ROSETTA NAVIGATION FOR THE FLY-BY OF ASTEROID 2867 ŠTEINS

Trevor Morley[(1)] and Frank Budnik[(1)]

European Space Operations Centre (ESOC), Robert-Bosch-Strasse 5, 64293 Darmstadt, Germany
[(1)]ESA/ESOC, E-mail:<first name>.<last name>@esa.int

ABSTRACT

Halfway on its 10 years journey to a rendezvous with comet 67P Churyumov-Gerasimenko, on 05 September 2008 Rosetta flew by the small, main-belt asteroid, 2867 Šteins, one of two secondary scientific targets of the mission.

Until one month before the fly-by, the navigation was based upon the quite separate determinations of the orbits, using conventional radiometric data for the spacecraft and ground-based astrometric observations of the asteroid. The Šteins orbit solution proved to be untrustworthy because of apparent systematic errors in its declination measurements.

The targeting during the final approach relied primarily on optical data derived from images acquired by on-board cameras - the first time optical navigation was employed for an ESA mission. The processing of the first few data from 04 and 07 August led to a substantial improvement in the prediction of the time of closest approach although the reason was not properly understood until much later. The final targeting was based on a total of 340 good quality images obtained by three on-board cameras through to one day before the fly-by. The spacecraft trajectory was modified twice by small manoeuvres on 14 August and 04 September.

Using optical data from images during the fly-by, mainly from yet a fourth camera, the relative trajectory was reconstructed with high precision. At closest approach, Rosetta was 2.4 AU from the Earth and only 6.6 km from the target location. The miss-distance was just 2.6 km higher than the desired 800 km. The fly-by time was 4 seconds later than had been predicted.

The reconstruction also allowed a better solution for the asteroid's heliocentric orbit which indicated that the right ascension coordinates of the astrometric measurements were also biased. Other recent research has proven that most asteroid orbit solutions are biased because of unexpectedly large zonal errors in some star catalogues commonly used to reduce the astrometric data.

1. INTRODUCTION

1.1 Rosetta mission

Rosetta was injected directly into an Earth escape trajectory on 02 March 2004. To reach comet 67P Churyumov-Gerasimenko, the mission design [1] called for three Earth swing-bys and one Mars swing-by. The first Earth swing-by [2] was one year after launch. The Mars swing-by [3] occurred on 25 February 2007. It actually decreased the heliocentric orbital energy and was essentially a phasing manoeuvre for the second Earth swing-by on 13 November 2007. The final Earth swing-by will be on 13 November 2009.

Only after launch were the asteroid targets, 2867 Šteins and 21 Lutetia, chosen for close fly-bys from a list of candidates, according to scientific interest, fly-by geometry, operational feasibility and the additional cost of propellant for the trajectory modifications. At that time, it was then known how little fuel was needed to correct the Ariane-5/G1 launch vehicle dispersion and thus it could be predicted more accurately how much was available for the excursions past secondary targets.

Rosetta is three-axis stabilised with two very large solar arrays as power source. Deep space communications in normal mode are via a steerable, two-degree of freedom high-gain antenna. Attitude measurement and control makes use of autonomous star trackers and ring laser gyros with three or four reaction wheels running when in normal mode.

The spacecraft carries four cameras: two identical, so-called NAVCAMs, whose primary purpose is for optical navigation; and two cameras of the OSIRIS (**O**ptical, **S**pectroscopic, and **I**nfrared **R**emote **I**maging **S**ystem) science instrument, the Narrow-Angle Camera (NAC) and the Wide-Angle Camera (WAC).

1.2 Asteroid 2867 Šteins[1]

Šteins was discovered on 04 November 1969 by N. S. Chernykh at Nauchnyj. Its original designation was 1969 VC. The asteroid was named in memory of Karlis Augustovich Šteins (1911-1983), director of the Latvian University's Astronomical Observatory from 1959, well known for his work on cometary cosmogony. He also studied the rotation of the Earth and designed astronomical instruments.

According to various estimates, the asteroid's absolute magnitude is in the range 12.4-13.3. Based on observations made mainly at Earth-bound observatories, it was thought to be a relatively uncommon E-type object with a high albedo. Estimates of its diameter lay in the range 4.6-6.0 km and its rotation period was expected to be 6.05 hours with no indication of deviation from a principal axis rotation state. (These expectations concerning the basic characteristics were subsequently confirmed from the fly-by science data as being quite accurate.)

2. TRAJECTORIES

Rosetta's 2nd Earth swing-by on 13 November 2007 raised its aphelion to 2.26 AU so that it would make its first excursion through the main asteroid belt. Ten days later the swing-by errors were cleaned up by a 1.53 ms^{-1} manoeuvre. Another manoeuvre of 0.25 ms^{-1}, on 21 February 2008, put the spacecraft on course to fly by Šteins, based on the then best knowledge of the asteroid's orbit.

Šteins has an orbital period of 3.3 years. Its heliocentric orbit is inclined by 9.9° to the ecliptic and has an eccentricity of 0.1455. Its perihelion distance is 2.02 AU and aphelion distance is 2.71 AU.

Fig. 1 is an ecliptic projection of the orbits. The solid lines show the trajectories of the spacecraft, asteroid and Earth over a period of 70 days centred on the fly-by date.

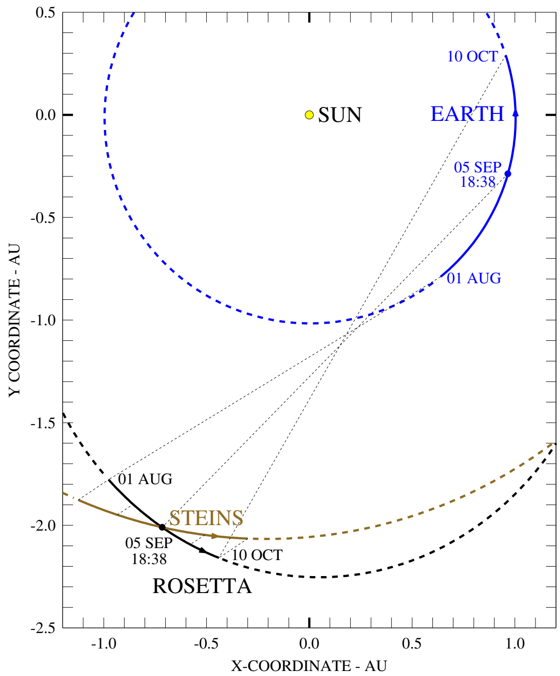

Fig. 1. Orbits of Rosetta, Šteins and the Earth

The magnitude (8.6 kms^{-1}) and direction of the Rosetta velocity relative to Šteins at the fly-by was fixed when the spacecraft's trajectory was designed [1] and could not be changed. Of the free parameters, the distance at closest approach, or miss-distance, was planned to be 800 km, the minimum possible taking into account the constraints on the maximum spacecraft slew rate (including some margin for navigation errors). The scientists wanted Rosetta to cross the Sun-asteroid line, i.e. to pass through zero solar phase angle (or as close as possible to zero). Fig. 2 shows the ecliptic projection of the planned relative trajectory over an interval of about 10 minutes around closest approach.

At the planned miss-distance, the orbital perturbation due to Šteins' gravity was expected to be negligible and over the fly-by interval the relative trajectory is virtually a straight line.

For the fly-by it was intended to put the spacecraft into Asteroid Fly-by Mode (AFM) in which there is an on-board, closed-loop control to keep the payload boresights pointing to the asteroid, with a NAVCAM in the control loop [4].

1. The diacritical mark of the caron above the leading "S" is often omitted.

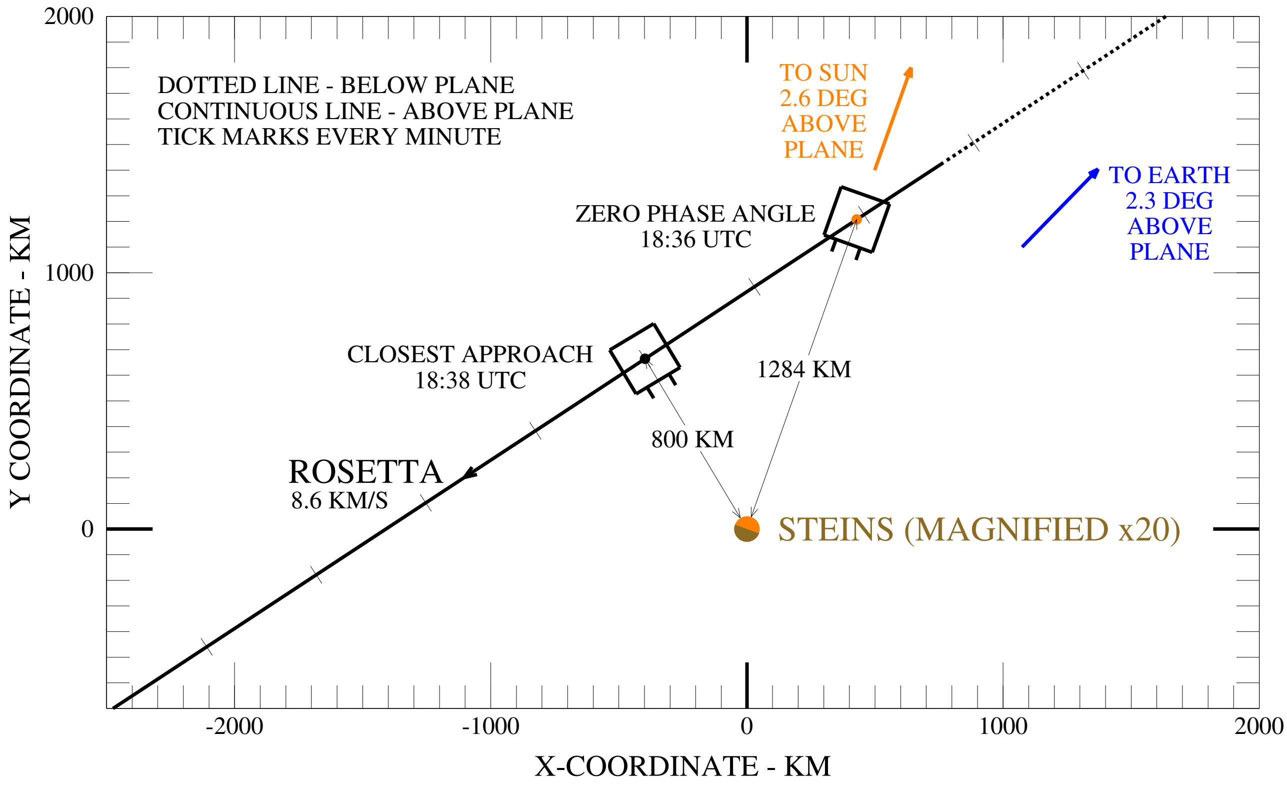

Fig. 2. Planned Rosetta trajectory past Šteins on 05 September 2008

3. CONVENTIONAL ORBIT DETERMINATION

3.1 Spacecraft heliocentric orbit

During quiet cruise phases, Rosetta is tracked only by ESA's 35 m deep space antenna (DSA) at New Norcia (NNO) in Western Australia. Following the February 2008 manoeuvre, Rosetta was in Near Sun Hibernation Mode (NSHM) until 02 July and tracked just once per week. During this time the orbit determination accuracy was degraded, not just because of the infrequent tracking but also because in NSHM the attitude is controlled by occasional thruster pulses that are not modelled. During July, in normal mode using reaction wheels, the spacecraft was tracked on each working day and the 8th check-out of the payload was conducted. From 07 August onwards, NNO tracking was daily and the angular momentum of the wheels was off-loaded once per week. The orbital disturbance due to these operations is almost always less than 1 mms^{-1} because the thruster system is well-balanced.

During critical phases, additional support is provided by the NASA Deep Space Network (DSN) complexes. From 08 August to 10 September, there were daily passes of mostly 4 hours duration, using various stations at Madrid up to 31 August, and thereafter using stations only at Goldstone. Also, ESA's 35 m DSA at Cebreros, near Madrid, supported three passes, on 19 August (of less than 1 hour duration) and two 5 hours passes on 04 and 05 September.

All the stations acquired coherent two-way Doppler and range data that were used to determine the heliocentric orbit with ESOC's interplanetary, infrastructure software [5]. This relies on high fidelity modelling of the dynamics and signal path that closely follows the formulations in [6]. At the beginning of August the start of the tracking data arc was set at the time of the resumption of normal mode operations and not changed until well after the asteroid fly-by.

3.2 Asteroid heliocentric orbit

Up to the summer of 2008, the measurements of Šteins consisted only of classical astrometric observations of the asteroid's topocentric right ascension and declination. Since the first (pre-discovery) observation of Šteins on 28 November 1951, there was a total of 1264 observations from 26 different observatories up to and including May 2008 when a detailed orbit determination study was made [7].

The observations obtained since 11 November 1999, around the last 7 oppositions, accounted for 1199 (95.3%) of the total. Of these, 416 were made at the LINEAR Observatory.

The Šteins orbit was determined by finding the best fit of the trajectory to almost all the astrometric data using a weighted least squares algorithm. Six measurement pairs were omitted because the residual corresponding to one of both coordinates exceeded three times the default standard deviation. Modern astrometric data are more accurate than older data so were given higher weight. In the absence of any objective weighting scheme, the standard deviation of the random measurement error on each coordinate of an observation pair was assigned to be 1 second of arc (1") for data after 1990 and 2" for the 15 earlier observations. This weighting scheme was conservative.

For modelling the dynamics, as well as the main gravitational attraction of the Sun, the gravitational perturbations of all the planets, Pluto, the Moon and the so-called "big 3" asteroids (Ceres, Vesta and Pallas) were taken into account. The planetary positions were taken from the JPL DE405 ephemerides. The positions of the perturbing asteroids were taken from the small body ephemerides, kindly provided by JPL.

At an epoch close to the projected fly-by time, the solution for the asteroid's position was compared to the JPL solution (based on a slightly different subset of data) using their online Horizons System [8]. The difference was just 18 km. Also, at the epoch 2008 May 14.0 (TDB), the difference from the position given on the (Italian) Asteroids - Dynamics web site (AstDys) [9] was 28 km.

As expected, the longest axis of the asteroid's position uncertainty ellipsoid at the fly-by time was closely aligned to the along track direction. Its 3σ value was 202 km, much higher than the differences between the independent orbit solutions.

There was, though, one very unsatisfactory aspect of the orbit determination result: as shown in Table 1, the mean value of the declination residuals was distinctly positive instead of being close to zero. The "processed" row applies to results for the observations and the "normalised" row applies to results for the weighted observations.

Table 1. Residual statistics from Šteins orbit determination (arc seconds)

Residuals	Mean		Root Mean Square		
	R.A.cos(δ)	Declination (δ)	R.A.cos(δ)	Declination (δ)	Both
Processed	-0.004	+0.185	0.521	0.535	0.528
Normalised	-0.002	+0.188	0.507	0.511	0.509

The weighted least squares process provides optimum, unbiased estimates only if certain conditions are fulfilled. Measurement errors should be random, with no systematic component, and there should be no correlation between measurement errors. The latter condition is certainly not perfectly satisfied [10]. When these conditions are satisfied, the residuals show a random scatter around a zero mean value. Conversely, when the residuals do not exhibit this behaviour there cannot be confidence that the estimates are unbiased. For Šteins the declination bias was not small: an error in the prediction of the asteroid's geocentric declination of 0.185" at the time of the Rosetta fly-by, when the geocentric distance was 2.4 AU, would have corresponded to a position error on the plane-of-sky of 320 km.

A series of parametric orbit determination runs [7], using different data arcs, different data weighting schemes and other variations in the data processing resulted in no appreciable reduction in the mean declination residual apart from one case, when data only from the two most recent oppositions (since 18 September 2006) were used. But with such a short data arc the uncertainty estimates were unacceptably large. These runs also led to some solutions that differed from the nominal result by amounts inconsistent or only marginally consistent with the error statistics.

In order to get a more general picture of asteroid orbit solutions, the trajectories of a small number of other main belt asteroids were determined. The choice of asteroids was not random but consisted of 21 Lutetia, the target for Rosetta's 2nd asteroid fly-by, and those additional 12 asteroids that were considered as possible targets at the time the Rosetta mission was being re-designed following the one-year launch delay. Without exception, the mean value of the declination residuals was positive, with the value for Šteins being about the average value for all 14 asteroids.

Independent confirmation of apparent biases of the order of 0.2" on many asteroid declination measurements, at least since 2000, was given by the JPL Solar System Dynamics Group Supervisor [11]. The problem is also discussed in [10] but until quite recently no plausible cause was known - see section 6. The main consequence during the preparations for the Rosetta-Šteins fly-by was reduced confidence in the accuracy of the asteroid's orbit solution despite the conservative weighting of the data.

3.3 Target estimates and uncertainties

Until early August 2008, the Rosetta navigation relied on the completely separate determinations of the orbits of the two bodies. The then targeting status is conveniently shown with respect to the so-called B-plane or target plane. This plane passes through the centre of the asteroid and is perpendicular to the direction (vector **S**) of the relative velocity. The "B-vector" is a vector in that plane from the asteroid centre to the piercing point of the relative trajectory. The abscissa, **T**, is the projection of the J2000.0 ecliptic onto the target plane and 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 error along **S** is converted to a time-of-flight error by dividing by the relative speed.

After 14 May 2008, only 11 more ground-based astrometric observations of Šteins were obtained, the last on 25 July[2], when the solar elongation was 87°. Their processing caused only insignificant changes in the orbit solution.

Fig. 3 shows the situation in the target plane using radiometric data up to 04 August. The target on the red 800 km contour accords to the desired phase angle condition. The black cross was the estimate for Rosetta's location, 155 km from the target and corresponding to a miss-distance of 683 km.

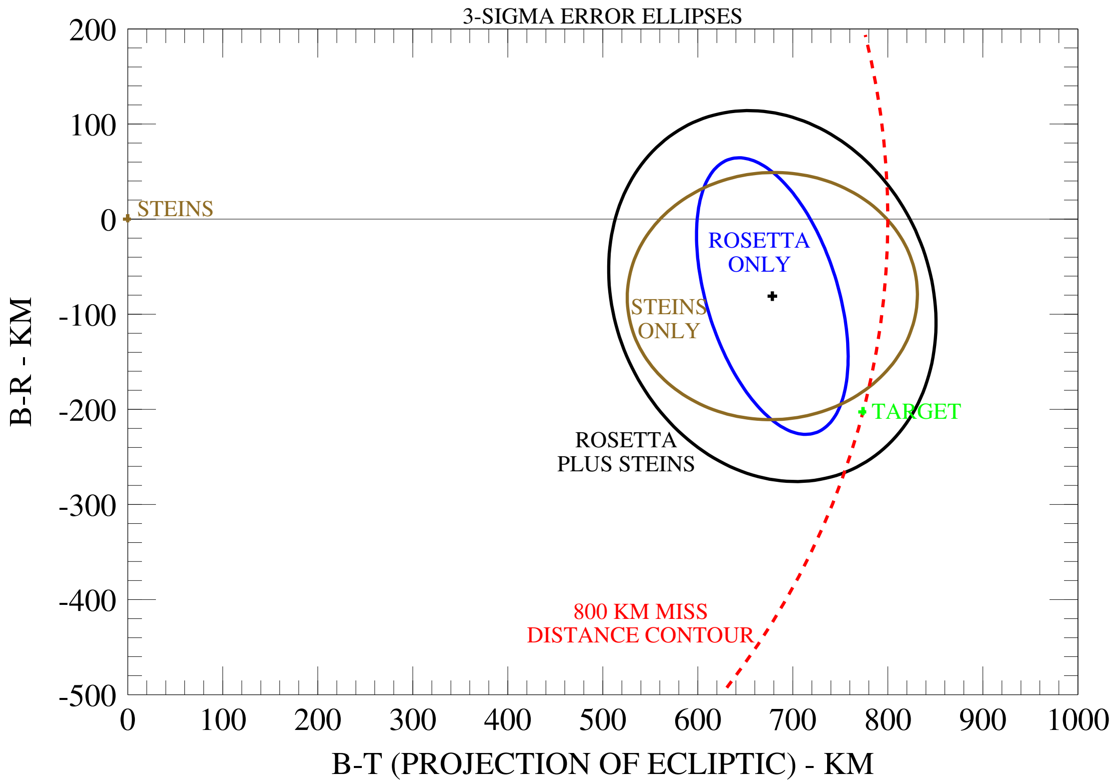

Fig. 3. Rosetta-Šteins fly-by target estimate using data up to 04 August 2008

2. This was disappointing because the asteroid's solar elongation stayed above 63° through to the fly-by so Šteins remained visible in dark sky conditions for most Earth-based telescopes. The first astrometric observations during the opposition were obtained on 19 November 2007, when the elongation was just 48°. Also, by comparison, the last astrometric data of comet Churyumov-Gerasimenko at its most recent apparition were obtained when the solar elongation was only 32°.

The brown error ellipse was the contribution to the overall uncertainty from the Šteins formal covariance matrix. The blue error ellipse came from the spacecraft covariance matrix. The relative state uncertainty, shown by the black ellipse, came from the sum of the covariance matrices. It just encompassed the target point

The estimated time of closest approach was 18:38:04.9 UTC on 05 September. The contribution to the 3σ uncertainty was 18.1 s from Šteins and 4.0 s from Rosetta. The combined 3σ uncertainty was 18.5 s. The low uncertainty from Rosetta was due to favourable geometry: the line-of-sight from Earth was closely aligned to the relative velocity direction (Fig. 2) so that the Doppler data provided an accurate estimate of the component of the spacecraft's orbital velocity along that direction.

4. ASTEROID APPROACH PHASE

To try and ensure precise targeting for the fly-by, optical imaging of the asteroid was planned using both Rosetta NAVCAMs and the OSIRIS NAC. The CCD pixels of the NAVCAMs correspond to an angular size of 0.005°. The main advantage of also using the NAC for navigation purposes was its almost five times better resolution. The processing of the images on ground and the data reduction to direction measurements are described in detail in [4]. The end result from each good image was spacecraft-centred measurements of right ascension and declination of the target object, Šteins, together with a two-by-two covariance matrix for weighting purposes.

The strength of such optical data is the direct tie between the states of the spacecraft and the target body. On the assumption of no *a priori* uncertainty information, a linearised analysis [12] showed that, for a fixed error in the measurement of the direction from the spacecraft towards the asteroid, the error for the prediction of the fly-by location in the target plane reduces in proportion to the time remaining up to closest approach. But the error in the prediction of the time of closest approach reduces with the square of the remaining time. This means that significantly improving the prediction of the fly-by time was expected to be possible only very shortly before closest approach and certainly too late to change the timings of the scientific observations.

4.1 Planning

Optical imaging sessions were planned to take place twice per week, starting on 04 August 2008, and then daily from 23 August onwards. It was expected that Šteins would not be bright enough to be detected on the initial NAVCAM images but there was hope that early detection would be possible using the more sensitive NAC.

In July, five time slots for trajectory control manoeuvres (TCMs) were identified [4] and criteria established for deciding whether a TCM would be executed or not. For the first slot on 14 August, the TCM would be designed irrespective of whether the initial optical data acquisition and processing were successful or not in reducing the navigation uncertainties.

It was agreed that at the time the first TCM was being optimised, the then predicted time of closest approach would be made widely available and thereafter be treated as the target time. The planning of any subsequent TCMs then had to respect this constraint. This was necessary in order to optimise on an absolute time scale the sequence of scientific measurements at the fly-by.

A concern at this stage was the reliability of the prediction for the fly-by time and its uncertainty given that both results were largely dependent on the asteroid orbit solution that was known to be unduly influenced by systematic errors.

4.2 Relative orbit determination

The ESOC orbit determination software [13] is not a stand-alone program that processes all the different data types within a single batch. For each run, the spacecraft's heliocentric state was determined using all the radiometric data acquired since the start of the data arc. Similarly, but quite separately, the asteroid's heliocentric state was determined using the ground-based astrometric data.

Then, the determined states of the two bodies were mapped to an epoch shortly before the expected time of closest approach and were used as *a priori* estimates for the orbit determination using the optical data. In a corresponding way, the *a posteriori* covariance matrices (that included the effects of consider parameters) were mapped to the same epoch and subsequently used as *a priori* uncertainties. Thus, they constrained the final solution. This method is equivalent to processing all the data types in a single run so long as certain conditions are met like remaining within the linear regime of the differential correction process. The final orbit determination provided estimates of the heliocentric state vectors of both bodies (and updates for other parameters previously estimated for the spacecraft, such as manoeuvre components) and estimates of their uncertainties. Then, the estimate of the relative state and its uncertainty was derived, for the latter taking proper account of the cross-covariance terms.

4.3 Initial results

Unexpectedly, the asteroid could be detected on images acquired by both NAVCAMs on 04 August. The NAC also obtained images but, due to an on-board data handling anomaly, they were lost. Three days later all three cameras acquired images that were processed to provide the desired direction measurements. The reduction of earlier NAVCAM test images of the stellar background, made in December 2007, achieved measurement direction accuracies of better than one-tenth of a pixel [4]. The root-mean-square values of the post-fit residuals of the Šteins measurements confirmed these results, as well for the NAC, and this accuracy level was maintained throughout the approach phase.

Also unexpectedly, the estimate for the time of closest approach changed significantly, by +11 s, and its 3σ uncertainty diminished by 5.4 s to 13.1 s. A similar behaviour had previously been seen in the results of optical navigation tests using simulated data [14] but, at the time, the cause for the apparent improvement was not understood. Only long after the fly-by was a satisfactory explanation forthcoming - see section 5.2.

On 12 August, the predicted fly-by time was announced to be 18:38:16 UTC on 05 September. Thereafter, and very much in line with expectations, the accumulation of more optical data led to hardly any change in the predicted time and its uncertainty.

4.4 Evolution of navigation results

During operations, official navigation results were disseminated after each occasion when newly acquired optical data had been processed. Here, just a summary is given.

Fig. 4 shows the situation in the target plane using data up to 25 August.

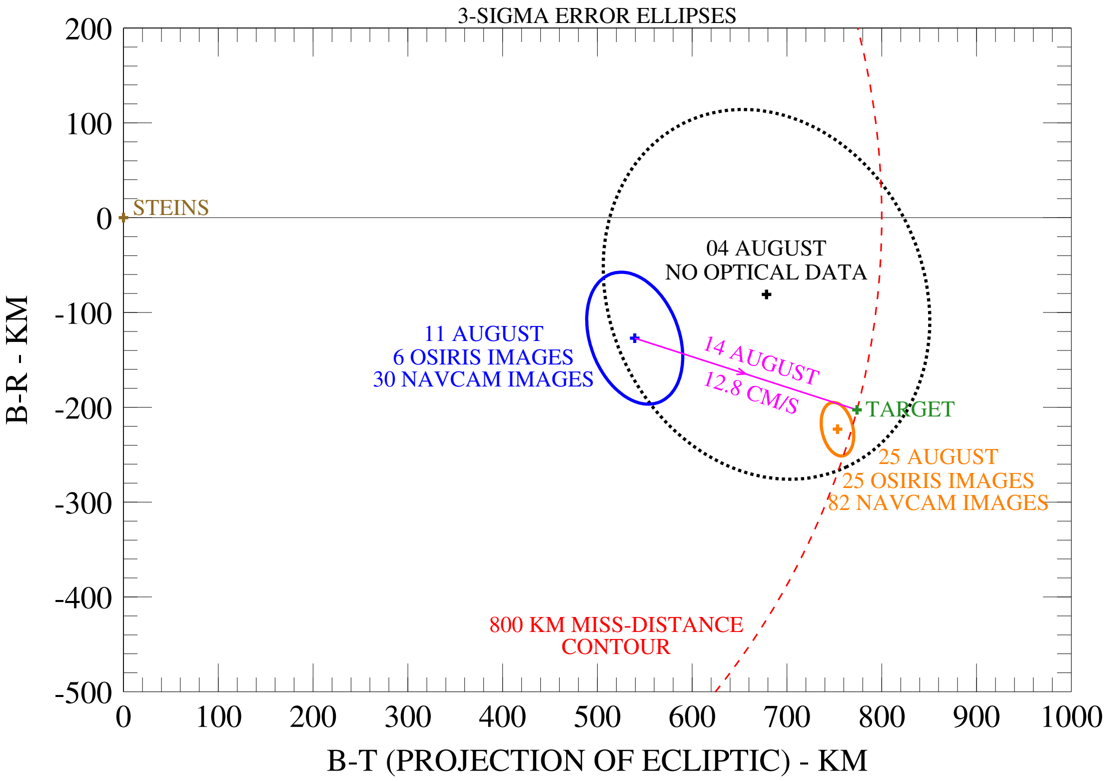

Fig. 4. Rosetta-Šteins fly-by target estimates using data up to 25 August 2008

The blue cross and associated error ellipse was the solution on 11 August. Although the ellipse intersects the black one, it is not nested within it, which is evidence for inconsistency. As already discussed, the likely cause was a somewhat biased solution without optical data. On 14 August, when Rosetta was still 16 million km from Šteins, the 12.8 cms^{-1} manoeuvre was executed to move the target plane location by 246 km. The solution on 25 August was 32 km from the target and corresponded to a miss-distance from the asteroid of 786 km.

With time, and the diminishing distance between the spacecraft and asteroid, the sizes of the error ellipses reduced at the expected rate. The target lay just outside the 25 August error ellipse boundary. Partly because there were slight inconsistencies between some of the consecutive solutions and between results obtained using the optical data individually from each camera, the TCM slot on 28 August was not used.

Fig. 5 shows the situation up to 04 September, about 24 hours before the fly-by. The scale of Fig. 5 is ten times that of Fig. 4. The result on 03 September, shown by the black cross and associated error ellipse, was 14.9 km from the target and corresponded to a miss-distance of 791.4 km. Early in the morning of 04 September, when the separation distance was 1.1 million km, the last TCM of magnitude 11.8 cms^{-1} was executed. After the manoeuvre, at around 11:30 UTC, 5 NAC images were acquired. The navigation solution using these additional measurements is shown by the purple cross and associated error ellipse. The estimated location was just 1.9 km from the target and corresponded to a miss-distance of 800.7 km. The error ellipse encompassed the target position. It is hardly smaller than the black ellipse due to the *a priori* uncertainties assumed for the manoeuvre performance - 3% in magnitude and 1.7° in direction (both 1σ).

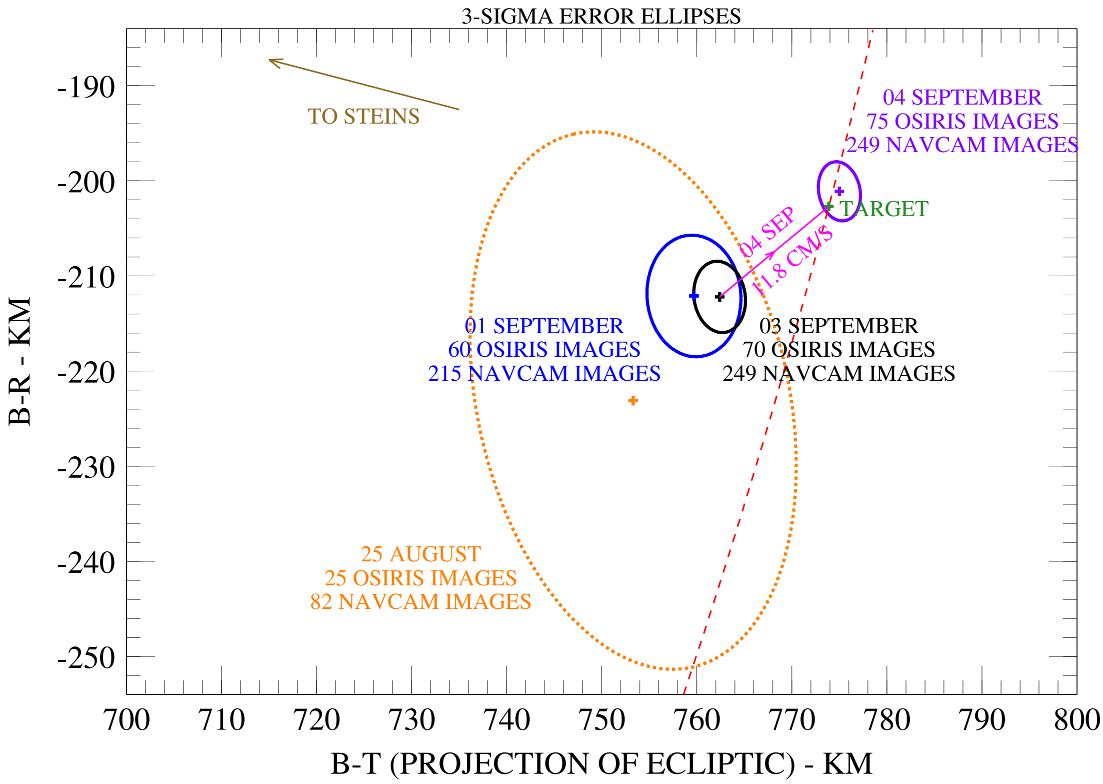

Fig. 5. Rosetta-Šteins fly-by target estimates using data up to 04 September 2008

The navigation result was then extremely close to the desired fly-by conditions. It was an easy decision to discard the last possible TCM slot, allocated just 12 hours before closest approach, that in any case had been foreseen to be used only in the case of an emergency.

5. ASTEROID FLY-BY AND AFTERWARDS

5.1 Trajectory reconstruction

Between 15:00-17:00 UTC on 04 September, 16 more NAVCAM images were acquired. Afterwards, these cameras were not further used for navigation purposes. Images up to 10 minutes before closest approach were obtained by the NAC and around the whole fly-by by the OSIRIS WAC, both sets primarily for scientific purposes. Many of these images were subsequently processed to provide direction measurements (18 from the NAC over the interval 18:19:19 to 18:28:20 UTC on 05 September and 35 from the WAC over the interval 18:20:32 to 18:54:22 UTC, i.e. up to 16 minutes after closest approach). The WAC has a resolution only marginally worse than the NAVCAMs - one pixel has an angular size of 0.006° - so that the measurements at comparatively small separation distances allowed a very precise reconstruction of the relative fly-by trajectory.

The final navigation result is illustrated in Fig. 6 whose scale is five times that of Fig. 5. The orange cross and associated error ellipse was the solution based upon all the spacecraft radiometric data, asteroid ground-based astrometric data and optical navigation data acquired up to and including 04 September. The black cross and associated error ellipse is the reconstructed solution that additionally used the optical data around the fly-by. The location is 6.6 km from the target.

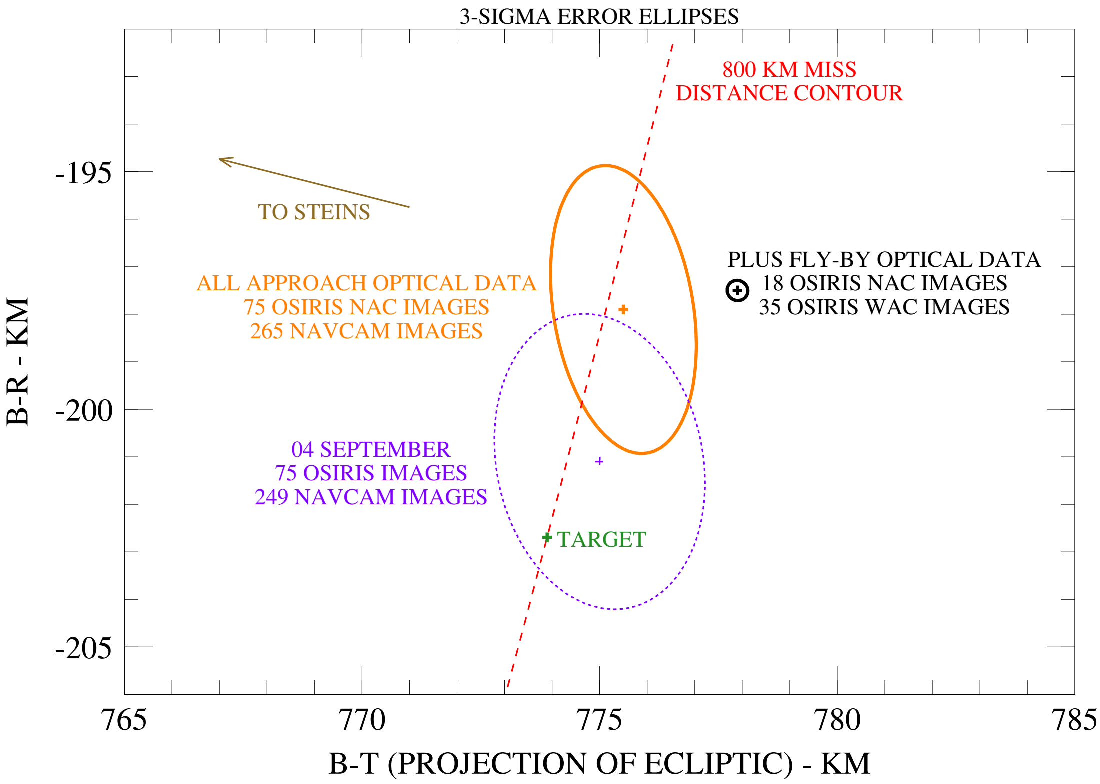

Fig. 6. Rosetta-Šteins fly-by final target estimates

Rosetta flew past Šteins with a miss-distance of 802.6 ± 0.2 km (3σ). The plane of the fly-by trajectory relative to Šteins was tilted from the desired plane by 0.43°. Rosetta flew south of the asteroid-Sun vector so that the minimum phase angle was 0.27 ± 0.01° (3σ). Minimum phase angle occurred 117.00 s before closest approach. The closest approach time was 18:38:20.07 UTC ± 0.06 s (3σ).

The distinct separation between the orange and black error ellipses means that the last predicted and reconstructed results are inconsistent with each other. This is thought to be due to small systematic errors in the direction measurements derived from the optical data during approach [4], particularly those at the end of the approach phase since they have the highest information content.

5.2 Evolution of closest approach time estimates

The actual time of closest approach was just 4 s later than the official prediction made 24 days before the fly-by. Fig. 7 shows the evolution of the predictions, with ±3 σ error bars, in terms of the differences from the reconstructed time. The first result on 04 August was without optical data. As already mentioned in section 4.3, except for the first two sets of optical data, the prediction times and their uncertainties remained almost constant throughout the optical navigation campaign.

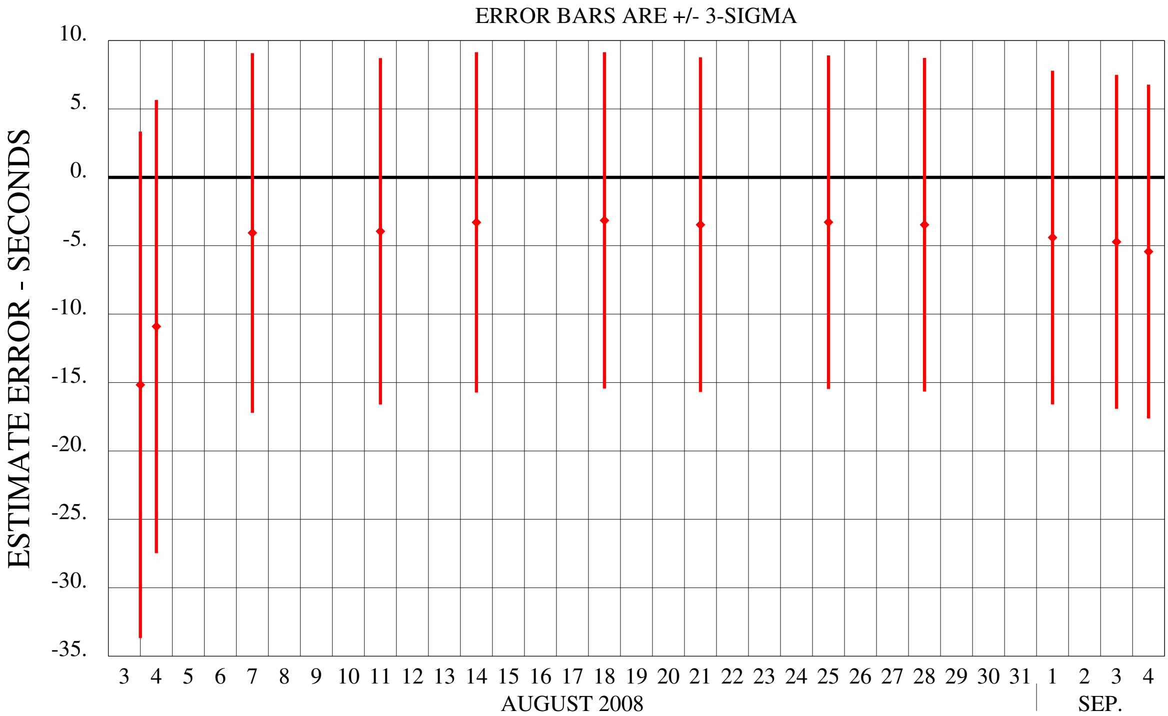

Fig. 7. Evolution of closest approach time estimates

The explanation for the initial improvement was provided by the JPL Outer Planet Navigation Group Supervisor [15] and is also given in [16]. It is a correlation effect between the direction of the relative velocity (**S**) and the orientation of the asteroid's uncertainty ellipsoid. As mentioned in section 3.2, the longest axis was closely aligned to the along track direction and thus close to perpendicular to the Sun direction. The initial, main contribution to the arrival time uncertainty arises from the projection of the uncertainty ellipsoid along **S**. For Rosetta-Šteins, the projection angle between the longest axis and **S** was 38° (Fig. 2). When the first optical data were used, the precise direction measurements effectively created a narrow tube through the ellipsoid along the viewing direction and had the immediate effect of reducing the error in the target plane (see the reduction from the black ellipse to the blue ellipse in Fig. 4). However, this also had the effect of reducing the projection normal to the target plane to the long dimension of the tube through the error ellipsoid. Furthermore, this correlation gave the data the power to adjust the arrival time estimate by sliding the along track position estimate of the asteroid to lie within the tube.

Normally, more optical data have no appreciable, further effect because the narrowing of the tube becomes incremental. In Fig. 7, the second apparent improvement on 07 August can be explained by the first availability of the NAC measurements with their five-fold higher accuracy.

Interestingly, according to [15], JPL tends to be wary of the correlation and has not used the effect to update encounter sequences.

5.3 Spacecraft pointing during the fly-by

During the fly-by, the on-board AFM software estimated the inertial line-of-sight from Rosetta to Šteins every 0.125 seconds. Using the reconstructed fly-by trajectory, the residuals of the right ascension and declination estimates were computed. The results were then rotationally transformed to residuals in and perpendicular to the fly-by plane and are shown in Fig. 8.

In the out-of-plane direction the pointing was apparently very accurate: the maximum error of just 0.025° occurred at closest approach. On the other hand the in-plane pointing error reached a maximum of more than 0.4° about 95 s earlier, and exceeded the specified required accuracy of 0.3° over an interval of nearly two minutes. A detailed analysis of this mispointing is given in [4] - the root cause is believed to have been blooming on the NAVCAM CCD.

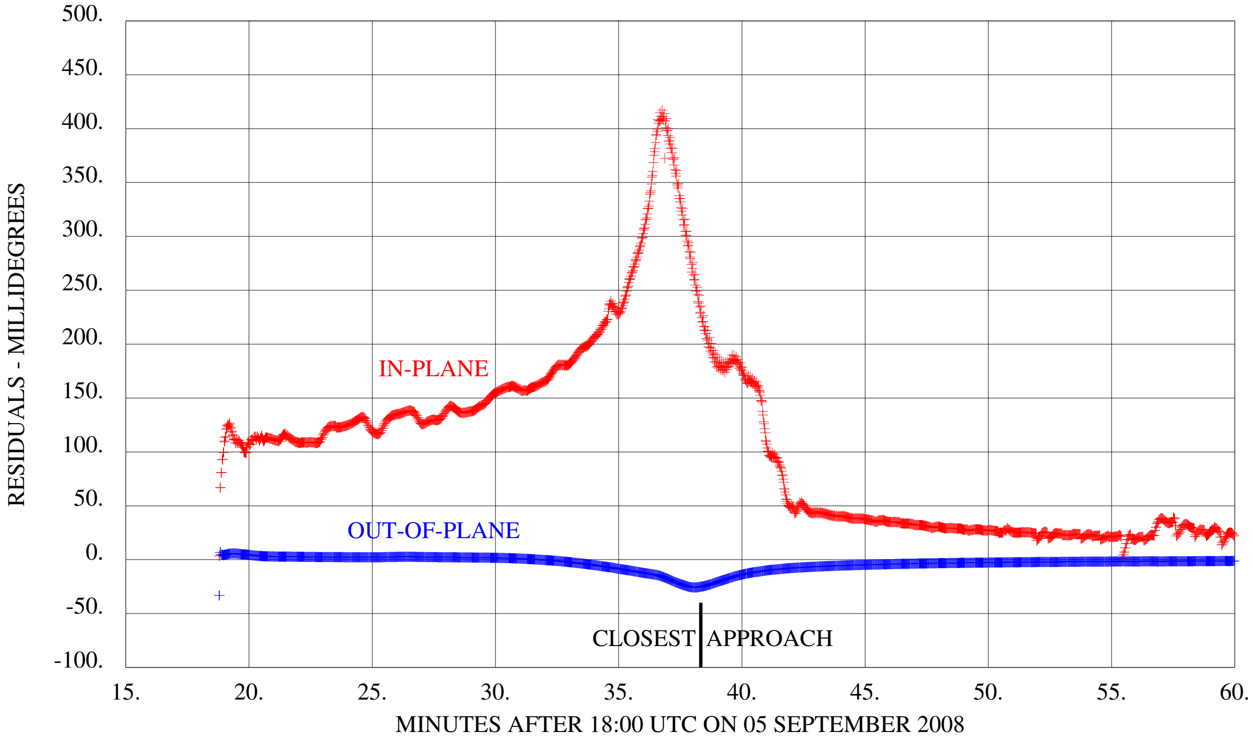

Fig. 8. Rosetta on-board pointing angle residuals

Without Asteroid Fly-by Mode, the pointing performance would have been much worse. With open-loop pointing based on the optical navigation results, alone due to the prediction error in the arrival time, the in-plane pointing error would have been 2.5° at closest approach.

5.4 The boon of optical data

Fig. 9 illustrates what the final targeting would have been without the benefit of the optical data.

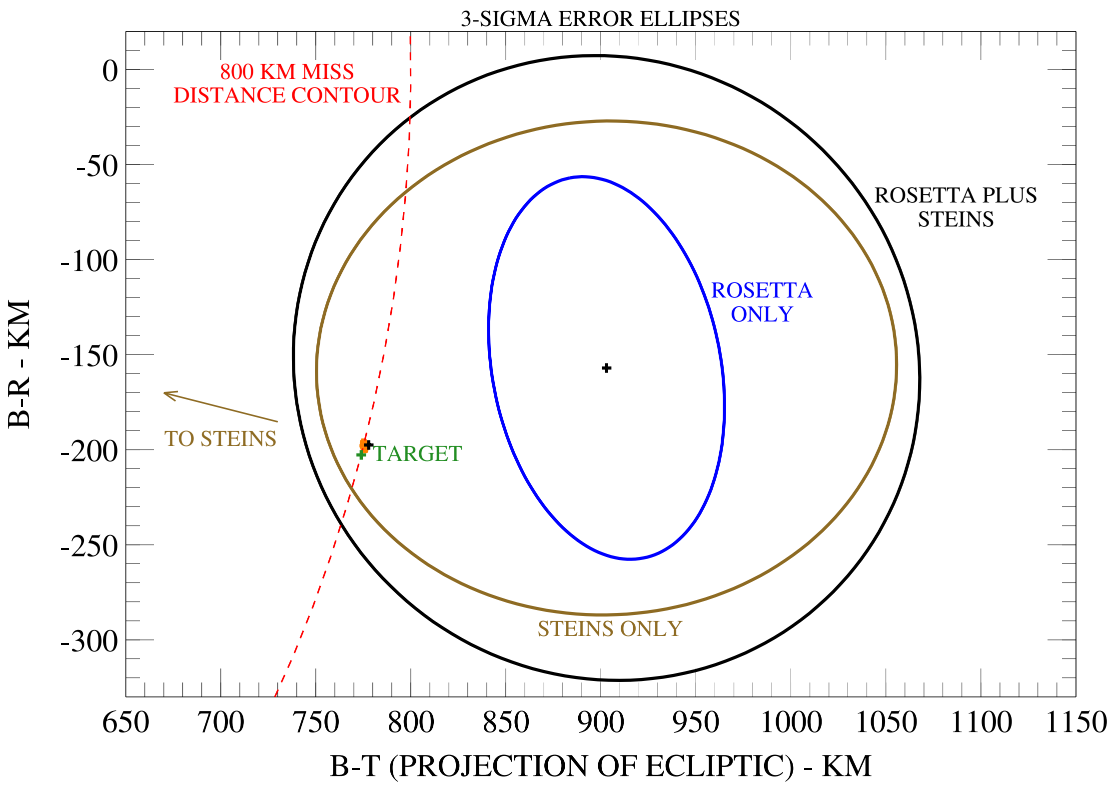

Fig. 9. Rosetta-Šteins fly-by target estimate without optical data

The Šteins error ellipse dimensions are the same as in Fig. 3. The Rosetta error ellipse is smaller than in Fig. 3 due to the radiometric data obtained during the last month of the approach. The estimated location would have been 137 km from the target that itself lies within the overall error ellipse, but only just.

If optical navigation had failed, the predicted time of closest approach would have been too early by more than 15 s and the minimum solar phase angle during the fly-by would have been 3.0°. The miss-distance would have been 116.5 km lower than desired. (Of course, under such circumstances, the target miss-distance would have been raised to allow a much larger margin for navigation uncertainties.)

In short, the optical data improved the navigation accuracy by more than an order of magnitude.

5.5 Update of Šteins heliocentric orbit

It appeared very likely that the apparently biased navigation result obtained when the optical data were omitted was due to the hitherto unexplained systematic errors in the Šteins orbit determination and this was investigated further.

A better estimate of the asteroid's heliocentric state at the fly-by was computed by subtracting the estimate of the relative state from the estimate of Rosetta's heliocentric state. It was better because the relative state uncertainty was so small that the uncertainties in the heliocentric states of the spacecraft and asteroid became virtually identical and the spacecraft state error estimates using the radiometric data were smaller than the asteroid state error estimates using the astrometric data. This changed the inertial position of Šteins at the fly-by epoch by 204 km. In geocentric coordinates, its distance became 103 km higher, its right ascension decreased by 0.099" and its declination increased by 0.018".

The asteroid's updated heliocentric state vector was used as the starting point for a propagation of the orbit back through the entire time span of the astrometric data and their residuals were recomputed. The residual statistics are summarised in Table 2.

Table 2. Residual statistics from Šteins updated orbit propagation (arc seconds)

Residuals	Mean		Root Mean Square		
	R.A.cos(δ)	Declination (δ)	R.A.cos(δ)	Declination (δ)	Both
Processed	+0.092	+0.212	0.542	0.550	0.546
Normalised	+0.097	+0.217	0.521	0.523	0.522

The root mean square of the weighted residuals is just 2.5% larger than from the determined orbit, as given in Table 1. The mean declination residual is 0.027" higher but the main difference is that the mean right ascension residual is no longer close to zero.

The optical navigation solution gives an improved estimate for the heliocentric state of Šteins around the time of the Rosetta fly-by but, it could be argued, not necessarily an improved estimate for its orbit in general. Deficiencies in the modelling of the dynamics can cause any improvement to be lessened with the duration of the propagation away from the fly-by epoch. However, the apparent bias on the right ascension residuals was most evident over the most recent five years and especially during the last opposition.

6. ASTEROID ASTROMETRIC DATA BIASES

Analysis of the astrometric measurements and determined orbit of the asteroid 99942 Apophis[3] [17] revealed a systematic offset of +0.2" in the declination residuals. Astrometrists then focused on potential systematic errors in star catalogues commonly used in the measurement reduction process. It was thought that zonal errors could, at least in part, explain the Apophis biases.

3. Of special interest because of its very close approach to the Earth in 2036.

If the declination bias seen in the astrometric data residuals of Šteins and other main belt asteroids is indeed a measurement bias caused by systematic errors in star catalogues, then there is reason to suppose that the right ascension coordinates can also be affected by systematic errors. The difference is that right ascension bias does not show up when making the orbital fit.

Usually, one can expect that the sum of squares of residuals, corresponding to a measurement type or component, will take its minimum value when the mean of the residuals is close to zero. So, if there are biases on the measurements these will not appear in the residuals if the fitting process is unconstrained in allowing the mean residual to be close to zero. In the case of astrometric right ascension measurements, a mean residual close to zero can always be achieved by rotating the orbit by an appropriate amount around the celestial pole. With the exception of 5538 Luichewoo, for all 14 main belt asteroids whose orbits were determined [7], the mean right ascension residual was not far from zero.

For the declination component the situation is different and here illustrated by Šteins. From the orbit determination using only astrometric data, the residual statistics were split into two groups, those corresponding to measurements when the geocentric declination was positive, and those corresponding to measurements when the geocentric declination was negative. They are shown in Table 3.

Table 3. Šteins mean residuals (arc seconds)

Mean residuals	Number	R.A.cos(δ)	Declination (δ)
Northern hemisphere	824	+0.044	+0.150
Southern hemisphere	445	-0.102	+0.249
All	1269	-0.004	+0.185

If, for example, the orbit is rotated around the line of nodes (with respect to the equator), the mean declination residual of the northern hemisphere measurements can be reduced but only at the expense of increasing the mean declination residual of the southern hemisphere measurements, or vice versa. There is not a mechanism for adjusting the orbital parameters so that the overall mean declination residual can be reduced.

The suspicion was that asteroid astrometric data are quite likely to suffer from systematic errors in both coordinates. In the fitting within the orbit determination, any right ascension bias is not revealed but compensated within the orbit solution whereas the declination bias is revealed because the orbit solution cannot be amended to remove it.

Very recently, compelling evidence has been presented in [18, 19] for significant, local systematic errors in both coordinates of the USNO A1.0, A2.0 and B1.0 star catalogues. These catalogues have been used in the reduction of about 70% of 58 million CCD-based asteroid observations. Following an effort to debias the astrometric data, there were several indications of an improvement in orbit determination results: the significant correlations between closely-spaced observations of the same object from the same observatory, demonstrated in [10], were substantially reduced; data fits over three oppositions led to more accurate predictions of the positions during a fourth opposition; and trials concerned with asteroid mass determinations led to estimates that were closer to the best available values. In the case of Apophis, the bias in post-fit residuals was removed (and decreased by a factor of ~5, the already tiny probability of impact with the Earth in 2036).

7. CONCLUSIONS AND OUTLOOK

The first-ever optical navigation campaign in support of an ESA mission was very successful. The accumulation of optical data during Rosetta's asteroid approach phase continuously led to improvement in the targeting accuracy and the desired fly-by geometry at Šteins was achieved with notable precision. One aspect not properly appreciated at the start of the campaign was the mechanism by which the initial optical data led to a better prediction of the time of closest approach but this was clarified after the fly-by - a lesson learned for the future.

Without the optical data, the miss-distance would have been too low by more than 100 km and the targeting barely within the 3σ uncertainty domain. A biased orbit determination result for the asteroid was suspected due to apparent systematic errors in its declination measurements. Using the reconstruction of the relative fly-by trajectory, an error in the asteroid's heliocentric position could be established that was hardly compatible with the formal uncertainty. A subsequent orbit propagation confirmed with high probability that the biased solution was due to systematic errors in both coordinates of the astrometric measurements.

Recent, independent research by asteroid and astrometry experts has proven that very many asteroid observations are biased due to local errors in star catalogues popularly used for the data reduction. For planning the Rosetta fly-by of 21 Lutetia, with the aid of their technique for debiasing the data, perhaps a better orbit determination will be made before the advent of the optical data than was the case for the Šteins fly-by.

Rosetta's second asteroid fly-by will occur on 10 July 2010. Passing through zero solar phase angle is again a targeting objective but the planned miss distance will be much higher than at Šteins, 3160 km, driven by the need to keep the entire asteroid, with an expected diameter of 95 km, within the maximum window of the NAVCAM when in Asteroid Fly-by Mode.

8. REFERENCES

[1] Schoenmaekers, J. and Bauske, R., *Re-design of the Rosetta Mission for Launch in 2004*, ESA SP-548, 227-232, 2004.

[2] Morley, T. and Budnik, F., *Rosetta Navigation at its first Earth Swing-by*, ISSFD19, Kanazawa, Japan, 2006.

[3] Budnik, F. and Morley, T., *Rosetta Navigation at its Mars Swing-by*, ISSFD20, Annapolis, MD, USA, 2007

[4] Lauer, M. et al., *Optical Measurements for the Fly-by Navigation of Rosetta at Asteroid Steins*, ISSFD21, Toulouse, France, 2009.

[5] Budnik, F., Morley, T. A. and Mackenzie, R. A., *ESOC's System for Interplanetary Orbit Determination*, ESA SP-548, 387-392, 2004.

[6] Moyer, T. D., *Formulation for Observed and Computed Values of Deep Space Network Data Types for Navigation*, Monograph 2, Deep-Space Communications and Navigation Series, JPL 00-7, 2000.

[7] Morley, T., *2867 Šteins Orbit Determination*, RO-ESC-TN-5550, Issue 2, ESA/ESOC, 2009.

[8] http://ssd.jpl.nasa.gov/?horizons.

[9] http://hamilton.dm.unipi.it/cgi-bin/astdys/astibo.

[10] Carpino, M. et al., *Error statistics of asteroid optical astrometric observations*, Icarus, 166, 248-270, 2003.

[11] Yeomans, D., private communication, 11 June 2008.

[12] Morley, T., *Rosetta - On the Asteroid Fly-bys and Optical Navigation*, RO-ESC-TN-5502, Issue 1, ESA/ESOC, 1998.

[13] Mackenzie, R., *AMFIN - Optical Navigation Software for the ROSETTA Asteroid Fly-bys*, FDD Working paper 647, ESA/ESOC, 2004.

[14] Cano Mananes, D. et al., *The endeavour to ascertain a successful navigation for Rosetta's fly-by at asteroid Steins*, ISSFD21, Toulouse, France, 2009.

[15] Bhaskaran, S., private communication, 16 March 2009.

[16] Murrow, D. W. et al., Galileo Asteroid Encounter Navigation, AAS 89-406, Advances in the Astronautical Sciences, 71, Part 1, 605-618, 1990.

[17] Tholen, D. J. et al., *Where is Apophis?*, Paper 27.02, 40th Meeting of the AAS Division for Planetary Science, 11-15 October 2008, Ithaca, New York.

[18] Chesley, S. R. et al., *Treatment of Star Catalog Biases in Asteroid Astrometric Observations*, 40th AAS DDA Meeting on Dynamical Astronomy, Virginia Beach, Virginia, Bulletin of the American Astronomical Society (Abstract), Vol. 41, No. 2, 2009.

[19] Chesley, S. R., private communication, 19 August 2009.