On Possibilities for a Follow-Up to the Giotto-Extended-Mission GEM

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Abstract

This paper is the outcome of studies into the future of Giotto conducted at ESOC in July 1992. A scenario is proposed that comprises an Earth gravity assist maneuver in July 1999 followed by a flyby of comet P/Schwassmann-Wachmann 3 in May 2006.

It is possible that vital spacecraft systems, their design life span already exceeded by far, will fail to survive until 2006 or even 1999. Also, it is not foreseeable now whether appropriate resources will be available for the necessary operations at those periods.

The intention of the study was to find an opportunity for a potentially feasible mission. It was to serve as a baseline for further more detailed studies had the decision for a go-ahead been taken.

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1. Introduction

The Giotto spacecraft was originally designed for the purpose of executing a close flyby at comet P/Halley, gathering data with its experiment payload during the encounter phase and transmitting them to the Earth. When Giotto survived the 1986 flyby with most systems and experiments still operational, it was decided to initiate the Giotto Extended Mission GEM, consisting of an Earth swingby in July 1990 and an encounter of comet P/Grigg-Skjellerup in July 1992.

This mission having been successfully completed, the still good technical spacecraft condition and the amount of fuel available (15.2 kg) warranted studies into a follow-up to GEM. In this paper a proposal for such a mission, named GE^2M in the following, is made.

The study comprises the design of the maneuver strategy to lead the spacecraft back to the Earth, the selection of a target comet, the calculation of the Earth swingby parameters and a study of the encounter conditions at the designated target.

Due to the critical fuel situation the maneuver strategy had to be carefully optimized. Minimization of the Δv-requirements was the overriding objective and had priority over certain operational considerations.

1. Introduction

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Current Status

The strategy developed in this paper calls for prolonged spacecraft hibernation periods from September 1992 through March 1999 and again from July 1999 through early 2006. The loss of redundancy for several vital components, the tight fuel budget and the high age of the spacecraft, which in 1999 and 2006 will be respectively 14 and 21 years old, reduce the chances for successful completion of such an ambitious mission.

After weighing the mission potential against the uncertainty of success and the considerable expenditure incurred by continuing operations until the end of September 1992 esa took the decision not to implement the strategy laid out in this paper.

Instead, it was decided to execute a maneuver on July 21, 1992 to bring the spacecraft as close as possible to the Earth in July 1999. The maneuver date is about two months earlier than the optimum epoch to perform it. On the resulting trajectory, a close Earth swingby would necessitate a plane change burn in 1999 requiring about 11 kg of fuel. The fuel mass remaining after the hibernation maneuvers is currently estimated at 4 kg $\pm$ 3 kg. Even conceding that the fuel budgeting has so far been conservative and that the fuel mass is therefore likely to be higher that 4 kg, any possibility for a third cometary flyby is now out of the question. Therefore, the findings in this paper concerning the options for an add-on mission must be seen under the heading "What might have been feasible".

2. Basic Mission Design

The experiments aboard the Giotto spacecraft were designed to gather scientific data during a close encounter with a comet. The type and function of the experiment hardware does not warrant any other type of mission. This is especially true now that the HMC (CCD camera and telescope) is unusable.

One type of follow-up to the GEM would be to adjust the orbit using the thrusters such that it would eventually lead to a another comet encounter. Unfortunately no opportunity was found for this most simple strategy to lead to an encounter until the year 2010.

Significant changes to the orbit can be achieved via a gravity-assist maneuver. The Earth is the only massive celestial body attainable by the Giotto spacecraft. Currently, the period of the Giotto orbit is 409.7 days. This gives a 41:46 commensurability with the Earth orbit. Without an intervention, the spacecraft would come back to the Earth in 2036, 46 years after the 1990 swingby.

The ratio of 41:46 is almost equal to 8:9, so the spacecraft passes relatively close to the Earth every 9 years. The flyby distance at any of these occasions can be further reduced by adjusting the orbital period. The earliest opportunity for a close Earth flyby not requiring a maneuver of prohibitive proportions occurs in mid-1999.

The gravity-assist maneuver had to be designed to modify the heliocentric orbital elements such that the new orbit would lead to a close encounter with a target comet. This encounter could have taken place after multiple revolutions on the new orbit. As gravity-assist maneuvers give scope for significant changes to the spacecraft orbit, several candidate targets were identified. A list of candidates, together with the selected mission and the reasons for its selection is presented in the following chapter.

3. Selection of a Target Comet

Table 1 contains a subset extracted from "Yeomans Comet File", a database containing the osculating orbital elements for 114 comets with well-known orbital elements and 587 perihelion passes. The Yeomans file is used within ESOC for the design of other comet missions such as ROSETTA. The subset includes all comets from this database that can be reached within reasonable time from the current Giotto orbit via an Earth swingby in July 1999.

The apohelion and perihelion values given in the table are those of the Giotto transfer orbit between Earth swingby and comet encounter.

Comet name	Encounter date	Solar range (AU)	Earth range (AU)	ESSA (deg)	Swingby height (km)	Apohelion (AU)	Perihelion (AU)
Boethin	2008/12/05	1.16	0.66	58.1	12400	1.39	1.00
Crommelin	2011/07/24	.78	1.58	32.6	26900	1.02	.76
Denning-Fujikawa	2005/07/11	.85	1.59	35.1	1700	1.09	.85
Finlay	2008/06/30	.98	1.45	44.5	14500	1.06	.77
Giacobini-Zinner	2005/06/30	1.04	1.43	45.4	37300	1.19	1.00
Grigg-Skjellerup	2008/03/24	1.12	0.59	62.8	8600	1.59	1.02
Hartley 2	2010/10/18	1.07	0.17	59.5	127000	1.08	.92
Schw.-Wachmann 3	2001/01/15	.95	1.80	22.0	13700	1.04	.71
Schw.-Wachmann 3	2006/05/24	.96	.14	109.5	8400	1.03	.66

Table 1. Possible GE2M Target Comets: The values were obtained via an analytical analysis of Keplerian transfer orbits. The numerical simulations may yield minor differences.

Candidate targets should offer an early encounter at a solar range of below 1 AU with good visibility from the Earth and a Earth-Spacecraft-Sun angle (ESSA) ideally in the range between 44° and 136° to avoid unacceptable Sun aspect angles with subsequent thermal and power problems. If these criteria are applied, three viable options can be filtered from Table 1:

1. Schwassmann-Wachmann 3 (May 2006)
2. Denning-Fujikawa (July 2005)
3. Giacobini-Zinner (June 2005)

Schwassmann-Wachmann 3 (January 2001) appears attractive but is disqualified due to the low Earth-Spacecraft-Sun Angle of 22° and the high Earth range (1.8 AU) at encounter.

In this paper, the mission to comet P/Schwassmann-Wachmann 3 (May 2006) was selected as baseline as it offered the highest compatibility with the requirements and constraints imposed by the spacecraft. The P/Giacobini-Zinner flyby would have had the disadvantage of taking place at a greater distance from the Sun while the P/Denning-Fujikawa flyby, taking place 10 months earlier and at a solar range of only 0.85 AU, would have required too close an Earth swingby and featured an ESSA of only 35°.

The Earth-Sun-Spacecraft angle of 110° and the low Earth range of 0.14 AU (21.4 million km) for the May 2006 P/Schwassmann-Wachmann 3 encounter would have granted some liberty when designing the attitude strategy and facilitated communication with the spacecraft during the encounter phase.

P/Schwassmann-Wachmann 3 is currently the prime target for the ROSETTA mission scheduled for the comet's apohelion pass in 2008. The May 2006 encounter would occur about two weeks prior to the perihelion crossing preceding the ROSETTA landing and might thus have yielded some additional data for ROSETTA.

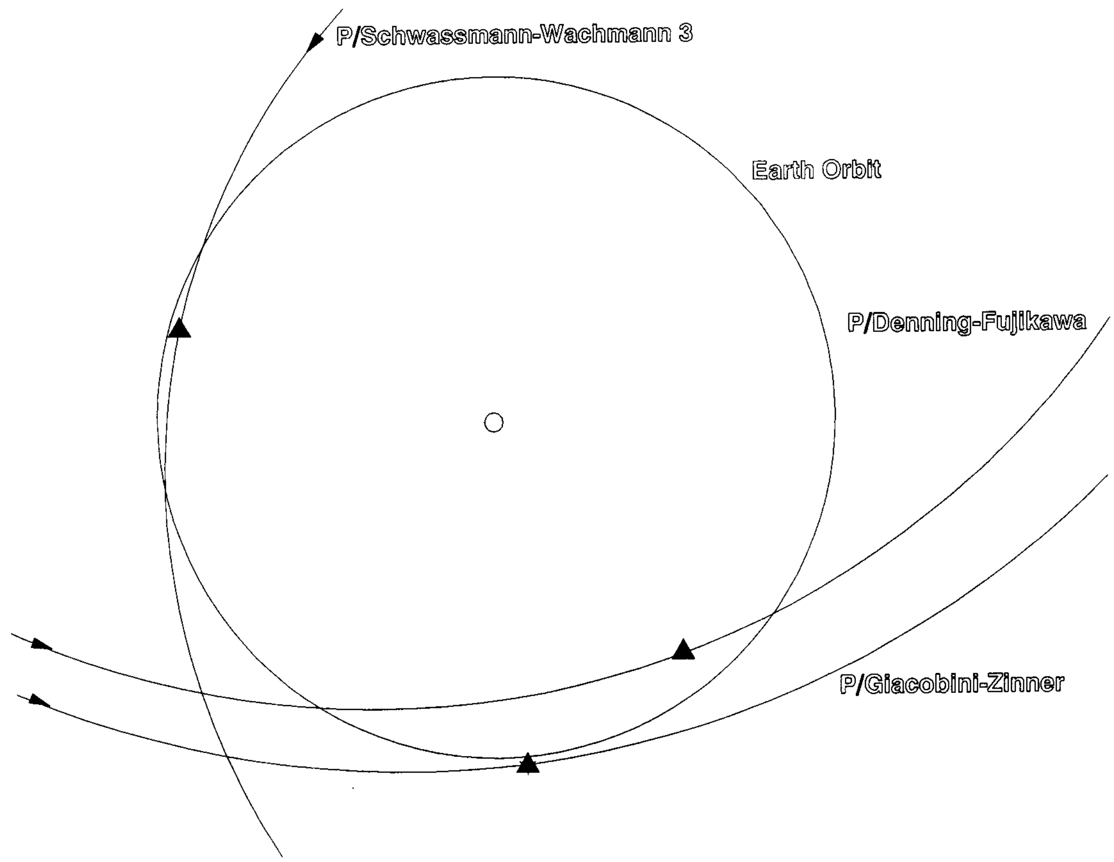

Figure 1. Trajectories of Three Candidate Targets: The encounter points are marked. Note that the plot does not fully represent the true geometry as the inclinations of the comet orbits wrt. the ecliptic are not incorporated.

The orbital period of P/Schwassmann-Wachmann 3 is about 5.3 years. The next perihelion crossing will take place in September 1995, at a solar range of 0.93 AU, another in January 2001. Astrometric measurements made at these occasion could have served to better determine the orbit and to refine the GE²M mission planning.

4. The Baseline Mission to Comet P/Schwassmann-Wachmann 3

The baseline mission was studied using the numerical orbit propagation software that already contributed to the highly precise navigation displayed in the Giotto and GEM missions. The program takes into account the gravitational perturbations by all planets, the Sun and the Moon, the solar radiation pressure effects, small attitude control maneuvers, large hibernation and de-hibernation slews and the trajectory control maneuvers (TCM's).

A single maneuver in 1992 bringing the spacecraft within the immediate vicinity of the Earth in 1999 would be incompatible with the fuel budget. The optimal strategy was found to consist of a large axial burn in 1992 followed by a small radial maneuver in 1999 to obtain the necessary plane change. Key dates for the planned mission are given below, those for de-hibernation and TCM-2 being approximate.

- 15 September 1992: Axial trajectory correction maneuver
- 19 September 1992: Slew to hibernation attitude
- 1 March 1999: De-hibernation and slew to firing attitude
- 1 March 1999: Second trajectory control maneuver (TCM-2)
- 1 July 1999: Earth swingby
- 24 May 2006: Flyby at comet P/Schwassmann-Wachmann 3

4.1 The Trajectory Control Maneuvers

Axial Burn: Increase of Orbital Period

A numerical simulation of the orbital evolution shows that with no intervention, the Earth would be passed at a minimal distance of 19 million km on April 4, 1999. An axial maneuver in 1992 would slightly increase the orbital period and reduce the Earth flyby distance in 1999. The orbital geometry in 1992 was such that an X-band downlink was feasible with the available non-DSN ground stations only up to the end of September. Therefore the axial burn was timed for mid-September in a quasi-tangential attitude, although minor savings could have been achieved be performing the maneuver at the end of September[1].

The effects of an axial burn at the above epoch on the flyby point are shown in Figure 2 on page 6. The flyby point is projected in the Earth-fixed target plane named B-plane (see appendix A for definition). The achieved flyby parameters move along the plotted line depending on the size of the maneuver. As can be seen, the accuracy of the flyby is extremely sensitive to variations in the axial maneuver. This is due to the propagation of errors over the six orbital revolutions between the maneuver and the Earth swingby.

It would have been imperative that an orbit determination or at least an assessment of the maneuver accuracy using the Doppler readout be done and that the detected errors be corrected through a trim maneuver. The failure to eliminate the maneuver errors would incur a penalty in Δv beyond the capacity for correction remaining in 1999.

The duration of the axial burn impinged on the size of the March 1999 maneuver and was selected to minimize the total Δv, the sum of all performed maneuvers. The parameters of the burn to be executed on September 15, 1992 are given in Table 2.

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[1] The optimality of September 29, 1992 as the epoch for the axial burn was shown by Mats Rosengren of ESOC in a study related to the optimization of the Giotto maneuver strategy.

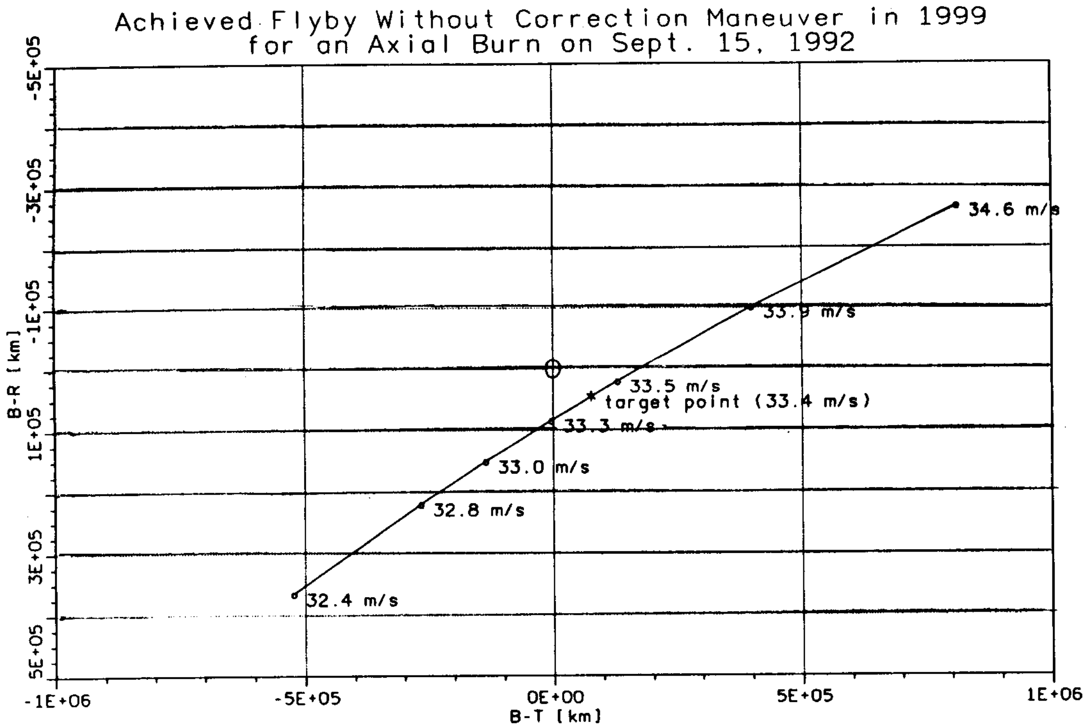

Figure 2. Sensitivity of Flyby wrt. Axial Maneuver Accuracy: The Earth is in the center of the graph at B-T = B-R = 0.

Second TCM: Final Targeting

A change of the orbital plane is required to achieve a flyby at a point off the line shown in Figure 2. As the epoch around September 1992 is not favorable for such a maneuver it would have required far more propellant than available if performed in combination with the axial burn.

A tradeoff between conflicting requirements was necessary. On one hand, a radial burn executed around January 1, 1999 would have been minimal. On the other hand, the hibernation attitude guarantees a spacecraft Earth aspect angle of about 44° early in March 1999, thus allowing a significant simplification of the dehibernation activities by obviating a large slew maneuver. Furthermore, the greater proximity to the Earth (18.3×10^6 km as opposed to 27×10^6 km) would have facilitated command access and might even have permitted telemetry downlink via the low gain antenna. Therefore, March 1, 1999 was selected as the date for the radial burn.

The maneuver was designed to lead to the flyby parameters given in the following chapter. The maneuver parameters are summarized in Table 2.

Parameter	Axial Burn	Radial Burn
S/C Right Ascension [°]	-7.5	-110
S/C Declination [°]	3.5	58
Duration	14680 s = 4 h 5′	10790 s = 3 h
Δv [km/s]	33.4	6.2
Firing Azimuth [°]	-	-102
Sun Aspect Angle [°]	92	92.1
Earth Aspect Angle [°]	45.2	44.2
Fuel consumption [kg]	9.7	1.9
Earth Range [km]	204.5×10^6 km = 1.37 AU	18.3×10^6 km = 0.122 AU

Table 2. Parameters of the Two Trajectory Control Maneuvers: Note that a further 1.2 kg of fuel are consumed during attitude maneuvers.

4.2. Earth Swingby and Resulting Heliocentric Orbit

With the outlined maneuver strategy, the Earth flyby would have taken place on July 1, 1999, with the point of closest approach crossed at around 11:00 UTC. A hyperbolic arrival velocity of 3.47 km/s was computed. The following target flyby parameters were selected for the P/Schwassmann-Wachmann 3 mission:

- B-T: -33,466 km
- B-R: 1,435 km

These target parameters would have been subject to minor modifications after gaining further information on the comet orbit and the finalization of the comet encounter details.

The gravity-assist maneuver would have significantly modified the heliocentric orbit. Important orbital parameters, pre- and post-swingby, are compared in Table 3. The orbits are plotted in Figure 3 on page 8 as seen from above the ecliptic plane.

Parameter	Pre-Swingby	Post-Swingby
Semi-major axis [km]	161.9×10^6	126.3×10^6
Orbital period [d]	411.3	283.4
Eccentricity	0.081	0.215
Apohelion radius [AU]	1.17	1.03
Perihelion radius [AU]	0.99	0.66

Table 3. Change of the Heliocentric Orbit Through Earth Swingby: The values follow from a precise orbit propagation. Note that the axial burn on September 15, 1992 would have increased the orbital period from 409.7 days to 411.3 days.

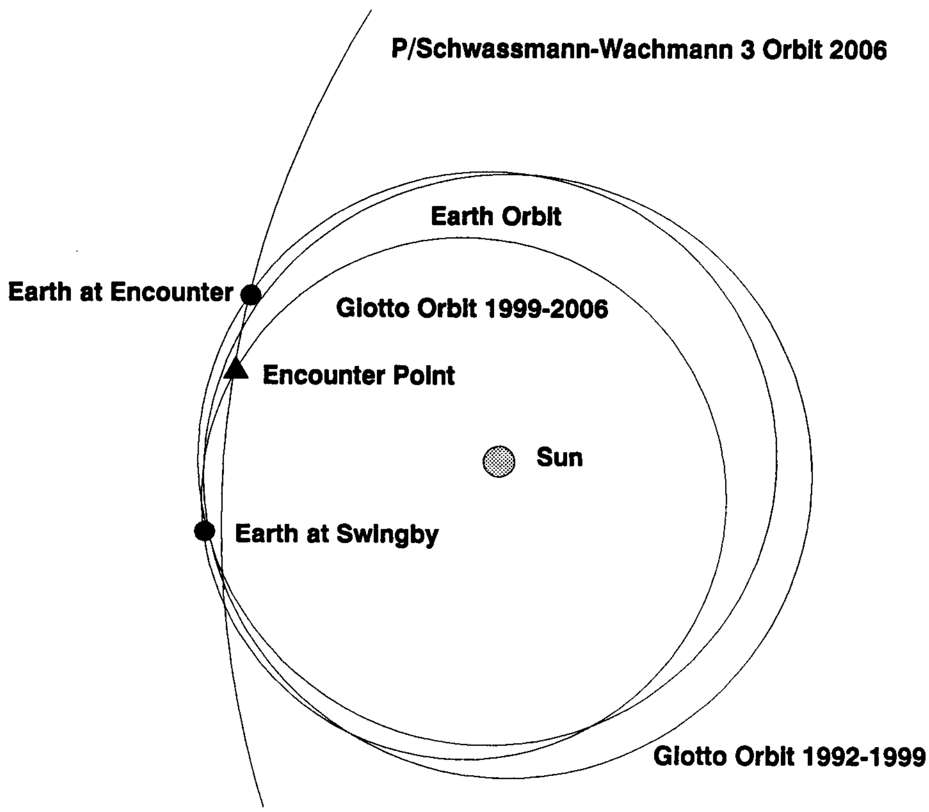

Figure 3. The Pre- and Post-Gravity-Assist Heliocentric Giotto Orbits

4.3. Flyby at Comet P/Schwassmann-Wachmann 3

At this point the exact epoch and position of the comet encounter cannot be given, as the comet ephemerides are not known accurately enough and would have to be updated using observations from the 1995 and 2001 perihelia. Some basic data concerning the flyby are given below:

Approximate encounter date:	May 24, 2006
Heliocentric range:	0.96 AU
Geocentric range:	0.14 AU
Earth-Spacecraft-Sun angle:	110 deg
Flyby angle:	170 deg
Relative velocity	14.6 km/s

Figure 4 on page 9 shows the geometry of the flyby. The value referred to as "flyby angle" above defines the angle between the comet velocity vector relative to Giotto at encounter and the Earth direction. A value of 44.2° signifies an Earth-pointing attitude with full protection of the spacecraft by the bumper shield. At the given value of 170° other spacecraft components would inevitably be exposed to particles of cometary origin crossing its course. In any case, the advent of a crippling or even fatal damage to Giotto at this stage would probably have been greeted with general indifference as there could have been no conceivable further use for the spacecraft.

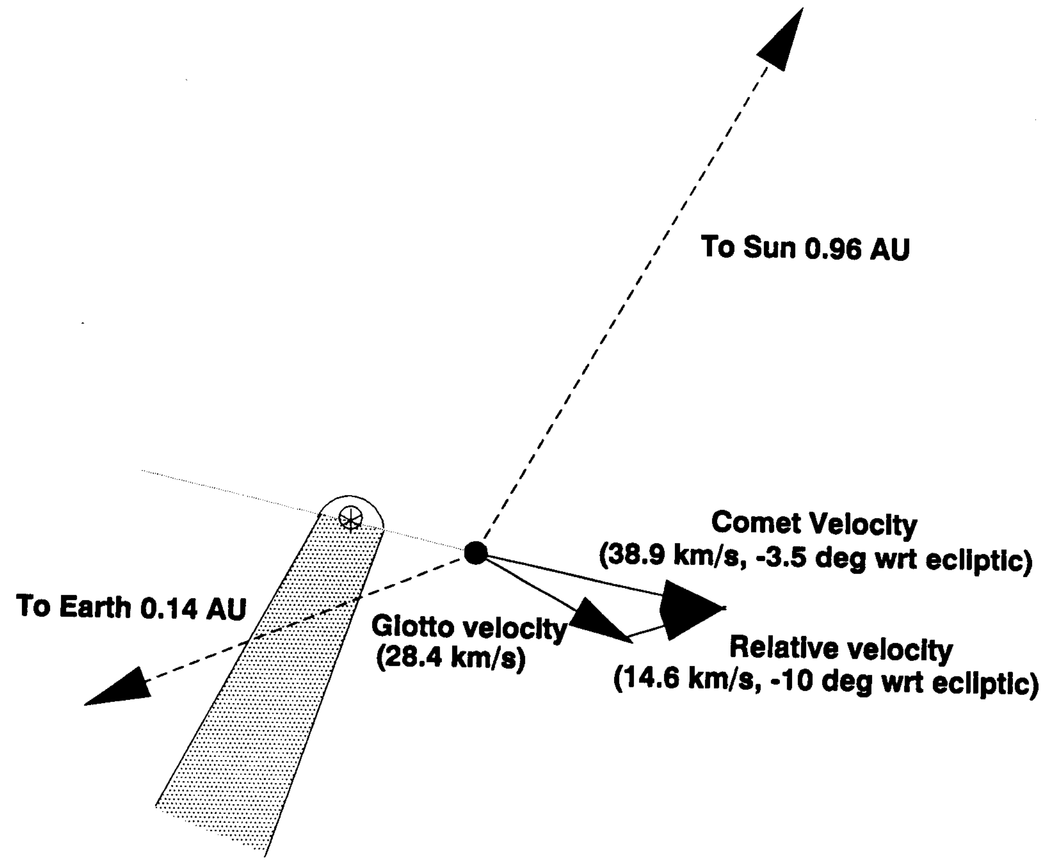

Figure 4. Geometry of the P/Schwassmann-Wachmann 3 Flyby in May 2006: Note that for the sake of simplicity, only the components within the ecliptic plane are shown. The comet and relative velocities have significant out-of-plane components as indicated in the labels.

5. Summary

In this paper the outcome of a study into "GE^{2}M", a hypothetical follow-up to the Giotto Extended Mission (GEM), is described. GE^{2}M comprises a second Earth gravity assist in July 1999 and a flyby at comet P/Schwassmann-Wachmann 3 in May 2006. Other candidate comets were regarded but the selected target P/Schwassmann-Wachmann 3 would have complied best with the numerous constraints imposed mainly by the spacecraft systems. This comet is of special interest as it is also the current baseline target for the ROSETTA mission.

The maneuvers required to achieve the ambitious mission were computed by means of a precise numerical orbit generator taking into account all major perturbation sources. The optimal maneuver strategy yielding minimal Δv-requirements would have consisted of an axial burn performed in September 1992 and an radial maneuver in March 1999. The epoch for the latter was chosen to facilitate the dehibernation activities.

The main obstacle faced by the mission design was the difficulty to achieve compatibility between the fuel believed to be remaining in the spacecraft tanks and the minimum requirements for GE^{2}M. The obtained solution, taking into account all trajectory and attitude control maneuvers would have required 12.8 of the available 15.2 kg up to the Earth swingby.

As the error margin in the fuel mass estimate is believed to be up to 3 kg, the remaining propellant might just have sufficed for the GE^{2}M mission. In the worst case, the spacecraft would have run out of fuel around the Earth swingby epoch. However, there are strong indications that the fuel budgeting has so far been conservative. Therefore, the remaining fuel mass would probably have been rather higher than estimated.

The possibility of a controlled Earth swingby as outlined in this paper was weighed by esa authorities against the probabilities of success. Factors like the likelihood of survival for systems vital to the spacecraft operations and the cost of providing ground segment support during the operational phases were taken into consideration. As the chances to successfully achieve such a mission were deemed remote, the decision was taken to discontinue operations by July 23, 1992 and thus avoid the considerable expenditure incurred by the otherwise necessary activities lasting through September 1992.

An axial maneuver was performed on July 21, 1992, followed by a small trim maneuver on July 23 to eliminate the misperformance. The aim was to minimize the flyby distance from the Earth. This precludes another scientific mission as it would necessitate a plane change burn of prohibitive size in 1999. The spacecraft will pass (barring errors in the orbital state and the maneuvers) within 217,000 km from the Earth on July 1, 1999. With the selected flyby there might be a chance of retargeting the spacecraft after dehibernation early in 1999 to perform a lunar flyby, also on July 1. Depending on the orbital state in 1999 this option could be just within the fuel budget.

Appendix A. Definition of the B-plane

The B-plane is a commonly used reference plane to define the target point for a hyperbolic planetary flyby. The origin of the plane is fixed to the center of the target planet. and therefore moves along the planet trajectory.

The coordinate frame *rst* and the hyperbolic orbital elements describe the spatial orientation of the B-plane. The s-axis is parallel with the direction of the incoming asymptote and normal to the B-plane, which therefore contains the *r* and *t* axes. The *t*-axis direction is perpendicular to both ecliptic North and the *s*-axis, while the *r*-axis completes the right-hand set.

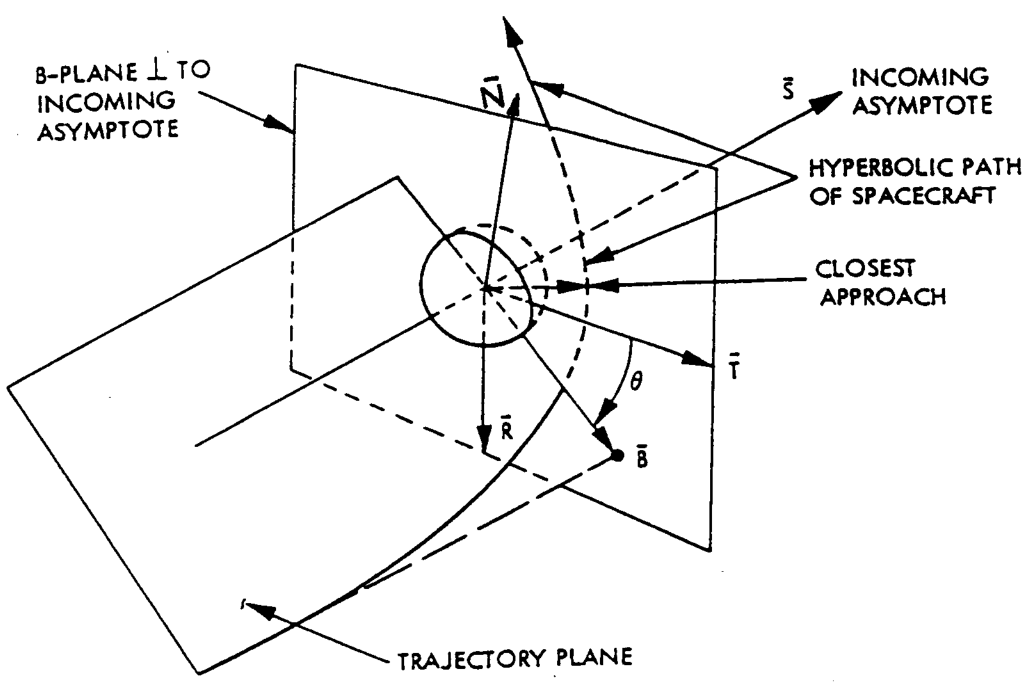

Figure 5. The B-Plane or Target Plane