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ROSETTA NAVIGATION AT ITS FIRST EARTH SWING-BY

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Abstract

The navigation of Rosetta during the first year of its mission is described, culminating in the successful first swing-by of the Earth that increased the spacecraft's heliocentric velocity by 3.8 km/s. The main emphasis is on the last trajectory correction before the approach to the Earth and the subsequent evolution with time of the targeting estimates.

After the swing-by it was found that to obtain a good fit of the tracking data over both the inbound and outbound trajectories, it was necessary to include an artificial prograde manoeuvre at perigee that increased the outward asymptotic velocity by 1.8 mm/s. The same phenomenon of an apparently anomalous acceleration at Earth swing-by has been experienced with at least two NASA missions. The results are compared and some thoughts presented on possible causes of the anomaly, in addition to ones already dismissed by previous studies.

1. Introduction

Rosetta was launched directly into an interplanetary trajectory by an Ariane-5/G1 on 02 March 2004. The one year launch delay necessitated a re-design of the mission [1] to comet 67P/Churyumov-Gerasimenko, rather than to 46P/Wirtanen, as originally foreseen. In order to gain sufficient orbital energy to rendezvous with the comet, the revised mission included an additional Earth swing-by (gravity assist manoeuvre) one year into the mission, on 04 March 2005. The initial heliocentric orbit was slightly eccentric with an aphelion of 1.09 AU and perihelion of 0.89 AU (Fig. 1).

Rosetta is three-axis stabilised with a steerable, two-degree of freedom high-gain antenna (HGA). Throughout the first phase of heliocentric cruise, conventional 2-way, X-band Doppler and range data were acquired via the HGA during daily passes with ESA's 35 m antenna at New Norcia (NNO), near Perth, that is the prime ground station for the mission. The same data types were acquired by various antennas of the NASA, Deep Space Network (DSN) complexes at Madrid and Goldstone. Many passes at these stations were scheduled during the launch and early orbit phase, around the time of the main deep space manoeuvre, and during the spacecraft's approach to the Earth. At other times, the additional ground station support was just occasional.

Navigation of the spacecraft is based on the interplanetary orbit determination system [2] that had been developed at the European Space Operations Centre (ESOC) over several years in order to support all the Agency's deep space missions that include Mars Express, Smart-1 and Venus Express, as well as Rosetta.

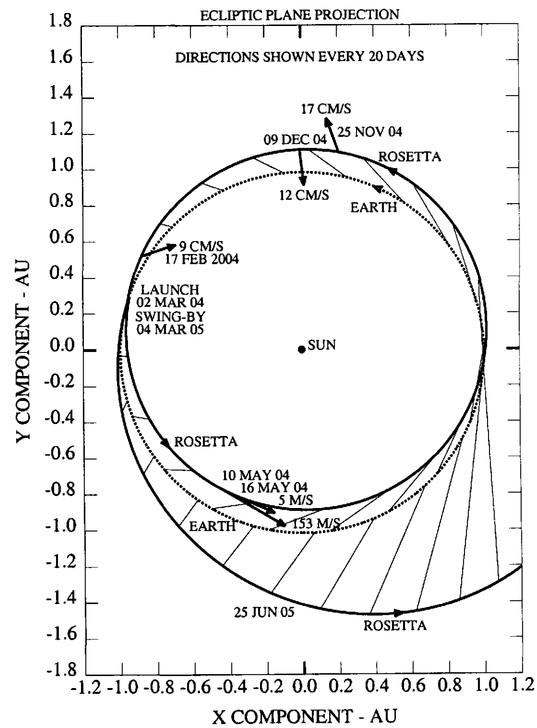

Fig. 1. Rosetta heliocentric trajectory

2. Trajectory Control

The launcher performance was excellent: the magnitude of the asymptotic, escape velocity was less than 2 m/s different from that desired. This meant that no extra manoeuvre was needed to correct the dispersion, a slight modification to the deep space manoeuvre planned for 10 weeks after launch being quite sufficient.

Up to December 2004, five trajectory control manoeuvres (TCM) were performed (Table 1), all with 10 N thrusters mounted on the -Z face of the spacecraft with a line of action along the +Z body axis.

For the 1 m/s TCM-1 test manoeuvre, executed the day after launch, Rosetta was orientated so that the ΔV was along the Earth - spacecraft direction. This allowed a precise calibration using the Doppler data and an accurate comparison with the magnitude estimate from the accelerometer that was used to control the burn duration.

Table 1. Trajectory control manoeuvres

TCM	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%

TCM-2 and -3 were executed near perihelion and were really one deterministic, prograde manoeuvre split into two parts. The design of the much smaller 2nd part took into account the calibrated performance of the main first part.

TCM-4 was the first stochastic manoeuvre. It was planned to be 8.6 cm/s and executed near aphelion, the fuel-optimum time to refine the trajectory preparatory to the Earth swing-by. It was intended to move the expected coordinates in the B-plane by 889 km (see next section) in a direction approximately radially outwards from the Earth. In the event, due to an on-board software bug that corrupted the pulse counting control method, the burn did not stop at the expected time, but continued until a time-out limit was reached and caused the spacecraft to go into safe mode. The situation was corrected 14 days later with the execution of TCM-5.

TCM-6 is described in section 3.2.

Rosetta attitude control uses reaction wheels whose angular momentum has to be frequently dumped by desaturation manoeuvres using thrusters. During the first year, 72 reaction wheel offloadings (WOLs) were made, on average once every 5 days. Nominally, the WOLs should be pure torque, thus causing no perturbation to the orbit. Nevertheless, calibrations are routinely made within the orbit determination. These typically show a ΔV of up to a small fraction of a mm/s, which testifies to the good balance achieved with the thrusters.

3. Targeting for the First Earth Swing-by

Because of the much lower geocentric distance, spacecraft navigation preparatory to an Earth swing-by is nowhere near as demanding as for a planetary swing-by. Nevertheless, it is not a routine exercise and is classified as a critical mission phase. For Rosetta, the orbital geometry during the Earth approach was relatively unfavourable in that the spacecraft's geocentric declination was not far from zero - well known to be undesirable for tying down the position component in the north-south direction when relying only on line-of-sight tracking data. Between 05 February and 03 March 2005 the declination was continuously between 2° and 3°.

No explicit requirements were placed on the navigation accuracy but it was desired to be as precise as possible in order to minimise the size of any clean-up manoeuvre after the swing-by. Two slots were identified for TCMs, the first on 17 February 2005, 15 days before Earth arrival, that definitely would be used, and a second one 8 days before arrival, essentially foreseen as a back-up in case of bad performance of the first manoeuvre or unexpected and substantial changes in orbit solutions.

3.1 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 Earth mean equator of J2000.0; 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 the orbit determination estimate and covariance matrix into the expected coordinates and the 3σ error ellipse in the B-plane.

3.2 TCM-6

The fuel-optimum magnitude for TCM-6 was about 6 cm/s. But then the manoeuvre direction would have been almost perpendicular to the Earth-to-spacecraft vector. So that a significant component of the manoeuvre, about 70%, could be monitored directly from the Doppler frequency change, it was decided to accept a 2.5 cm/s penalty and set the burn direction exactly 45° from the Earth direction. The component of the manoeuvre parallel to the orbital velocity then brought forward the arrival time at Earth by 13 seconds.

The final planning for TCM-6 was made based on the orbit determined using data until 11 February 2005. Except for two short Goldstone passes, only NNO had been tracking the spacecraft during the previous 6 weeks.

Fig. 2 shows the situation in the B-plane. The annotations give the dimensions of the semi-axes of the error ellipses. The box symbol and dashed error ellipse are the location and 3σ uncertainty as they were estimated at the time TCM-6 was planned. The inner ellipse and its centre are the estimates using data up to the day of the manoeuvre. The lower ellipse and its centre are what was expected immediately after the manoeuvre. In mapping the errors to after the manoeuvre, the 3σ dispersion was assumed to be 3% on the manoeuvre magnitude and 5° in direction, both of which were conservative.

Because of the change in the orbit solution, it was then expected to end up 4.2 km away from the optimum target location.

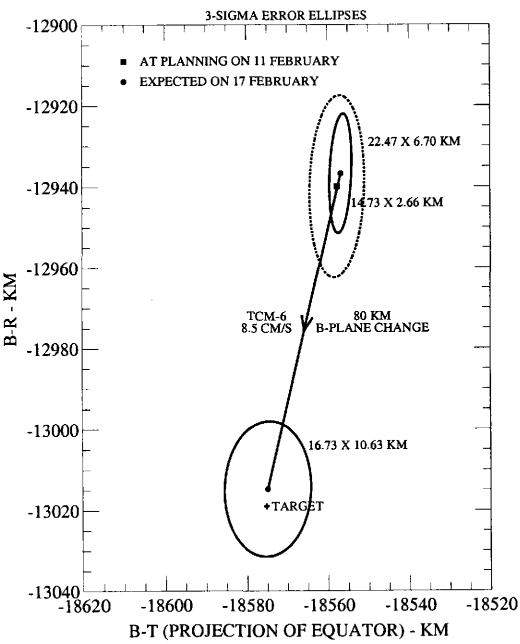

Fig. 2. Rosetta B-Plane - TCM-6 targeting

3.3 Evolution of B-plane estimates and errors

Fig. 3 shows the subsequent variations in the estimates over the period up to the swing-by and the accompanying reduction in the uncertainties. The outer ellipse is the same as the post-manoeuvre ellipse of Fig. 2, with a plot scale magnification of about 3 times. Beginning on 21 February, the tracking was augmented with data from the DSN stations at Madrid and, mainly, Goldstone. On 27 February, the signal was switched to S-band and between 02 and 06 March, a low-gain antenna (LGA), with hemispherical coverage, was used rather than the narrow beam HGA.

The final estimate was based on data up to and including the NNO pass after the perigee passage.

3.4 Navigation results

The final location in the B-plane was 3.7 km from the optimum target with an uncertainty of the order of 30 metres. The perigee distance was 8331.796 km (perigee altitude ~1954 km). This distance was 1.8 km lower than the optimum target and its 3σ uncertainty was less than 10 metres. The time of perigee passage on 04 March was 22:09:14.119 UTC. This was 0.34 seconds earlier than was expected at the time TCM-6 was planned. The 3σ uncertainty in the perigee time was less than 0.005 seconds.

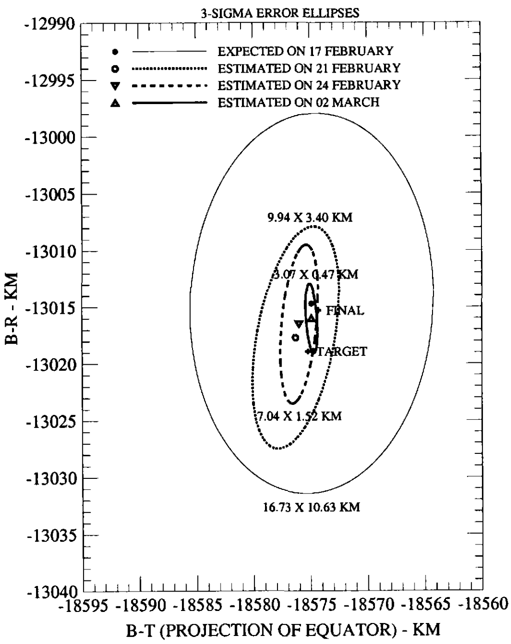

Fig. 3. Rosetta B-Plane estimates for 1st Earth swing-by

No manoeuvre was needed after the swing-by. The cost of the small swing-by errors was less than 1 cm/s and is mainly absorbed into the next foreseen, deterministic manoeuvre of 32 m/s in September 2006.

4. Earth Swing-by Trajectory

Fig. 4 shows the ecliptic projection of the trajectory over a 6 hours interval centred at the time of perigee passage. Table 2 lists the swing-by parameters (osculating at the epoch of perigee). The orbital elements are with respect to the J2000.0 Earth mean equator.

During the swing-by, the payload instruments were maintained pointing towards the Moon. Using the navigation camera, test images were obtained of the Moon and then the Earth during the interval it occulted the line-of-sight to the Moon. Starting 3 hours after the swing-by, the Moon was tracked in closed-loop with the spacecraft in Asteroid Fly-by Mode (AFM). This was the only possible in-flight test of AFM before the fly-bys of asteroids 2867 Steins on 05 September 2008 and 21 Lutetia on 10 July 2010.

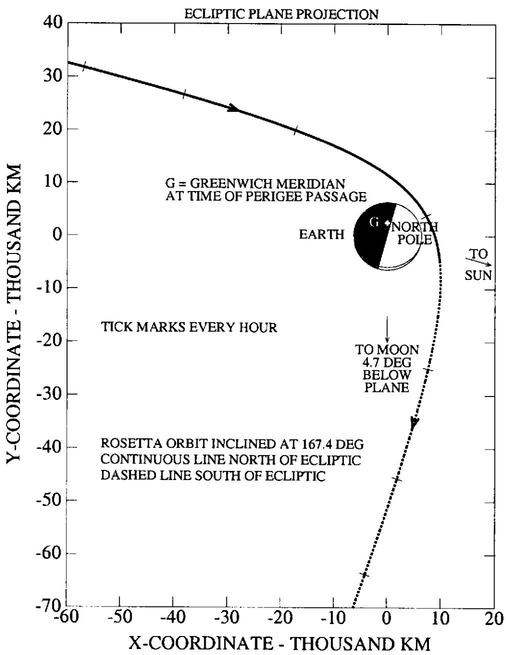

Fig. 4. Rosetta first Earth swing-by trajectory

Table 2. Swing-by parameters

Perigee on 2005 March 04	22:10:18.303 (TDB)
Perigee Radius	8331.796 km
Velocity at Perigee	10.517 km/s
Perigee Longitude	113.26° W
Perigee Latitude	20.21° N
Semi-major Axis	-26704.055 km
Eccentricity	1.312005
Inclination	144.932°
R. A. of Ascending Node	170.172°
Argument of Perigee	143.099°
Asymptotic Velocity	3.863 km/s
Semi-deflection Angle	49.658°
Heliocentric: Velocity Vector Change	5.889 km/s
Velocity Increase	3.797 km/s
Velocity Direction Change	8.106°

5. Orbit Determination Anomaly

All the determinations of the Rosetta orbit up to perigee passage were normal and satisfactory in the sense that the solutions remained stable and consistent with each other. Also, both the range and range-rate residuals were scattered around zero, with no obvious trends or signatures, and with standard deviations close to expected values.

But when additional tracking data acquired after the swing-by were introduced, it was found impossible to achieve a good fit using normal processing methods. The results are illustrated here using only the range-rate residuals but the range residuals exhibit corresponding features.

Fig. 5 shows the post-fit 2-way range-rate residuals corresponding to the data acquired over an arc of about 9 days centred roughly on the time of perigee passage. The fit is obviously bad, both in terms of the amplitudes and the signatures over individual passes. This is despite the fact that there was some freedom to adjust the dynamics through the estimates of the WOLs.

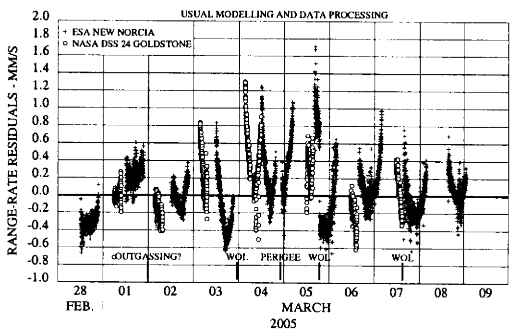

Fig. 5. Post-fit 2-way S-Band range-rate residuals - usual modelling and data processing

For each WOL individually, the *a priori*, 1σ uncertainty was set to 1 mm/s on each of 3 orthogonal axes and the components estimated, treated as an impulsive ΔV. The *a priori* values of the estimates were set to zero.

Only the WOL on 05 March was made during station visibility and Fig. 5 clearly shows a discontinuity in the residuals at the execution time.

Also, some outgassing was suspected around zero hours on 02 March when the spacecraft attitude was flipped through close to 180°. This was treated in the same way as the WOLs except that the *a priori*, 1σ values were set to 0.1 mm/s.

Fig. 6 shows the residuals obtained when the post-perigee data were assigned zero weight and so had no influence on the solution. The first of these data were obtained at 22:44 UTC on 04 March, 35 minutes after perigee passage. (In this case there is no ΔV at the WOLs on 05 and 07 March.)

Within a day or so after perigee passage, the residuals flatten out with an offset of about 3.6 mm/s from the pre-perigee residuals.

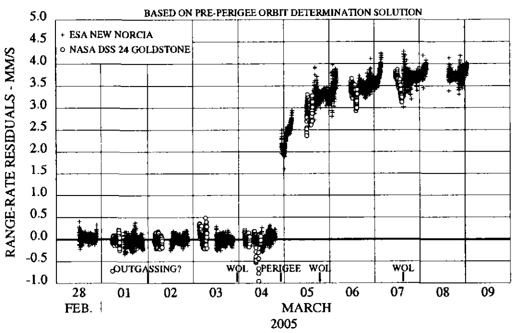

Fig. 6. Post-fit 2-way S-Band range-rate residuals - with post-perigee data zero-weighted

5.1 Artificial ΔV at perigee

The ESOC orbit team knew that navigation anomalies had been observed during the Earth swing-bys of some NASA missions but was unaware of the details.

After many trials, it was found that a reasonable fit through all the data could be achieved by introducing an artificial, impulsive manoeuvre at the time of perigee. At first, 3 components of such a disturbance were estimated. The direction of the estimated ΔV turned out to be very close to that of the orbital velocity. Then, a new run was made with the ΔV constrained to be exactly prograde and only its magnitude estimated.

Fig. 7 shows the residuals obtained when the artificial, prograde manoeuvre was included.

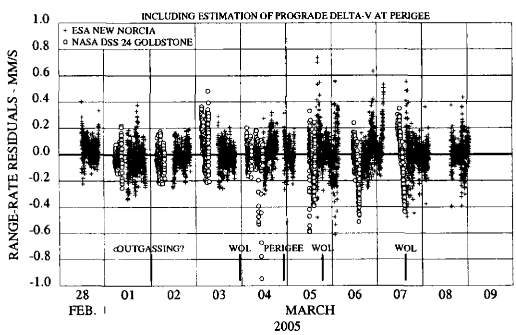

Fig. 7. Post-fit 2-way S-Band range-rate residuals - with artificial prograde ΔV at perigee

The result for the ΔV was 0.67±0.02 mm/s (1σ). If there were a prograde ΔV at perigee of the hyperbolic trajectory, then the equivalent increase in the asymptotic velocity is this ΔV factored by the ratio of the velocity at perigee to the asymptotic velocity, in this case a factor of 2.722 (see Table 2). This means that the estimate for the increase in asymptotic velocity was 1.82±0.05 mm/s (1σ). Towards the outward asymptote of the hyperbola, the orbital velocity direction is not far from the station-spacecraft direction, so on 2-way range-rate residuals one would expect to see an increase of about 3.6 mm/s, as appears in Fig. 6.

The residuals in Fig. 7 are not entirely satisfactory in that the appearance is not fully random, especially those corresponding to the NASA DSS 24 Goldstone data. Although it was not tried, a slightly better fit could probably be achieved by including a constant prograde acceleration over an estimated time period.

Of course, if the cause is dynamical in nature, then it is likely to be a variable acceleration over a short interval around perigee.

5.2 Anomalous velocity increase at other swing-bys

A few days after the Rosetta swing-by and after the discovery of how the orbit fit could be radically improved, the by no means well-known results from the earlier missions were found. They too showed similar anomalous features that could only be removed by introducing an artificial velocity increase.

The details on the Galileo and NEAR swing-bys are given in [3]. Reference to the anomaly is also made in [4], including the additional example of Cassini but in its case the uncertainty on the ΔV is apparently high, casting doubts about its existence. For Stardust, the dynamical noise due to the use of thrusters for attitude control would have obscured any small effect. Table 3 gives a summary of all the mentioned missions.

Table 3. Earth swing-bys with velocity changes

Satellite	Date	Perigee Altitude (km)	V_∞ change (mm/s)	Remarks
Galileo	Dec '90	960	+4.3	[3]
Galileo	Dec '92	303	-5.9	Drag [3,5]
NEAR	Jan '98	539	+13.0	[3]
Cassini	Aug '99	1173	+0.11	[4]
Stardust	Jan '01	5950	?	Thruster Control
Rosetta	Mar '05	1954	+1.8	-

Most recently, MESSENGER made an Earth swing-by on 02 August 2005, with a perigee altitude of 2347 km, but no anomalous effect was apparent [6].

6. Discussion

A variety of possible sources for the velocity anomaly has been investigated, as reported in [3]. Perturbing forces, specific to the near-Earth environment, such as tidal and relativistic effects, atmospheric drag and Earth radiation pressure can be ruled out because the acceleration levels are several orders of magnitude too small. Other sources that have been tentatively dismissed are orbit determination software errors, e.g. in numerical integration or round-off, uncalibrated media effects and spacecraft-specific operations. Furthermore, adjustments to low order and degree Earth gravity coefficients to remove the anomaly were found to be unrealistic in that the value changes were up to 300 times their associated uncertainties.

With the exception of Galileo's 2nd Earth swing-by, one common feature of the cases in Table 3 is that the ΔV is positive. The Galileo result was very close to the *a priori* prediction for the drag-induced change, based on the Jacchia-Roberts model. But taking into account the uncertainty of the model, a drag decrease of up to -10 mm/s was still considered reasonable so that an anomalous ΔV of up to +4 mm/s could be consistent [5].

Also in all the cases, the swing-by increased the heliocentric velocity but it is merely speculative whether this has any connection with a positive ΔV.

No similar anomaly has been reported for spacecraft swing-bys at planets other than the Earth. In such cases, the navigation uncertainties are higher because of the large geocentric distances. A common practice is to include adjustment to the pre-computed planetary ephemeris. Without correction to the planet's position, a good fit to the range data is unlikely unless a large range bias is allowed. Similarly, if fits of the pre- and post swing-by data give different estimates for the inbound and outbound asymptotic velocities, these can be matched by introducing an increment to the velocity of the planet along the direction from its centre to the pericentre of the spacecraft trajectory (in a negative sense if the outbound velocity is higher).

For the Rosetta Earth swing-by, a good fit to the data can be achieved if, for the dynamical modelling only, such an increment of -1.4 mm/s is added to the Earth's velocity. However, this adjustment is not valid because a change in the Earth ephemeris also affects the modelling of the observables - an essential difference between Earth and planetary swing-bys. This makes the differential correction procedure complicated and is not presently within the capabilities of the ESOC orbit determination software.

Analysis of the consequences of errors in the Earth ephemeris, though, remains intriguing because it is not mentioned as a possible source of the anomaly in [3] and all of the at least 4 independent programs [3], that have verified the anomaly, use the same planetary ephemerides - those of JPL.

In the same context, the effect of an error in the position of the solar system barycentre is of interest. This is particularly relevant because most interplanetary orbit determination software use formulations referred to the solar system barycentric relativistic frame of reference [7]. Ideally, it should be investigated whether the anomalous ΔV is also needed to obtain a satisfactory fit when the data are processed with software using the alternative formulation referred to the local geocentric relativistic frame of reference [7]. Although such software exists at ESOC, the fidelity of the modelling is below the level of precision described in [7], which would cast doubt on the credibility of any results.

In contrast to the well-publicised Pioneer anomaly [8], of an unexplained sunward direction acceleration of 8.7×10^{-13} km s^{-2}, the anomalous increases in velocity during Earth swing-bys are not well known. There are at least two common characteristics: they have no effect on the ability to navigate the spacecraft successfully but, perhaps as a consequence of no urgent need to solve the curious puzzles, their underlying causes have now remained a mystery for 15 years. For lack of any hard evidence to the contrary, it cannot be discounted that the causes of the two anomalies are related.

7. Conclusions

Rosetta's first Earth swing-by was very successful, with an insignificant cost in propellant to compensate for small targeting inaccuracies.

The artificial and anomalous ΔV that had to be introduced at perigee turned out to be the same recourse that was adopted for two, and perhaps more, previous NASA missions, to fit satisfactorily a trajectory to the tracking data. Because the cause is still unknown, the Rosetta orbit team will have a heightened awareness for potential anomalies at the Mars swing-by on 25 February 2007 (periapsis altitude of 250 km) and especially at the Earth swing-bys on 13 November 2007 and 13 November 2009. The perigee altitudes of 5302 km and 2482 km respectively, will be higher than at the first Earth swing-by.

Acknowledgement: The support of the NASA/DSN and JPL in providing radiometric data for Rosetta is very much appreciated.

8. References

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