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Stardust, NASA's first dedicated sample return mission to a comet, successfully flew past Wild-2 on January 2, 2004, sending back data on the gas and dust particles of the comet, as well as the most detailed pictures of a comet nucleus to date. The spacecraft flew within 236 km of the comet, meeting the mission requirement of 250±50 km on flyby distance. The spacecraft will return to Earth on January 15, 2006 and deliver a Sample Return Capsule (SRC) containing comet dust particles sampled from the coma.

Stardust is a 3-axis stabilized spacecraft and maintains its attitude by firing unbalanced thrusters. Thruster firing produces undesired along-track and cross-track small forces, which are difficult to precisely model. This poses a great challenge to the maneuver design and trajectory predictions. To accomplish the mission objective, a flexible and robust maneuver strategy was evolved and implemented. The Wild-2 encounter maneuver sequence consisted of a large Deep Space Maneuver (DSM-3), which was implemented in two parts on June 17, and 18, 2003, and a series of Trajectory Correction Maneuvers (TCMs) during the 30 days prior to the encounter. In addition to the small forces, both maneuver design and execution were influenced by number of other factors, including the comet ephemeris uncertainty, contamination of Optical Navigation (OPNAV) camera, unplanned change of attitude events, and changes in the desired flyby distance. Maneuver design processes, including contingency plans, and maneuver performance characteristics are discussed in this paper.

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INTRODUCTION

The Stardust spacecraft was launched on February 7, 1999 with the primary objective of collecting 500 dust particles during the close encounter with comet Wild-2 and returning them to Earth. The Stardust spacecraft was designed, built, and is operated by Lockheed Martin Astronautics (LMA), Denver, CO. The Jet Propulsion Laboratory (JPL) of California Institute of Technology is responsible for project management, mission design, navigation, and mission management. Mission operations are being conducted with strong interaction between JPL and LMA. The Deep Space Network (DSN), managed by JPL, provides tracking, telemetry, and telecommunication support. The spacecraft operation control center is located at LMA, Denver, CO (Ref. 1).

The spacecraft was expected to perform other tasks, in addition to collecting comet particles, during the Wild-2 flyby namely: a) obtain images of the nucleus of comet Wild-2 during the flyby, b) measure quantity and quality of particles impacted during flyby using the Dust Flux Monitor Instrument (DFMI), and c) Perform spectroscopic analysis of chemical composition of particles observed using the Cometary and Interstellar Dust Analyzer (CIDA). The spacecraft was also expected to collect interstellar samples before and after Wild-2 flyby. Most of these objectives were accomplished by January 2, 2004 after flying through the Wild-2 comet dust tails. The spacecraft is on its way back to earth with abundance of comet coma particles based on the number of particle hits seen in the DFMI. The return is scheduled for January 15th 2006 (Ref. 1).

The Stardust trajectory was adjusted to fly past the asteroid Annefrank on November 2, 2002 at a distance of 3078 km (Ref. 2). The spacecraft took several images of the asteroid during the flyby. This flyby was accomplished by best use of the spacecraft trajectory while not risking to the primary mission objective of encountering Wild-2 comet to collect its particles. Also this flyby was used as a "dress rehearsal" for the Wild-2 flyby.

The science requirement on Wild-2 flyby distance was 250 ± 50 km to collect specific number of comet particles (500 particles) and successful completion of other experiments. The requirement on flyby distance was changed twice before settling at the above distance at three days prior to the encounter when images of the comet clearer. This requirement posed a great difficulty due to several challenges. It was noted that the uncertainties in thruster related activities were larger than pre-launch studies had predicted (Ref. 3). This caused difficulties in trajectory predictions, maneuver design, and maneuver implementation. The second challenge was the contamination of OPNAV camera, the stray light, and low throughput of the periscope. The net effect of this problem was degraded quality of Wild-2 images leading to larger than expected orbit determination (OD) uncertainties. The third problem was solar conjunction during August-September 2003. It was not possible to receive clean OD data during this period.

A highly robust maneuver strategy and targeting philosophy was developed for the Wild-2 approach to meet the above challenges. Four TCMs with contingencies were scheduled during the final 30 days prior to the encounter to achieve B-plane target within acceptable time-of-flight uncertainties. Because the OPNAV images were most critical to achieve the desired target near the comet for both dust collection and flyby imaging, the first maneuver (TCM-10) of the above four TCMs was not scheduled until Wild-2 was visible from the spacecraft. This plan could accommodate an adjustment of the targeted flyby distance up to two days prior to the encounter.

This paper will discus in detail the maneuver strategy used for the successful flyby of Wild-2 and the discussion will include the contingencies planned, results of the Monte-Carlo analysis which support this strategy, and the performance of maneuvers.

SCIENCE REQUIREMENTS ON WILD2 FLYBY

The main objectives of the science were to collect at least 500 particles and to acquire quality images of the comet. Initially, the flyby distance requirement (Ref. 4) was set at 150 ± 50 km based on ground observations of the comet. This requirement was changed to 300 ± 50 km based on first few OPNAV images. Again this requirement was changed to 250 ± 50 km when clear images were available 3-4 days prior to encounter. Maneuver strategies were designed to adapt these changes during the encounter phase.

MISSION TRAJECTORY

The Stardust trajectory was designed to complete two orbits around the Sun before encountering Wild-2 comet (Fig. 1). Stardust began collecting interstellar dust for four months beginning from August 5, 2002 during its second orbit. Also the trajectory was slightly adjusted to flyby the asteroid Annefrank on November 2, 2002 (Ref. 2). The Stardust made its rendezvous with comet Wild-2 with a flyby distance of approximately 236 km on January 2, 2004, shortly after the beginning of the third orbit. The spacecraft is on its way out to the aphelion of the third orbit before heading back to the Earth for re-entry on January 15, 2006 (Ref. 4).

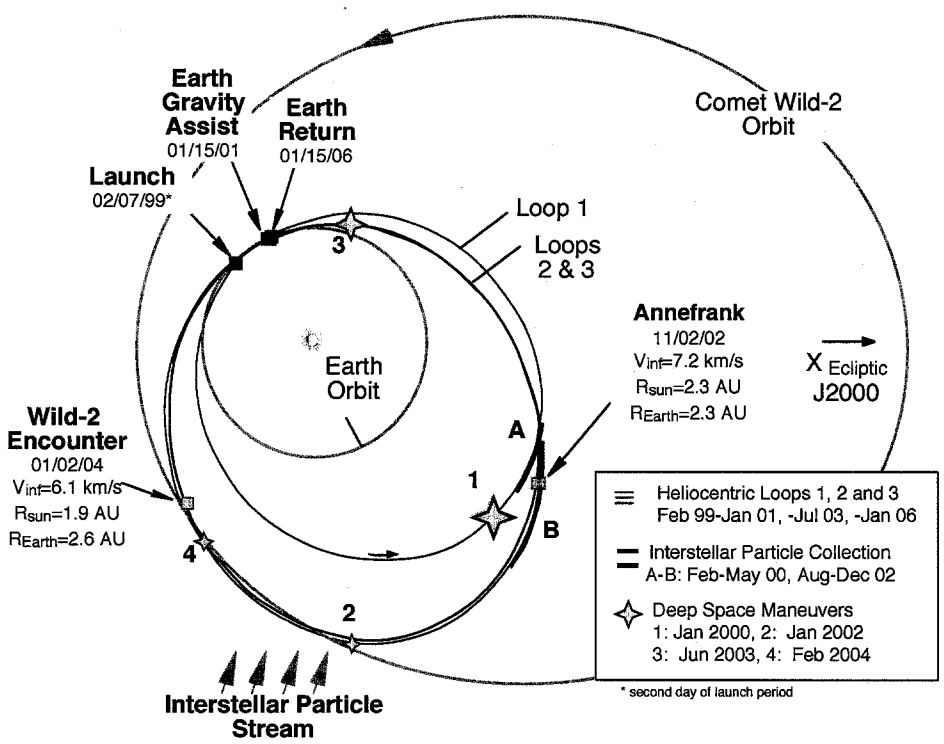


Figure 1. Stardust Mission Trajectory

SPACECRAFT CHARACTERISTICS

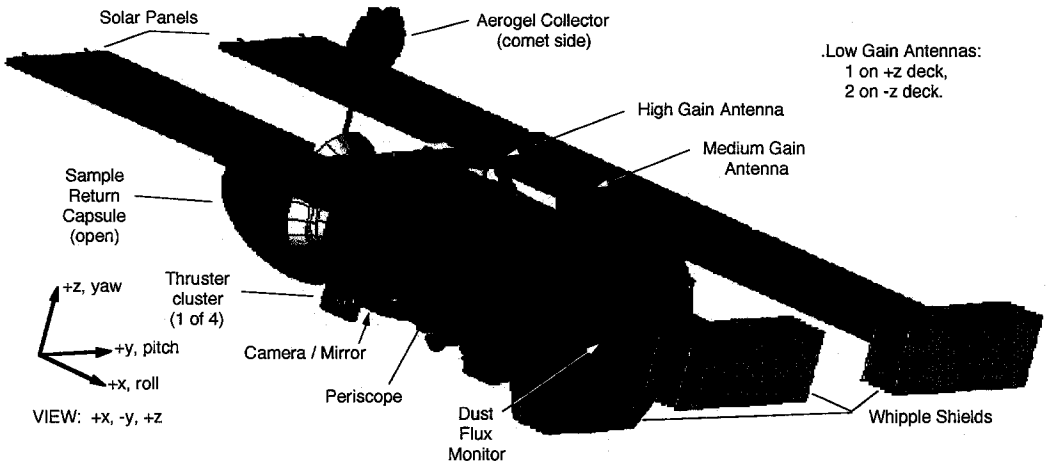


Figure 2. Stardust Spacecraft (+z Axis Normally Pointing Toward sun or earth

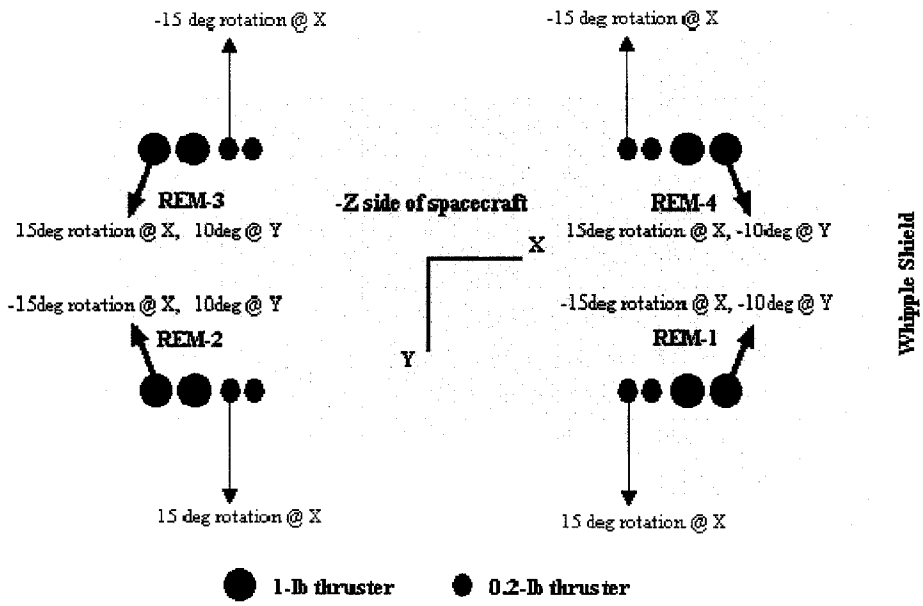


Figure 3. Thruster Configuration

The Stardust is a three-axis stabilized spacecraft (Fig. 2), whose main bus is in the shape of a "rectangular box". All science instruments, telecommunication systems, the Sample Return Capsule (SRC) and other systems/components are mounted on this box (main bus). Two large solar arrays are mounted on either side of the bus and provide power to all systems. The Whipple shields are mounted on front edge of solar panels to protect the panels and other science instruments from particle impacts during

the flyby. The Attitude Control Systems (ACS) includes star trackers, backup analog sun sensors, and an Inertial Measurement Unit (IMU). IMU includes gyros and accelerometers, which allow for close-loop control. The spacecraft coordinate system is defined with respect to solar panels and Whipple shields. The +Z axis is along the solar panel normal, +X axis is along the normal to Whipple shield, and +Y axis completes the orthogonal coordinate system. The thrusters are mounted on opposite side of the solar panels and the sample collector to minimize contamination of samples (Ref. 5).

Stardust has eight 1-lb thrusters and eight 0.2-lb thrusters (Fig. 3). Thrusters are housed in four clusters and each cluster contains two 1-lb and two 0.2-lb thrusters. 1-lb thruster are used for all Trajectory Correction Maneuvers (TCMs), Deep Space Maneuvers (DSMs), and for large attitude turns or slews. The 0.2-lb thrusters are used in Limit Duty Cycle (LDC) mode to maintain 3-axis stabilization and during smaller attitude turns. The LDC or dead band control has been employed to maintain attitude within dead-bands of various sizes. Smaller attitude turns are accomplished by slowly adjusting the dead-band box to move towards a target attitude (dead-band walk). Dead-band control is also used at earth pointing for communication or downloading science data (Ref. 5).

All thrusters are canted (Fig. 3) and all re mounted on bottom side of the spacecraft to avoid contamination of the Aero-gel Collector grid. Therefore, the unbalanced alignments of these thrusters do not produce-balanced torques during attitude maintenance (dead-band activity), attitude turns (slew, dead-band walks), and TCMs. These activities contribute translational ΔVs that lie nominally in the direction of +Z axis. The cumulative effect of these small forces is non-negligible and must be accounted in trajectory prediction, orbit determination, and maneuver design. All the small force thrusting events are computed on-board the spacecraft using a pre-set algorithm. Navigation Ancillary Information Facility (NAIF) of Jet Propulsion Laboratory (JPL) generates and delivers the reconstructed small force file by extracting and reformatting the information from the small force packets generated by the spacecraft on-board algorithm (Ref. 5).

The OPNAV camera must make use of the periscope for the spacecraft to remain in its planned attitude in which Whipple shields (+x axis) facing the direction of flight during flyby for safety of the spacecraft. The Aero-gel, to collect dust particles of the comet, was to be deployed three days prior to the encounter. The Project decided, based on the recommendations from Spacecraft Team (SCT), to implement roll-only maneuver (corrects only the flyby distance and not time-of-flight uncertainty) from TCM-12 onwards. This decision was taken not to contaminate Aero-gel and not to deviate from the orientation required during the flyby for spacecraft safety. It was decided to correct time-of-flight uncertainties by adjusting the encounter sequence for the encounter time.

ORBIT DETERMINATION AND PREDICTION

The OD was done using X-band 2-way Doppler and Range data, differenced Doppler data (2-way-3-way Doppler data), and during the encounter phase, optical data (optical images taken by spacecraft camera). Nominally, OD was done once a week during cruise phase (except during solar conjunction period) and frequently (one to four times a day) during last few days of the Wild2 encounter phase (Ref. 6).

The dynamic model used in OD and prediction includes models for the Newtonian point -mass, the relativity effects, the solar radiation pressure, the impulsive maneuver, the finite maneuver, and the small force. Gravitational acceleration of the spacecraft due to the nine planets is computed in the Newtonian point-mass model. The comet Wild-2 was also included in the point-mass model. The planetary ephemeredes are defined by the JPL DE405 planetary ephemeris. Wild-2 ephemeris was provided by Dr Steve Chesley of JPL and updated three times during Wild-2 encounter phase. The relativistic effects caused by the sun and Jupiter is included. The solar radiation pressure is computed treating spacecraft as four components (three flat-plates for the bus and one for solar panels). The impulsive model is used to model the predicted

translational ΔVs when spacecraft turns to do TCMs and turn back to earlier orientations. The finite maneuver model is used to model predicted and reconstructed ΔVs due to TCMs. The small force model is used to model predicted and reconstructed ΔVs due to dead-band activities for attitude maintenance, dead-band walks, and attitude turns made for any reason other than for TCMs.

The spacecraft has to be turned towards Earth from Sun for tracking, commanding and telecommunications, to implement a TCM or DSM, take optical images, and downloading of science or optical data. These turns generate small forces and must be accounted for trajectory modeling. Therefore, all events have to be planned in advance to generate small force model to be used in prediction. This posed a great challenge to Navigation team. JPL and Lockheed Martin Astronautics (LMA) developed a prediction model for the small forces, as a result of extensive analyses, prior to the launch. This model was updated several times after the launch using observed data and to account for changes in the predicted attitude events (Ref. 6).

Impulsive ΔVs (small forces), finite ΔVs, scale factors of solar radiation pressure model, and Wild-2 ephemeris during encounter phase were updated whenever OD was done. Updates to the small force model used for prediction were done when OD-updated small force trends significantly differed from predicted trends. OD results, dynamic models for prediction, planetary and Wild-2 ephemeris used for OD etc are supplied to design an upcoming maneuver. E-mail is sent to the maneuver design team indicating the names and locations of those files and directories.

MANEUVER DESIGN PROCEDURE

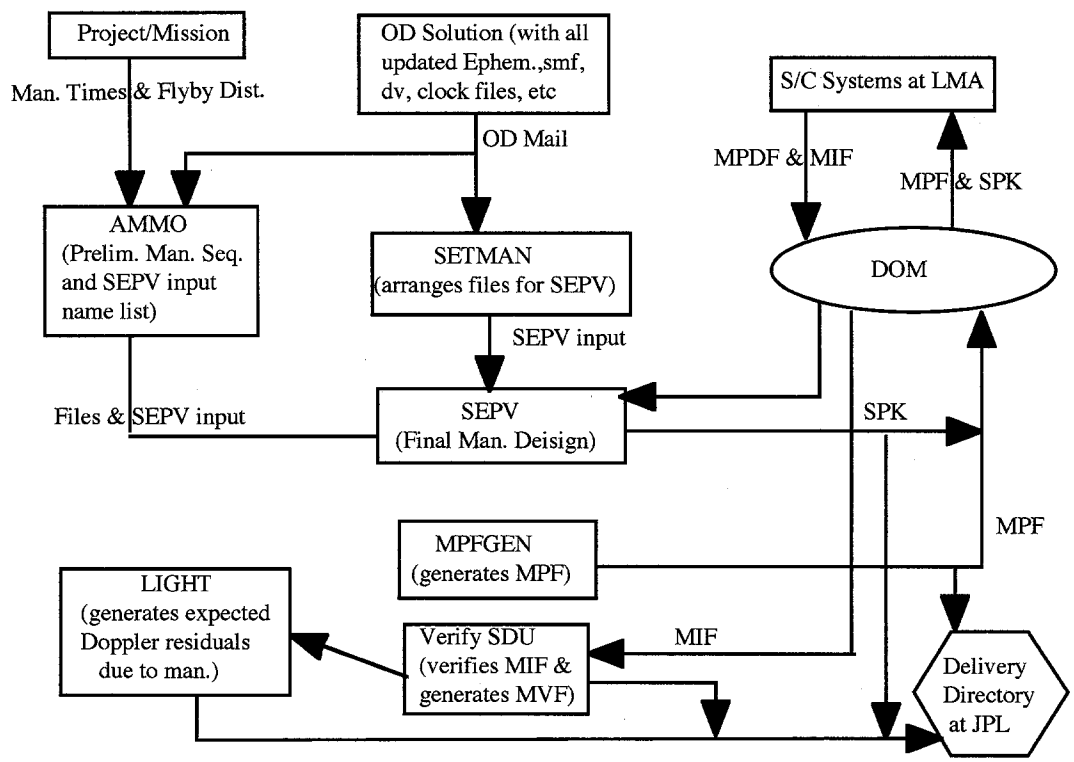


Figure 4. Maneuver Design Process

AMMO (An Automated Multiple Maneuver Optimization System) reads the e-mail sent by the OD team and extracts all files needed to design a deterministic maneuver sequence needed for Wild2 encounter and then to Earth return. AMMO (Ref. 7) generates an optimized maneuver sequence satisfying all constraints (Fig. 4). These maneuver estimates are input to SEPV (Ref. 8), a JPL precision maneuver search and targeting program, to update the deterministic maneuver sequence consistent with all dynamic models. Trajectory modeling is consistent with that used by the OD process including Wild-2 ephemeris. However, AMMO was not used during the 30-day period prior to Wild-2 encounter to save time needed for a maneuver design in a compressed maneuver design timeline (Ref. 9). A new program called SETMAN (Ref. 10) was developed to prepare and arrange all inputs to SEPV using OD results sent by e-mail.

The final maneuver design was done through SEPV using Maneuver Parameters Determination File (MPDF), which contains thruster and mass flow rate data, sent by LMA via DOM. All operational files exchange was done through DOM (fig. 4). The Maneuver Profile File (MPF) and SPK (trajectory) files (Ref. 11) were generated immediately after the maneuver design and supplied to LMA (via the DOM) and to the JPL delivery directory. Maneuver Implementation File (MIF) generated by LMA based on the corresponding MPF. This MIF file (Ref. 11) is verified and Maneuver Verification File (MVF) is generated and verification is done using the trajectory program. Expected Doppler shift with its uncertainty is generated after the maneuver verification.

The number of maneuvers and their epochs are specified based on trajectory sensitivity data, which describe how B-plane (the plane at encountering body normal to the incoming trajectory, shown in Figure 6) parameters can be varied by a maneuver at a given epoch along the trajectory. The Wild2 planned maneuver sequence was modified several times after the launch. The maneuver sequence was made more robust to absorb unexpected errors due to unplanned ACS activities and larger than expected uncertainties from small forces. The planned maneuver sequence two weeks prior to DSM-3 is shown in Figure 5. DSM-3 was only the deterministic maneuver at that time and rest were statistical maneuvers except TCM-14. TCM-14 was a contingency maneuver scheduled at 6 hours prior to Wild-2 encounter to deflect the spacecraft in emergency situations.

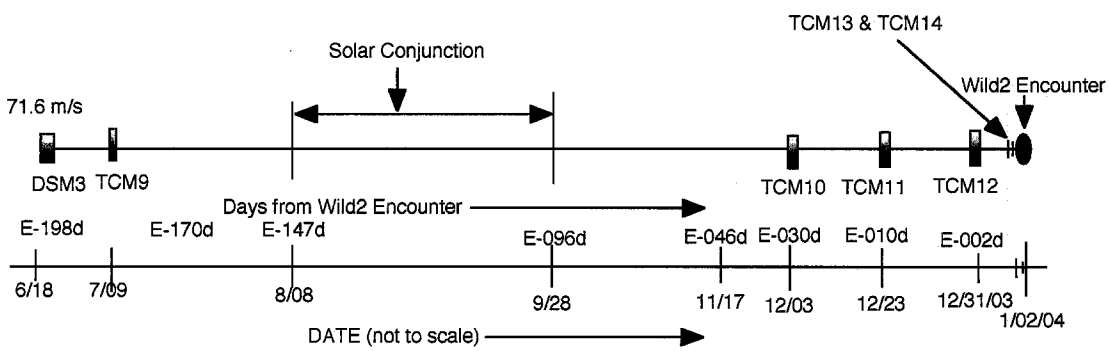


Figure 5. Planned Maneuver Sequence for Wild2 Encounter

The DSM3 (Ref. 12) targets the spacecraft to a Wild-2 flyby distance of 150 km to meet the then science requirement. 1 A.U. calibration tests (Ref. 13) were planned immediately after DSM-3 to assess the ACS and thruster performances to prepare for Earth return with precise entry conditions. TCM-9, scheduled on July 16, 2003, was to correct DSM-3 execution errors, accumulated ACS errors till that time, and uncertainties introduced by the 1. A. U. calibration tests. The Wild-2 ephemeris (Ref. 14) was updated using ground observations by Steve Chesley and provided few days (June 6, 2003) before DSM-3 and used for its design. TCM-10 was planned 30 days before the encounter. However, it was decided to implement TCM-10 only after the spacecraft is able to get few optical images of the comet (Ref. 15). TCM-11, TCM-12, and

TCM-13 were scheduled at 10-day, 2-day, and 18-hr prior to the encounter respectively. TCM-14 is a contingency maneuver and it would be implemented only if required.

MONTE-CARLO ANALYSES

The uncertainties due to OD, attitude turns, ACS thruster firings, modeling, and maneuver execution affect encounter conditions. These errors are assumed to be independent so that error sources can be added and linearly mapped to B-plane using K-matrix (partial derivatives of B-plane target parameters (Fig. 6) with respect to state vector at a given time). The statistical maneuver analysis (using 5000 samples) estimated the ΔV budget and propellant required for Wild-2 encounter. This analysis was performed after implementation of each maneuver from DSM-3 to Wild-2 encounter. The results of the statistical analysis were used to evolve a maneuver strategy for upcoming maneuvers and to handle contingency situations.

Statistical maneuvers have been inserted in Wild-2 encounter sequence (after DSM-3) to compensate for error sources and to precisely achieve the fly-by distance about Wild-2. The deterministic maneuver parameters were computed using AMMO and SEPV. The statistical maneuver parameters were determined using LAMBIC (Linear Analysis of Maneuvers with Bounds and Inequality Constraints) program through Monte Carlo analysis (Ref. 16). The current maneuver is always a deterministic maneuver; for example, TCM-9 becomes a deterministic maneuver immediately after DSM-3.

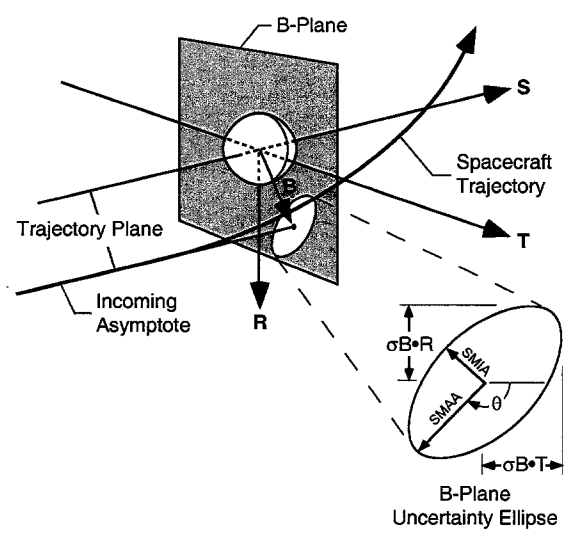


Figure 6. B-Plane Coordinate System (including Error Ellipse

Error Sources

In real world, the trajectory propagation and maneuver design are influenced by error sources. The maneuver performance mainly influenced by OD uncertainty and maneuver execution errors. Using these two types of errors, statistical maneuver analyses are carried out. The uncertainties of small forces influenced both OD results and the maneuver execution.

OD Errors

Errors in OD solutions are estimated through covariance analyses using simulated tracking data, a priori uncertainties, and uncertainties due to dynamic modeling. The resulting covariance matrix is mapped to various required times. A set of OD covariance matrices was generated prior to the launch (Ref. 17) at proposed maneuver times. These covariance matrices were updated (Ref. 18) after DSM-3, to reflect changes in dynamic modeling and maneuver times. The data cut-offs for generating these OD covariance matrices vary between 10-day to 0.5-day of the maneuver epoch based on the maneuver timeline (Fig. 5). The OD covariance matrix for the current maneuver is generated with OD results and this covariance matrix replaces the old in the maneuver analyses.

Maneuver Execution Errors

Every TCM is a turn-burn-turn or slew-burn-slew. Spacecraft is slewed to burn direction and slewed back to original orientation after the burn using thrusters. The spacecraft is accelerated to a maximum turn rate near the initial attitude with corresponding deceleration and settling near the burn attitude. Similar procedure is followed while slewing back to the original attitude (either sun or earth pointing). These slews generate translation ΔVs, which has been difficult to predict accurately. These uncertainties generated a large fixed error for the maneuver. The fixed error was originally estimated (Ref. 17) to be only 2 mm/s (1σ), before the launch, has grown as large as 7.5 cm/s, after reconstruction of TCMs. This large fixed error plays a dominant role on error analysis. In addition to this fixed error, there are other induced errors, which affect the achieved from the desired ΔV. The execution errors can be divided into two main categories:

a) Magnitude Error
b) Pointing Error

Table 1. Maneuver Execution error Model used for Wild2 Maneuver Sequence

Error Sources	Values (1σ)
Fixed Magnitude Error	7.5 cm/s
Proportional Magnitude Error	2.0%
Fixed Pointing Error (per axis)	7.5 cm/s
Proportional Pointing Error (per axis)	6.0 mrad

The magnitude error is along the maneuver direction and pointing error lies in the plane orthogonal to the maneuver direction. Each one of these components is further decomposed into two parts (Table 1). The fixed part is the same regardless of the size of a maneuver, and the proportional part is dependent on size of the ΔV. Each one of the four parts is treated as scalar random variable with Gaussian distribution while modeling execution errors. The fixed parts are given in velocity units, the proportional magnitude part in percent (of the desired ΔV), and proportional pointing error in radians.

Results of Monte-Carlo Analysis

Table 2. ΔV Statistics

Event	Deterministic ΔV (m/s)	Ideal ΔV (m/s)		
		Mean	1σ	99 %
TCM10 (E-30d)	1.44	1.54	0.60	3.04
TCM11 (E-10d)	0.00	1.61	0.80	4.07
TCM12 (E-2d)	0.87	1.57	0.87	4.06
TCM13 (E-18hr)	0.0	1.12	0.59	2.72
Total ΔV	2.31	5.82	1.53	10.11

Table 3. Delivery statistics due to OD uncertainties (alone)

Event	OD Cut-off (days)	σ B.R (km)	σ B.T (km)	σ LFT (sec)	SMAA (km)	SMIA (km)	Angle (deg)
TCM10 (E-30d)	TCM-9d	612.35	666.56	185.62	669.73	608.89	-13.48
TCM11 (E-10d)	TCM-8d	136.47	201.67	47.87	215.50	113.37	-24.49
TCM12 (E-2d)	TCM-12hr	51.16	56.91	33.65	58.10	49.80	-23.00
TCM13 (E-18hr)	TCM-08hr	11.92	10.65	33.10	12.08	10.47	70.96

Table 4. Delivery Statistics (OD errors + maneuver execution errors)

Event	σ B.R (km)	σ B.T (km)	RHO	σ LFT (sec)	SMAA (km)	SMIA (km)	Angle (deg)
TCM10 (E-30d)	637.00	704.00	-0.04	189.20	706.00	635.00	-9.9
TCM11 (E-10d)	151.00	209.60	-0.39	48.90	223.00	130.50	-24.49
TCM12 (E-2d)	53.14	59.47	-0.10	48.89	60.49	51.96	-21.00
TCM13 (E-18hr)	12.91	11.74	0.07	48.89	13.05	11.58	71.6

The spacecraft detected the comet (Wild-2) a few days prior to scheduled TCM-10 at E-30 days. For spacecraft safety reasons, the Project in consultation with scientists decided to change the fly-by distance to 300 km from 150 km based on optical images of the comet. It was also decided to change the fly-by

distance using TCM-12 at E-2 days. This is to allow some time to study the additional images (taken at close distances) to finally decide on fly-by distance. Also, it was expected that the uncertainty of comet ephemeris would be reduced by that time due to additional optical images. Therefore, TCM-12 became a deterministic maneuver at the time of TCM-10 to change the flyby distance (150 to 300 km). In addition, it was also decided by the project that TCM-12 and subsequent maneuvers would be roll-only maneuvers, meaning that these maneuvers would correct only flyby distance in the B-plane and not the time of flight. Sample results of the Monte-Carlo analysis done at the time of TCM-10 are shown in Table 2, 3, and 4. The delivery statistics were useful in deciding maneuver strategy and contingency plans. There was not much variation in delivery statistics with the implementation of each maneuver as there were no changes in the error assumptions.

The Table 2 provides deterministic and statistical mean values of ΔV, 1-σ, and 99% value of ΔV for each maneuver since TCM-10 till Wild-2 encounter. There was no concern about the fuel budget but concern was how to achieve precisely the targeted flyby distance. Table 3 provides delivery statistics only due to OD uncertainties. σ B.R and σ B.T are the uncertainties of components of the flyby distance in the B-plane and σ LFT is the uncertainty of the time of flight at encounter. SMAA, SMIA, and Angle provide the semi-major axis, semi-minor axis, and orientation of the error ellipse on the B-plane (Fig. 6). RHO indicates the value of correlation coefficient between B.T and B.R. The requirement was to have the flyby distance at encounter 300 ± 50 km (50 km being approximately 3-σ value of the 16 km delivery error, RSS of SMAA and SMIA), meaning 1-σ of the flyby distance to be within 16 km. It is clear from delivery statistics (Table –4) that this requirement met with TCM-13. The OD uncertainty dominates TCM13 delivery statistics (Table-3 and 4).

MANEUVER STRATEGY

The maneuver strategy that evolved during 30-day Wild-2 encounter period primarily depended on comet sighting by the spacecraft (Ref. 15). Stardust may not see the comet Wild-2 until few days (4-10) days prior to encounter due to large uncertainties in the comet ephemeris and its brightness. It is to be noted that the Wild-2 ephemeris was updated based on ground observations. The resolution of ground images is poorer than that from the spacecraft. Therefore, it was decided not to execute TCM-10 until the spacecraft sees the comet Wild-2, though TCM-10 was scheduled at E-30 days as a placeholder date. It was planned to cancel TCM-10 if the comet is not seen by that time and directly move to TCM-11. In other words, TCM-11 would be backup maneuver for TCM-10 in case of a contingency situation. The maneuver strategy as a function of Wild-2 visibility is summarized in Figure 7. The maneuver strategy, proposed for each maneuver including contingency, during 30-day period prior to Wild-2 encounter is summarized in Table-5.

TCM-12 is a roll only maneuver scheduled at two days prior to the encounter. This maneuver is used to increase the flyby distance based on science requirement at its design time. An 8-hour maneuver design template was developed, based on tested 18-hour design template for TCM ORT (Operational Rehearsal Test) conducted during Annefrank flyby (period (October 2002 to January 2004). TCM-12 would be full maneuver in case of late comet sighting with extreme ephemeris shift and 2.5-day design template would be used. TCM-13 would be its backup maneuver (see Table-5)

TCM-13 is also a roll-only maneuver and it was decided to follow 8-hr maneuver time-line to accommodate as much optical images as possible in OD solution, required for the maneuver design (Ref. 15). TCM-13 may be delayed until 12 hours prior to the encounter in case of operational problems. TCM-13 would be cancelled in case of further delay and that would result in TCM-14 implementation (one of 'canned' maneuvers).

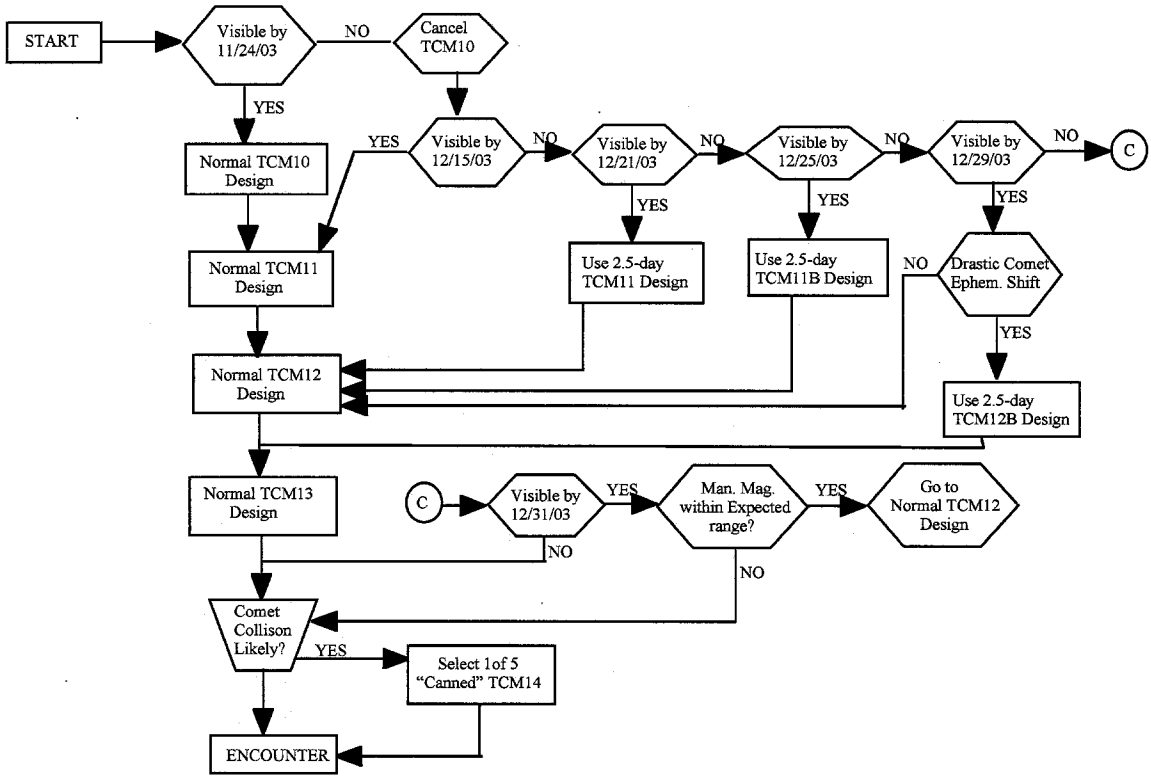


Figure 7. Maneuver Strategy as a Function of Wild2 Visibility

TCM-14 is a contingency maneuver scheduled at E-6 hrs to be implemented only if spacecraft is in danger. This maneuver will push spacecraft away from Wild-2 so that spacecraft is not damaged from heavy dust particles of the comet. It was decided to design several 'canned' (designed well in advance) maneuvers to move the spacecraft away by 100 km, 200km, ------ 1000 km. Five 'canned' maneuvers were to be selected after TCM-12 time and they would be up-linked to the spacecraft. One of them would be implemented, if required, based on then situation. TCM-14 will be roll only maneuver; hence it will not correct the time of flight.

Go/No-Go Criteria

TCM-10 was implemented after collecting few optical images and getting first update of the comet ephemeris. TCM-11 was implemented after another update of comet ephemeris using several optical images. Both TCM-10 and 11 were full maneuvers and supposed to correct flyby distance as well as the time-of-flight. There was no plan to apply Go/No-Go criteria based on delivery uncertainties as the difference between predicted and targeted points on the B-plane expected much larger than delivery errors

TCM-12 was originally defined as a full design, supposed to correct both flyby distance and time-of-flight. To ensure spacecraft safety and to avoid contamination of Aero-gel, it was decided to design TCM-12 as roll-only maneuver (Ref. 15). In other words, TCM-12 would correct only the flyby distance. It was determined that the best method to correct for time-of-flight is to adjust encounter sequence start time based on a pre-encounter OD solution, obtained using optical images of the comet. Although, the Project had decided, at the time of TCM-10, to change the flyby distance to 300 km from 150 km, it was proposed and decided to target to this new flyby distance using TCM-12 and not through TCM-10 or TCM-11 to have option to change the flyby distance by that time, as late as possible. Based on the geometry of the

Table 5. Summary of Maneuver Strategy Applied during E-30 day period

Maneuver	Epoch	OD Cutoff	Backup(s)	Backup Epoch(s)	Considerations
TCM-10	3-Dec-03 (W2-30d)	M-9d	TCM-11	23-Dec-03 (W2-10d)	Do not execute any such TCM unless comet Wild 2 seen by STARDUST prior to nominal OD cutoff time; opportunity to test 2.5-day TCM design template if real TCM not feasible at this time.
TCM-11	23-Dec-03 (W2-10d)	M-8d (or ~M-2d)	TCM-11b, TCM-12	27-Dec-03 (W2-6d or M+4d), 31-Dec-03 (W2-2d)	Nominally the last fully designed TCM prior to Wild 2 and the last opportunity to affect time of flight; may use 2.5-day design template if comet sighted late.
TCM-12	31-Dec-03 (W2-2d)	M-12h (or ~M-2d)	TCM-13	2-Jan-04 (W2-18h)	Nominally a roll-only maneuver designed with 8-hour template and last opportunity to adjust closest approach target distance (150 --> 300 km); full design based on 2.5-day template possible if late comet sighting with extreme ephemeris shift.
TCM-13	2-Jan-04 (W2-18h)	M-8h	Delayed TCM-13, TCM-14	2-Jan-04 (Hourly delays through W2-12h; W2-6h)	Roll-only maneuver designed in less than eight hours (after W2-26h OPNAV image); if delay in execution no later than W2-12h, delivery error only degrades by 50%; beyond that, default to one of the pre-canned maneuvers for TCM-14 (W2-6h) as final backup in
TCM-14 (contingency)	2-Jan-04 (W2-6h)	M-8h	n/a	---	One of several "canned" escape maneuvers, always directed away from Wild 2; pre-designed by target aimpoint shift at intervals of 100 km through 1000 km (3-5 ultimately to be selected for upload to spacecraft no later than W2-2d).

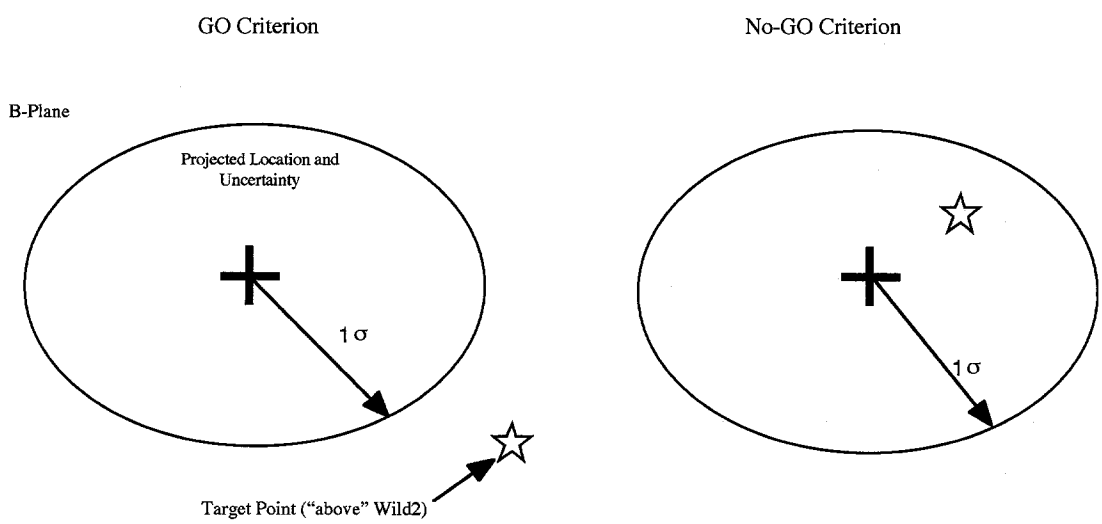


Figure 8. GO/No-GO Decision Criteria for TCMs during 30-day Period Prior to Encounter

spacecraft, Sun, and Earth, the biased maneuver direction of TCM-12 to increase the flyby distance would be closer to Sun and Earth. This would reduce an associated operational risk of turning far off Sun. In fact, the Project has decided change the flyby distance to 250 km from 300 km at the time of TCM-12 design. However, the GO/No-GO decision would be taken based on post-TCM-11 OD to verify that whether a 1-σ uncertainty encloses the new flyby distance from Wild-2 in the encounter B-plane, as illustrated in Figure 8 (Ref. 9).

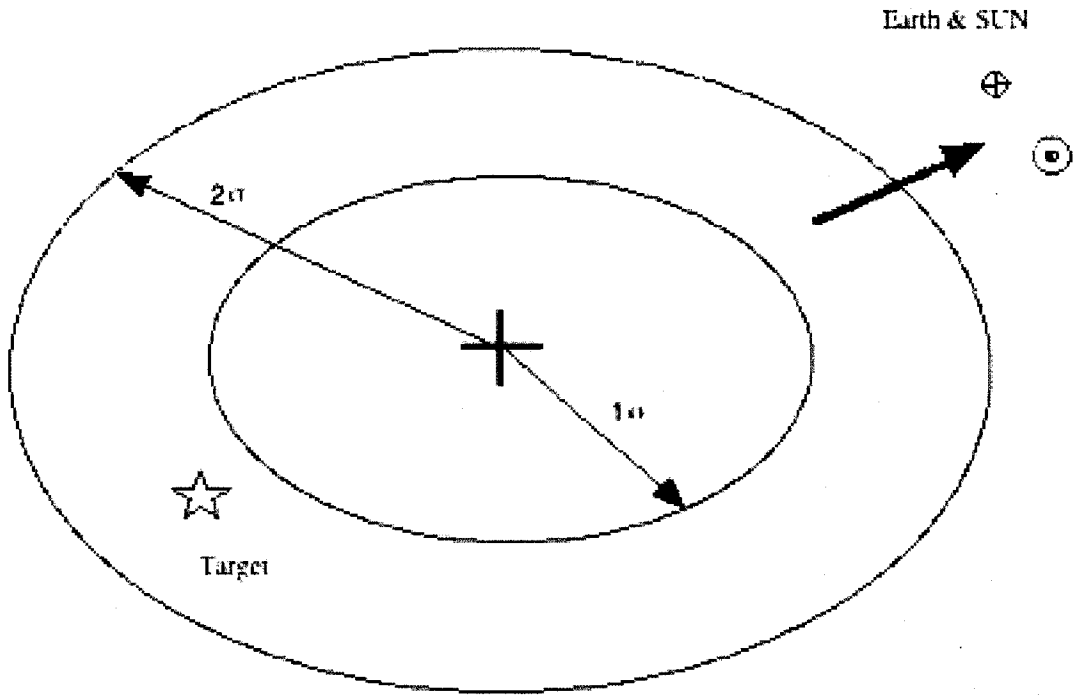
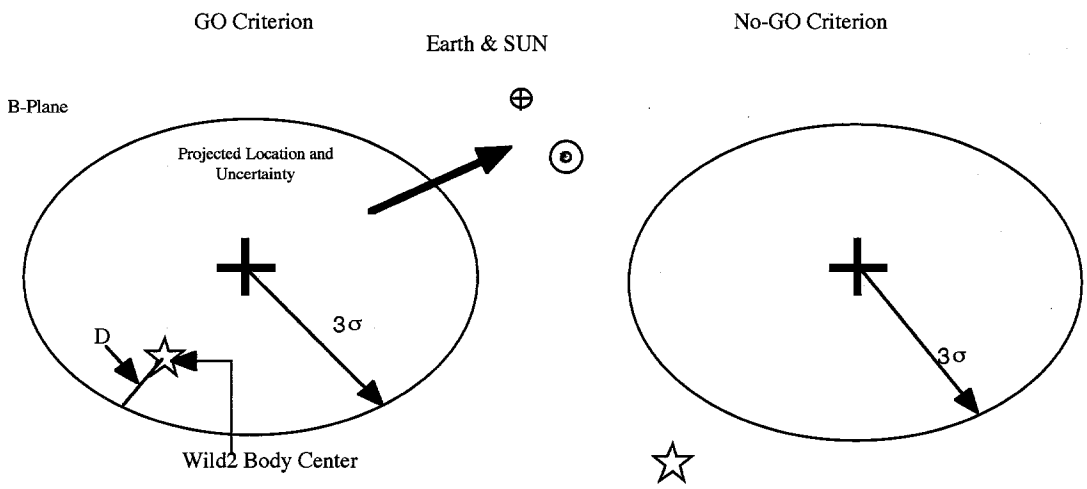


Figure 9. Possible Secondary No-GO Decision Criterion for TCM-13

The GO/No-GO decision criterion for TCM-13 is similar to that of TCM-12, but is now based on the OD-estimated B-plane position after reconstruction of TCM-12, beginning with an OPNAV image and OD data cut-off at E-26 hours (Ref. 9). A secondary criterion would be applied based on whether or not a roll angle of greater than 90 deg is required to execute TCM-13. This criterion (Figure 9) would be invoked at the discretion of the Project Manager, if a large roll angle (> 90 deg), which turn the spacecraft turn away from Sun and Earth, is too risky. Note that TCM-13 could be delayed to E-12 hour to avoid such situations. A 2-σ threshold is proposed for directions away from the Sun and the Earth (Figure 8), but whether to apply secondary criterion would be considered at the time of TCM-13.

TCM-14 is a contingency maneuver only, invoked only if there is a risk for the spacecraft colliding with the comet nucleus or flying within some minimum safe range (to be decided at the time TCM-14) where spacecraft might be damaged. The likelihood of needing this maneuver was expected to be low (<< 1%); however, there was a possibility of an anomaly, which disables the spacecraft or some unforeseen event, which results in an excessive risk to spacecraft safety during the encounter period. Five "canned " were designed in the range from 5 to 47 m/s to allow B-plane shift in the range of 100 to 1000 km directly away

from the nominal location on the B-plane. The direction of all maneuvers lies along Wild2 encounter attitude. These "canned" maneuvers were up-linked to the spacecraft three days prior to the encounter. One of the five canned maneuvers would be selected, no later than E-12 hours, based on GO criterion for exercising TCM-14 contingency (Figure 10). The criteria are based on a 3-σ confidence level and if the spacecraft flyby within 3-σ dispersion ellipse about Wild-2, TCM-14 would be implemented. Invocation of TCM-14 does not mean abandonment of the final nucleus tracking update and execution of the encounter sequence; such activities may continue in parallel, even if TCM-14 is executed.



Decision Criterion (if GO): Pick smallest "canned" maneuver which shifts the location out by at least D

Figure 10. GO/No-GO Decision Criterion for TCM-14

Note that this same set contingency "canned" maneuvers, designed for TCM-14, also provided capability to ensure spacecraft safety in the event that Navigation support incapacitated by an earth-quake and other catastrophe. In such contingency situation, one of these maneuvers would exercise earlier than E-6 hours with corresponding larger effect on encounter B-plane displacement. For this purpose, the set of five canned maneuvers were up-linked at the time of TCM-11.

MANEUVER IMPLEMENTATION

Each maneuver is a turn-burn-turn or slew-burn-slew. A small ΔV is generated with any slew of the spacecraft due to un-balanced thrusters. It is to be noted that spacecraft is slewed or turned using thrusters only. To account for these ΔVs during slews for the burn, the designed ΔV is split into three parts during implementation. The spacecraft team assesses the ΔV generated during slew to burn and slew back from the burn and accounts for these small ΔVs while assessing how to implement the designed burn. In other words, the implemented ΔV would have three parts given by the following.

$$\text{Implemented } \Delta V = \text{Slew1_}\Delta V + \text{Burn_}\Delta V + \text{Slew2_}\Delta V$$

The vector sum of these three ΔVs and directions would be equivalent to that of the designed maneuver.

The Wild-2 encounter phase started with DSM-3. DSM-3 (Ref. 12) was designed after an update to the Wild-2 ephemeris using ground-based observations collected till June 6, 2003 (Ref. 4). This maneuver targeted the spacecraft to a Wild-2 flyby distance of 150 km (the then science requirement). The size of the maneuver was of the order of 71 m/s and therefore, it was decided to split DSM-3 into two maneuvers, DSM-3A and DSM3-B, to avoid power constraints. DSM-3A and DSM-3B were implemented on June 17 and June 18, 2003 respectively (Figure 11).

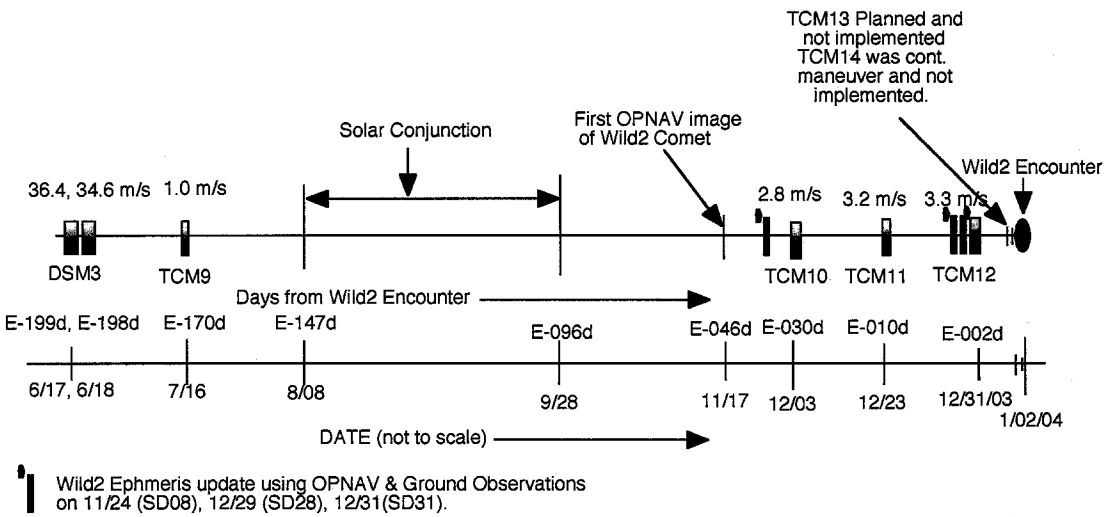


Figure 11. Implemented Wild2 Encounter Maneuver Sequence

The spacecraft was expected to cruise at approximately 1 A.U. solar distance between DSM3 (June 17-18, 2003) and TCM-9 (July 16, 2003). It was decided to schedule 1 A.U. calibration tests (Ref. 13) to get ready for earth return in January 2006. The solar radiation pressure and thermal effects were expected to match conditions near the earth, affording the best opportunity to characterize the attitude control behavior prior to actual Earth approach and entry. This calibration tests were conducted between June 23 and July 3, 2003. The spacecraft was pointing towards earth during most time of the calibration tests. These tests introduced a deviation in the trajectory predictions. The DSM-3 clean-up maneuver TCM-9 was scheduled on July 16, 2003. The maneuver was slightly higher than 1 m/s and the direction was close to the Earth-line. The Project decided to use this maneuver as a part of 1 A.U. calibration test (Ref. 13). Therefore, TCM-9 served as an additional target of opportunity for performing an Entry Maneuver Demonstration (EMD). It was decided to implement exactly 1 m/s at TCM-9 by pointing the spacecraft in the Earth direction. This served to clean up DSM-3 execution errors, while providing a calibration opportunity and not jeopardizing the chances of achieving the target near comet Wild-2. As the spacecraft was already pointing towards Earth before the maneuver, TCM-9 was just a burn and not a slew-burn-slew.

Stardust saw the comet for the first time on November 17, 2003. However, it is to be noted that the resolution of the comet was low because of the distance of the comet from the spacecraft. It was decided to update the Wild-2 ephemeris using optical images of the comet by the spacecraft before TCM-10. Steve Chesley delivered updated ephemeris (Ref. 19), SD08 on November 24, 2003. OD also was done using this updated ephemeris and optical images to determine a better estimate of the spacecraft relative comet distance. The Project, in consultation with scientists, decided to change the target Wild-2 flyby distance to 300 km from 150 km. It was also decided to change this flyby distance using TCM-12 scheduled at E-2 days to allow for any late changes using additional optical images till that time. Therefore, TCM-10 targeted the spacecraft to 150 km flyby distance. The post maneuver dispersions on the B-plane were expected to be 637X704 km (see earlier section on error analysis). However, the initial post TCM-10 OD solutions

indicated that the mapped flyby distance was of the order of 2600 km. It was realized later that the small forces generated from the geometric calibration tests (unplanned), done on December 4, 2003, were not modeled in the trajectory. Also small forces that would be generated from encounter demonstration tests (on December 11, 2003) and photometric calibration tests (on Dec. 18, 2003) were not modeled. It was decided to correct the deviations due to the above sources using TCM-11.

The Wild2 encounter TCM plan (Ref. 20) was rehearsed with Operational Readiness Test (ORT) conducted during November 4-6, 2003. These tests were very useful for TCM-12, as the 8-hr time line was followed for this maneuver. In this timeline, the maneuver design process had only 20 min. The ORT built confidence, which was helpful during the real implementation of TCM-12.

Optical images acquired after TCM-10 became noisy as the OPNAV camera was powered on for a long time, heating the CCD. TCM-11 was designed using OD results obtained using these noisy data. TCM-11 was implemented nominally as scheduled on December 23, 2003. Post TCM-11 OPNAV data were much cleaner as power cycling of OPNAV camera was resumed. Post TCM-11 OD solutions using OPNAV data indicated that the B-plane aim-point is slowly departing from the targeted. The offset was of the order of 500 km, which was larger than the expected. It was decided to correct any residual offset and to increase the flyby distance using TCM-12.

With improved quality of OPNAV images, the Project had a final meeting with scientists to decide about the flyby distance. It was agreed, based upon latest images before TCM-12 design, that the target flyby distance would be 250 km instead of 300km (which was TCM-12 target flyby distance since TCM-10). In addition, all attitude events occurring a few hours past the Wild-2 encounter were planned and included in the trajectory modeling. The Wild-2 ephemeris was also updated twice during this period using available OPNAV images (Ref. 21 and 22). TCM-12 was designed using the latest updated ephemeris model and it was implemented as scheduled at E-2 days (Dec. 31, 2003).

The post TCM-12 OD results indicated that the target distance was achieved within the requirement of 250 ±50 km. Pre-TCM-13 OD solutions further confirmed this assessment and the Navigation Team recommended that there was no need to implement either TCM-13 or TCM-14, the contingency maneuver. The Project adopted this recommendation and TCM-13 and TCM-14 were cancelled. The encounter sequence was adjusted for the encounter time, based latest OD solution obtained just before the up-link of this sequence, to enable nucleus tracking. The encounter time was changed by 2 min. 33 secs from the planned encounter time 19:20:00 ET on January 02, 2004.

MANEUVER PERFORMANCE

The maneuver performance from DSM-3 onwards till Wild-2 encounter is summarized in Table 6. The spacecraft team, at LMA, divides the designed maneuver into three parts (slew1, burn, and slew2) based on the Maneuver Profile File (MPF) supplied by the Navigation Team at JPL for implementation (Ref. 23). The expected performance of every maneuver was provided by LMA, before actual implementation. The three segments of a maneuver (slew1-burn-slew2) were re-constructed during OD process after each maneuver.

TCM-13 and TCM-14 were cancelled as post-TCM-12 OD results (Ref 6) indicated that delivery accuracy was meeting the requirement of 250±50 km. The spacecraft encountered Wild2, as planned, collected sufficient amount of dust particles (nearly a thousand) and acquired several close images of the comet. The post encounter OD solution indicate that the Stardust flew by Wild2 comet on January 2, 2004 at –66.2 km B.R, 226.6 km in B.T, at a radial distance of 236.1 km and at the time of closest approach 19:22:36 ET (Ref. 6).

Table 6. Maneuver Performance of Encounter Sequence

Maneuver	Design (m/s)	Expected Performance			Reconstructed Performance			Comments
		Slew1 (cm/s)	Burn (m/s)	Slew2 (cm/s)	Slew1 (cm/s)	Burn (m/s)	Slew2 (cm/s)	
DSM-3A	36.324	14.6	36.137	14.8	8.0	36.178	12.0	Under Performance During Slews (3-7 cm/s)
DSM-3B	34.592	15.1	34.391	15.1	7.8	34.455	10.6	Under Performance During Slews (3-7 cm/s)
TCM9	1.000	-----	1.000	------		1.0007		No Slews
TCM10	2.768	12.3	2.604	12.5	12.7	2.602	12.2	Estimation of slew performance was difficult due to limited tracking data.
TCM11	3.239	6.4	3.229	6.1	8.6	3.228	8.8	Over Performance During Slews
TCM12	3.287	3.1	3.229	3.4	3.0	3.228	3.3	Slightly under performance during slews

The performance of the burn segment was close to expected for all maneuvers. However, large variations were seen in slew segments. There was under performance during slew segments of DSM-3A and DSM-3B in a range of 3-7 cm/s (Table 6). Only the burn segment was used for TCM9, as there were no slews. The performance of TCM-9 was excellent (Ref. 23). It was difficult to estimate TCM-10 as unplanned geometric calibration to reduce the contamination of OPNAV camera was done on December 4, 2003, a day after TCM-10. The reconstruction process did not accurately estimate the expected performance due to limited amount of post TCM-10 tracking data. Over performance was observed during slew segments of TCM-11 in a range of 2-3 cm/s. The reconstruction of the maneuver segments of TCM-12 was soft due to the limited amount data used for the process. However, the results indicated that there was slightly under performance during slew segments of TCM-12.

CONCLUSIONS

It was a great challenge to evolve a maneuver strategy to ensure a successful encounter with comet Wild2, meeting the mission requirement of 250 ± 50 km. The precise modeling of the Stardust trajectory was difficult to achieve because of the presence of small forces. There was contamination of OPNAV camera during Wild-2 encounter phase, which led to optical data to be noisy before the decontamination process was complete. Unplanned attitude turns were made to decontaminate the camera. The maneuver design and implementation was not easy due to above reasons. The maneuver magnitudes of TCM-10, TCM-11, TCM-12 (Table 6) were all larger than expected because of un-planned attitude events like ACS calibrations, geometric calibrations, attitude turns to decontaminate OPNAV camera, etc, which perturbed the trajectory. The mission requirement on flyby distance was also changed two times during the encounter phase (150-300-250 km).

The maneuver strategy was flexible enough to address all the above uncertain situations and corrected the majority of trajectory uncertainties leading to the successful flyby. This indicates that the maneuver strategy was robust. In fact, it was possible to meet mission requirement on flyby distance without TCM-13. The encounter sequence was appropriately adjusted so that there was no image loss while nucleus tracking. Stardust took several images of the comet, provided details on gas and dust particles, and collected what is thought by Project scientists to be more than 1000 dust particles during the encounter. The spacecraft is on the way back to Earth with Wild2 dust particles. The spacecraft Sample Return Capsule will land on January 15, 2006.

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