MARS RECONNAISSANCE ORBITER AEROBRAKING DAILY OPERATIONS AND COLLISION AVOIDANCE[†]

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The Mars Reconnaissance Orbiter reached Mars on March 10, 2006 and performed a Mars orbit insertion maneuver of 1 km/s to enter into a large elliptical orbit. Three weeks later, aerobraking operations began and lasted about five months. Aerobraking utilized the atmospheric drag to reduce the large elliptical orbit into a smaller, near circular orbit. At the time of MRO aerobraking, there were three other operational spacecraft orbiting Mars and the navigation team had to minimize the possibility of a collision. This paper describes the daily operations of the MRO navigation team during this time as well as the collision avoidance strategy development and implementation.

1.0 Introduction

The Mars Reconnaissance Orbiter (MRO) launched on August 12, 2005, onboard an Atlas V-401 from Cape Canaveral Air Station. Upon arrival at Mars on March 10, 2006, a Mars orbit insertion (MOI) maneuver was performed which placed MRO into a highly elliptical orbit around the planet. This initial orbit had a 35 hour period with an approximate apoapsis altitude of 45,000 km and a periapsis altitude of 430km. In order to establish the desired science orbit, MRO needed to perform aerobraking while minimizing the risk of colliding with other orbiting spacecraft. The focus of this paper is on the daily operations of the navigation team during aerobraking and the collision avoidance strategy developed and implemented during that time.

Aerobraking utilized the atmospheric drag to reduce the spacecraft velocity and orbit period. The goal for the aeroraking phase was to reduce the apoapsis altitude from 45,000 km to 450 km and move the local mean solar time (LMST) of the ascending node from 8:30 PM to 3:00 PM. Once the target apoapsis altitude and LMST were met on August 30, 2006, the spacecraft performed a 25 m/s aerobraking termination maneuver (ABX). During aerobraking, MRO would pass through the orbital paths of the other spacecrafts orbiting Mars and the moons. A collision avoidance strategy was developed by the navigation team. This was the first mission to implement such a process for use at Mars.

ABX was followed by five planned transition maneuvers over the next four months to adjust the orbit into the final Primary Science Orbit (PSO). MRO is currently in the final PSO which is a sun synchronous, frozen orbit that has a 3:03 PM local mean solar time at the ascending node, a 250 km periapsis altitude, and a 315 km apoapsis

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altitude. The primary science phase (PSP) will last until 2008, followed by the Relay phase from 2008-2010, and then the Extended Mission phase until 2015.

2.0 General Aerobraking Description

MRO was the third JPL mission to use the aerobraking technique at Mars, preceded by Mars Global Surveyor (MGS) in 1997-1999 and Odyssey (ODY) in 2001-2002. Table 1 shows an aerobraking summary of all three missions.

Aerobraking started on March 30, 2006, three weeks after MOI. The MRO aerobraking baseline trajectory was developed using the post MOI orbit determination solution and the latest spacecraft, atmosphere, gravitational, and non-gravitational models. The goal during aerobraking was to stay as close to the baseline as possible and within the heating rate limits of the spacecraft in order to finish with the desired orbital parameters.

Table 1. Aerobraking Summary for MRO, ODY, and MGS

	MRO			MRO All Phases	ODY All Phases	MGS All Phases
	Walkin	Main Phase	Walkout			
Date Range (mm/dd/yy)	3/30/06-4/13/06	4/14/06-8/22/06	8/23/06-8/30/06	3/30/06-8/30/06	10/27/01-01/11/02	09/15/97-02/04/99
Duration (days)	15	131	8	154	76.1	299
Orbit Range (Total Orbits)	14-23 (9)	24-352 (329)	353-445 (93)	14-445 (431)	5-338 (332)	4-1292 (891)
Periapsis Altitude Range (km)	112.1-428.3	97.4-108.7	99.1-111.6	97.4-428.3	95-158	100-149
Period Range (Hours)	34-35.5	2.5-34	1.9-2.5	1.9-35.5	1.9-18.5	1.7-45.1
Median Heat Rate (W/cm^2)	0.02	0.14	0.06	0.12	0.16	0.07
Number Maneuvers	6	13	7	26	33	92
ABM Delta-V (m/s)	14.5	2.77	1.83	19.1	26.6	32.3
ABX deltaV (m/s)				25	20	61.9
Transition deltaV (m/s)				75	86	22
LMST at ABX (hh:mm)				3:10 PM (LMST)	3:04 PM (LTST)	2:19 AM (LTST)

Four types of maneuvers were possible during aerobraking. The most common type was the corridor control aerobraking maneuver (ABM) which slightly raised or lowered the periapsis altitude to maintain the desired rate of aerobraking. These maneuvers were pre-built and pre-tested prior to the start of aerobraking and sub sets were selected each week for use. An Immediate Action (IA) aerobraking maneuver was available to raise the periapsis altitude by one scale height, typically about 7 km, in response to a solar array temperature thermal limit violation seen after a drag pass in the playback telemetry or a dust storm notification by the Atmosphere Advisory Group (AAG). The Manual Pop-up maneuver was available to raise the periapsis out of the atmosphere to an altitude of 160 km in the event of unsafe spacecraft anomalies. And finally, the Autonomous Safe Mode Pop-up maneuver was available to also raise the periapsis altitude to 160 km and would be initiated by the onboard fault protection after an attitude initialization and a predetermined number of orbits in safe mode.

There were four sub-phases to the MRO aerobraking phase; Walkin, Main phase, Walk out, and Transition. The Walk-in phase lowered the periapsis altitude into the atmosphere with six down maneuvers occurring over two weeks. The Main phase lasted for about four months and included the majority of the apoapsis reduction due to atmospheric drag. During the Main phase, 10 down maneuvers and 3 up maneuvers were executed for either heating rate corridor control or collision avoidance. During the Walk-out phase the rate of aeroraking slowed down in order to maintain a 2 day orbit lifetime. The Walk-out phase lasted about one week and consisted of 3 down maneuvers and 4 up maneuvers for heating rate corridor control, collision avoidance, or maintaining the 2 day lifetime constraint. Down maneuvers during walk out are not typical but were required for MRO due to collision avoidance issues. The Transition phase lasted about four months and brought MRO into the final primary science orbit (PSO). The maneuver performance was excellent throughout aerobraking. All maneuvers had execution errors less than the allowable limit of 2% maneuver ΔV (proportional error) + 2cm/s (fixed error). References [1] and [2] contain more details about the overall MRO aerobraking design and Reference [3] describes the transition sub-phase in detail.

2.1 General Aerobraking Operations

MRO aerobraking operations involved several teams at various locations. Operations took place at both the Jet Propulsion Laboratory (JPL) in Pasadena, CA and Lockheed Martin Space Systems (LMSS) in Denver, CO. Staff at the NASA Langley Research Center (LaRC) supported operations in the areas of flight dynamics,

aerodynamics, and thermal analysis. Daily atmosphere trending was performed independently by the navigation team and also by the Atmosphere Advisory Group (AAG) which consisted of scientists at various universities and institutions. Also, there was nearly continuous tracking coverage from the Deep Space Network (DSN).

An Aerobraking Planning Group (APG) meeting was held daily at 1:00pm (PDT) and involved members from all teams. The meeting consisted of a spacecraft health and status check, an atmosphere report from the AAG, and a trajectory status and maneuver recommendation from the navigation team. Prior to this meeting, the navigation team and staff from LaRC would tag up at 8:00am (PDT) to discuss and compare results from their independent software tools and concur on a recommendation for that day. Also, a navigation team member would participate in the daily 11:00am AAG meetings to present the navigation status and gather information on the Mars atmospheric weather conditions.

A Weekly Reset meeting was held every Wednesday at 9:00am (PDT) and involved members from all teams. This meeting consisted of a review of the updated spacecraft parameters, spacecraft power and thermal trends, upcoming uplink windows and the maneuver schedule. Also, the navigation team would present the maneuver ΔV menu for that week including the immediate action and manual pop-up maneuvers, the glide slope parameters and corridor limits, and the trajectory predictions for the next week and out to the end of aerobraking based on the Monday orbit determination solution.

3.0 Collision Avoidance Strategy Development

The MRO aerobraking trajectory slowly changed over six months from a large elliptical orbit to a nearly circular orbit around Mars as shown in red in Figure 1 below. During this process, it was possible that MRO would cross the orbital paths of the three other operational spacecraft orbiting Mars or the two Martian moons. The navigation team had to develop a plan to minimize the possibility of a collision. It should be noted, however, that there were also a number of non-operational spacecraft orbiting Mars at this time that could not be included in the collision avoidance (COLA) analysis because their positions were unknown.

Both Mars Global Surveyor (MGS) and Mars Odyssey (ODY) are NASA/JPL missions and were in near circular, sun synchronous, frozen orbits around Mars during this time. MGS had a 370 km by 432 km orbit with a LMST of 2:00am at the descending node. ODY had a 387 km by 455 km orbit with a LMST of 5:00pm at the descending node. Mars Express (MEX) is a European Space Agency mission. It had a 320 km by 10,100 km orbit with a rotating argument of periapsis. The MEX orbit shown in blue in Figure 1 below is at the start of aerobraking in April 2006. By the end of aerobraking in August 2006, the MEX argument of periapsis had rotated over from 218 deg to 121 deg. The Martian moons, Phobos and Deimos, have near circular, near equatorial orbits with radii of approximately 5980 km and 20070 km respectively.
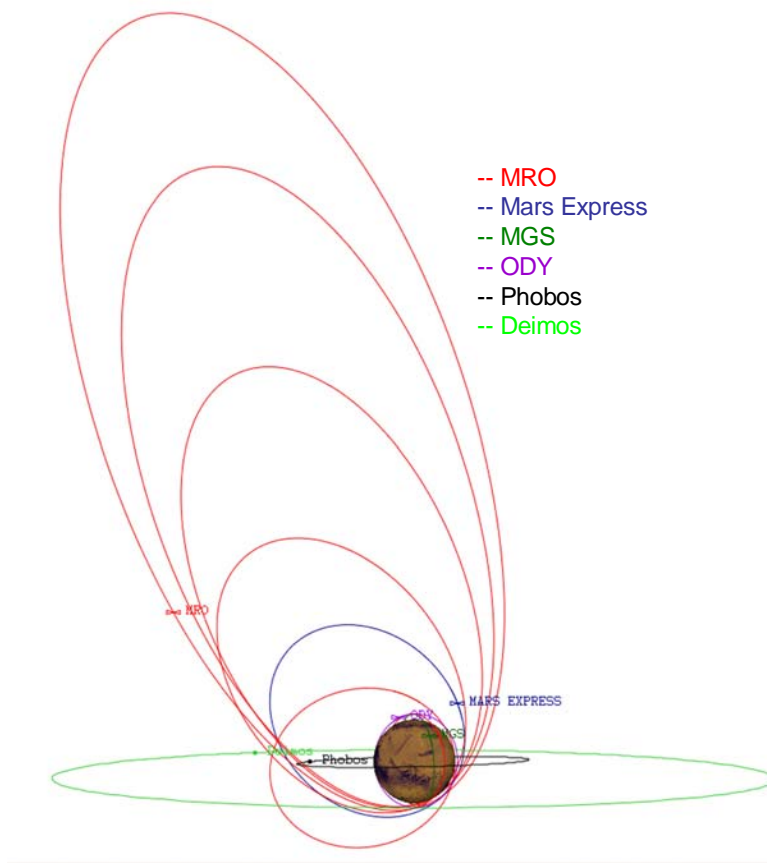

Figure 1. Progression of MRO aerobraking orbit, including MGS, ODY, MEX, Phobos, and Deimos

The first step in developing a COLA strategy was to understand the MRO orbit prediction uncertainties. The

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biggest factor in the orbit prediction uncertainty was the variability in the Mars atmosphere. At each periapsis, MRO passed through the atmosphere at an altitude of about 100km and experienced significant drag effects. The drag reduced the spacecraft velocity, which in turn reduced the apoapsis altitude. If the atmosphere density were higher or lower than predicted, the expected apoapsis altitude change would be affected.

The latest Mars Global Reference Atmosphere Model (MarsGRAM) developed by Dr. Jere Justus at Marshall Space Flight Center was incorporated into the navigation software for orbit predictions. More details about the MarsGram 2005 version can be found in Reference [4]. Throughout aerobraking, a density scale factor was applied to the MarsGRAM to improve the orbit prediction uncertainty. The density scale factor was updated frequently based on the latest trends representing a constant offset, a longitude dependent wave model, and/or a linear trend, as shown in Figure 2.

From the MGS and ODY aerobraking experiences, the navigation team knew to expect some uncertainty with atmosphere predictions. ODY experienced a 3σ variation of 60-120% on their atmosphere predictions (Reference [5]) and MGS experienced a 3σ variation of 105% (Reference [6]). At the start of aerobraking, the MRO navigation team decided to use a 3σ variation of 100% on the atmosphere prediction for orbit uncertainty calculations based on the MGS and ODY experiences. This assumption was used when developing the collision avoidance process discussed in Section 3.1. However, after gathering about 200 orbits worth of MRO aerobraking data, the navigation team felt comfortable reducing the 3σ variation to 60%.

Figure 2 below shows both the predicted (green) and reconstructed (red) density scale factors throughout aerobraking. The "error" in the predicted density scale factor is shown in blue; a value higher than 1 represents an under prediction and a value lower than 1 represents an over prediction. This error represents the uncertainty in the atmosphere prediction. Based on all the data from the 445 aerobraking orbits, the 3σ variation was 69% so the navigation estimate of a 3σ variation of 60% after just 200 orbits was quite reasonable. Further discussion about Figure 2 and density scale factors can be found in Reference [7].
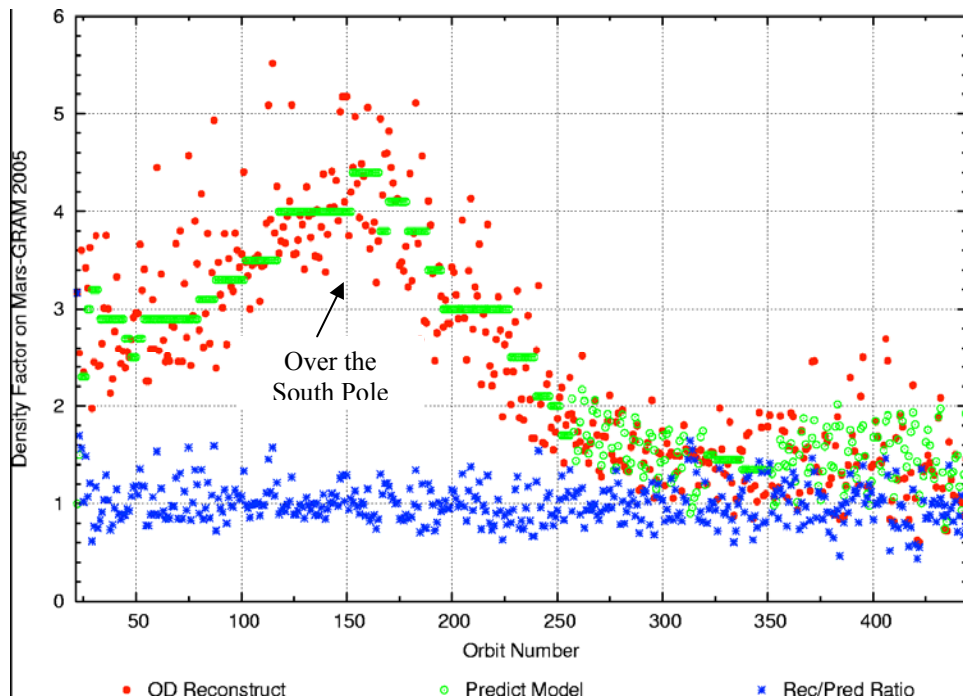

Figure 2. Density Scale Factor applied to MarsGRAM 2005 during MRO aerobraking

As mentioned, at the start of aerobraking the atmosphere variability had been quantified at 100%, 3σ. The next step in developing a COLA process was to determine how this related to the MRO orbit prediction uncertainties. A 3σ orbit prediction uncertainty would result from a 100% atmosphere variation from the prediction, i.e. either no atmosphere or double the atmosphere.

The navigation team was able to estimate the 3σ uncertainty per orbit by differencing consecutive orbits in the aerobraking baseline trajectory. The baseline trajectory was built with the latest MarsGRAM atmosphere predictions and the difference between consecutive orbits reflects the orbital effect of the predicted atmosphere. If

the actual atmosphere variation were 100% (3σ) lower than the prediction, i.e. no atmosphere, the difference between consecutive orbits in the baseline trajectory represents a 3σ uncertainty due to an over prediction. The position vector differences between the consecutive orbits can be expressed in the downtrack, crosstrack, and radial directions. Atmosphere variability mainly affected the downtrack and radial uncertainties which were quite large but had little effect on crosstrack uncertainty. The cross track uncertainty was less than 0.5km (1σ), therefore it could be ignored for COLA analysis.

Since the crosstrack (out of plane) uncertainty was negligible, the only areas of concern for collision avoidance were where the orbit planes cross. The points of interest can be found by crossing the angular momentum vector of the two orbits. An example with MRO and ODY is shown in Figure 3 below. The MRO radial uncertainty (RU) at these two points must be determined for collision avoidance analysis.
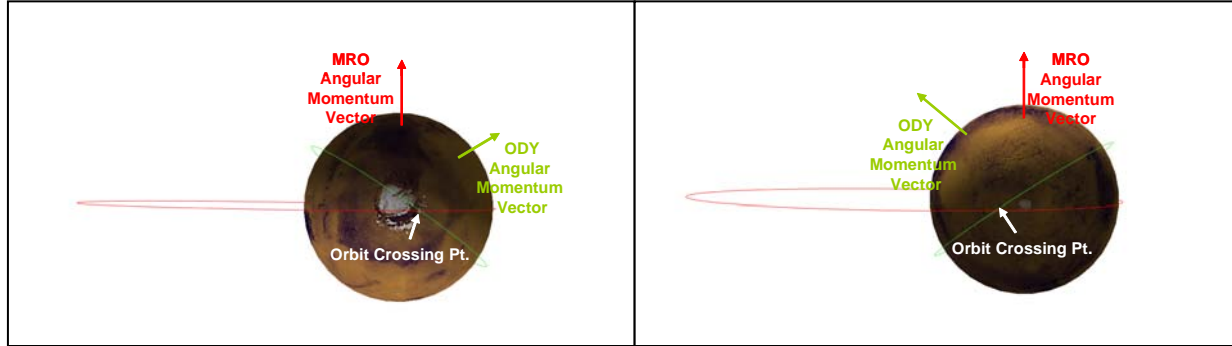

Figure 3. Orbit plane crossing examples between MRO and ODY as viewed from the north and south poles.

The 3σ radial uncertainty (RU) can be determined by first calculating the radial distance of MRO to Mars for two consecutive orbits at a given true anomaly and then differencing the results as shown in the equation below.

$$3\sigma \text{ RU per orbit} = \frac{a_2 * \left(1 - e_2^2\right)}{\left(1 + e_2^2 * \cos(\upsilon_2)\right)} - \frac{a_1 * \left(1 - e_1^2\right)}{\left(1 + e_1^2 * \cos(\upsilon_1)\right)} \qquad (1)$$

where
a_2 = semi major axis for orbit 2 $\qquad$ a_1 = semi major axis for orbit 1
e_2 = eccentricity for orbit 2 $\qquad$ e_1 = eccentricity for orbit 1
υ_2 = MRO true anomaly at crossing pt for orbit 2 $\qquad$ υ_1 = MRO true anomaly at crossing pt for orbit 1 (same as υ_2)

The navigation team decided to use 5σ RU values rather than 3σ values when comparing the MRO orbit to the other orbiters to further reduce to collision risk. Therefore, the results from equation (1) would be multiplied by 5/3 to obtain 5σ values which related to a 167% variation in the atmosphere.

Five sigma corresponds to a less than 1e-6 probability of collision based on a Guassian distribution. The navigation team's selection of 5σ was based on two references available. For planetary quarantine purposes, the launch vehicle targets are required to be biased to insure that the launch vehicle upper stage has less than a 1e-4 probability of impacting Mars. Also, the Genesis Earth Return mission had to select a target that had less than a 1e-7 probability of landing near populated areas. For the MRO aerobraking situation, 5σ seemed reasonably conservative since there would obviously be serious ramifications if a collision took place such as simultaneous failure of two Mars orbiters, loss of science data, potential debris field at prime science altitudes, and downstream implications for lander relay.

The MRO baseline trajectory was used to generate an overview of the 5σ RU throughout aerobraking for true anomalies ranging from 0 deg (periapsis) to 180 deg (apoapsis). Results are shown in Figure 4 below; the legend contains the orbit number, the periapsis altitude, and the orbit period. A variation in the periapsis drag pass atmosphere caused the largest uncertainty near apoapsis.

If a collision issue was identified, the team would need time to react. Therefore, the radial uncertainty had to be propagated out over several orbits using the equation below.

$$\text{Accumulated } 5\sigma \text{ RU over N orbits} = \left(5\sigma RU * \sqrt{N}\right) \qquad (2)$$

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5-Sigma Radius Uncertainty, per Orbit
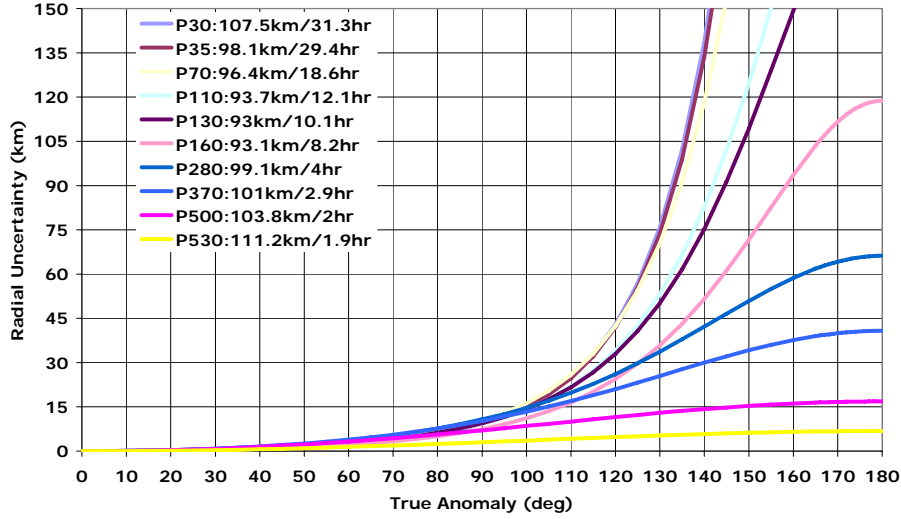(Approximated by 167% Atmospheric Uncertainty)

Figure 4. 5 σ Radial Uncertainty Per Orbit Throughout Aerobraking At Various True Anomalies

If the radial distance between MRO and another spacecraft or moon was within +/- 5σ RU, the next step was to check if they would be at the orbit crossing point at the same time. For this check the MRO downtrack uncertainty must be included. However, instead of computing the downtrack uncertainty in terms of distance, the navigation team used time (i.e. MRO is predicted to be at the orbit crossing point within +/- X seconds instead of within +/- X km in the downtrack direction.).

To determine the 3σ timing uncertainty (TU) per orbit due to a 100% atmosphere variation, the difference in orbit period between two consecutive orbits was calculated. As mentioned previously, the navigation team decided to use 5σ uncertainty values so the delta orbit period between two consecutive orbits should be multiplied by 5/3 to simulate a 167% atmosphere variation. Figure 5 shows the 5σ timing uncertainty throughout aerobraking. The equation below was used to propagate the timing uncertainty out over several orbits, assuming that the atmosphere short term prediction error was a simple white noise stochastic random model.

$$\text{Accumulated 5σ TU for N orbits} = \sum_{1}^{N} \sqrt{\frac{5}{3} * \Delta P^2 * (N-1)^2} \qquad (3)$$

Where
ΔP = change in orbit period per orbit

5 Sigma Timing Uncertainty, Per Orbit
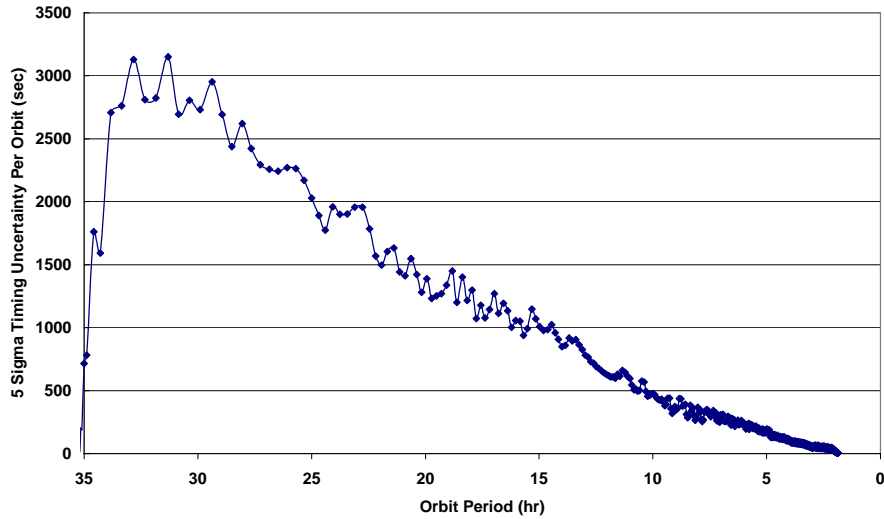**(Approximated by 167% Atmosphere Uncertainty)**

Figure 5. 5σ Timing Uncertainty Per Orbit Throughout Aerobraking

3.1 COLA Process and Tools

The MGS, ODY, and MEX navigation teams had a collision avoidance process in which they regularly checked their predicted closest approaches to each other (body to body position difference). All three spacecraft are in stable primary science orbits above the influence of the atmosphere. They all have very small orbit prediction uncertainties so the simple closest approach check was sufficient. Unfortunately, this would not work during MRO aerobraking due to the large radial and downtrack uncertainties described above. No other missions had a strategy or tools that we could directly apply for collision avoidance during aerobraking.

For closest approach analysis, the MGS and ODY navigation teams used a software program called 2body_closap that wrapped around a periapsis search event routine. Given the trajectories of any two bodies, it found the periapsis of body 1 around the central body 2. The output was the closest approach time and distance between body 1 and body 2.

Modifications to the 2body_closap program provided the MRO navigation team with orbit crossing information needed for aerobraking collision avoidance analysis. A sample of the 2body_closap output is shown below in Table 2. The output still included the time of closest approach between the two bodies and the closest approach distance but as mentioned, the MRO uncertainties are too large to rely on this information alone. The additional output included the orbit crossing distance in the radial direction for both orbit crossing points (only one is shown in the sample below) and the MRO true anomaly at the orbit crossing point. The true anomaly is required to determine the 5σ radial uncertainty using Figure 4. If the orbit crossing distance is less than the MRO 5σ radial uncertainty, then the team would check if the two bodies will be at the orbit crossing point at the same time. For this we looked at the orbit crossing timing difference and compared the results to the MRO 5σ timing uncertainty.

Table 2. Sample 2boday_closap Output

Body	Time of Closest Approach (UTC)	MRO Periapsis Number	Closest Approach (km)	Orbit Crossing Distance (km)	Orbit Crossing Timing Difference (sec)	Time of Orbit Crossing by MRO (UTC)	Time of Orbit Crossing by Other (UTC)	MRO TA at Orbit Crossing (Deg)
MGS	8/20/2006 23:47:19	P337+8m	5444.3	65.6	1827	8/20/2006 23:50:39	8/20/2006 23:20:12	43.6
ODY	8/16/2006 20:51:10	P303+2m	1103.6	8.9	1421.8	8/16/2006 21:01:48	8/16/2006 20:38:06	46.83
MEX	8/20/2006 22:41:47	P337-57m	1713.4	1286.6	593.6	8/20/2006 22:48:54	8/20/2006 22:39:00	136.04

The following procedure was developed by the team for use during aerobraking and is shown in a block diagram in Figure 6 below. The procedure was reviewed and approved by both MRO Project and Navigation Section management.

Step 1. Each week use the MRO weekly reset trajectory and run 2body_closap for the weekly reset time period, and identify if the radial distances between the orbiters at the orbit crossing points are less than the thresholds listed in Table 3 below. If so, proceed to step 2. Note that the threshold values are very conservative and only signify that further analysis should be done. The values were developed based on preliminary analysis of orbit crossing distances and 5σ radial uncertainties using the MRO baseline trajectory and long term predictions for MGS, ODY, MEX, Phobos, and Deimos.

Table 3. Weekly Reset Thresholds for Radial Distance at the Orbit Crossing Points

Start	End	Orbit Period	Threshold for Radial Distance At Orbit Crossing
3/20/2006	7/16/2006	35hr-8.2hr	7km
7/16/2006	8/9/2006	8.2-4.6 hr	10km
8/9/2006	8/26/2006	4.6-2.9hr	40km
8/26/2006	9/8/2006	2.9-2.0hr	30km
9/8/2006	9/14/2006	2.0-1.88hr	20km

Step 2. Each day use the latest MRO trajectory and run 2body_closap for a time span of at least one day (typically we looked at 4 days). Check if the orbit crossing distance is less than the 5σ radial uncertainty at the orbit crossing point. If it is, then check the timing difference between when MRO is at the orbit crossing point and when the other spacecraft is at the orbit crossing point. If the timing difference is less than the 5σ MRO timing uncertainty, consider performing a corridor control ABM a day or two prior to the COLA event.

A corridor control ABM performed a day or two prior to the COLA event can adjust the MRO timing by approximately 100-300 seconds depending on how soon the maneuver is performed and the size. The maneuver should adjust the timing difference at the orbit crossing point such that it would be greater than the MRO 5σ timing uncertainty. The corridor control ABMs can also adjust the radial distance by a few km. This plan assumes the atmosphere will behave as predicted. Therefore, the navigation team will re-run the 2body_closap program with every periapsis reconstruction leading up to the closest approach to monitor the situation.

If the atmosphere prediction was off and the COLA event remains an issue, then consider an immediate action ABM sometime between 0.5 -2.5 orbits before the COLA issue. An immediate action ABM will raise the periapsis altitude by one scale height, typically 7km, which should increase the orbit crossing distance to more than the 5σ radial uncertainty as well as increase the timing difference. The selection of the ABM orbit depends on how long the team needs to generate, review, and approve the maneuver sequence, as well as the effective radial distance and timing change required from the ABM to move MRO outside the 5σ uncertainty.
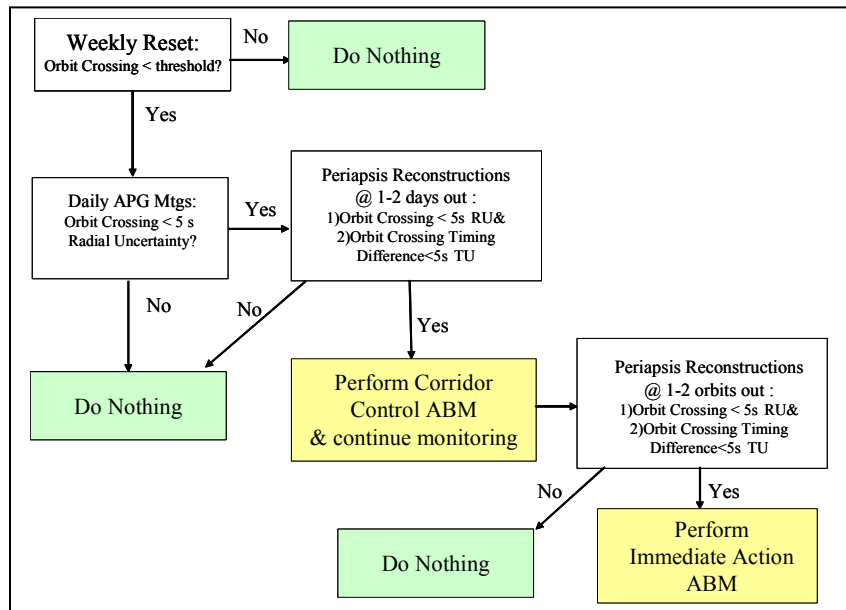

Figure 6. MRO Collision Avoidance Process

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The whole navigation team was trained on the COLA process and tools. It was important for everyone to know when to track the COLA issues and how to run the 2body_closap program. During the last two weeks of aerobraking in particular, there were a number of COLA issues and the navigation team had to work 24/7 to reconstruct each orbit and analyze the situation.

4.0 MRO Aerobraking Preliminary COLA Analysis

Prior to the Walk In subphase, the navigation team performed a preliminary COLA analysis, focusing only on the orbit crossing distances. The MRO aerobraking baseline trajectory was used for the analysis along with the long term prediction trajectories for MGS, ODY, and MEX, and long term predictions for Phobos and Deimos. Time frames were identified for when the MRO baseline trajectory was predicted to cross the orbital paths of MGS, ODY, MEX and Phobos. MRO did not have any potential orbit crossing with Deimos.

About half way through aerobraking, the project decided to move the aerobraking baseline end date up by two weeks. The main reason was to allow for additional time for instrument checkout before the start of solar conjunction. The extra time also allowed for HiRISE observations of the proposed Phoenix landing sites. The observations showed that the PHX team needed to select a new site due to numerous large rocks. Moving the date of ABX earlier also removed a DSN coverage conflict with the planned launch of the Solar Terrestrial Relations Observatories (STEREO) in late August 2006.

The navigation team redid the preliminary COLA analysis using the new MRO baseline trajectory along with long term prediction trajectories for MGS, ODY, MEX, Phobos, and Deimos. The overall COLA situations were the same and the results are shown in Figure 7 below. The same number of orbit crossing issues existed as in the previous analysis; the issues were just moved up a few days. The COLA "seasons" seem to be correlated to the relative orbit geometries. As long as the navigation team kept the trajectory close to the baseline, we knew when to be aware of potential COLA issues. Table 4 lists the dates for the predicted COLA issues from this analysis based on orbit crossing distance only as well as a summary of the actual events which are discussed in Section 5.0.
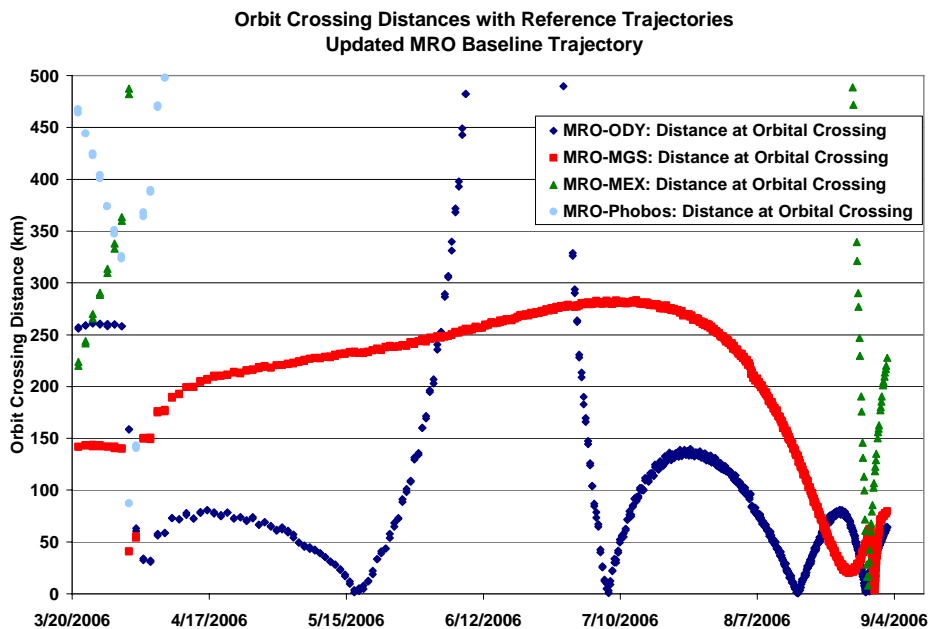

Figure 7. Aerobraking COLA Analysis with update MRO Trajectory

Table 4. Summary of Predicted (Baseline) and Actual COLA Issues

Issue #	Body 2	Date of Predicted COLA Issue	Date of Actual COLA Issue	Actual Closest Approach (km)	ΔV Required (m/s)
1	Phobos	3/31/2006	3/31/2006	8055.3	
2	ODY	5/16/2006	5/14/2006	1353.6	0.1093
3	ODY	7/7/2006	7/8/2006	46.8	
4	ODY	8/15/2006	8/15/2006	187.4	0.1093
5	MGS	8/25/2006	8/25/2006	60.6	
6	ODY	8/29/2006	8/25/06-8/26/06	20.99	0.1840
7	MEX	8/29/2006	8/27/2006	2859.3	
8	ODY	8/30/2006	8/27/06-8/28/06	40.1	0.7878
9	MGS	8/30/2006	8/28/2006	6056.6	

5.0 COLA Process Implementation During Aerobraking Operations

In an effort to avoid having to do large immediate action ABMs for COLA issues, the navigation team would sometimes recommend the smaller corridor control ABMs a day or two before the COLA issue to tweak the orbit enough to increase either the radial distance or the timing difference beyond the 5σ uncertainties. This approach had the risk of performing unnecessary maneuvers due to the atmosphere uncertainty at the time of the analysis a few days out and it did not completely eliminate the possibility of needing an immediate action ABM. However, the team felt this was preferable in order to reduce the likelihood of performing a large immediate action maneuver which would move MRO off the baseline trajectory completely and require aggressive aerorbraking to catch up again.

Below is a description for each of the MRO COLA issues listed in Table 4. The navigation team was able to keep MRO very close to the baseline trajectory throughout aerobraking so the COLA issues all occurred near their predicted times.

Issue 1) Predicted COLA issue with Phobos on 3/31/06. The navigation team started monitoring the issue closely starting on 3/30/06 with the reconstruction of orbit #14, just one orbit prior to the COLA issue. The COLA process was still being developed at this time, but the orbit crossing distance and the closest approach values were much larger than the orbit uncertainty at one orbit out, so no action was required.

Issue 2) Predicted COLA issue with ODY on 5/16/06. The navigation team started monitoring the issue closely on 5/8/06. The actual COLA issue moved to 5/14/06 and the minimum orbit crossing distance was predicted to be 0.94 km which was less than the 5σ radial uncertainty of 1km at that time. A 0.1093 m/s down maneuver was recommended at apoapsis #46 on 5/10/06 mainly for heating rate corridor control but also to improve the COLA issue. The maneuver was predicted to increase the radial distance above the 5σ uncertainty. The COLA process was finalized during this time and the timing difference was calculated after the maneuver recommendation. The orbit crossing timing difference after the maneuver was 43.9 minutes which was much larger than the 5σ timing uncertainty of 2 seconds. No further action was required.

Issue 3) Predicted COLA issue with ODY on 7/7/06. The navigation team started monitoring this issue closely on 7/1/06. The actual COLA issue moved to 7/8/06 and the minimum orbit crossing distance was predicted to be 2km which was greater than our 5σ radial uncertainty of 1km at that time. Therefore, no action was required.

As mentioned earlier, after about 200 orbits the navigation team updated the 3σ atmosphere variation from 100% to 60%. A 5σ uncertainty now related to a 100% variation in the atmosphere instead of 167%.

Issue 4) Predicted COLA issue with ODY on 8/15/06. The navigation team started monitoring the issue closely on 8/10/06. The orbit crossing distance and the timing difference were both predicted to be less than the 5σ uncertainties. Therefore, a 0.1093 m/s up ABM was recommended at apoapsis #285 on 8/14/06 for both heating rate corridor control and COLA purposes. After the maneuver, the orbit crossing distances were predicted to be between 1.7 and 2.9km for orbit #293-296 which was still less than the 5σ radial uncertainty of 3km. However the orbit crossing timing differences were all predicted to be greater than the 5σ timing uncertainty so no further action was required.

Issue 5) Predicted COLA issue with MGS on 8/25/06. The radial difference with respect to MGS was predicted to be about 40km at this time which was well above our 5σ radial uncertainty. No action was required.

Issue 6) Predicted COLA issue with ODY on 8/29/06. The actual COLA issue moved up to 8/25/06-8/26/06. A 0.2389 m/s down maneuver was recommended for apoapsis #352 on 8/22/06 for heating rate corridor control purposes. The COLA analysis with the predicted trajectory and maneuver showed that on 8/25/06-8/26/06, the radial distances were less than the 5σ radial uncertainty but the timing differences were greater than the 5σ timing uncertainty. The COLA issues were still a few days away so the team continued to monitor the situation.

A 0.3100 m/s up maneuver had to be implemented at apoapsis #372 on 8/24/06 for heating rate corridor control purposes. Unfortunately, the maneuver affected the COLA results and at one day out from the COLA issue both the radial distance and timing difference were predicted to be less than the 5σ uncertainties for orbits 387 - 389.

The navigation team recommended a 0.1840 m/s up maneuver at apoapsis #379 on 8/25/06 to try and improve the COLA situation for orbits #387-389. With the maneuver, the COLA situation was predicted to improve but still required monitoring. The navigation team was working 24/7 at this time and reconstructed every orbit in order to monitor the COLA situation. At eight orbits, or approximately 16 hours, prior to the COLA event, the radial distances were still predicted to be less than the 5σ radial uncertainty but the timing differences were greater than the 5σ timing uncertainty of 296 seconds. No further action was required.

Issue 7) Predicted COLA issue with MEX on 8/29/06. The actual COLA event moved up to 8/27/06 (prior to ODY issue discussed below) The radial distance was predicted to be 4.2 km which was less than the 5σ radial uncertainty of 38km at 12 orbits out. However, the orbit crossing timing difference was predicted to be 4110 seconds which was much greater than the 5σ timing uncertainty 562 seconds at 12 orbits out. No action was required.

Issue 8) Predicted COLA issue with ODY on 8/30/06. The actual COLA event moved up to 8/27/06 and effected orbits 403-414. Based on the reconstruction of orbit #387, the navigation team recommended a -0.2389 m/s down maneuver at apoapsis #390 to improve the COLA situation. Without the maneuver, the radial distances and timing differences were both predicted to be less than the 5σ uncertainties for orbits 403-406. With the maneuver, the COLA issues shifted to orbits 404–407 and the situation improved. If the atmosphere predictions were accurate, the predicted radial and timing differences would be greater than the 5σ uncertainties by 4 orbits prior to the COLA event, but the situation still required constant monitoring until then.

Unfortunately, three orbits later based on the reconstruction of orbit #390, the navigation team had to recommend another -0.2389 m/s down maneuver at apoapsis #393 because the atmosphere prediction had not been very good. The previous three orbits experienced lower than expected atmospheric drag which essentially put us back in the same COLA situation that we started at earlier in that day. The density scale factor was updated and the maneuver recommendation was made to the project. The project rule was to only have one maneuver per day so an exception had to be made for this situation. With this maneuver recommendation, the predicted radial distances for orbits 403-407 were still less than the 5σ radial uncertainty but the timing differences were greater than the 5σ timing uncertainty by 8 orbits out. No further action was required for the COLA issues on orbits #403-407.

A side effect of the previous maneuver at apoapsis #393 was the creation of new COLA issues for orbits #410-414. Based on the reconstruction of orbit #399, the navigation team recommended a 0.3100 m/s up maneuver at apoapsis #404 to improve the COLA situation for these orbits. With the maneuver, the predicted radial distances were less than the 5σ radial uncertainty but the timing differences were greater than the 5σ timing uncertainty by 9 orbits out. No further action was required.

Issue 9) Predicted COLA issue with MGS on 8/30/06. The actual COLA event moved up to 8/28/06. The orbit crossing timing difference was predicted to be over 2000 seconds which is much greater than the 5σ timing uncertainty 281 seconds at 12 orbits out. No action was required.

6.0 MRO Transition and PSP COLA Analysis

Half way through aerobraking, the baseline trajectory was updated to end aerobraking two weeks early as mentioned previously. The collision avoidance analysis was redone and also included the transition phase. The results for the baseline transition phase are shown below in Figure 8. The transition phase baseline contained five maneuvers after ABX in order to obtain the primary science orbit, discussed in detail in Reference [3]. The baseline called for the ABX to be 25 m/s and occur when the apoapsis altitude reached 450km. Potential COLA issues were identified based on the orbit crossing distances with both MGS and ODY between the ABX and OA1 maneuvers. Shortly after ABX, the spacecraft would be commanded to the nadir-point configuration and no collision avoidance maneuvers could be performed. The navigation team looked into a number of options to eliminate the collision risk between ABX and OA1 and presented the results to the project management.

Orbit Crossing Distances Post ABX with Reference Trajectories
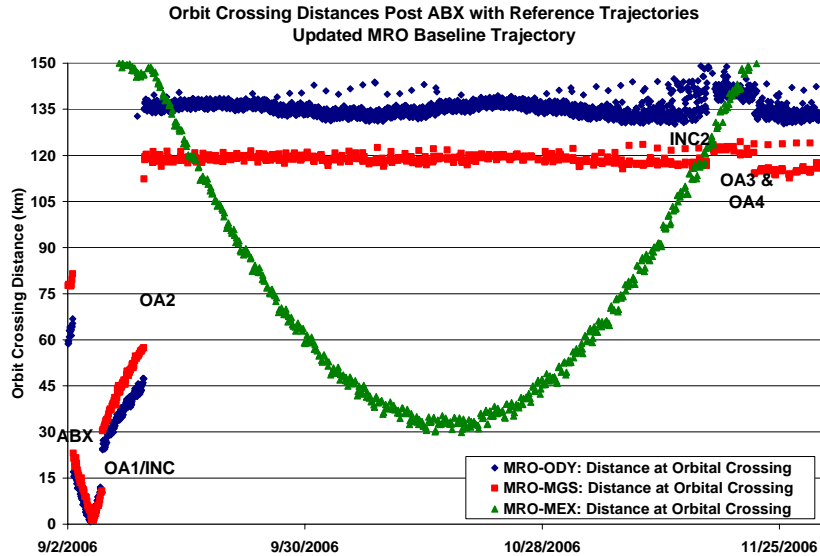**Updated MRO Baseline Trajectory**

Figure 8. COLA Analysis During Transition to PSP with MRO Baseline

Option 1 kept the ABX maneuver size at 25m/s but left a range of orbits available on which to execute the ABX maneuver. The final orbit would be determined based on the orbit crossing timing difference with both MGS and ODY. As we got closer to ABX, the 5σ timing uncertainty would decrease. We would monitor the situation with each orbit reconstruction and select a prime and backup ABX orbit with apoapsis altitudes somewhere between 450 to 600 km that had orbit crossing timing difference with MGS or ODY greater than the 5σ timing uncertainty. One disadvantage of this plan is that doing ABX on an orbit with an apoapsis altitude greater than 450 km could add up to 10m/s required to obtain the final PSP orbit due to the additional apoapsis altitude that must be removed.

Option 2 changed the ABX maneuver size to 45 m/s but maintained the orbit selection based on an apoapsis altitude of 450km. This option removed the COLA issues with MGS and ODY because the orbit crossing distances would be greater than the 5σ radial uncertainty of MRO. However, a 45m/s ABX increases the periapsis altitude more than desired for the planned transition sequence. Therefore this option also had the disadvantage of adding up to 10m/s required to obtain the final PSP in order to reduce the periapsis altitude.

Option 3 changed the ABX maneuver size to 5.5 m/s (immediate action maneuver size) but maintained the orbit selection based on an apoapsis altitude of 450km. This option would remove the COLA issues with MGS and ODY because the orbit crossing distance would be greater than the 5σ radial uncertainty. The disadvantage of this option was that this small of a maneuver would not take MRO out of the atmosphere completely, therefore daily aerobraking operations would have to continue until the OA1 maneuver 5 days later. However, this option lead to better optimization of the transition maneuvers and would require 20 m/s less delta velocity to obtain the final PSP.

Project management selected Option 1 because they wanted to avoid the risk associated with changing the pre-built, pre-tested ABX maneuver. This option required some intensive COLA analysis by the navigation team during the last few days of aerobraking.

6.1 ABX Orbit Selection

Two days prior to the ABX date, the navigation team had to make a preliminary recommendation for the ABX orbit. The navigation team took the trajectory from the reconstruction of orbit #417 and propagated it out, adding the ABX maneuver on each orbit with apoapsis altitudes between 450km and 500km as a start. The ABX maneuver size was 25 m/s with a possible 0.52 m/s execution error.

Before analyzing the COLA situation for each scenario, the 5σ radial and timing uncertainties had to be calculated. The radial and timing uncertainty calculations were slightly different than described in Section 3 due to the large ABX prior to the COLA issue. The ABX maneuver raised the periapsis altitude from 111 km to 215 km. At 215 km, the atmosphere effects are significantly reduced, therefore the post ABX orbits have much smaller uncertainties. The uncertainty per orbit pre ABX was accumulated over the number of orbits leading up to ABX and the uncertainty per orbit post ABX was accumulated over the number of orbits between ABX and the COLA event

and then the two uncertainties were summed. Then some margin was added to the uncertainties to account for the possible maneuver execution error.

All the scenarios had post ABX orbit crossing distances with MGS and ODY less than the 5σ radial uncertainty. However, the scenarios that placed ABX on orbits with apoapsis altitudes between 462km to 485 km had orbit crossing timing differences that were greater than the 5σ timing uncertainty. The navigation team had to select two possible orbits for the ABX maneuver, one primary and one backup. The primary and backup orbits had to be separated by about 4 hours (or two orbits) to allow time for spacecraft updates. Based on the initial analysis, the primary orbit was selected to be #442 with an apoapsis altitude of 481km and the backup orbit was selected to be #444 with an apoapsis altitude of 470. Figures 9 and 10 show the orbit crossing distances (left axis) and relative timing differences (right axis) between MRO/ODY and MRO/MGS for the primary and backup ABX orbit selection. The drop in orbit crossing distance near 8/31/06 is due to the ABX maneuver. The COLA issues were on 9/2/06 and the OA1/INC maneuver was scheduled on 9/5/06. To eliminate the COLA issue, the goal was to center the point where the orbit crossing distances reached 0km between the relative timing points which formed parallel lines at ~3 day increments.
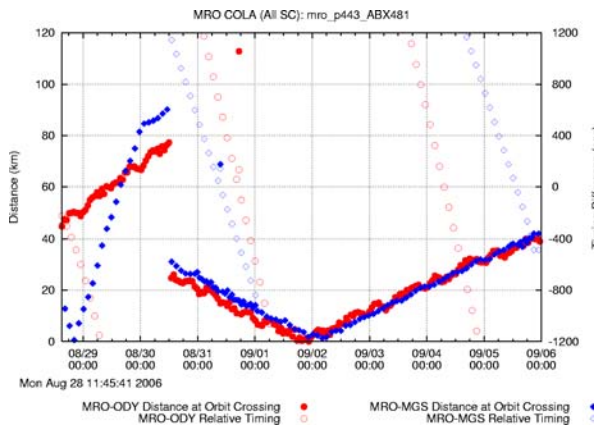

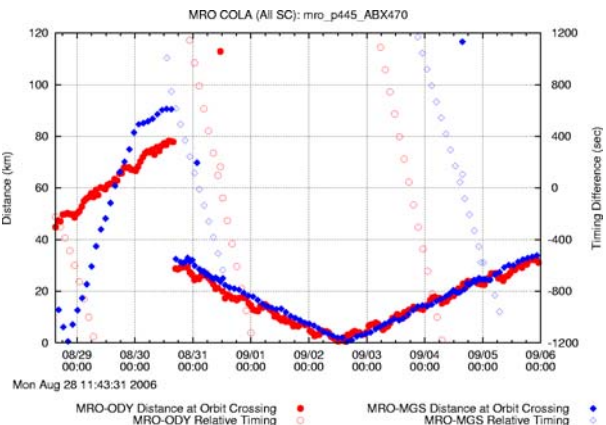Figure 9. COLA with ABX on Orbit 442 (481 km)

Figure 10. COLA with ABX on Orbit 444 (470 km)

One day prior to ABX, the navigation team repeated the analysis with the latest trajectory from the reconstruction of orbit #432. The atmosphere predictions had been slightly off the day before so the density scale factor was updated. With these updates, the results showed that the relative geometries were essentially the same; i.e same orbit crossing distance and timing situations, but everything was shifted out three orbits due to the atmosphere prediction updates as seen in Figures 11 and 12. At the APG meeting that day, the navigation team recommended that the primary orbit be #445 which had an apoapsis altitude of 479.9km and the backup orbit be #447 which had an apoapsis altitude of 471km.
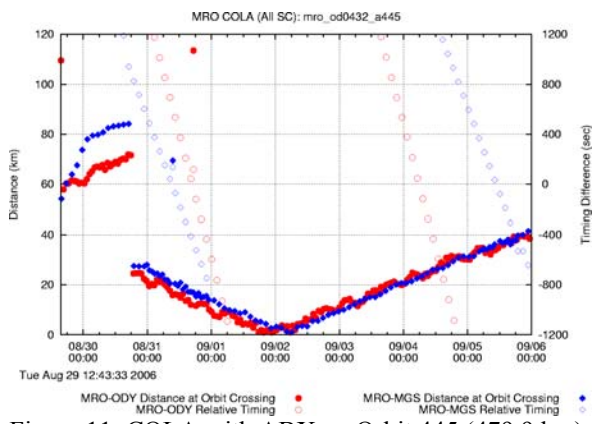

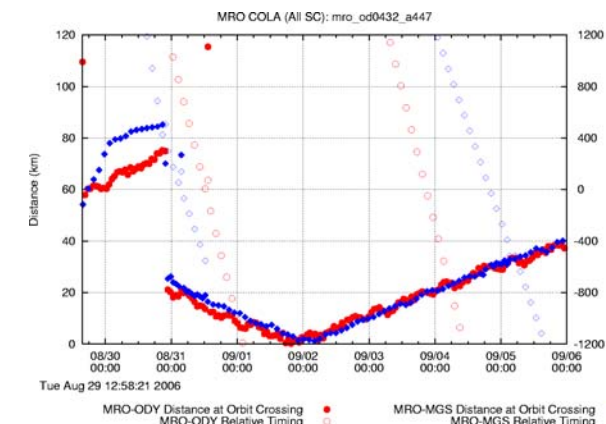Figure 11. COLA with ABX on Orbit 445 (479.9 km)

Figure 12. COLA with ABX on Orbit 447 (471 km)

That evening there was a special ABX Selection meeting at 9:00pm. The navigation team presented the final recommendation for primary and back up orbits based on the latest trajectory from the reconstruction of orbit #435.

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The atmosphere prediction updates from the morning were quite good and no updates to the model were needed. The analysis showed that orbits #445 with an apoapsis altitude of 481.5 km and #447 with an apoapsis altitude of 473km were still optimal for the ABX maneuver. Since this was the final recommendation, the team was really counting on the atmosphere prediction model to be accurate. Orbits #445 and #447 had to have apoapsis altitude between 462km and 485 km to guarantee no COLA issues post ABX with MGS and ODY.

The project had an ABX Go/No Go meeting the next morning about three hours prior to the ABX execution. The navigation team analyzed the COLA situation one last time using the latest trajectory from the reconstruction of orbit #441. Luckily, the atmosphere predictions had held up well for the last few orbits. The primary orbit, #445 had an apoapsis altitude of 483.1 km. Navigation was GO for ABX.

The reconstruction of the ABX maneuver and the following orbits show that the apoapsis altitude for orbit #445 was 486km and the minimum closest approach post ABX was with ODY at 26.5 km.

7.0 Reconstructed Results

The reconstructed trajectories of MRO, MGS, ODY, and MEX were used to analyze the actual closest approaches during aerobraking. The results showed that MRO got the closest to ODY with a closest approach distance of 20.99km on August 25, 2006. There were 26 other closest approaches with ODY that were under 100km. The closest approach to MGS was 60.6 km on August 26, 2006 and the closest approach to MEX was 213.39km on August 28, 2006. The analysis also looked at the closest approaches with Phobos and Deimos which were 724.85km on April 10, 2006 and 10233.21km on March 22, 2006 respectively. Figures 13−15 show the actual orbit radial distances, the spacecraft to spacecraft distances, and the MRO true anomaly at the orbit crossing points with respect to ODY, MGS, and MEX.
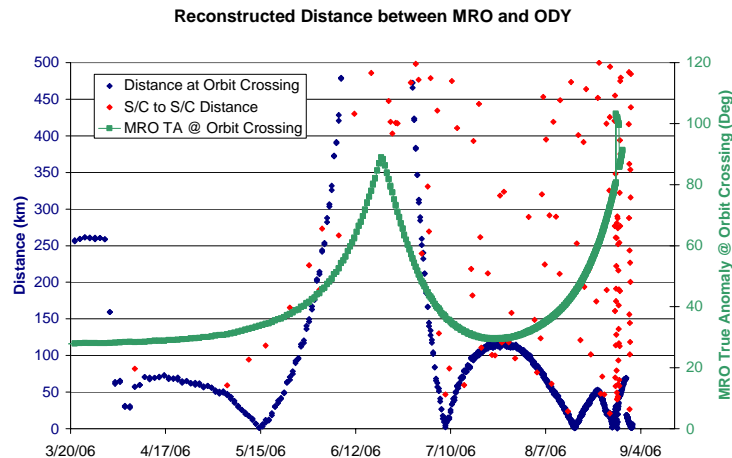

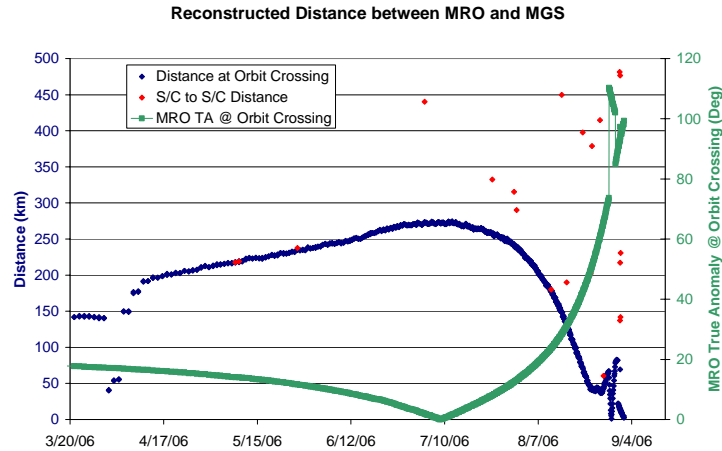Figure 13. COLA analysis with reconstructed MRO and ODY trajectories.

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Reconstructed Distance between MRO and MGS

Figure 14. COLA analysis with reconstructed MRO and MGS trajectories

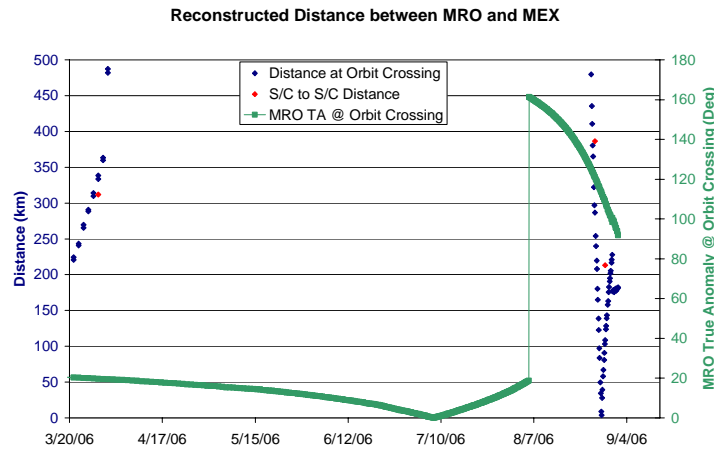**Reconstructed Distance between MRO and MEX**

Figure 15. COLA analysis with reconstructed MRO and MEX trajectories

8.0 Probability of Collision

Towards the end of aerobraking, a method was developed to evaluate the collision probability between two orbiters. It would be useful for future missions to show the probability analysis associate with each COLA situation when recommending corridor control ABMs or immediate action ABMs. The method uses the JPL Navigation B-plane targeting impact probability software (Planetary Quarantine (PQ)). The software inputs include the planet radius, the trajectory uncertainty ellipse, and the aimpoint. The program computes the probability based on an integral of bivariate Gaussian distribution about the aim point.

An example case for a MRO and ODY COLA issue during Walkout was generated. To compute the probability of collision between MRO and another spacecraft in two dimensions (radial and downtrack) some assumptions had to be made. A very conservative estimate of a 30 meter planet radius was used to represent the center to center dimensions for the two spacecraft. The uncertainty ellipse had to be defined by the 5σ radial and downtrack uncertainties. The example used a 5σ radial uncertainty per orbit of 5 km (based on a 77deg MRO true anomaly and an orbit period of 2.1hrs) and a 5σ timing uncertainty per orbit of 30 seconds. The propagation of these uncertainties over 12 orbits was computed. The radial and timing uncertainties are uncorrelated after more than 4 orbits.

The next step is to evaluate the impact probability with miss distances varying from 0 though 5σ away from the center of the target body. For the miss distance, only move the aimpoint in the downtrack direction; i.e. keep the radial uncertainty at 0, and calculate the downtrack uncertainties for 0 through 5σ. The results are shown below in Table 6. The results are equivalent when moving the aimpoint by the appropriate σ distance in the radial direction.

The probabilities would be smaller if the aimpoint was offset in both the radial and the downtrack direction. For example, at 12 orbits out, the probability of collision for a 3σ offset in the downtrack directions reduces from 3.1e-9 to 3.e-11 when also offset 3σ in the radial direction.

Table 6. Results from Probability of Collision Study

Separation Orbits Out	0σ	1σ	2σ	3σ	4σ	5σ
12	4.1066002e-07	1.7019474e-07	3.7975581e-08	3.1172253e-09	9.4132053e-11	1.045713e-12
11	4.5972702e-07	2.0379097e-07	4.5471916e-08	3.7325623e-09	1.127136e-10	1.2521354e-12
10	5.228819e-07	2.4842127e-07	5.5430278e-08	4.5499946e-09	1.3739791e-10	1.5263532e-12
9	6.0714909e-07	3.0950974e-07	6.906096e-08	5.6688691e-09	1.7118503e-10	1.9016932e-12
8	7.248661e-07	3.9627892e-07	8.8421782e-08	7.258102e-09	2.1917568e-10	2.4348221e-12
7	8.9940663e-07	5.2545968e-07	1.1724591e-07	9.62413e-09	2.9062356e-10	3.2285359e-12
6	1.1794577e-06	7.3004727e-07	1.6289557e-07	1.3371283e-08	4.0377776e-10	4.4855657e-12
5	1.6795525e-06	1.082831e-06	2.4161227e-07	1.9832744e-08	5.9889701e-10	6.6531449e-12

The results show that even if we were targeting the other body (i.e. a 0σ event), the probability of collision is quite low. However, it will be up to the project management on future missions to determine the appropriate acceptable risk while weighing the consequences of a collision.

9.0 Conclusions

The navigation team successfully guided MRO through the aerobraking phase and into the proper science orbit. While aerobraking has been done before at JPL with MGS and ODY, this was the first time it was done with an in depth look at collision avoidance. The development and implementation of the collision avoidance process for the aerobraking phase was a challenge for the MRO navigation team. The team gained valuable experiences and hopefully the process and recommendations will help future aerobraking missions.

10.0 References
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