# ROSETTA NAVIGATION AT ITS MARS SWING-BY

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## ABSTRACT

This paper reports on the navigation activities during Rosetta's Mars swing-by. It covers the Mars approach phase starting after a deterministic deep-space manoeuvre in September 2006, the swing-by proper on 25 February 2007, and ends with another deterministic deep-space manoeuvre in April 2007 which was also foreseen to compensate any navigation error. Emphasis is put on the orbit determination and prediction set-up and the evolution of the targeting estimates in the B-plane and their adjustments by trajectory correction manoeuvres.

## 1. INTRODUCTION

Rosetta is a planetary cornerstone mission in ESA's long-term space science program. Its destination is the injection into orbit around comet 67P/Churyumov-Gerasimenko. Launched in March 2004 with an Ariane-5/G1 it utilises four planetary swing-by manoeuvres (gravity assists) in order to get the correct Earth escape velocity to reach the comet in May 2014.

The first swing-by was around Earth and took place one year after launch on 4 March 2005. The navigation aspects from launch up to and including the first Earth swing-by are detailed in [1]. The second swing-by, around Mars, took place on 25 February 2007 and is the subject of this paper. It is followed soon after by an Earth swing-by on 13 November 2007. Finally, Rosetta will return to Earth in November 2009 to get its final boost to the comet.

In terms of navigation the Mars swing-by is the most demanding and critical exercise during Rosetta's whole long-lasting heliocentric cruise up until arrival at the comet. The reason for this is mainly that

1. it is the only swing-by around a distant planet which is always more difficult to navigate than an Earth swing-by; the geocentric distance of Rosetta at the Mars swing-by is 2.1 AU;

2. the nominal pericentre altitude is just 250 km above the surface of Mars which is by far lower than the pericentre altitudes required at all Earth swing-bys.

This paper focuses on the navigation aspects for the Mars swing-by. The next section describes the heliocentric trajectory and activities after the first Earth swing-by until the Mars swing-by. In this way this paper serves as a continuation of [1] in the chronology of the Rosetta mission. Section 3 gives details about the geometry of the swing-by trajectory whereas section 4 and 5 focus on the navigation aspects of the Mars swing-by.

## 2. HELIOCENTRIC TRAJECTORY FROM THE 1ST EARTH SWING-BY TO MARS SWING-BY

After the Earth swing-by Rosetta headed out to an aphelion of 1.7 AU which it reached in December 2005. Returning back to its perihelion at 1.0 AU, which it reached at the end of September 2006, a deterministic trajectory correction manoeuvre (TCM) of size 31.8 m/s was executed. This was TCM-7 in the chronology of the Rosetta mission. No TCM was required to compensate for any swing-by errors immediately after the Earth swing-by. The cost was less than 1 cm/s and it was completely absorbed in the design of TCM-7. Hence, Rosetta had a period of almost 19 months – one complete orbit around the Sun - without any TCM. During this period its maximum distance from the Earth was 2.7 AU.

Since Rosetta is a three-axis stabilised spacecraft with an attitude control that uses reaction wheels, momentum desaturation or wheel-off-loading (WOLs) manoeuvres are to be executed regularly to remove the accumulated angular momentum from the wheels. During this period of time this has been done on average once per week. Rosetta is equipped with a balanced thrust system so, nominally, the WOLs should exhibit pure torques without causing any perturbations on the trajectory. However, small orbital effects of the order of less than 1 mm/s are routinely observed in the orbit determination.

During this TCM-free period the demand on navigation and trajectory control was relatively low. The spacecraft activities were restricted to the platform or the payload. Form July to August 2005 and from May to July 2006 Rosetta was put into so-called Near Sun Hibernation Mode (NSHM). During the hibernation the spacecraft activities and contact periods are reduced to a minimum by doing a spacecraft health check just once per week. During NSHM the reaction wheels are spun down and the attitude control is based on thruster actuations. Not using the wheels will extend their lifetimes and is the main reason for having NSHM periods.

Rosetta has exhibited furthermore a superior solar conjunction from March to May 2006 with a minimum Sun-Earth-spacecraft angle of 0.54º which caused the signal between Rosetta and the ground station on Earth to come as close as 2.2 solar radii to the centre of the Sun. Due to turbulent plasma effects in the solar corona this caused a degradation of the tracking data quality and hence a degradation in the orbit determination and prediction performance. More details on Rosetta's solar conjunction period are given in [2].

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With TCM-7 on 29 September 2006 the Mars swing-by phase formally started. Fig. 1 shows the ecliptic projection of the Rosetta trajectory and the orbit of Earth and Mars during the Mars swing-by phase. Directions from Rosetta to Earth and Mars are given every 20 days. All TCMs are shown not to scale but with their corresponding components of directions in the ecliptic plane.

TCM-7 was a deterministic, retrograde manoeuvre at Rosetta's perihelion. Its purpose was to get the Mars swing-by conditions correct, i.e. it moved the expected coordinates in the B-plane by more than 450,000 km (the definition of the B-plane can be found in Section 5). The manoeuvre was executed with a slight over-performance (see Table 1), but since the manoeuvre was relatively big and the time until the swing-by was still quite long, Rosetta ended up in the B-plane still 756 km away from the fuel-optimum target point.

It was decided to make a touch-up manoeuvre rather early to move the expected coordinates in the B-plane close to the optimum target instead of doing it later, closer to Mars. TCM-8 was executed on 13 November 2006 with a magnitude of 9.9 cm/s. Unfortunately, two WOLs had to be placed relatively close before and after TCM-8 without any tracking data in between which made it impossible to calibrate TCM-8 in the orbit determination independently from the WOLs. Therefore the best estimate of the manoeuvre performance was unusually high (see Table 1) but also with a high formal 1σ uncertainty of 1.3 %. However, spacecraft telemetry indicated that the manoeuvre performance was rather close to nominal. After TCM-8 the expected coordinates in the B-plane were 36.3 km from the optimum target.

TCM-9 was executed on 09 February 2007, i.e. 16 days before the Mars swing-by and was of size 4.55 cm/s. It was designed specifically to get the swing-by conditions correct. It is further detailed in Section 5.2.

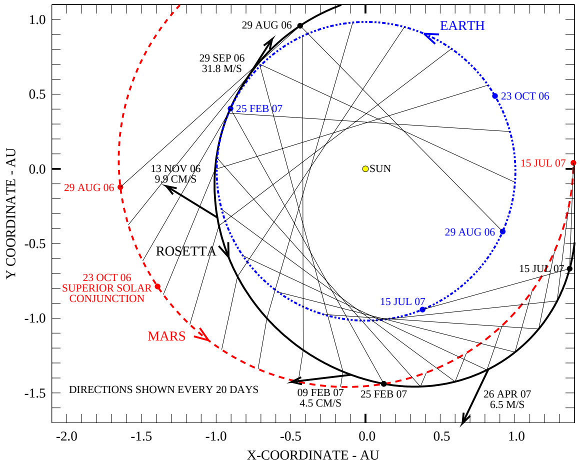

Figure 1: Ecliptic projection of Rosetta's heliocentric trajectory

Table 1: Trajectory control manoeuvres (TCMs). TCM 1 to 6 have been repeated from [1] for the reader's convenience; TCM 7 to 10 are described in this paper

| | Date | Size | Performance |
|---|---|---|---|
| 1 | 03 Mar 2004 | 1.0 m/s | -2.2% |
| 2 | 10 May 2004 | 152.8 m/s | +0.01% |
| 3 | 16 May 2004 | 5.0 m/s | +0.06% |
| 4 | 25 Nov 2004 | 16.6 cm/s | Anomalous |
| 5 | 09 Dec 2004 | 11.6 cm/s | +0.5 % |
| 6 | 17 Feb 2005 | 8.5 cm/s | +0.3% |
| 7 | 29 Sep 2006 | 31.8 m/s | +0.3% |
| 8 | 13 Nov 2006 | 9.9 cm/s | +2.4% |
| 9 | 09 Feb 2007 | 4.55 cm/s | +0.3% |
| 10 | 26 Apr 2007 | 6.5 m/s | +0.65 % |

TCM-10 was a partly deterministic and a partly stochastic manoeuvre and was executed on 26 April 2007 close to aphelion. The purpose of the stochastic part was to compensate any navigation error from the Mars swing-by. The purpose of the deterministic part was to obtain the correct phasing for the subsequent Earth swing-by in November 2007. The deterministic part was of size 6.3 m/s, the actual fuel optimised manoeuvre was 6.5 m/s, i.e. the navigation error at the Mars swing-by resulted in a Δv penalty of 0.2 m/s. With TCM-10, Rosetta's Mars swing-by phase was formally completed.

## 3. SWING-BY TRAJECTORY AND OPERATIONS

The Mars swing-by itself actually reduced the heliocentric velocity of Rosetta by 2.2 km/s. The swing-by parameters as determined after the swing-by are summarised in Table 2. The osculating orbital elements are based on the epoch of the pericentre passage and are given with respect to the mean Earth equator at J2000.

Table 2: Mars swing-by parameters

| | |
|---|---|
| Pericentre at 25 February 2007 | 01:59:04.46 TDB |
| Pericentre Radius | 3648.084 km |
| Pericentre Velocity | 10.053 km/s |
| Semi-major Axis | -551.986 km |
| Eccentricity | 7.609013 |
| Inclination | 156.827º |
| R.A. of Ascending Node | 135.369º |
| Argument or Pericentre | 154.902º |
| Asymptotic Velocity | 8.808 km/s |
| Semi-deflection Angle | 7.552º |
| Heliocentric: | |
| Velocity Vector Change | 2.315 km/s |
| Velocity Magnitude Change | -2.193 km/s |
| Velocity Direction Change | 1.856º |

Figure 2 shows the ecliptic projection of the swing-by geometry over a period of 6 hours centred at the time of pericentre passage. Tick marks are given every hour. The direction to the Sun and the Earth are given. The distances at the time of the swing-by were 1.4 AU to the Sun and 2.1 AU to the Earth. The latter corresponds to a 1-way light time of 17min 33s.

Also shown in Figure 2 are an eclipse and an occultation occurring during the swing-by. The occultation started 1min 48s before and lasted until 12min 38s after pericentre passage (14min 26s duration). The eclipse started 11s after and lasted until 25min after pericentre passage (24min 49s duration). The eclipse was considered as critical since Rosetta was not designed for eclipses. The spacecraft design was based on the original trajectory to comet 46P/Wirtanen which was free of eclipses. After the re-design of the mission [3] after a one year launch delay to the now actually flown mission, Rosetta had to cope with an eclipse at the Mars swing-by. It was and will be the only eclipse during the whole mission.

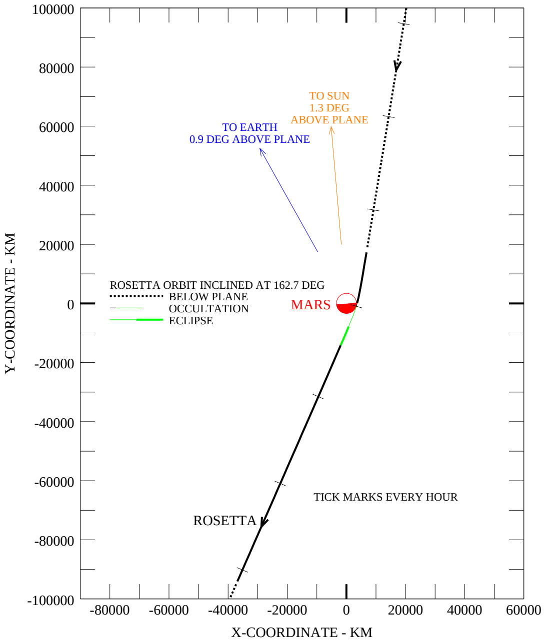

Figure 2: Ecliptic projection of Rosetta's Mars swing-by

Due to this criticality, all power-consuming devices on board that were not absolutely necessary during the eclipsed phase of the swing-by were switched off. Two of these were the X-band transmitter and the ultra stable oscillator (USO). The S-band transmitter was kept on during the whole time. The USO was switched off about 65 min and the X-band transmitter was switched off about 50 min before entering eclipse. The X-band uplink was intended to be kept until shortly before the occultation started and then to bring it down in a controlled manner. So the expectation was that 2-way coherent X band up and X band down tracking data would be acquired up until about 50 min before eclipse and 2-way coherent X band up and S band down tracking data would be acquired almost up until start of occultation. However, the on-board X-band receiver lost lock when the USO was switched off one hour before entering the occultation. This was an oversight in the flight operations procedure since this behaviour between USO and on-board receiver was known in advance but was overlooked when setting up the procedure. It was decided not to re-establish the 2-way link before the occultation, resulting in a lack of 2-way tracking data for more than one hour before the pericentre passage. After the eclipse when the X-band transmitter was switched on again the signal could be flawlessly re-acquired and a 2-way link was established soon afterwards. It was also intended to start ranging from then onwards. However, after having ranging started the range ambiguity in the tracking receiver on ground did not resolve. It was presumed that this was due to an instability in the tracking system and it was decided not to restart ranging for the remainder of the station pass in order not to destabilise ongoing operations.

The Mars swing-by was considered to be a good opportunity for payload activities. However, for the safety of the mission, it had to be ensured that the navigation process was not disturbed. It was agreed that payload activities were omitted entirely during the approach phase up until two days before the swing-by (see section 4.1). It was considered that activities two days before the swing-by would hardly have any effect on the navigation results or could lead to a situation that the orbital knowledge was lost to an extent that would jeopardise the mission. This approach also allowed omitting the execution of WOLs in the time period between TCM-9 and the start of the payload activities. This was possible because no spacecraft slews were performed and the reaction control wheels had just to cope mostly with the perturbing torques originating from the solar radiation pressure.

On 22 February the first WOL since 7 February was executed and the payload instruments were activated. On 23 February the spacecraft was slewed to allow the payload to perform calibrations of the instruments. The actual observations were performed in a four hours slot on 24 February 18:00 to 22:00 UTC, i.e. approximately four hours before pericentre passage when the spacecraft was at a distance of less than 250,000 km from Mars. At the start and end of the slot the spacecraft was slewed to and from a special observations attitude. But since Rosetta is equipped with a steerable, two-degree of freedom high-gain antenna, Earth communication and tracking could be maintained during the observations period. Only during the half hour duration of the actual slews was communication with the spacecraft lost.

For optical navigation, Rosetta is equipped with a 5º field-of-view navigation camera. Its purpose is to aid the navigation process when performing the two foreseen asteroid fly-bys at Steins in 2008 and Lutetia in 2011 and during the approach to comet 67P/Churyumov-Gerasimenko in 2014 and thereafter. Images from the target relative to the star background are then going to be used to determine accurately the relative position between Rosetta and the target body. In the original mission to comet 46P/Wirtanen, a foreseen possibility was to use the navigation camera to support the navigation at the Mars swing-by. A mission requirement stated that during the approach to Mars the radio-frequency tracking should be augmented with optical observables using the navigation camera system. However, an analysis was performed well before launch that concluded that neither the Mars limb nor the Martian Moons could be meaningfully used as target to aid the navigation process mainly because of poor geometric and illumination conditions. After the re-design of the mission to the now actually flown mission [3] the conditions during the Mars approach would have been favourable for optical navigation. Nevertheless, the possibility of using optical data was not re-considered because it was clear at that time that Delta Differential One-Way Range (ΔDOR) measurements will augment the conventional Doppler and range tracking data instead (see Section 4.3) to ensure successful navigation when approaching Mars. Nevertheless, the navigation camera was switched on and took images in the four hours active payload slot before the Mars swing-by, mainly for gaining experience with the camera in an operational environment and for public relations purposes. Figure 3 shows such an image of Mars. It was taken on 24 February 2007 at 18:32 UTC from a distance of 237,477 km. More details about the image are given in [4].

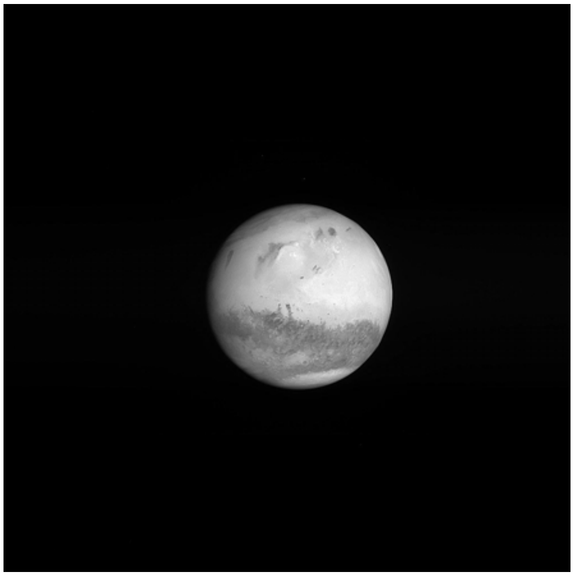

Figure 3: Mars as seen by Rosetta's navigation camera

Payload activities at closest approach were not possible because of the aforementioned critical power situation during the eclipse. However, one exception was the lander Philae that is mounted on Rosetta. Philae is due to land on comet 67P/Churyumov-Gerasimenko in 2014 after Rosetta has reached its destination. Therefore, Philae has its own power system that can cope with eclipses. During the pericentre passage Philae took spectacular looking images of Mars with parts of Rosetta in the foreground [5].

## 4. ORBIT DETERMINATION SET-UP

Navigation of the spacecraft for the Mars swing-by was based on the interplanetary orbit determination system [6] that had been developed to support all the Agency's recent deep space missions that include Mars Express (MEX), Smart-1 and Venus Express (VEX), as well as Rosetta. At the time of the Mars swing-by this system had been successfully used operationally for almost four years, especially during highly demanding navigation phases such as MEX Beagle-2 release and Mars approach and orbit insertion, Smart-1 Moon orbit insertion and controlled impact, VEX Venus approach and orbit insertion, as well as of course the first Rosetta Earth swing-by. The navigation software can therefore be considered as being quiet mature. Nevertheless, an extensive navigation assurance campaign has been executed prior to the Mars swing-by led by the ESOC Flight Dynamics internal test and validation group. Details about the navigation assurance campaign can be found in [7].

For the approach phase the orbit determination program was set up in a special pre-defined configuration that will be described in the following subsections.

### 4.1 Orbit Propagation

Starting with an *a priori* spacecraft state at a chosen epoch the equations of motion are integrated numerically. The following forces are taken into account:

- Newtonian point mass acceleration due to the Sun, all the planets, Pluto, and the Earth's Moon;
- perturbative relativistic acceleration due to the Sun;
- solar radiation pressure (SRP) based on a sophisticated spacecraft model built up out of a cubic spacecraft box, solar arrays, and a high gain antenna with optical properties provided by the spacecraft manufacturer prior to launch;
- accelerations due to TCMs and WOLs.

In cruise, a SRP acceleration scale factor along the Sun-spacecraft line was estimated during routine orbit determinations and indicated that the SRP model underestimates the actual acceleration by about 7.5%. However, this factor was relatively constant within a few tenths of a percent only when Rosetta was in its default Earth communications attitude. During periods when the spacecraft had a different attitude, especially over long periods of time in the order of a couple of days, different estimates down to 5% were obtained. The most likely cause for this discrepancy is the optical properties of the spacecraft's surfaces. Therefore more than one piecewise constant SRP acceleration factor had to be estimated within the orbit determination whenever the spacecraft was not in its default attitude. This had of course an impact on the navigation results and it was agreed (see Section 3) that during the approach phase no payload or platform activities were performed that required a slew of the spacecraft. Rosetta remained therefore in its default Earth communications attitude from 4 January to 22 February 2007.

As mentioned already in Section 2, WOLs must be performed approximately once per week. Due to the balanced thrust system, these should ideally not generate any perturbations on the orbit. Nevertheless, a $\Delta v$ with zero *a priori* components is estimated within the orbit determination whenever a WOL is executed. Almost all estimates of the $\Delta v$ magnitude were below 1 mm/s. Nevertheless, it was agreed that no WOL would be executed in the period from 7 February to 22 February 2007 (see Section 3) again to keep the orbital perturbations to a minimum.

During most of the approach phase the centre of integration was the Sun. The sphere of influence of Mars was entered on 24 February 2007 at 07:51:51 barycentric dynamical time (TDB), so at about 18 hours before pericentre passage. Then, the centre of integration was switched to Mars and it stayed like this until Mars' sphere of influence was left again after the swing-by. While being within Mars' sphere of influence the force model above was augmented by

- a 16x16 Mars gravity field expansion;
- Newtonian point mass attraction of Phobos and Deimos.

### 4.2 Uncertain Parameters

The orbit determination system uses a square root information filter (SRIF) that is based on an epoch-state formulation, i.e. the components of the spacecraft state vector are estimated at a fixed epoch (see [6] for more details). The spacecraft state vector can be augmented by a set of parameters that are also estimated during the orbit determination process ("solve-for" parameters). Additionally, another set of parameters can be chosen that are not estimated but their uncertainties contribute to the formal uncertainties of the solve-for parameters ("consider parameters"). The navigation results in the following are always based on the so-called "consider covariance", i.e. the uncertainties of the consider parameters are taken into account. It is evident that these uncertainties can have a major contribution to the navigation results but also the chosen set of solve-for parameters and their *a priori* uncertainties play a significant role. All used solve-for and consider parameters together with their (*a priori*) uncertainties are summarised in Tables 3 and 4 respectively.

A range bias per station pass has been estimated to absorb modelling errors originating from a poor knowledge of the transponder group delay, in particular its behaviour in different configurations and at different ambient temperatures. Furthermore, it absorbs group delays due to charged particles in the solar plasma. No solar plasma model has been applied when modelling the observables because its predictive capabilities are rather poor [2]. The observables have only been calibrated for ionospheric and tropospheric effects for which model parameter uncertainties have been considered (Table 4). Quasar directions uncertainties have also been considered that are relevant for ΔDOR measurements which are further explained in section 4.3.

Table 3: Estimated parameters and their *a priori* values and uncertainties

| **Estimated parameters** | ***A priori* value** | **1σ *a priori* uncertainty** |
|---|---|---|
| spacecraft state at epoch | taken from previous orbit determination | 1000 km<br>10 m/s |
| SRP factor along Sun-s/c | +7.5% | 3% |
| WOL | 0 | 1 mm/s along each spacecraft body axis |
| TCM | as commanded | 3% in magnitude<br>1.7 º in direction |
| range bias per station pass | 0 | 20 m (1-way) |

Table 4: Consider parameters and their uncertainties

| **Consider parameters** | **1σ uncertainty** |
|---|---|
| SRP factor perpendicular to Sun-s/c | 5% |
| ESA stations location | 10 cm in each direction |
| DSN stations location | as given in [8] |
| polar motion X and Y | 30 nrad |
| UTC-UT1 | 0.75 ms |
| quasar directions | as given in [9] |
| troposphere calibration<br>(zenith delay) | 4 cm (wet part)<br>1 cm (dry part) |
| ionosphere calibration | 25% |
| transponder group delay | 10 ns |
| Mars ephemeris<br>position<br>velocity | <br>1 km<br>0.01 mm/s |

## 4.3 Tracking Data

Another main driver of the navigation results are the types of tracking data that have been used as well as their quantity and quality.

### Tracking Data Types

During the Mars approach phase, Rosetta was tracked mainly from ESA's 35m antenna at New Norcia (Western Australia) and additionally from the NASA Deep Space Network (DSN). The DSN sites at Goldstone (California) and Madrid (Spain) were used mostly whereas, because of the overlapping times of visibility with New Norcia, antennas from the DSN site at Canberra (Eastern Australia) tracked Rosetta only occasionally. During the tracking passes conventional 2-way X-band Doppler and range data were acquired. Within the orbit determination all the Doppler data were compressed to 60 s count time whereas range data points were just taken every 20 min for ESA and every 3.5 min (on average) for DSN range data. The frequency of tracking passes steadily increased the closer Rosetta approached Mars, cumulating in around-the-clock tracking starting at 2 days before and extending to about 12 hours after pericentre passage.

The conventional tracking data were augmented by a radio interferometric type measurement called Delta Differential One-Way Range (ΔDOR). ΔDOR requires two widely separated ground stations to measure the difference in the arrival time of the signal from both Rosetta and a directionally close-by extragalactic radio source (quasar) whose inertial direction is precisely known. It provides a direct measurement of one coordinate of Rosetta's position in the plane-of-sky which is a perfect complement to the line-of-sight Doppler and range measurements.

Figure 4 shows a world map with the locations of the participating ground stations. Stations in red are ESA stations, those in blue are NASA/DSN stations. Also drawn with the same colour code are the projected baselines connecting two groundstations that have taken ΔDOR measurements.

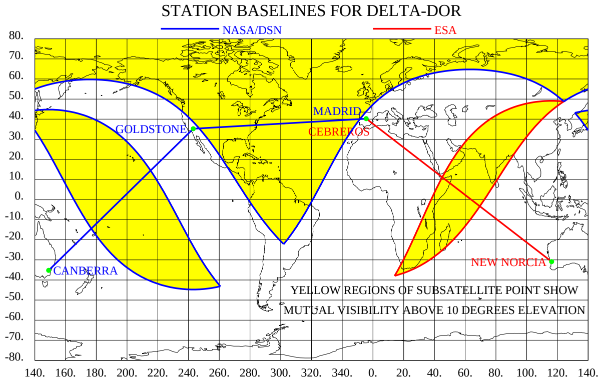

Figure 4: Tracking Stations and Baselines

The spacecraft position coordinate that is measured by a ΔDOR data point is along these baselines projected onto the plane-of-sky. Yellow areas in Figure 4 indicate subsatellite points for which two stations have mutual visibility above 10º elevation. The limiting geocentric latitude for usage of the baseline Goldstone – Madrid in the southern direction is -22º. Rosetta spent most of the time during the approach phase far down in the southern hemisphere moving southwards through -22º geocentric latitude on 17 December 2006, reaching a minimum of -24.3º on 17 January 2007 and moved across -22º northwards again on 19 February 2007. The consequence was that the baseline Goldstone – Madrid could only rarely be used. The last ΔDOR measurement from this baseline before mutual visibility was lost was taken on 18 December 2006 (with one station having elevations below 10º). The first ΔDOR measurement after the period of mutual invisibility was resumed on 20 February 2007, 5 days before the swing-by. Therefore, the majority of ΔDOR measurements during the entire approach phases were utilising the Goldstone – Canberra and New Norcia – Cebreros baselines. However, this was by no means a disadvantage because - as can be seen in Figure 4 - these baselines are almost perpendicular to each other and therefore providing information in two almost perpendicular directions on the plane-of-sky. How this improved the navigation solutions is further detailed in Section 5.1. As for the conventional tracking data, the frequency of ΔDOR measurements increased the closer Rosetta approached Mars, cumulating in two ΔDOR sessions per day over almost one week up until two days before pericentre passage.

### Tracking Data Arc

The used tracking data arc was a relatively long one starting on 14 November 2006, i.e. covering a period of 103 days until the swing-by. Orbit determination solutions using shorter arcs were also regularly made and compared but it turned out that the long arc solution provided the most stable and reliable results. In particular, the predictive capabilities of the long-arc solution were superior to those of short arc solutions. This was seen best when residuals of new tracking data were processed based on an orbit prediction of a previous solution (“pass-through”). The residuals based on orbit predictions of short arc solutions exhibited jumps and drifts indicating a less accurate orbit prediction. All navigation results used at that time and presented here are therefore based on the long-arc solutions.

In total, an orbit determination using the full long arc solution starting from 14 November 2006 up until the swing-by on 25 February 2007 made use of

- 4,188 2-way range measurements;
- 34,957 2-way Doppler measurements;
- 32 New Norcia – Cebreros ΔDORs;
- 40 Goldstone – Canberra ΔDORs;
- 5 Goldstone – Madrid ΔDORs.

All tracking data were acquired at X-band frequencies.

The last ΔDOR was taken in the morning of 23 February 2007. The last Doppler and range measurements prior to the swing-by were taken at 01:10 UTC on 25 February 2007, almost one hour before pericentre passage. No more 2-way data were acquired due to the oversight in the flight operations procedure as explained in Section 3. The orbit determination program is not able to process 1-way data that anyways is far less precise than 2-way data.

### Tracking Data Quality and Weighting

The expected accuracy of 2-way X-band range data is in the order of a couple of metres for both ESA and DSN data. The experience has shown that the ranging performance is slightly better at DSN stations then at ESA stations but nevertheless the measurement 1σ standard deviation of each range point was set to 5 m. The higher sampling frequency of the DSN range compared to the ESA range has taken account of the different ranging performances within the orbit determination. The *a posteriori* root mean square (RMS) value of all range residuals computed in an orbit determination using the long data arc of 103 days was 0.83 m.

The expected accuracy of 2-way X-band Doppler compressed to 60 s count time is in the order of 0.1 mm/s or better for both ESA and DSN data. The experience has shown equal data quality at both station networks. The 1σ standard deviation of each Doppler point was set conservatively to 0.2 mm/s within the orbit determination. The *a posteriori* RMS value of all 2-way range-rate residuals computed in an orbit determination using the long data arc of 103 days was 0.12 mm/s.

The 1σ standard deviation of the NASA/DSN ΔDORs was supplied for each measurement by JPL as recommended data weight and was followed in all cases. The actual ΔDOR measurement is a time delay and for all of them the recommendation was 0.25 ns. The *a posteriori* RMS value of all NASA/DSN ΔDOR residuals computed in an orbit determination using the long data arc of 103 days was 0.16 ns.

The capability to acquire DOR measurements at ESA stations is relatively new and the system is not yet as mature as the DSN system. It has been developed within ESA in a very short time frame to support the VEX Venus approach and orbit insertion in April 2006 which it did very successfully. The Rosetta Mars swing-by was the second opportunity to use this system in a critical and navigation demanding time period. The 1σ standard deviation of the ESA ΔDORs was also supplied for each measurement by the ESA ΔDOR team as recommended data weight and was followed in all cases. The recommendations varied between 0.4 ns and 3.7 ns but were on average about 0.6 ns. Standard deviations larger than 2.0 ns were recommended for 6 measurements. The reason for these relatively high measurement uncertainties originated from either an unexpected low level of correlated quasar flux, a not perfectly clean spacecraft carrier signal, a large spacecraft-Earth-quasar separation angle (> 10º), or a combination of these. Standard deviations of all other but one measurement were below 1 ns. The *a posteriori* RMS value of all ESA ΔDOR residuals computed in an orbit determination using the long data arc of 103 days was 0.53 ns. The accuracy requirement for the ΔDOR system development was stated to be 1.0 ns which was clearly met.

Figure 5 shows the *a posteriori* ΔDOR residuals from the 103 days long arc solution. Red crosses indicate ESA ΔDORs along the baseline New-Norcia – Cebreros, closed blue dots indicate NASA/DSN ΔDORs along the baseline Goldstone – Canberra, and open blue dots indicate NASA/DSN ΔDORs along the baseline Goldstone – Madrid. The ESA ΔDOR residuals that are larger in magnitude than 0.6 ns correspond to the ones with the aforementioned large standard deviations.

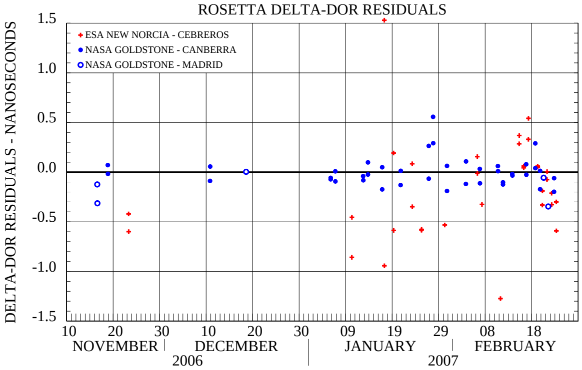

Figure 5: Rosetta ΔDOR Residuals

## 5. TARGETING FOR THE MARS SWING-BY

Navigation results when approaching a planet are typically described as B-plane coordinates. The B-plane is a plane passing through the target body centre and is perpendicular to the asymptote (vector **S**) of the incoming trajectory (assuming Keplerian 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 the orthogonal right-handed triad with **S** and **T**. Trajectory errors in the B-plane are characterised by 3σ dispersion ellipses.

The trajectory design group within the Flight Dynamics team defined the global fuel-optimum target point in the B-plane. The navigation group performed after each orbit determination a mapping of the estimated spacecraft state at epoch and its consider covariance matrix to the predicted time of closest approach. Thereby future uncertainties originating for instance from future WOLs were taken into account. The B-plane vector and its associated uncertainties in form of 3σ error ellipse parameters were then computed from the predicted state and consider covariance matrix at pericentre.

## 5.1 The Power of ΔDOR

It has been explained before that ΔDOR is a direct measurement of one coordinate of Rosetta's position in the plane-of-sky. How accurate were these position measurements at the Rosetta Mars swing-by? The accuracy is directly proportional to the length of the baseline connecting the two participating ground stations. The baseline New Norcia – Cebreros has a length of 11,625 km. The aforementioned *a posteriori* RMS of 0.53 ns for ESA ΔDORs translates then into an angular accuracy of 13.7 nrad or a position accuracy at Rosetta's distance at that time of 4.3 km. The baseline Goldstone - Canberra has a length of 10,589 km. The aforementioned *a posteriori* RMS of 0.16 ns for NASA/DSN ΔDORs translates then into an angular accuracy of 4.5 nrad or position accuracy at Rosetta's distance at that time of 1.4 km.

If only conventional Doppler and range tracking data were available then no direct measure of the plane-of-sky components would have been available. In this case the plane-of-sky information had to be deduced solely from the diurnal sinusoidal modulation of the Earth rotation on the range and Doppler data. From a complete pass this modulation indirectly gives information on the plane-of-sky components: the phase of the modulation is directly related to the spacecraft's geocentric right ascension and the amplitude to the spacecraft's geocentric declination. The determination of the spacecraft right ascension from a 12 hours pass of Doppler data with the aforementioned accuracy of 0.1 mm/s yields an accuracy of about 50 nrad. The determination of the geocentric declination is sensitive to the actual declination itself: it is worst when it approaches zero. During the Mars approach phase the situation was favourable because Rosetta was below -20 deg declination most of the time. Nevertheless, a 12 hours pass of Doppler data with the aforementioned accuracy would determine the declination even under these favourable conditions only to an accuracy of the order of 50 to 100 nrad. It needs to be stressed that – although the duration of visibility would have permitted it - none of the Rosetta passes had a duration of 12 hours but were more in the order of 6-10 hours due to scheduling constraints. DSN passes were only 4 hours long making it difficult to detect the sinusoidal modulation on the Doppler data to sufficient accuracy. Therefore, if no ΔDOR were available there would have been an impact on the station scheduling during the approach phase.

Figure 6 shows navigation results – best estimates of the target points and the corresponding 3σ uncertainty – in the B-plane using different sets of tracking data. This was done regularly during the approach phase to ensure consistency of the solutions. The particular example here has been generated with a data arc starting on 14 November 2006 up until 29 January 2007, so before TCM-9. As can be seen, the best estimates of the target points are about 58 km away from the optimum target (green cross) and it was the goal of TCM-9 to move these 58 km across the B-plane (see next section). The red dotted line in the upper right corner denotes the impact contour of the surface of Mars in the B-plane. The different data sets used to generate the displayed solutions were:

1. range & Doppler only (black ellipse);
2. as 1. plus NASA/DSN ΔDORs (orange ellipse);
3. as 1. plus ESA ΔDORs (brown ellipse);
4. as 1 plus ESA & NASA/DSN ΔDORs (blue ellipse; the annotation gives the dimension of the ellipses semi-axes).

Comparing the blue and the black ellipses clearly shows how ΔDOR improves the knowledge of the spacecraft trajectory. The area of the black ellipse corresponds to 7070 km$^2$; the area of the blue ellipse corresponds to 662 km$^2$, i.e. a reduction in size by more than one magnitude. Also visible in Figure 6 are the directions of the different baselines as they are projected into the B-plane (see also Figure 4). The majority of the NASA/DSN ΔDORs were obtained using the baseline Goldstone – Canberra which gives information in the B-plane mostly in the radial direction. The ESA ΔDORs were obtained from the baseline New Norcia – Cebreros which gives information almost perpendicular to the former one. This complementary characteristic of the ΔDOR datasets was a big advantage for the navigation process during the entire Mars approach phase.

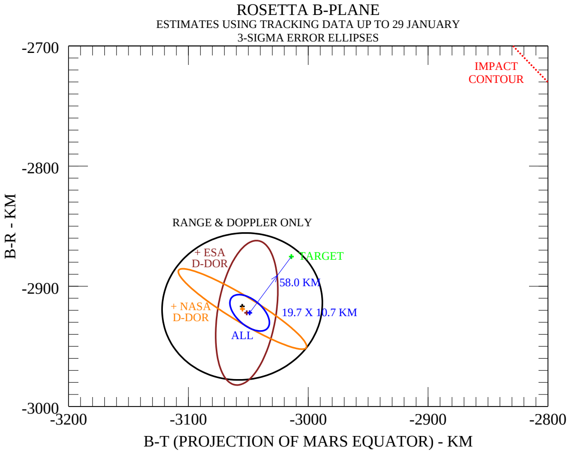

Figure 6: B-plane solutions using different data sets

## 5.2 Design of TCM-9

The final planning for TCM-9 was made based on an orbit determined using data up until 5 February 2007, i.e. data cut-off was 4 days before manoeuvre execution. Figure 7 shows the situation in the B-plane. The blue cross and error ellipse are the location and 3-σ uncertainty as they were estimated at the time TCM-9 was planned. The red ellipse and its centre are the estimates using data up to the time when the spacecraft slewed to the manoeuvre attitude shortly before TCM-9. The black ellipse and its centre are the results using additionally the Doppler data acquired up to almost three hours after the manoeuvre.

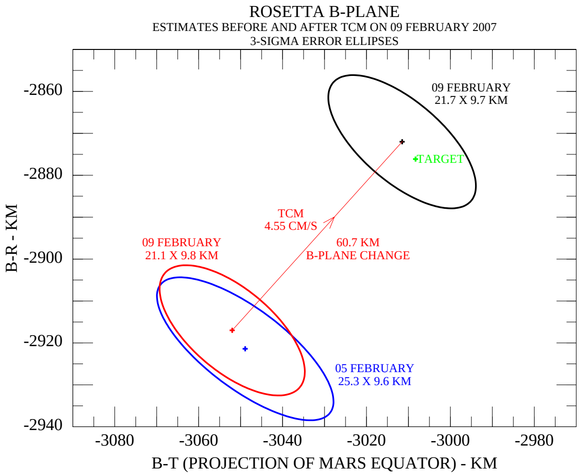

Figure 7: Design of TCM-9 in the B-plane

The thin red line denotes the movement of the target point within the B-plane of 60.7 km due to a nominal manoeuvre size of 4.55 cm/s. The end point of the red line and the black cross are not exactly at the same location but the difference is too small to be seen in the plot. In mapping the errors to after the manoeuvre, the 1σ dispersion (cf. Table 3) was assumed to be 3% on the manoeuvre magnitude and 1.7º in direction, both of which were conservative. Because of the orbital change between manoeuvre planning and execution, it was then expected to end up 5.2 km from the optimum target location (green cross in Figure 7).

### 5.3 Evolution of B-plane Estimates and Errors

After TCM-9 four more potential manoeuvre slots had been allocated: one week, three days, one day, and 6 hours before the swing-by. Associated with each manoeuvre slot was a Flight Rule that determined under which circumstances a manoeuvre should be executed. Having followed those rules, no further manoeuvre was executed prior to the swing-by although Rosetta was not heading towards the optimum target point. More details on the Flight Rules can be found in [7].

Figure 8 shows the variations in the estimates and the accompanying uncertainties after TCM-9 up to the swing-by. As before, the annotations give the time when the results were determined and the sizes of the error ellipses semi-axes. The black ellipse is the same as the post-manoeuvre ellipse of Figure 7. Note that compared to Figure 7 the scale in Figure 8 is halved. Progressively, the red, blue, orange, and green crosses and ellipses correspond to times when the Flight Rules for the manoeuvres slots were evaluated. The magenta cross and ellipse show the results a few hours before the swing-by. The ellipse size at that time has shrunk to an area of 283 $\text{km}^2$. The purple cross and ellipse are the results using data up to the morning of 26 February 2007, i.e. a little more than one day after the swing-by. The area of the post swing-by 3σ error ellipse is smaller than 0.008 $\text{km}^2$.

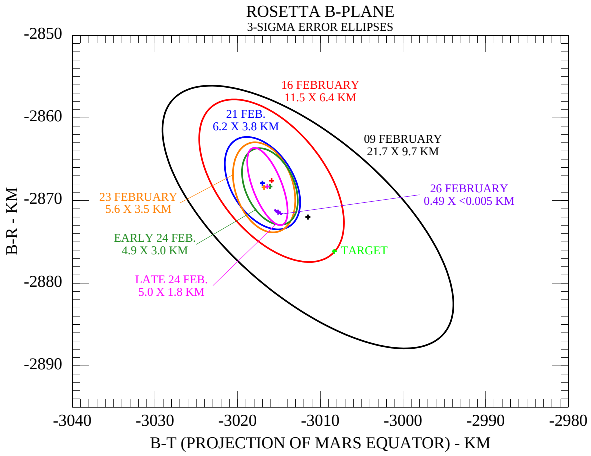

Figure 8: Evolution of B-plane estimates

### 5.4 Navigation Results

The final location in the B-plane was 8.3 km from the optimum target. The estimate for the altitude at closest approach was 250.6 km above Mars' surface with a 3σ uncertainty of 1.1 km. The estimate for the time of closest approach was 01:57:59.28 UTC on 25 February 2007 with a 3σ uncertainty of 0.02 s. The prediction provided for spacecraft operations on the occultation entry and exit times proved to be very accurate.

No extra manoeuvre was needed immediately after the swing-by. The cost of the swing-by errors was absorbed in the deterministic TCM-10 in April 2007 (Section 2)

### 5.5 Swing-by Anomaly

As detailed in [1] an anomalous prograde Δv at pericentre passage was observed at Rosetta's first swing-by around the Earth. This has also been observed by other non-ESA spacecraft when performing an Earth swing-by. The source of this anomalous Δv still remains unexplained.

To the knowledge of the authors these anomalies have not been observed at swing-bys around planets other than the Earth. Nevertheless, special attention was paid when a post swing-by orbit solution was generated using all available tracking data around Rosetta's Mars swing-by. It can be reported here that no anomalous Δv was detected. Whether this is due to the lack of tracking data close to the pericentre (Section 3) which would have been most sensitive to an alleged Δv or due to the fact that the swing-by body was not the Earth remains unknown. The authors are looking forward to Rosetta's next Earth swing-by in November 2007.

## 6. CONCLUSIONS

In terms of navigation, Rosetta's Mars swing-by has been considered as the most critical and demanding phase of the heliocentric cruise up until arrival at the comet in 2014. It was executed very successfully with a very small cost of propellant to compensate for targeting errors. The largest part of these have been known and accepted already in advance with the advantage of not having to execute another TCM shortly before the swing-by. It has been stressed that among other things the navigation went so flawlessly thanks to the frequent ΔDOR measurements that augmented the conventional Doppler and range tracking data.

## 7. REFERENCES

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