MARS EXPRESS NAVIGATION FOR BEAGLE 2 SEPARATION AND MARS ORBIT INSERTION

T. Morley[1], F. Budnik[1], R. Mackenzie[2], N. Faehling[3]

European Space Operations Centre (ESOC), Robert-Bosch-Strasse 5, 64293 Darmstadt, Germany
[1]ESA/ESOC, E-mail: Trevor.Morley@esa.int & Frank.Budnik@esa.int
[2]Science Systems (Space) Ltd., based at ESOC, E-mail: Ruaraidh.Mackenzie@esa.int
[3]EDS Operations Services GmbH, based at ESOC, E-mail: Norbert.Faehling@esa.int

ABSTRACT

The navigation of Mars Express (MEX) is described, concentrating on the orbit determination, although some aspects of trajectory optimisation are mentioned. The main emphasis is on the critical phase of Mars approach, Beagle 2 (lander) release, and Orbit Insertion (MOI).

Some features of the spacecraft dynamics are summarised and an example presented of the quality of the conventional radiometric tracking data. These were augmented by delta differential one-way range (ΔDOR) data points derived from NASA Deep Space Network (DSN) DOR measurements. Their benefit for reducing targeting uncertainties is demonstrated.

1. INTRODUCTION

ESA's first planetary orbiter, Mars Express, was launched directly into an interplanetary trajectory on 02 June 2003 and reached Mars on 25 December (Fig. 1). A novel feature of the mission was the release of a lander before reaching the planet so that the orbiter was on collision course up to less than 6 days before arrival. Within this short interval, MEX had to be re-directed, its changed trajectory confirmed and accurately determined.

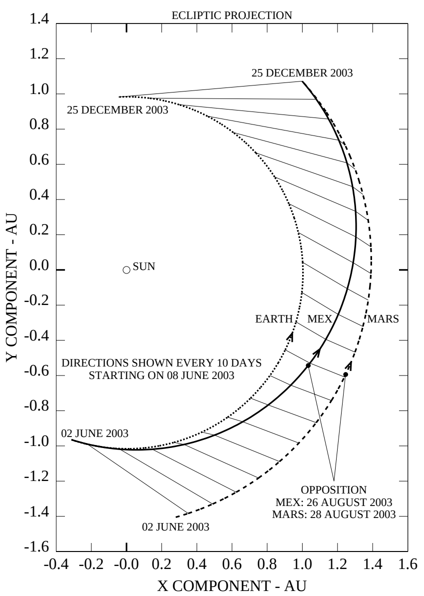

Fig. 1. Mars Express heliocentric trajectory

Another first was the operational use of ESA's new 35 m antenna at New Norcia (NNO), near Perth, as the prime ground station. The mission was also the first application for ESOC's interplanetary orbit determination software system, that had been extensively further developed in the preceding years and rigorously tested [1].

Successful testing was the result of a close collaboration with the Navigation Section of JPL. During the MEX mission, JPL also provided navigation assurance support [2], mainly solution comparisons from the Agencies' quite independent orbit determination programs. These activities were most intense shortly after launch, during a two weeks tracking campaign in August 2003 and during the last month before arrival at Mars.

2. DYNAMICS MODELLING ISSUES

MEX is 3-axis stabilised and all the thrusters are located on the -Z face with their line of action close to parallel to the +Z body axis. The system is unbalanced in that all thruster torques for reaction wheel off-loadings (WOLs) disturb the orbit. Moreover, the fixed, high-gain antenna's (HGA) bore sight is aligned 85° from +Z, so that, when Earth-pointing, only a small component of a WOL directly affects the Doppler shift.

During cruise, 48 WOLs were made (on average every 4.3 days), ranging in size from 4 to 61 mm/s (average 21 mm/s). The mean accelerations along each body axis component were estimated in the orbit determination for each individual WOL. The calibrations showed no systematic deviations from expected performance data.

Due to problems, mainly with the AOCS, the spacecraft entered safe mode several times during cruise. Each entry entailed attitude slews controlled by thrusters. *A priori*, no information was available on either the size or direction of the disturbance and the effective impulsive ΔV time was uncertain by several minutes. The disruption to the orbital knowledge was severe and the manoeuvre calibration difficult. On average, each safe mode changed the orbital velocity by about 15 cm/s.

The spacecraft's +Z face, where Beagle 2 was attached, was kept cold and not illuminated by the Sun except for a few occasions where special attitudes were needed for commissioning purposes and then the HGA was not Earth-pointing. On most of these occasions, 7 in all, discontinuities were apparent between the pre- and post-slew Doppler residuals, caused by outgassing. The component of the effective ΔV along the Earth-MEX direction ranged from 0.1 to 3.5 mm/s. The same kind of outgassing phenomenon is also being observed with Rosetta, several months after launch.

3. TRACKING DATA

Throughout heliocentric cruise, conventional 2-way, X-band Doppler and range data were acquired during daily passes at NNO, and frequently by various antennas of the NASA DSN complexes at Madrid and Goldstone. The Doppler data were compressed to 60 s count times.

Table 1 shows an example of the statistics of post-fit residuals from a long-arc orbit determination solution. Above 15° elevation, the residuals consistently appeared randomly scattered around zero mean. In the "weight" column are the conservatively chosen 1σ data noise values assigned for the processing. A constant range bias was estimated for each station pass. For the example data span, all the estimates were below 5 m, the average being less than 2 m (1-way).

Table 1. Example of post-fit data residuals' statistics

Data type		Number	RMS	Weight
Doppler (mm/s) 10 Nov. to 18 Dec.	NNO	17296	0.057	0.20
	DSN	13048	0.051	0.20
Range (m) 10 Nov. to 18 Dec.	NNO	923	1.076	10.0
	DSN	4778	0.258	10.0
ΔDOR (ns) 11 Nov. to 24 Dec.	E-W	28	0.089	0.25
	N-S	20	0.115	0.25

3.1 Delta Differential One-Way Range (ΔDOR)

On 54 occasions, NASA/DSN acquired DOR data [3] from MEX and one of four quasars using antennas on the Goldstone-Madrid (E-W) and Goldstone-Canberra (N-S) baselines. JPL reduced the data so that, within the ESOC orbit determination software, a conversion to 2 ΔDOR observables per occasion was usually possible and, in total, 105 ΔDOR data points were produced.

These data are the double differences between the arrival time of the spacecraft signal at the two stations and the arrival time of the signal from a quasar in a near-by direction. As such, the 1σ error is in time units (Table 1). In effect, each data point is an extremely accurate measure of the component of the angular separation on the plane-of-sky between the quasar and spacecraft, in the plane containing the baseline. An error of 0.25 ns is equivalent to an angular error of about 9 nrad for the E-W baseline and 7 nrad for the N-S baseline.

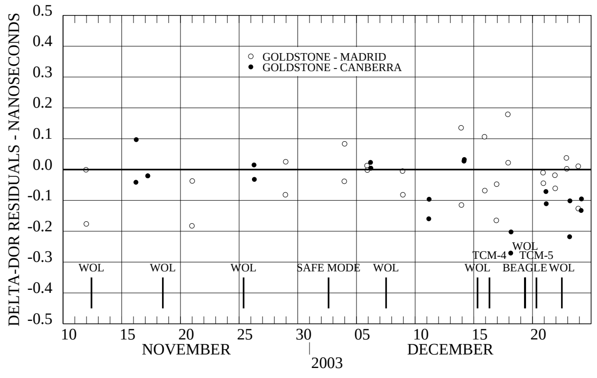

Fig. 2. Mars Express post-fit ΔDOR residuals

Fig. 2 shows the post-fit ΔDOR residuals from a 44 days arc orbit determination (that also included Doppler and range data) up to just before MOI. The residual statistics are listed in Table 1 and again it can be seen that the data weighting was conservative.

4. TARGETING AT END OF CRUISE

A 3 m/s test firing of the main engine was made on 27 October 2003 and trajectory correction manoeuvre 3 (TCM-3) was executed 14 days later. The expected effect of the test firing on the orbit had been anticipated since long before the operation. However, the orbital disturbances due to both planned and unplanned entries into safe mode, especially those that occurred in late October, could not be forecast in previous trajectory optimisations. Counteracting the effects of these disturbances was the predominant factor for the TCM-3 magnitude of 0.965 m/s.

Using a five weeks long tracking data arc up to 01 December 2003, the final calibration of TCM-3 was made. The burn was very precise, the direction error being at most a small fraction of a degree. An under-performance of 0.21% was estimated but with a 1σ uncertainty that was almost as large as this value.

4.1 B-plane Definition

Planet approach trajectories are typically described in aiming plane coordinates referred to as "B-plane" coordinates. The B-plane is a plane passing through the target body centre and perpendicular to the asymptote (vector **S)** of the incoming trajectory (assuming two-body conic motion). The "B-vector" is a vector in that plane, from the planet centre to the piercing point of the trajectory asymptote. The B-vector specifies where the point of closest approach would be if the target planet had no mass and did not deflect the flight path. The abscissa, **T**, is specified here to be the projection of the Mars equator of date; the ordinate, **R**, completes an orthogonal right-handed triad with **S** and **T**. Trajectory errors in the B-plane are characterised by n-σ dispersion ellipses. (In this paper, all plots are shown with n=3).

The trajectory optimisation team defined the optimum target coordinates in the B-plane. The orbit team mapped each estimate and covariance matrix into the expected coordinates and the 3σ error ellipse in the B-plane.

4.2 Targeting at the Start of December 2003

On 01 December, the best estimate of the MEX position in the B-plane was about 35 km from the target. The 3σ error ellipse had semi-axes of 28x22 km. The next and nominally last orbit correction before Beagle 2 release, TCM-4, was planned for 08:00 UTC on 16 December, 3 days before the release. One day earlier, a WOL was planned, the last such manoeuvre prior to release. If the B-plane estimate did not change, it was calculated that TCM-4 would need to be only about 6-7 cm/s.

This advanced planning was destroyed when the spacecraft went into safe mode on 02 December. The then unknown orbital perturbation seriously degraded the prediction accuracy.

By 08 December, with 6 additional days of tracking data, including two pairs of E-W and one pair of N-S ΔDOR measurements, the orbital knowledge had largely been regained. The best estimate in the B-plane was now 175 km from the target. The calibrated size of the safe mode was an effective ΔV of 12.83 cm/s. Its direction turned out to be close to the Earth-spacecraft direction.

The daily comparison between ESOC and JPL of independently derived orbit determination solutions started on the same day. Both teams had the same set of DSN and NNO tracking data at their disposal along with all auxiliary information but were free to choose the details of the data processing, for example the data weighting and assumed uncertainties assigned to consider parameters. On 08 December, the B-plane solutions differed by just 1.5 km.

5. TARGETING FOR BEAGLE 2 RELEASE

5.1 TCM-4

Fig. 3 shows the situation in the B-plane on 15 December when the final preparations were made for TCM-4. Based upon the estimate at that time, to reach the target called for a change in the B-plane of 179 km with a manoeuvre of magnitude 34.0 cm/s lasting 29 seconds. Since the main effect was to counteract that of the safe mode, its direction was only 4° from the spacecraft-Earth direction. This was very favourable because the direct measurement of the change in the Doppler would straightaway give a good indication of the performance.

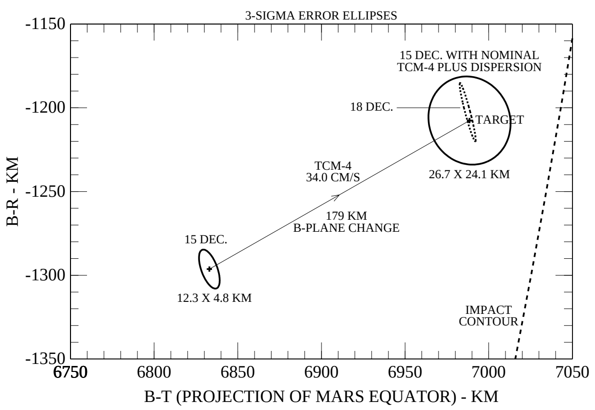

Fig. 3. MEX B-plane - TCM-4 targeting preparatory to Beagle 2 release

The impact contour on Fig. 3 is an arc of a circle centred on Mars. Ignoring the atmosphere, it corresponds to hyperbolic trajectories whose pericentre distance is the radius of Mars. Any point on the B-plane inside this contour (to the left of the contour in Fig. 3) corresponds to a trajectory which, with no control, leads to impact.

The near circular ellipse in the top right of Fig. 3 represents the 3σ error expected immediately after the manoeuvre. The 1σ dispersion on the manoeuvre was assumed to be 3% of its nominal magnitude with a spherical distribution. This assumption was very conservative considering the much better performance of previously calibrated manoeuvres. Its contribution to the size of the error ellipse was significantly larger than that due to the uncertainty ellipse before the manoeuvre.

TCM-4 was executed at 08:05:05 UTC, spacecraft time, on 16 December. On the same day, the spacecraft's geocentric declination passed through zero - the worst possible geometry for determining this parameter from line-of-sight measurements alone. The thin, dashed ellipse is the 3σ dispersion achieved using three more days of tracking data, including 3 pairs of E-W and one pair of N-S ΔDOR measurements. From the position of the centre of this ellipse it can be seen that TCM-4 was accurate, the best estimate being a slight over-performance together with a small direction error.

5.2 Navigation up to Beagle 2 Release

The target in Fig. 3 has coordinates:

B-T = 6988.5 km
B-R = -1207.6 km

The centre of the dashed ellipse is the solution based on the last orbit determination before Beagle 2 release. It has coordinates:

B-T = 6987.4 km
B-R = -1202.6 km

so was just 5.1 km from the target. The 3σ error ellipse has semi-axes 17.9x1.5 km. The JPL solution differed by only 1.3 km and the error ellipse was virtually identical, both in size and orientation.

Over the previous days, several solutions had been exchanged between ESOC and JPL and some were not so compatible, with coordinates in the B-plane differing by up to about 7 km. Also, the JPL solutions appeared more stable. An intensive analysis revealed a correlation between the differences and the time that had elapsed since the Earth orientation parameters (polar motion and UT1 - UTC) had been updated (rather than using predicted data). The orbit solutions made with ΔDOR measurements excluded were especially sensitive in this respect. Measures were taken to make sure that updates were made daily after which all ESOC-JPL comparisons were very consistent.

More targeting data in the Beagle 2 B-plane, that includes the separation velocity plus other dispersions, is given in [4]. Therein, it is shown that the 3σ error ellipse lay well inside the contours representing the allowed limits on the flight path angle at atmospheric entry - the most important constraint that had to be satisfied.

5.3 Beagle 2 Release

Around the time of release, DSS 43 (the 70 m. antenna at Canberra) acquired the unmodulated, 2-way S-band signal via a MEX low-gain antenna (LGA). The Doppler residuals (the differences between the measurements and expected values assuming no release) were displayed in near real time, courtesy of JPL.

The reactive force on the orbiter due to Beagle 2 separation was expected to cause a ΔV of 1.81 cm/s. The direction was 27° from the spacecraft-Earth vector, so the expected change in the 1-way range-rate was

-1.61 cm/s. For the S-band downlink frequency, this was equivalent to a change in the 2-way Doppler shift of +0.247 Hz (but the sign was changed in the display).

Originally, the Doppler residuals were displayed at one sample per second, but Fig. 4 shows them compressed to 60 s integration time which substantially reduces the noise. From the original data it can be seen that the drop in the residuals started within one second of 08:39:28 UTC, ground receive time on 19 December. Since the down-leg one-way light-time was 496 seconds, Beagle 2 was released at 08:31:12. This was about 2 seconds later than expected.

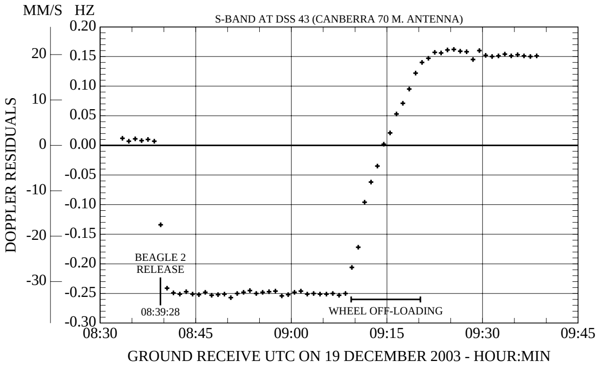

Fig. 4. MEX near real time 2-way Doppler residuals at Beagle 2 release

Taking into account that the residuals before release are slightly positive, it can be seen in Fig. 4 that the change in the Doppler shift was marginally larger than expected. A subsequent orbit determination using data up to almost one day after the release gave a calibration value for the reactive ΔV of $1.29\% \pm 0.05\%$ (1σ) higher than expected. This result was obtained assuming that the direction was perfectly known.

30 minutes after Beagle 2 release a WOL was initiated by on-board commands. Based upon the estimated reactive torque on the spacecraft caused by the release, the predicted ΔV was 3.6 cm/s in a direction opposite to the release ΔV. The change in the displayed Doppler shift was predicted to be +0.5 Hz. Fig. 4 shows that the observed change was +0.4 Hz: the reactive torque was lower than anticipated.

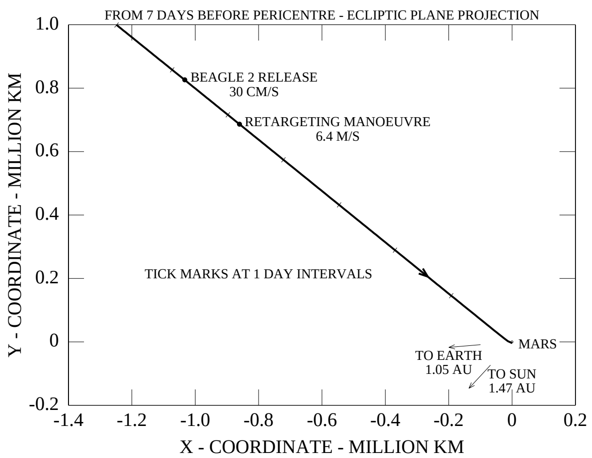

Fig. 5. Mars Express Mars approach trajectory

6. TARGETING FOR MOI

Fig. 5 shows the ecliptic projection of the trajectory during the last 7 days before reaching Mars.

Beagle 2 was released almost 6 days before arrival when it was still more than 1.3 million km from its destination. One day later, the trajectory of the orbiter had to be changed, aiming at the optimum target for MOI. This called for a manoeuvre of 6.355 m/s, the largest of the mission hitherto but similar to the magnitude of TCM-1.

The scale of Fig. 5 is such that the separate trajectories of Beagle 2 and MEX cannot be distinguished (Mars is drawn to scale in the plot).

6.1 TCM-5

Fig. 6 shows the situation in the B-plane early on 20 December. The tiny error ellipse at the bottom left surrounds the estimate of the coordinates after Beagle 2 release. TCM-5 was designed to move the location in the B-plane by 2311 km.

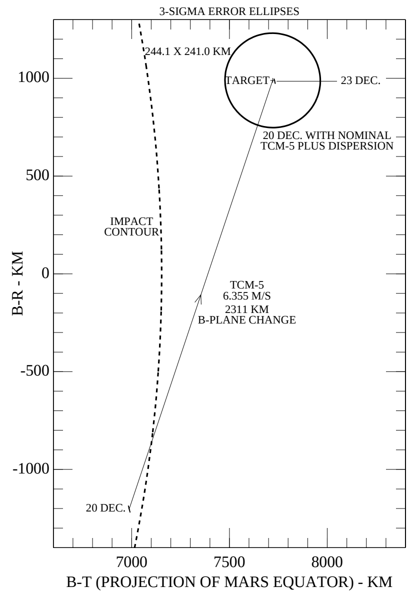

Fig. 6. MEX B-plane - TCM-5 targeting for MOI

TCM-5 was executed at 08:06:07 UTC, spacecraft time, on 20 December and lasted 282 seconds. The near circular ellipse in the top right of Fig. 6 represents the 3σ error expected immediately after, using the same very conservative manoeuvre dispersion assumption as for TCM-4.

The tiny error ellipse just to the right of the target point surrounds the estimate of the B-plane coordinates made 3 days later. The additional tracking data used in this solution included 3 pairs of E-W ΔDOR measurements (from consecutive evenings on 20, 21 & 22 December), one pair of N-S ΔDOR measurements from the morning of 21 December and the first of the pair of N-S ΔDOR measurements from the morning of 23 December. The closeness of this ellipse to the target testifies to the precision with which TCM-5 was executed.

6.2 Estimates without ΔDOR Measurements

The standard orbit determination solutions, that by now were being generated two to three times each day, were based on all the data types. When time permitted, additional solutions were generated with the ΔDOR measurements omitted. The purpose was to ensure that consistent solutions were obtained and to determine the extent to which the additional ΔDOR measurements reduced the navigation uncertainties.

Fig. 7 shows the results of one such comparison made on 23 December. The smallest error ellipse, based on all the data types, is the same as the one on Fig. 6.

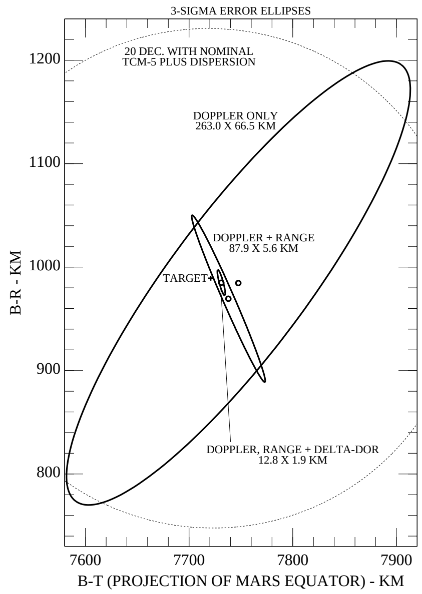

Fig. 7. MEX B-plane estimates on 23 December 2004

It is possible to determine the orbit using Doppler data alone, but the resulting error ellipse is exceedingly large. The addition of range measurements drastically reduces the semi-major axis of the Doppler-only solution. Since range data primarily provide accurate information on the spacecraft's geocentric distance, the direction vector from the Earth to spacecraft must map into roughly the SW-NE orientation on the MEX B-plane. As a result, the orientation of the Doppler plus range error ellipse is quite different.

Of most interest is the effect of the additional contribution from ΔDOR data. They provide much more precise information on the spacecraft's state components on the plane-of-sky. On the MEX B-plane they led to a reduction in the size of the error ellipse semi-major axis by a factor of 7. The orientations of the two ellipses, though, are similar.

6.3 Final B-plane Solutions for MOI

The B-plane coordinates and error ellipse shown for the 23 December were based on an orbit determination whose data cut-off occurred at 03:35 UTC on that day. This solution was particularly important because it was the one used for the nominally final optimisation of the MOI burn and the uplink of all the TC parameters associated with it into the on-board mission time-line. Nevertheless, frequent orbit determinations continued, to check that the B-plane solutions remained stable.

Also, by this time it was known that the nominal target had not been precisely reached. However there were no severe requirements for the exact target and it had already been decided that as long as no major anomaly occurred there was certainly no need for a touch-up manoeuvre. Much more important than reaching a particular point in the B-plane was the accuracy of the knowledge of the estimated B-plane coordinates so that the MOI burn parameters could be optimally tuned for the determined trajectory.

The final two B-plane solutions are shown in Fig. 8, as well as the 23 December solution, magnified 34 times compared with Fig. 7.

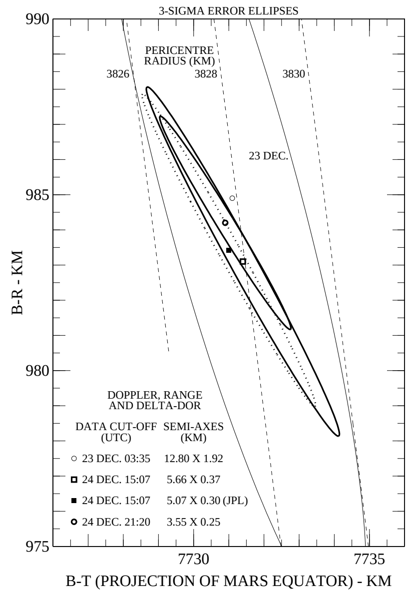

Fig. 8. MEX B-plane - final estimates for MOI

The original target (outside the plot) has coordinates:

B-T = 7720.8 km
B-R = 989.2 km

The final solution has coordinates:

B-T = 7730.9 km
B-R = 984.2 km

and was thus 11.3 km from the original target. It lies only 0.7 km from the 23 December solution.

Fig. 8 clearly shows the substantial reduction in the size of the error ellipses over the final 1.75 days. 3 E-W and 2 N-S ΔDOR measurements were obtained during this period. More than 2 days before MOI, MEX entered the sphere of influence of Mars (radius ~580 000 km): at the time of the final data cut-off it was within 60 000 km of the planet. The small bending of the trajectory due to Mars gravity provided additional information for pin-pointing the trajectory. The anti-clockwise rotation of the orientations of the error ellipses' semi-major axes is also likely to be due to this effect.

Extra test runs treated corrections to the NASA/JPL DE405 Mars ephemeris as uncertain. The results showed that the B-plane estimates were insensitive to small ephemeris errors, moving by, at most, 1 km. They also indicated that any ephemeris errors were indeed small. (Later, range bias estimates, included within orbit determination solutions made during the first two days after MOI, showed that the geocentric distance of the Mars ephemeris at that time was in error by just -330 m.)

The penultimate estimate, was the final one for which a comparison was made with JPL, whose solution is also shown in Fig. 8 (with the error ellipse dotted). The Agencies' solutions differed by just 0.5 km.

At this time, JPL was using the DE410 planetary ephemerides[1]. The Mars ephemeris is somewhat more accurate than that of DE405. But JPL had previously confirmed from internal comparison tests that the solutions differed very little depending upon the ephemeris used.

Also shown on Fig. 8 are contours of constant pericentre radius. The values of the osculating pericentre distance (at the epoch of pericentre) include the nominal effect of the main engine burn at MOI which was to begin about 22 minutes before pericentre passage. Corresponding to the final solution, a pericentre distance of 3901.8 km would have been expected with no MOI burn: the braking manoeuvre was expected to reduce the pericentre distance by 74 km. It would also cause the pericentre passage time to be later by 100 seconds.

6.4 MOI Performance and the Post-MOI Orbit

As Fig. 8 shows, the 3σ uncertainty in the pericentre distance was less than 2 km. Later orbit determination solutions, using data before and after MOI, showed that the actual pericentre distance was 3828.6 km (433 km altitude), with very small uncertainty. This was about 0.9 km higher than expected. The small difference was only partly due to the orbit determination error. The acceleration during the MOI burn was slightly lower than predicted and so the reduction in pericentre distance due to the manoeuvre was also less than expected. Since the burn end time was controlled by accelerometers, the underperformance was automatically compensated by extending the burn duration by 28 seconds.

The MOI main engine burn was expected to last 33 min. 42 s with an integrated ΔV of 806.762 m/s. During the burn, MEX was rotated to keep alignment of the thrust close to opposite to the orbital velocity vector.

Fig. 9 shows the ecliptic projection of the trajectory over a 4 hours period around pericentre that occurred at 03:07:28 UTC on 25 December 2004. The occultation began 50 seconds after the actual end of MOI and lasted 42.5 minutes. 97 minutes later, there was an umbral eclipse of 52 minutes duration.

The low inclination, 10-days period orbit reached after MOI was exceedingly close to the planned one. The errors in all the angular elements were below 0.24°. The apocentre distance of 185 371 km was 1415 km higher than planned which means the MOI underperformed. But to put into context how small the underperformance was, an additional ΔV of only 0.358 m/s at pericentre would have been needed to reach the planned value. At an epoch shortly after the end of MOI, the osculating pericentre distance was 3.7 km lower than planned. This was predominantly due to the 28 s long burn extension.

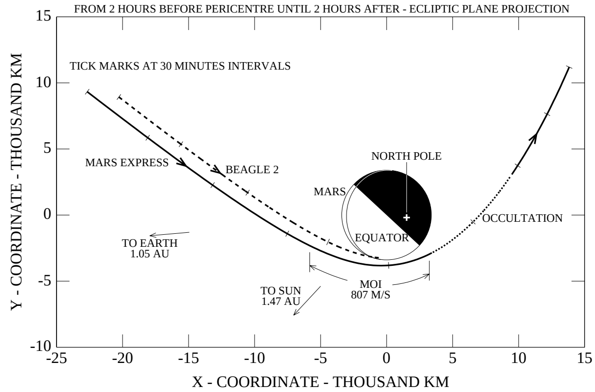

Fig. 9. Mars Express Mars orbit insertion (MOI)

7. CONCLUSIONS

For both Beagle 2 release and MOI, the navigation of Mars Express was successful and very accurate. (All involved parties agree that spacecraft navigation errors can be excluded as a contributory cause for the lander's subsequent demise.)

The addition of ΔDOR measurements confirmed the correctness of solutions obtained using only the classical, line-of-sight, radiometric data but led to very substantial reductions in the targeting uncertainties.

The comparisons of orbit determination solutions with those of JPL were continuously consistent, the differences being tiny compared with the error statistics. Above all else, these navigation assurance activities boosted the confidence of the ESOC team during the critical phases of the mission.

Acknowledgement: The outstanding support of many at NASA/DSN and JPL, particularly the small, dedicated navigation team, technically led by Don Han, is warmly appreciated.

8. REFERENCES

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3. Thornton C. L. and Border J. S., *Radiometric Tracking Techniques for Deep-Space Navigation*, Monograph 1, Deep-Space Communications and Navigation Series, JPL 00-11, 2000.

4. Cramm R., et al. Reconstructed Beagle 2 Trajectory, ISSFD 2004, *ESA SP-548*, 2004.

[1] DE410 is not an "export" version of the JPL series of planetary ephemerides. For this and various other reasons it was not adopted for ESOC Mars Express operations.