MARS ATMOSPHERIC VARIABILITY ABOVE 250 KM ALTITUDE

D. E. Highsmith[(1)], A. S. Konopliv[(1)], D. Han[(1)], M. K. Jah[(1)], D. E. Craig[(1)]

[(1)]Member Technical Staff, Jet Propulsion Laboratory, 4800 Oak Grove Drive, Pasadena CA 91109 (USA), firstname.lastname@jpl.nasa.gov

ABSTRACT

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 goal is to validate the covariance analysis assumption of atmospheric variability for the 2005 NASA Mars Reconnaissance Orbiter (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.

1. 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 arc during Feb. 2004 and the MRO frozen science orbit. The close proximity of the MEX periapsis altitude to the lower portion of the MRO science orbit allows for a virtually direct comparison of the atmosphere through that region.

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.

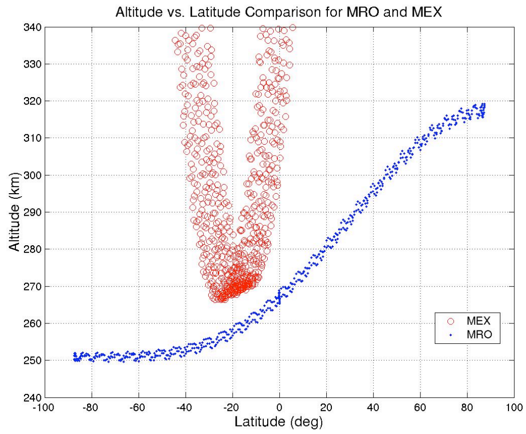

Fig. 1. Comparison of altitude vs. latitude profile of MEX orbit during Feb. 2004 and MRO science orbit. The MEX apoapsis altitude is 11,570 km.

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

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

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.

2. 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.

3. MEX ORBIT RECONSTRUCTION

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.

3.1 Fit Span & Characteristics

Orbit reconstructions were performed on arcs of tracking data between 1-29 Februrary 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.

3.2 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.

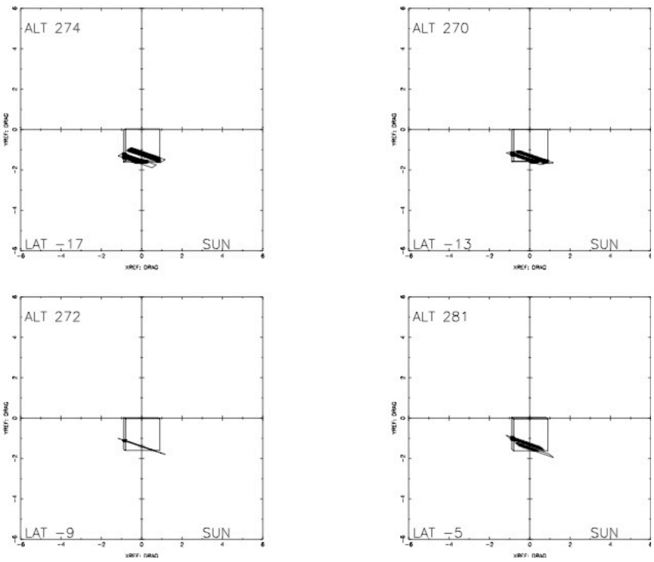

Fig. 2. Graphical output from shadow program for a MEX science (non-tracked) pass. View is along the drag direction with shadowed components shaded. Altitude is indicated in km, latitude in deg N. "SUN" indicates that the spacecraft is in full Sun.

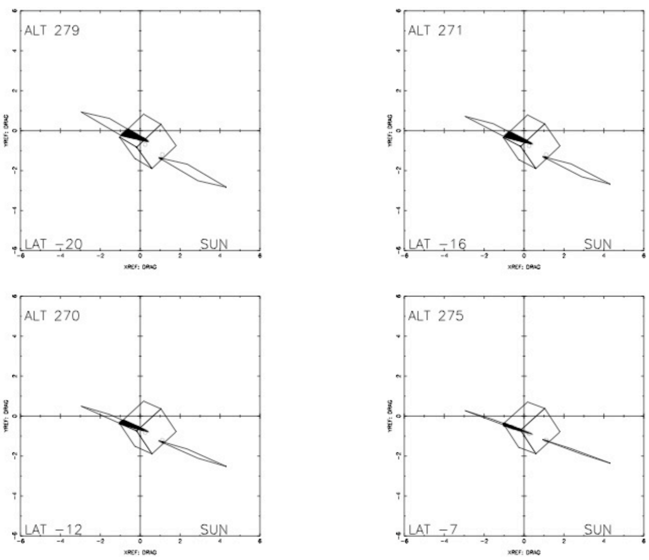

Fig. 3. Graphical output from shadow program for a MEX Earth-comm (tracked) pass.

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.

3.3 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).

3.4 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.

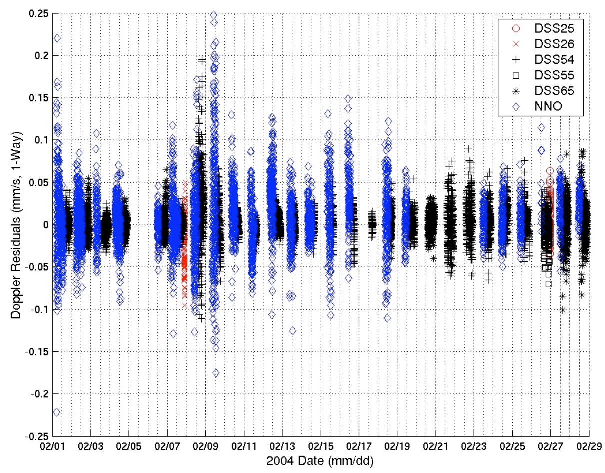

Fig. 4. Post-fit 2-way X-band Doppler residuals for MEX orbit reconstruction. 1σ noise is 0.029 mm/s, one-way (0.0016 Hz).

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.

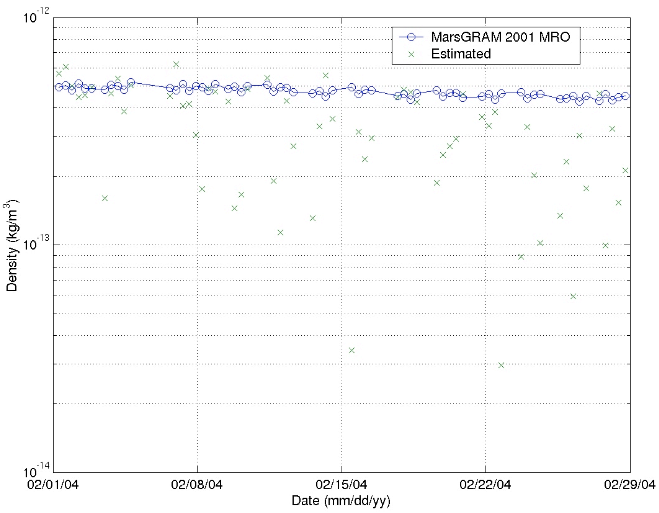

Fig. 5. Reconstructed periapsis density versus density modelled by MarsGRAM 2001 MRO at periapsis.

4. SCALE FACTOR TRENDS

4.1 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.

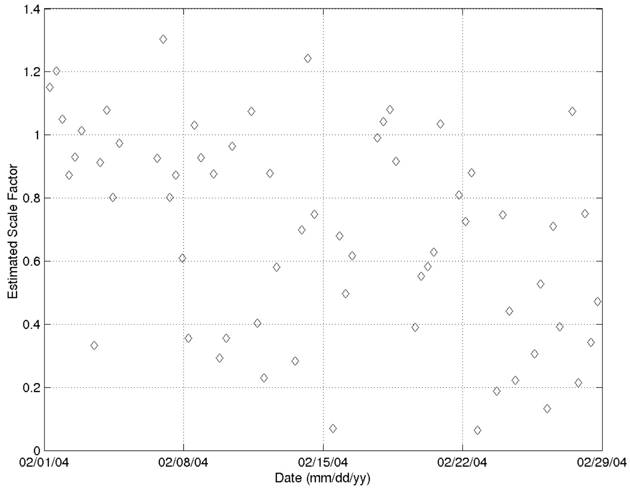

Fig. 6. Estimated scale factor vs. time.

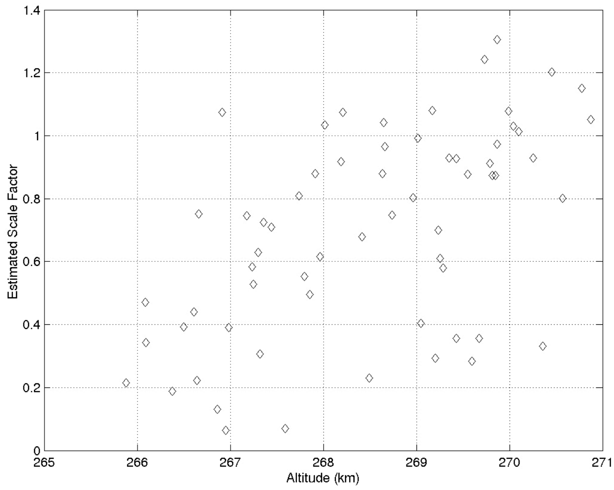

Fig. 7. Estimated scale factor vs. altitude of periapsis.

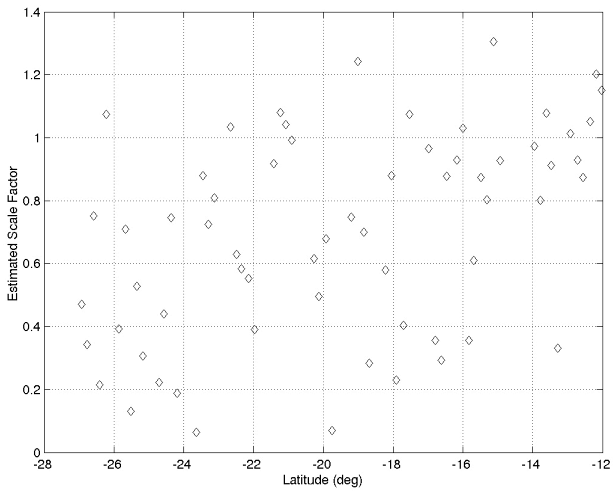

Fig. 8. Estimated scale factor vs. latitude of periapsis.

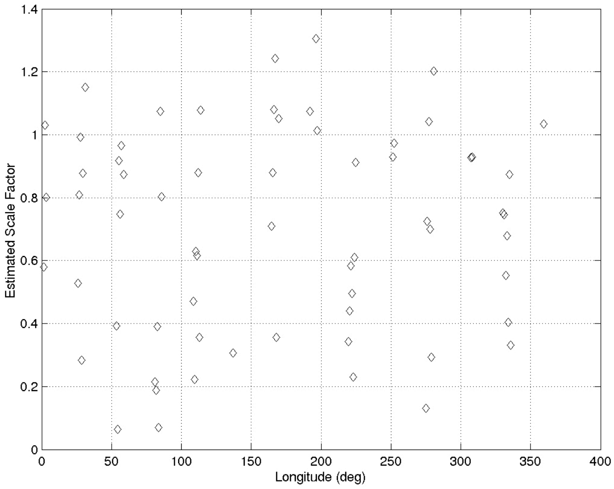

Fig. 9. Estimated scale factor vs. longitude of periapsis. Note the repeated longitudes.

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.

4.2 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.

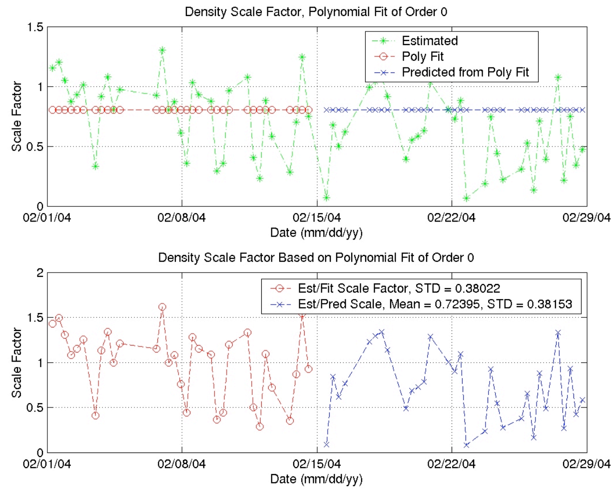

Fig. 10. Test density scale factor prediction from zeroth order polynomial fit to first 14 days of arc.

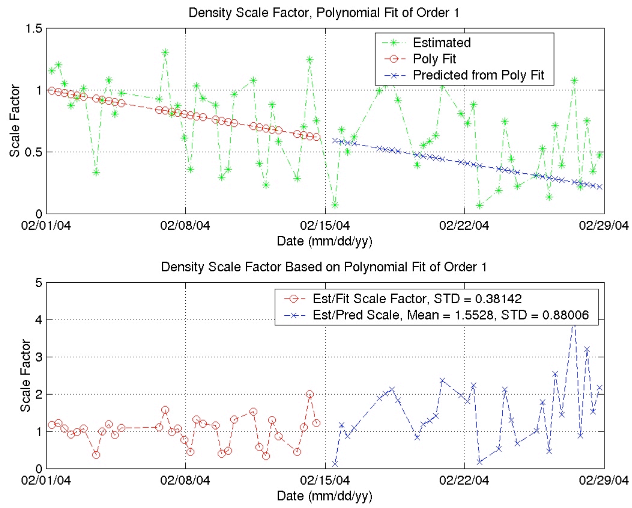

Fig. 11. Test density scale factor prediction from first order polynomial fit to first 14 days of arc.

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.

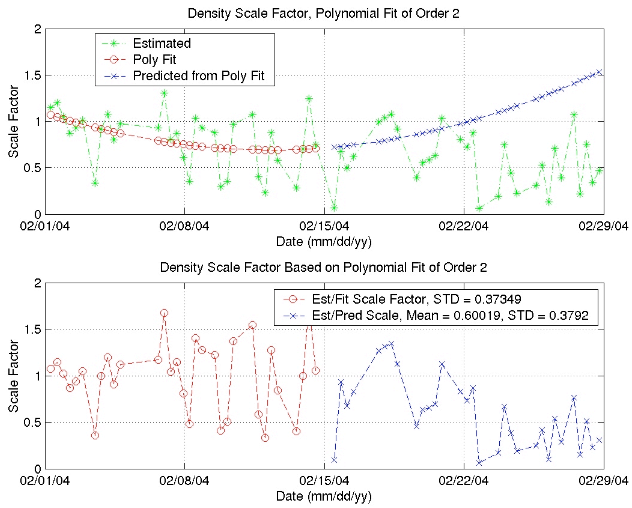

Fig. 12. Test density scale factor prediction from second order polynomial fit to first 14 days of arc.

5. CONCLUSIONS

The orbit reconstructions from the MEX science orbit have provided valuable insight into the variability in atmospheric density at MRO science orbit altitudes. This analysis has verified that the atmosphere model used by MRO produces densities within a factor of two of the reconstructed densities in the 270 km altitude regime. In addition, this analysis has shown that the assumption of 35% per orbit variability is appropriate, with no obvious correlations visible within the noise.

6. ACKNOWLEDGEMENTS

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REFERENCES

1. Justus C. G. and Johnson D. L., Mars Global Reference Atmospheric Model 2001 Version (MarsGRAM 2001): Users Guide, NASA/TM-2001-210961, April 2001.

2. Morley T., et al. Mars Express Navigation for Beagle 2 Separation and Mars Orbit Insertion, *Proceedings of the 18th International Symposium on Spacecraft Flight Dynamics*, Munich, Germany, 11-15 Oct. 2004.

3. Han D., et al. Mars Express Interplanetary Navigation from Launch to Orbit Insertion: The JPL Experience, *Proceedings of the 18th International Symposium on Space Flight Dynamics*, Munich, Germany, 11-15 Oct. 2004.

4. Konopliv, A. MGS85H2 Gravity Field, Planetary Data System, http://pds-geosciences.wustl.edu/ geodata/mgs-m-rss-5-sdpv1/mors_1019/sha/ jgm85h02.lbl