GAINING CONFIDENCE IN NAVIGATING ROSETTA AT MARS SWING-BY

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ABSTRACT

The Mars swing-by in the early morning of the 25th of February 2007 was one of the most critical events the Rosetta mission has experienced so far on its way to the comet Churyumov-Gerasimenko. The closest approach took place at a distance of only 250 km from the planet's surface. Missing the optimal target would have translated into considerable fuel cost. In order to achieve confidence in operating through this highly critical mission phase, a navigation analysis exercise was carried out beforehand. This paper describes the purpose and the chosen approach for this preparatory Flight Dynamics activity. It presents and discusses results of the analysis. Emphasis is put on the question of what is needed to simulate a valuable data set representative for operations. The results of the navigation analysis are compared with real data obtained during swing-by operations.

1. INTRODUCTION

ESA's Rosetta mission was launched in March 2004 with a planned encounter with comet 67P/Churyumov-Gerasimenkov in May 2014. On its way to the comet the Rosetta spacecraft successfully completed an Earth swing-by in March 2005, followed by the Mars swing-by (MSB) on the 25th of February 2007. Two more Earth swing-bys will follow, one in November 2007 and the last one two years later in 2009 [1]. The Mars swing-by took place at a distance of 2.1 AU to the Earth, with a minimum distance to the Martian surface of approximately 250 km height. The hyperbolic velocity of the spacecraft with respect to Mars was 8.9 km/s. The swing-by decelerated the spacecraft in the heliocentric system corresponding to a Δv manoeuvre of 2.3 km/s. Further details on the overall Mars swing-by scenario are described in [2].

In general any departure from the optimal target at a swing-by implies a two-fold risk. Firstly, a planetary impact of the spacecraft must be avoided. Secondly, excessive fuel spending puts the progress and objectives of the mission at risk. Any deviation from the optimal swing-by target translates into fuel that needs to be spent later by performing a trajectory correction manoeuvre. This fuel cost can be significantly reduced by performing pre-swing-by correction manoeuvres for a spacecraft re-targeting, provided that adequate orbital knowledge of the actual trajectory exist. However, manoeuvring the spacecraft shortly before the swing-by always means operational risks and might interfere with scientific observations. In order to find a balance between minimizing this risk for Rosetta at MSB and saving fuel, the flight rules as given in Table 1 were established, constrained by a total fuel allocation of 25 kg for MSB navigation. In the last seven days before swing-by four manoeuvre slots were reserved. The decision on executing such a pre-swing-by manoeuvre depends on the amount of fuel that can be saved when performing it, compared to correcting the trajectory after the swing-by. Only if the fuel saving exceeds the threshold given in the flight rule is the manoeuvre executed.

Table 1: Rosetta flight rules during Mars approach.

Manoeuvre at	Criterion
MSB – 1 week	If fuel saving > 5 *kg* or pericentre height < 200 *km*
MSB – 3 days	If fuel saving > 10 *kg* or pericentre height < 200 *km*
MSB – 1 day	If fuel saving > 15 *kg* or pericentre height < 200 *km*
MSB – 6 hrs	If fuel saving > 25 *kg* or pericentre height < 200 *km*

It is evident that the evaluation of a potential pre-swing-by manoeuvre depends significantly on the orbital knowledge of the actual spacecraft trajectory. Hence, a navigation analysis by ESOC's Flight Dynamics division was carried out, following the three objectives:

(I) *Analysis*: Examining navigation accuracy and evolution of orbital knowledge during the Mars approach phase. This directly impacts the decision on executing trajectory correction manoeuvres. Their execution depends on flight rules (cf. Table 1).

(II) *Test:* Although the software is operationally proven and the members of staff are experienced, it is the first time that the Flight Dynamics system operates this specific scenario, specifically a planetary swing-by. The navigation analysis exposed both team and software to this scenario.

(III) *Training*: Familiarization with the Mars swing-by scenario and authentication of Flight Dynamics procedures and schedules.

This analysis was based on a set of simulated tracking data. In order to find a valid and valuable test set-up two points are specifically addressed in the following: the compatibility between simulated and modelled data and the controlled mis-modelling of simulated data. The term mis-modelling describes the application of environmental or dynamical models in the data simulation process that are not modelled in the operational software. By applying mis-modelling it is tried to expose the operational system to a quasi-realistic scenario where the applied environmental models or dynamics do not perfectly capture the real processes.

In section 2 of this paper the software for observable modelling and tracking data simulation is described. Its applications are explained with emphasis on its compatibility with operational results. In section 3 the specific Rosetta Mars swing-by scenario is elucidated and the chosen set-up for the navigation analysis is presented. Test results are presented and compared with operational results in section 4. Conclusions are finally drawn in section 5.

2. TRACKING DATA SIMULATION

The Flight Dynamics division at ESOC features a Test and Validation (T&V) group with the primary task to validate operational software and data products in both pre-launch and post-launch phases. On principle the T&V software is coded and operated independently from the software that is used operationally. The T&V group designs tests that involve the whole Flight Dynamics system or individual subsystems. Moreover, it is responsible for the delivery of input test data, such as is needed for the navigation analysis that is discussed here. Generating a set of simulated test tracking data comprises the following three steps:

1. *Orbit propagation*: in order to set up a reference trajectory that is the basis for the exercised scenario.
2. *Observable modelling* based on the reference trajectory, used ground station information and environmental models.
3. *Tracking data*: representation of observables in the context and format of the various tracking types and systems.

In order to run the navigation analysis T&V software has been used for each of the three steps. The T&V software was developed especially for the support of ESA's interplanetary missions but is not restricted to this kind of mission profile. Key software items for the generation of test data in this context were an orbit propagator (covering step 1 above), a library for observable modelling (covering step 2) and the tracking data simulator (covering step 3). The library for observable modelling is not only used by the tracking data simulator but also by other T&V applications in order to verify consistency between orbit determination solutions and observations. The observable modelling library and the tracking data simulator support various tracking types such as range, Doppler, antenna angles, differences one-way range (DOR), or measurements from an optical navigation camera. The tracking data simulator handles formats of different tracking systems as well. Additionally, meteorological measurements and station calibrations can be simulated.

The T&V software base used for the Rosetta navigation analysis has been successfully used for many missions during various phases. Launch activities of the ESA missions ROSETTA, MARS EXPRESS, SMART-1 and VENUS EXPRESS have been supported as well as preparatory tests for NASA's DAWN mission. Furthermore, planetary orbit insertions at Mars and Venus have been prepared, special analysis for ROSETTA's first Earth swing-by and an assessment of the MARS EXPRESS orbit determination performance during solar conjunction were carried out.

Due to the fact that the T&V software was coded independently, an assessment of the compatibility with operational software is essential. Cross-verification tests of ESOC's operational navigation software against operational software at JPL were repeated with the T&V software, cf. [3]. The tests included trajectory propagation and observable modelling. It was demonstrated that the results from models and algorithms used in the T&V software are compatible with operational software results, especially below the targeted modelling accuracies mentioned in Table 1 of [3].

Figure 1 exemplifies the aforementioned compatibility between T&V software and operational software. Operational two-way Doppler data from the Rosetta heliocentric cruise pass on the 27^{th} of April 2007 have been selected for this illustration. The spacecraft was approximately 1.8 AU away from the Earth and had a relative velocity component towards the Earth of 13.6 km/s. The tracking pass was recorded by ESA's 35m antenna in New Norcia (Australia), using X-Band up- and downlink. Based on given spacecraft trajectory information, two-way Doppler observables have been modelled and subtracted from the actual observation. The resulting residuals are displayed.

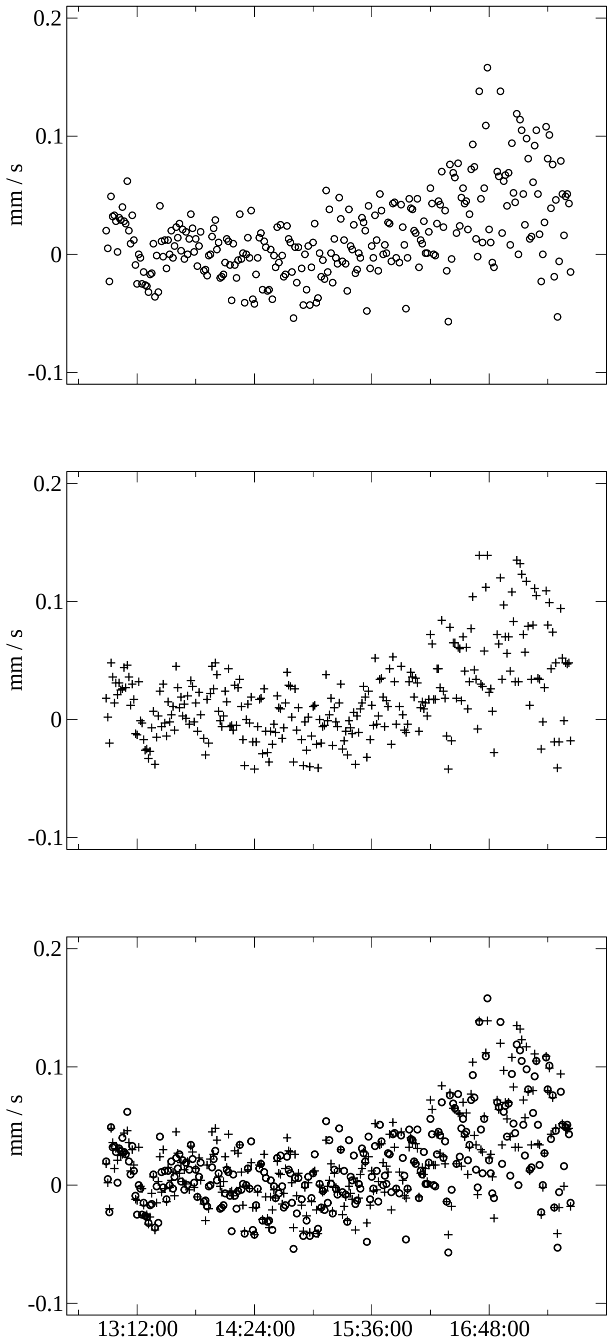

Fig. 1: Rosetta two-way Doppler residuals on 2007/04/27, computed by operational software (circles) and T&V software (crosses).

The upper panel shows residuals from operational software, the middle panel the residuals from T&V software, and the lower panel an overlay of both data sets. Though not fully identical it can be seen that the observable modelling shows a high level of compatibility. The maximum occurring difference of 0.04 mm/s between an operationally and a T&V modelled residual can be explained by numerical accuracy limits as a result of the time representation as a double precision number in the software. The two-way Doppler data with 60 seconds count time can be modelled to a numerical accuracy of 0.02 mm/s in both T&V and operational software during this period of the mission.

A high level of compatibility between software used to generate test data and software processing and analysing the data is a prerequisite for meaningful testing. Combined with identical input data it demands identical modelling results. Any deviations then allow an assessment of compatibility, or tracking down problematic algorithms or deficient set-up of either the T&V or the operational software.

Before running tests or analyses with simulated tracking data, it is generally good practice to run first through a test scenario with the highest possible compatibility in order to prove proper set-up and agreement of algorithms. However, a test scenario with full compatibility is only of marginal benefit when trying to deduce navigational knowledge from the test, because operational software uses algorithms that match the algorithms that have been used to simulate the data perfectly. In reality the operational software uses models as adequate as possible to model the underlying processes and environment, but cannot match the observations perfectly. Therefore the simulation of data for an analysis shall strive for a set-up with changed model parameters and alternative models/algorithms compared to the operational software, i.e. to introduce mis-modelling. Thus, after the compatibility run a new simulation run should be set-up for the realistic scenario that is applied for the actual analysis. How this was done for the navigation analysis is described in the following chapter.

3. SCENARIO FOR THE NAVIGATION ANALYSIS

The navigation analysis covered the time span from 2007-01-01 until closest approach on 2007-02-25. After the last trajectory correction manoeuvre (TCM) in November 2006 the next slot for a TCM was reserved at MSB-16 days (2007-02-09). This manoeuvre was simulated to take place. The decision on the execution of further TCMs was subject to analysis considering the flight rules (cf. Table 1). Without going into details of the software set-up only the most relevant issues on the test set-up are described here, reflecting the employment of mis-modelling with respect to the nominal case. The term "nominal" describes the assumed condition by the operational software when evaluating the test data.

3.1 Dynamics Modelling

First, a reference spacecraft trajectory was set-up serving as input for the tracking data generation. In order to introduce mis-modelling on the dynamics the following non-gravitational effects were chosen:

Initial state

The trajectory has been propagated with an initial state vector on 2007-01-01. The initial state was perturbed with respect to the nominal one by 9 km in the position and 3 mm/s in velocity.

Trajectory correction manoeuvre

The simulated TCM at MSB-16 days had an assumed nominal magnitude of 5 cm/s and was simulated with a performance of +1.8%. The manoeuvre's direction with respect to the spacecraft-Earth line was 85 degrees. No direction error of the manoeuvre was simulated.

Wheel off-loadings

Rosetta as a three-axis stabilized spacecraft performs regular wheel off-loading manoeuvres (WOL) in order to de-saturate the momentum wheels. The spacecraft is fitted with a balanced thrust system that ideally produces a pure torque during these manoeuvres. In real operations, however, a finite net Δv can be observed due to small thruster imbalances. Seven WOL manoeuvres were simulated in total, each with a net Δv between 0.5 and 1.0 mm/s.

Solar radiation pressure

Operationally a constant solar radiation pressure (SRP) acceleration scale factor is estimated per specific arc. A one-arc solution was pursued for this analysis, using a pre-defined spacecraft attitude profile. This allowed a consistent nominal SRP effect in both simulated and operational orbit propagation. In order to simulate dynamics that are not fully covered by the operationally applied models, a time varying scale factor was introduced in the simulation. The simulated SRP acceleration was thus related to the nominal acceleration according to:

$$a_{SRP}^{sim} = a_{SRP}^{nom} \cdot (1.075 + \gamma(t)) \qquad (1)$$

The time dependent term γ has been computed as auto-correlated noise. The evolution of $\gamma(t)$ over the course of the analyzed time span is shown in Figure 2. Each point in the graph represents the applied γ for an integration step. Basically this means that on top of the constant SRP scale factor of 1.075 (cf. equation 1) a varying component of almost 1% over the simulated time period has been added by applying the γ term. From operational experience this is a pessimistic assumption for the time dependent component. The simulated constant scale factor of 1.075 has been adopted from recent operational estimates, which ranged between 1.07 and 1.08.

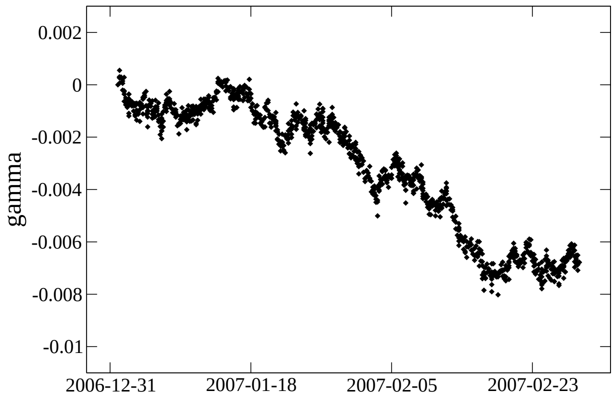

Fig. 2: Time evolution of γ in the solar radiation pressure simulation.

The above described set-up for the orbit propagation results in a closest approach at 2007/02/25 01:59:05.2 TDB with a pericentre radius of 3654.6 km, a height of 258.5 km above the planet's surface. The sub-satellite point is at 44 deg northern latitude.

3.2 Observables and Tracking Data Modelling

The simulated tracking data comprised two-way range, two-way Doppler, spacecraft and quasar DOR measurements. The latter were formed to ΔDOR by the operational software. The involved ground stations were the two ESA deep space stations Cebreros (Spain) and New Norcia (Australia), plus one antenna from each of the three NASA DSN complexes in Goldstone (California), Madrid (Spain) and Canberra (Australia). The data were simulated according to the operational tracking schedule between January and MSB. This resulted in

- 32 range/Doppler passes from New Norcia
- 25 range/Doppler passes from Madrid
- 9 range/Doppler passes from Goldstone
- 34 ESA ΔDOR (New Norcia – Cebreros baseline) (17 slots, each with two ΔDOR)
- 32 NASA ΔDOR (Goldstone-Canberra baseline) (16 slots, each with two ΔDOR)
- 2 NASA ΔDOR (Goldstone-Madrid baseline)

As for the orbit propagation, the simulated tracking data also featured mis-modelling. The following items have been modified in the simulation set-up:

Station displacement

The New Norcia, Madrid and Goldstone stations were simulated with a displacement ranging from 7 to 20 cm, while for Cebreros and Canberra nominal ground station coordinates have been used. This is a pessimistic assumption. The applied displacements are somewhat larger than the uncertainties of the ground stations' positions, plus the tectonic plate motion uncertainty.

Earth orientation parameters

The Earth orientation parameters (EOP), i.e. the Earth rotation expressed as UTC-UT1 and polar motion X and Y angles are operationally read from data files retrieved from the IERS on a daily basis. A pre-defined set of these data was used for the navigation analysis, allowing a consistent nominal modelling of the Earth rotation in both simulated and operational observable modelling. However, when an operational orbit determination is performed the EOP of the last days are just preliminary estimates that need later refinement and are thus afflicted with an error. Therefore the simulation software has used a modified set of EOP values. The daily polar motion angles X and Y were offset by a maximum of +/- 1 mas, and the UTC-UT1 quantity differed by a maximum of +/- 1.5 s from the nominal one.

Media corrections

Since the radio link is in X-Band the charged particle effects in the ionosphere or the interplanetary plasma are small compared to the dominating effect of the troposphere. Therefore any corrections due to charged particles were disregarded for this analysis and only tropospheric effects were considered for the observable modelling. Each ground station had had a nominal meteorological (meteo) data profile assigned, i.e. temperature, humidity and pressure. The meteo data are used to compute a zenith correction value for the propagation delay. This is then mapped to the actual elevation of the observation. If both simulation and operational software had used the same meteo profiles, the same algorithms for computing zenith corrections, and the same mapping functions, the simulated tropospheric effects would have been perfectly reproduced by the operational data modeling process. Consequently no mis-modelling would have taken place. In operations, however, the observable modelling usually suffers most from shortcomings in modelling the troposphere. Therefore the tracking data were simulated with varying tropospheric models on a pass by pass basis. Compared to the nominal troposphere modelling process, modified meteo profiles have been used and/or different algorithms to compute the zenith corrections from it and/or different mapping algorithms.

Bias and random noise

Two-way range data were simulated with a constant bias and with random noise. Each ground station was simulated to bias the two-way range data during each visibility pass by up to 11 meters. This quantity was kept constant during one pass, but could differ for distinct passes. The simulated random noise is of the order 2m to 6m (two-way), also varying from pass to pass. The two-way Doppler data were simulated only with random noise that spans from 0.05 mm/s to 0.19 mm/s for a 60 s count time. Again, the applied magnitude varies from pass to pass. Just like the Doppler data, the DOR observables were not biased with a constant value but each individual DOR observable was simulated with random noise of up to 0.5 ns. It should be noted that additionally to the random noise the tropospheric and the EOP mis-modelling have also a considerable effect on individual DOR measurements.

Figure 3 depicts the effect of the applied mis-modelling in radiometric tracking data, using the example of four days' Doppler data. The residuals in the lower panel are residuals from simulated data, based on the trajectory used for the simulation of the tracking data. In order to compute the residuals, the observables were modeled according to the nominal setup in terms of station position, EOP and media corrections. However, during the simulation of the data, mis-modelling for each of these items were applied. Therefore the residuals in the lower panel show directly the effects of the mis-modelling on the observables, with random noise added. Without any mis-modelling the residuals would show purely the random noise and would be perfectly distributed around the zero mean. For illustrative purposes, the upper panel shows residuals for the same period of time from real spacecraft operations, thus not linked to any simulated data of the navigation analysis. The used trajectory for this purpose was a determined heliocentric arc over several weeks. It is apparent that the application of the described mis-modelling causes residual patterns that resemble operational patterns.

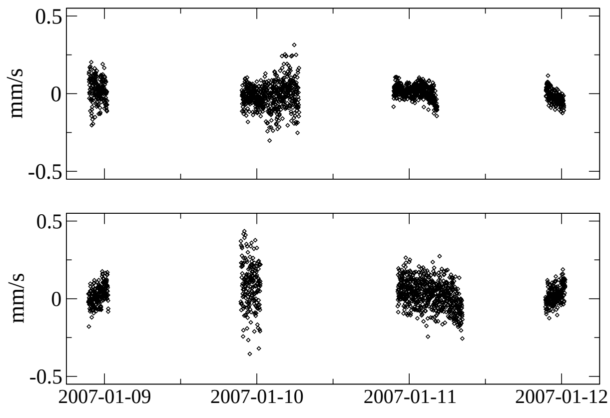

Fig. 3: Operational (upper panel) and simulated (lower panel) Doppler residuals for four New Norcia passes.

4. RESULTS

Based on the simulated tracking data arc several orbit determination (OD) runs with data cut-off times before MSB were done. The cut-offs were chosen such that they allow for checking of flight rules and/or optimising a manoeuvre in case of a TCM execution. The following cut-off times were selected for the last three weeks before MSB:

- OD#1: data cut-off at 2007/02/05 00:00:00 UTC
- OD#2: data cut-off at 2007/02/16 08:00:00 UTC
- OD#3: data cut-off at 2007/02/21 06:00:00 UTC
- OD#4: data cut-off at 2007/02/23 06:00:00 UTC
- OD#5: data cut-off at 2007/02/24 08:00:00 UTC
- OD#5DR: as OD#5 but only Doppler and range solution, no consideration of ΔDOR

In addition to a state vector each orbit determination also estimates the SRP scale factor, the TCM at MSB-16 days manoeuvre (where applicable) and the WOLs performed during the arc. It was assessed that the estimated quantities are - within their uncertainties - in agreement with the simulated values. Instead of giving the individual estimates here in detail, this chapter focuses on a more relevant aspect for the navigation analysis, i.e. the "B-plane" mapping. Additional to the orbit determination after each data cut-off, the orbit was further propagated, considering nominal future manoeuvres, in order to be mapped to the B-plane. The concept of the B-plane is often used to describe planetary approaches or swing-bys. It is a plane passing through the target body (Mars) and is perpendicular to the asymptote (vector **S**) of the incoming trajectory. 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**. The plane's origin coincides with the centre of Mars.

The simulated B-plane point is at R = -2869.1 km, and T = -3013.8 km. The differences between the simulated B-plane point and the B-plane points according to the determined and mapped trajectories are given in Table 2. Additionally the 3-σ uncertainties of the estimates are displayed. The corresponding Figure 4 gives the absolute B-plane impact points and illustrates the 3-σ error ellipses of the given OD mappings. The error ellipse of OD#1 is only partly visible as its size exceeds the plotted range. The solutions of OD#3, OD#4 and OD#5DR are omitted in order to avoid an overloading of the figure. The simulated B-plane point is labelled as "Truth". The mapped OD#1 impact point is additionally labelled as "Target" because the procedure that is followed to map OD#1 is exactly what is done in operations to match the swing-by target point in the B-plane: OD#1 is the last OD before the TCM at MSB-16 days. This TCM is designed to re-target the spacecraft to its optimal swing-by trajectory. Therefore the mapping of OD1 in the B-plane takes into account the nominal TCM that is designed such that this trajectory in fact matches the target.

From Table 2 and Figure 4 it is evident that the deviation of the estimated point from the "Truth" becomes smaller the closer the data cut-off is relative to the swing-by time. The orientation of the error ellipses' semi-major axis is approximately perpendicular to the radial direction in the B-plane. Indeed, the solutions vary, mainly along the most uncertain direction. Moreover, the importance of the ΔDOR measurements is brought out by the results of OD#5DR. Only range and Doppler measurements were used, no DOR measurements were considered. Only 18 hours before closest approach the B-plane point displacement and the uncertainties are very large. Further details on Doppler and range solutions without ΔDOR are described in [2].

Table 2: Differences between estimated and simulated B-plane points, and 3-σ uncertainties of the estimates.

	Diff. B-plane point (km)	3-σ error ellipse (km x km)
OD#1	5.3	24.6 x 16.5
OD#2	2.4	9.1 x 5.3
OD#3	1.6	7.2 x 3.0
OD#4	0.8	6.6 x 2.8
OD#5	0.8	6.4 x 2.6
OD#5DR	42.5	62.0 x 25.3

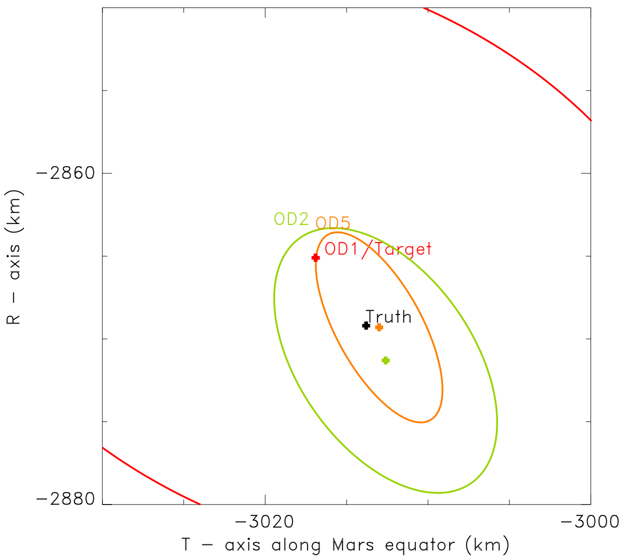

Fig. 4: B-plane impact points and 3-σ error ellipses, based on simulated data.

In order to check the flight rules (cf. Table 1) after OD#2 through OD#5 two assessments were required. First it was checked whether the pericentre was higher than 200 km. Then the fuel cost was evaluated. The latter was done by comparing the actual B-plane point with the target point. The target point used in this analysis was the nominal B-plane mapping of OD#1 as described above. Differences between the mapped B-plane point for the individual ODs and the target point are shown in Table 3. The approximation for the fuel cost is deduced from a rough rule of thumb that was applicable for the MSB. Representing the B-plane points in polar coordinates, the differences in the radial B-plane direction and the B-plane phase translate to "*0.5 kg fuel penalty per km radial difference*", and "*12.5 kg fuel penalty per degree phase difference*". Thus, correcting deviations in the radial direction cost more fuel. This rule holds for small deviations around the nominal B-plane point and relates to a clean-up manoeuvre after MSB. Considering the results from Table 3 and taking into account that the estimated pericentre height was never below 200 km, the flight rules did not trigger any further TCM.

Table 3: Differences in B-plane of the estimates with respect to the target and associated fuel cost.

	Radial diff. (km)	Phase diff. (deg)	Approx. fuel cost (kg)
OD#2	1.2	-0.10	1.9
OD#3	-0.8	-0.08	1.4
OD#4	-0.1	-0.07	0.9
OD#5	-0.1	-0.08	1.1

The spacecraft entered the Martian sphere of influence at around 08:00 on 2007/02/24, i.e. about 18 hours before closest approach. There is a period in time from that onwards the influence of Mars' gravity on the trajectory becomes so large that the spacecraft's position relative to Mars can be determined with less and less ambiguity. The question by when this effect starts was tried to be answered by monitoring Doppler residuals based on previous orbit determinations and predictions. Therefore the OD#5 orbit solution was used to compute residuals of observations done after the OD#5 data cut-off, i.e. between 2007/02/24 08:00 and MSB. Figure 5 visualises the most interesting section of the result. The bending is visible around 22:30 UTC ground receive time. However, this method depends on the quality of previous ODs and the prediction accuracy. The better this accuracy, the later the bending is visible.

During the course of the navigation analysis operational timelines and procedures were established and validated. As an outcome a re-scheduling of DOR measurements was requested and latest delivery times of tracking data were agreed. This ensured the best possible orbit determination estimates for evaluating the flight rules.

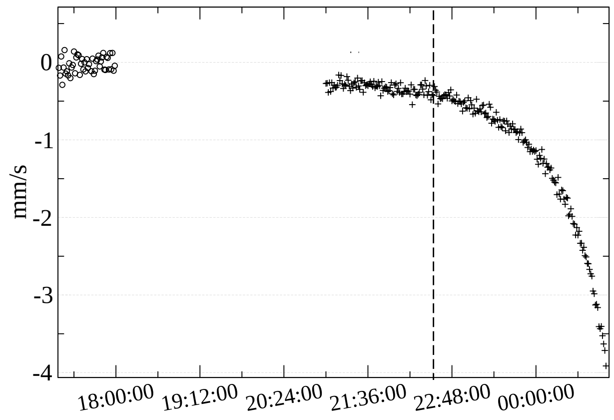

Fig. 5: Trajectory from OD#5 used to compute Doppler residuals for observations made after OD#5.

4.1 Comparison with operational results

A comparison with operational results achieved during the proper MSB is difficult, because the B-plane results of the analysis refer to the "simulated truth", while the "operational truth" remains unknown. A post-MSB orbit determination based on tracking data until about 1 day after the swing-by serves instead as a "best estimate" reference. Figure 6 shows operational B-plane mapping results. The mapped OD solutions correspond to the solutions and data cut-off times from the navigation analysis. While the interpretation of operational results is subject of [2], a comparison of Figure 6 with Figure 4 assesses how representative the navigation analysis is.

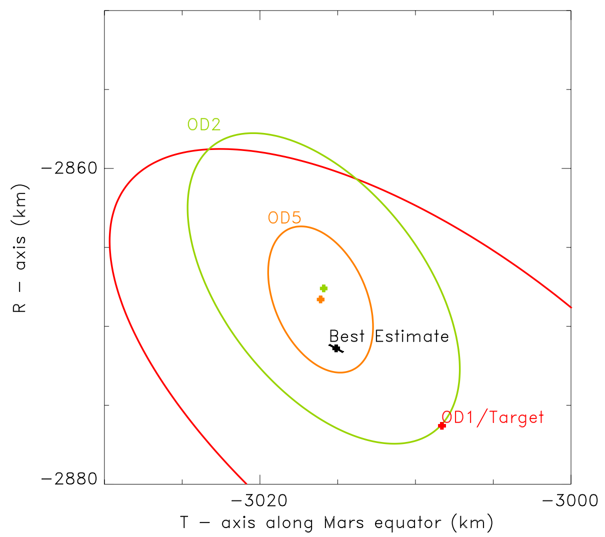

Fig. 6: B-plane impact points and 3-σ error ellipses, based on operational data from the MSB proper.

The absolute position of the target points differ by about 14 km in the B-plane. This is due to the simulation set-up and has no relevance on the validity of the navigation analysis as the overall swing-by geometry is not affected. It is rather the relative position between the solutions that is of relevance for the navigation analysis. It can be seen that the differences between target point, mapped OD solutions and “simulated truth” or “best estimate”, respectively, are slightly larger in Figure 6 than the test results from Figure 4. The differences are, however, of the same order of magnitude. Also the relative displacement vectors have the same orientation, subject to a different sign. The navigation accuracy in terms of size and orientation of the error ellipses could also be suitably predicted by the analysis. Evaluation of the flight rules yielded that after the TCM at MSB-16 days no further TCM was required, in agreement with the analysis results.

The issue by when the Mars gravity leaves a signature on the tracking data so that the spacecraft’s state relative to the planet is unambiguously known was operationally tackled by using a different method as presented in Figure 5. The evolution of the error ellipses’ size in the B-plane was monitored. From a certain point in time the error ellipses start to shrink considerably. This is the point in time when the spacecrafts’ state is undoubtedly constrained by the planet’s gravity. Figure 7 demonstrates the evolution of the 3-σ error ellipse area versus the data cut-off times. We consider the method of monitoring the error ellipses’ area versus time more appropriate than the pass-through of Doppler data according to Figure 5 as it does not depend on prediction accuracy of previous solutions. In contrast to the results presented in Figure 5 a strong shrinking of the area is visible already at about 16:30 hrs.

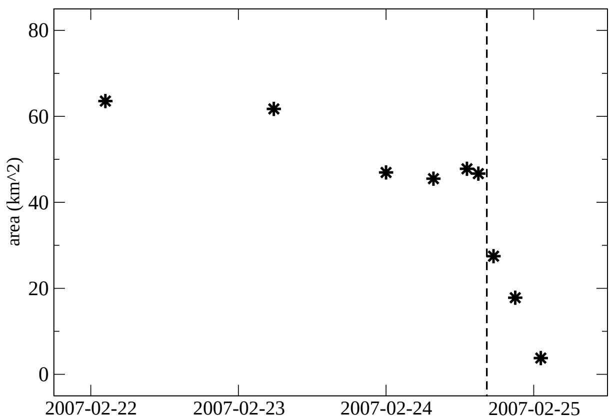

Fig. 7: Area of mapped OD error ellipses versus data cut-off times.

5. CONCLUSIONS

The controlled implementation of mis-modelling in the simulated data set led to a “quasi-realistic” scenario, to which the operational orbit determination team was exposed to. Despite of some pessimistic assumptions for the mis-modelled quantities the navigation analysis gives slightly more optimistic results than actual operations brought to light. Still, the differences between test and operational results are small. The similarities of results confirm that the chosen approach for the data simulation produced a valuable data set for analysis. Comparison of results from simulated data with operational results - such as was done in Figure 3 and in the pair of Figures 4 and 6 - substantiates the significance of the simulated test data. It enabled ESOC’s Flight Dynamics team to draw several conclusions such as refinement of operational procedures, tracking schedule and data delivery times. Furthermore it allowed gaining insight into various navigational aspects on the background of the flight rules and mission safety.

The evaluation of the flight rules on the basis of the B-plane impact points shows that the orientation of error ellipses in the B-plane is such that the uncertainty is largest in the direction that is cheaper to correct. Along the more fuel-expensive radial direction the orbit determinations have lower uncertainties. Furthermore, the navigation analysis clearly indicated that the risk of planetary impact due to navigation uncertainties is virtually zero.

The high approach velocity of the spacecraft causes that the strong bending on the tracking data due to the Mars gravity can be observed only a few hours before swing-by. Doppler data after this time give valuable information on the spacecraft’s state relative to Mars. In terms of operating the spacecraft this is, however, very late in order to determine the trajectory, design and command further trajectory correction manoeuvres. This circumstance underlines the criticality of the MSB. Still, the analysis’ results show that without severe spacecraft contingencies no significant navigation errors were to be expected. It rather gives evidence that a safe MSB navigation could be guaranteed. With the chosen tracking schedule the orbital knowledge evolves adequately in order to design the TCM at MSB-16 days and to decide on further TCM according to the flight rules. Subject to the condition that the TCM at MSB-16 days shows only a moderate mis-performance, no further TCM shall be necessary. Data from actual MSB operations confirmed the validity of these results.

Abbreviations

AU	Astronomical Unit
DOR	Differenced One Way Range
DSN	Deep Space Network
EOP	Earth Orientation Parameters
ESA	European Space Agency
ESOC	European Space Operations Centre
IERS	International Earth Rotation and Reference Systems Service
MSB	Mars swing-by

OD	Orbit Determination
SRP	Solar Radiation Pressure
T&V	Test and Validation
TAI	International Atomic Time
TCM	Trajectory Correction Manoeuvre
TDB	Barycentric Dynamical Time
UT1	Universal Time No.1
UTC	Coordinated Universal Time
WOL	Wheel off-loading (de-saturation)

References

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