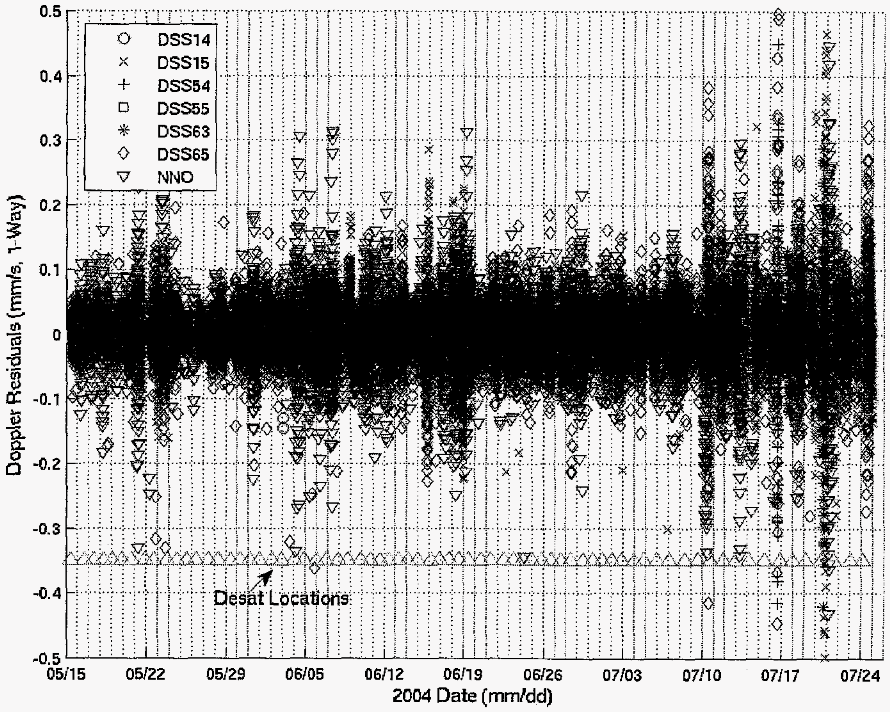

Figure 13. Post-fit two-way X-band Doppler residuals from New Norcia (NNO) and DSN stations in Goldstone (14, 15) and Madrid (54, 55, 63, 65). 1σ noise is 0.058 mm/s one-way (0.0032 Hz).

Figure 14 shows the densities obtained by the MarsGRAM model versus those scaled by the density scale factor estimated from the tracking data. The plot shows negative densities because the filter solved for negative scale factors. Clearly, density scale factors should be positive. This is an indication that mismodelling of other forces has aliased into the scale factor estimates. However, the overall scale factor mean of 0.49 is in the same direction as the value of 0.70 obtained for the February arc, demonstrating some consistency in the general nature of the bias of the MarsGRAM model.

Scale Factor Correlations

The search for correlations and predictability in the February arc showed the task to be a difficult one. For this south polar arc, the scale factor estimates are daily means, instead of per-rev, and the periapsis longitudes are much closer to each other. Thus, there may still exist a signal amidst the apparent noise. Figures 15-17 show the estimated scale factor plotted against time, altitude, and latitude, respectively. The mean longitude for each of these arcs is not particularly meaningful and, thus, is not plotted against scale factor. Figure 15 shows the high variability of the daily biases, and no obvious correlation can be seen in the altitude plot of Figure 16, or in the latitude plot of Figure 17.

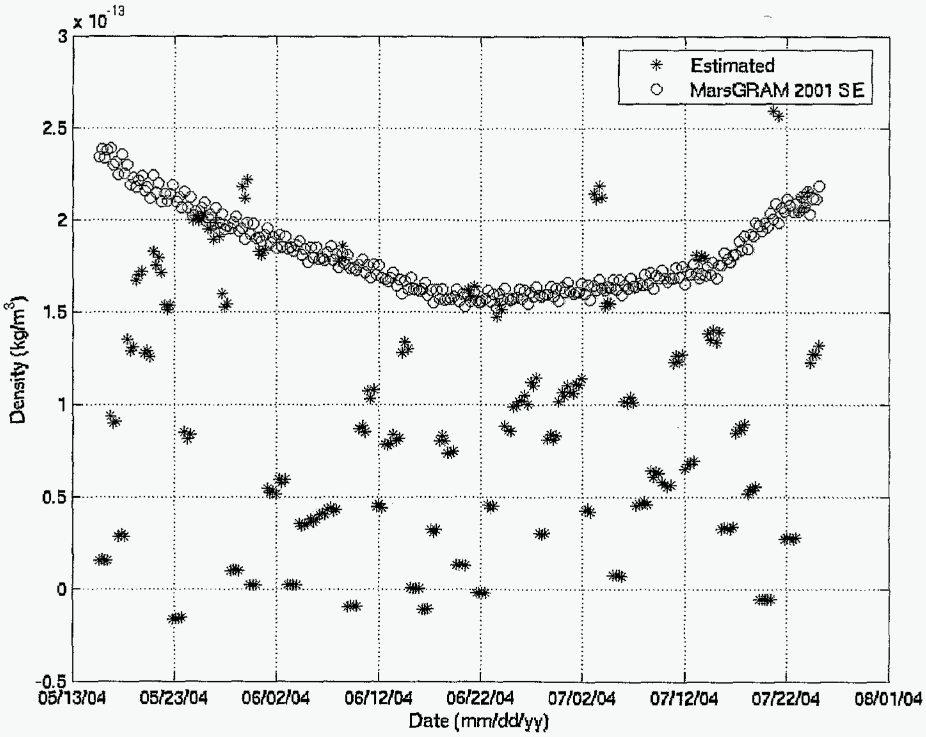

Figure 14. Periapsis densities from the MarsGRAM model versus those scaled by the estimated density scale factors. The groupings are due to the constant scale factor that was estimated for three or four consecutive periapses. Note the negative values resulting from apparent dynamic mismodelling, which led to negative scale factor estimates.

Potential correlation frequencies are identified by a power spectral density (PSD) of the estimated scale factors, as shown in Figure 18. Because the average time span included in the estimates is approximately one day, the peak frequencies obtained by the PSD can be converted to periods in terms of days. The most isolated peak occurs at a period of 13.3 days, with others occurring at 5.0, 7.2, and 28.6 days. Figures 19 and 20 show the result of taking a 13-sample (~13-day) running mean of the scale factors and plotting them against time and latitude, respectively. Figure 19 clearly shows a periodic structure in time with a frequency of about 37 days, while Figure 20 shows a more uniform behavior of the scale factor with latitude. These plots possibly indicate density correlation over 13-day time spans. However, this behavior could also be an artifact of a repeat groundtrack coupled with local gravity mismodelling, or some other phenomenon associated with passing through the south polar region. Nevertheless, it is a promising step towards identifying trends in orbit reconstructions near the altitudes of the MRO periapsis.

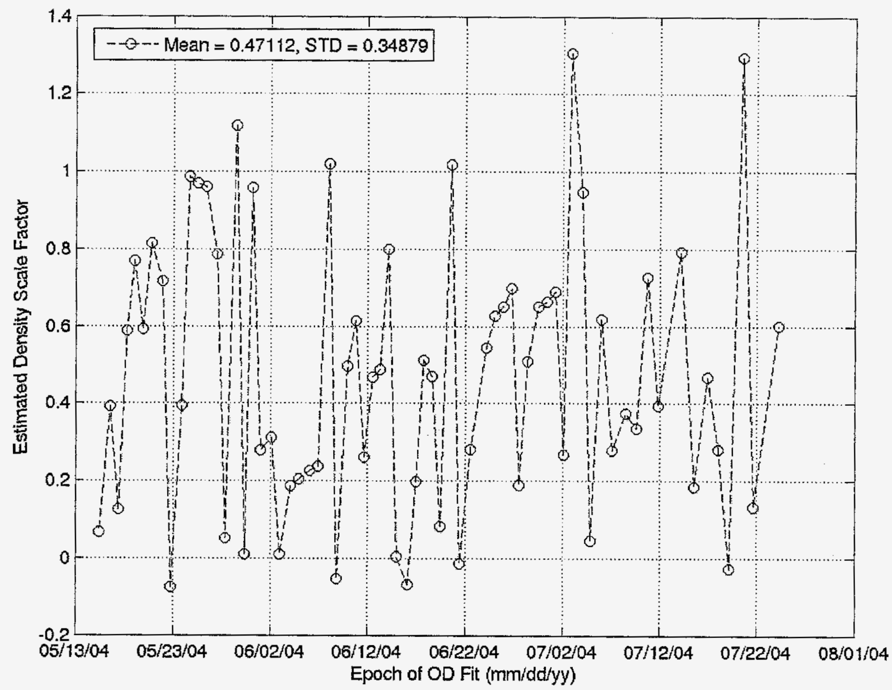

Figure 15. Estimated density scale factor bias versus the epoch of its respective fit span.

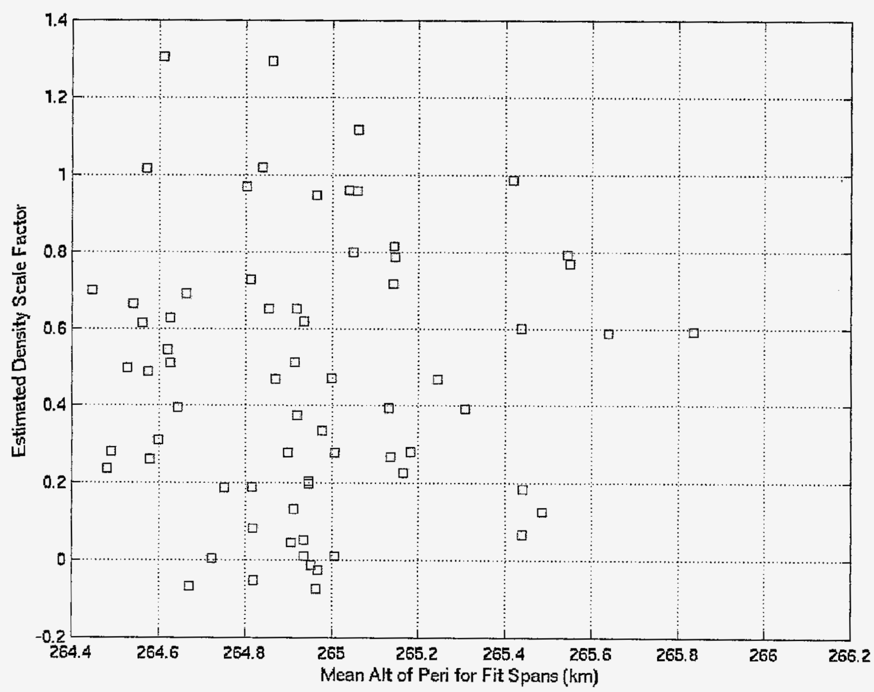

Figure 16. Estimated density scale factor versus mean altitude of periapsis for each fit span. The mean altitude decreases then increases through the minimum latitude.

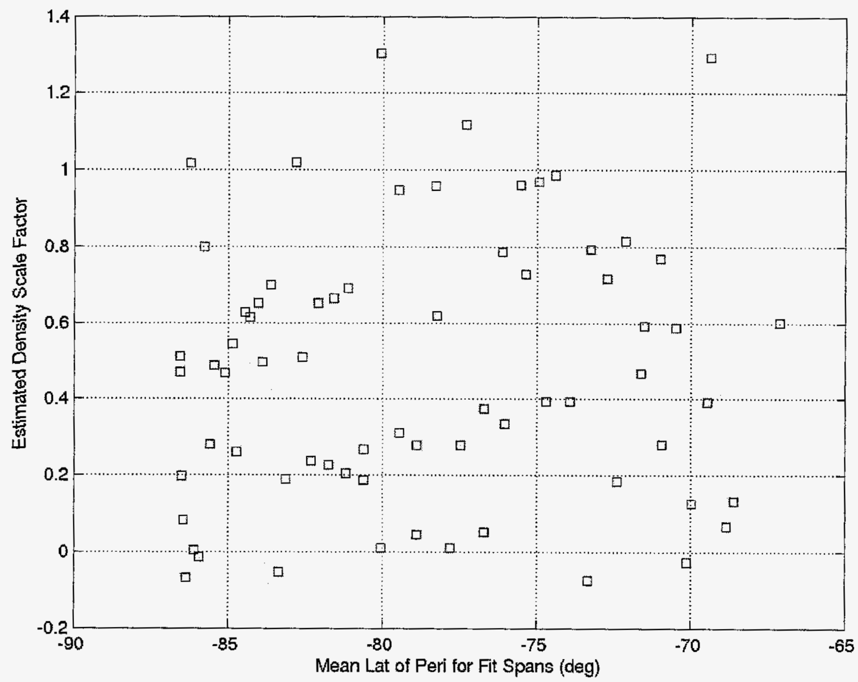

Figure 17. Estimated density scale factor versus mean latitude of periapsis for each fit span. Latitude progresses from -69 to -86 deg then back to -66 deg.

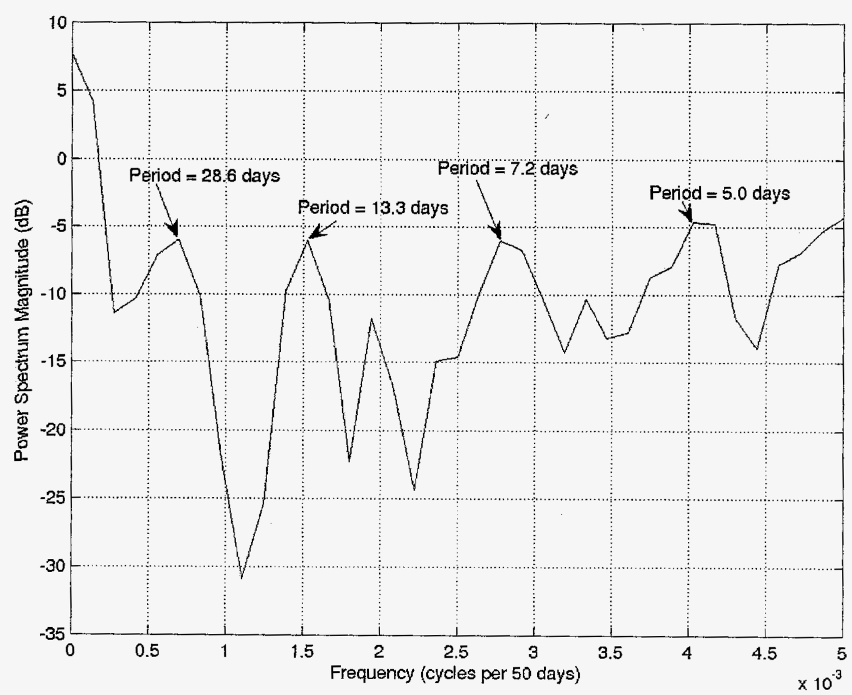

Figure 18. Power spectral density of scale factor estimates. Peaks identify potential correlation frequencies.

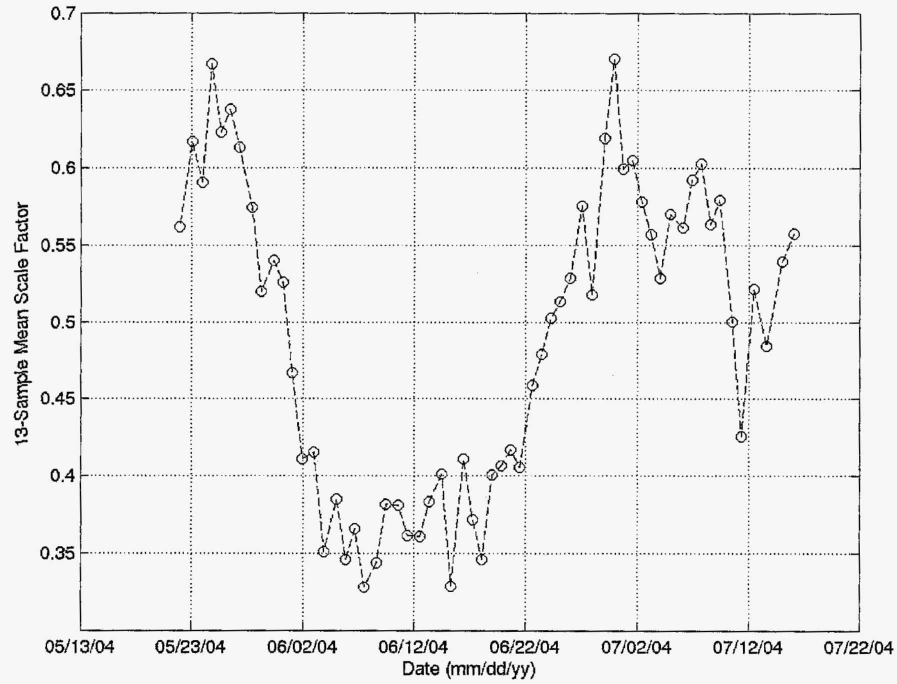

Figure 19. Thirteen-sample running mean of scale factor estimates versus time. Compare to Figure 15.

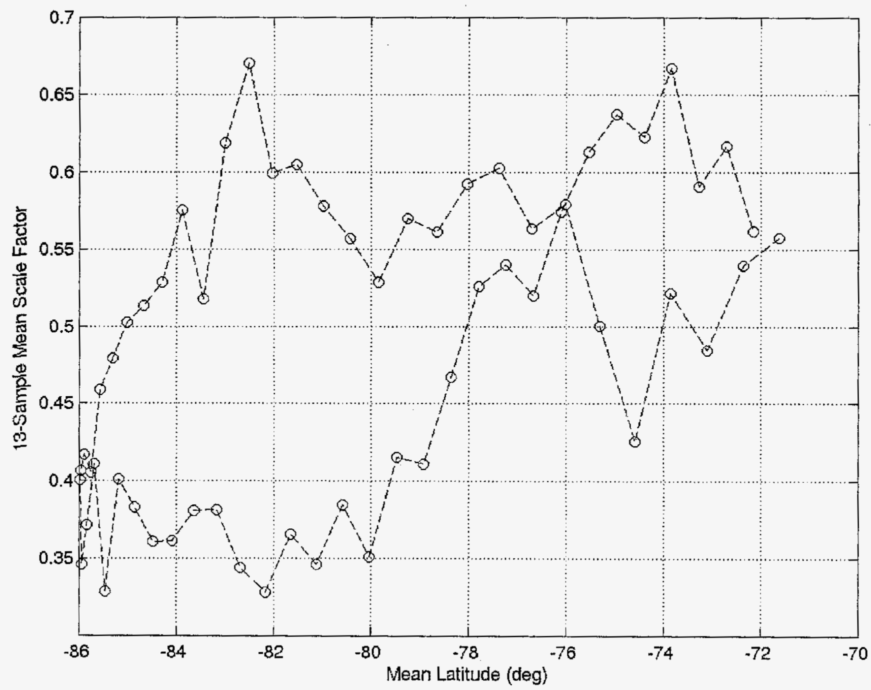

Figure 20: Thirteen-sample running mean of scale factor estimates versus mean latitude of included periapses. Compare to Figure 17.

CONCLUSIONS

Orbit reconstructions from the MEX science orbit have provided valuable insight into the variability of atmospheric density at MRO science orbit altitudes. This analysis indicates that the atmosphere model used by MRO produces densities within a factor of two of the long-term average reconstructed densities in the 265 km altitude regime, where the MRO baseline model is slightly conservative. In addition, this analysis has shown that the assumption of 35% per orbit variability is an appropriate assumption for covariance analysis. Most importantly, perhaps, this analysis has demonstrated the potential for long-term trending of the atmosphere near the South Pole. Finally, it has illustrated the difficulty that MRO will face in precisely estimating, trending, and predicting the drag effect at the science orbit altitudes, highlighting the significance of gravity tuning, precise spacecraft modeling, and a quiet spacecraft.

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