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STARDUST-NEXT: LESSONS LEARNED FROM A COMET FLYBY MISSION

Aron A. Wolf*, Timothy Larson†, Paul Thompson‡, Timothy McElrath§, Shyam Bhaskaran**, Steven Chesley††, Kenneth P. Klaasen‡‡, Allan Cheuvront§§

The Stardust-NExT (New Exploration of Tempel) mission, a follow-on to the Stardust prime mission, successfully completed a flyby of comet Tempel-1 on 2/14/11. However there were many challenges along the way, most significantly low propellant margin and detection of the comet in imagery later than anticipated. These challenges and their ramifications forced the project to respond with flexibility and ingenuity. As a result, the flyby at an altitude of 178 km was nearly flawless, accomplishing all its science objectives. Lessons learned on Stardust-NExT may have relevance to other spacecraft missions.

INTRODUCTION

The Stardust prime mission collected a coma sample from comet Wild 2 during a flyby in 2004 and returned the sample to Earth in January, 2006 by jettisoning a sample return capsule, which landed successfully on the Utah Test and Training Range. The spacecraft bus continued in a 1.5-year heliocentric orbit, with a planned return to Earth in January, 2009. Subsequently, it was found that the 2009 Earth flyby could be used to retarget the Stardust spacecraft to fly by comet Tempel 1 in February, 2011. This mission concept was proposed as Stardust-NExT (**N**ew **Ex**ploration of **T**empel) as a Discovery Mission of Opportunity and selected by NASA in July, 2007, by which time the S/C had been in space for over 8 years since its launch on Feb. 7, 1999. Despite unforeseen challenges, the flyby of Tempel 1 was resoundingly successful; however, the experience teaches some new lessons that should benefit future missions, and reinforces some old ones learned during the prime mission and previous missions. Most of these were driven home during the intensive 60-day period on approach to encounter. The discussion below compares operational experiences with original plans for the Stardust-NExT mission, summarizing lessons learned in ***bold italics***.

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* Stardust-NExT navigation lead, GNC Section, JPL, Caltech, Pasadena, CA.
† Stardust-NExT project manager, JPL, Caltech, Pasadena, CA.
‡ Mission Design and Navigation Section, JPL, Caltech, Pasadena, CA.
§ Mission Design and Navigation Section, JPL, Caltech, Pasadena, CA.
** Supervisor, Outer Planets Navigation Group, Mission Design and Navigation Section, JPL, Caltech, Pasadena, CA.
†† Mission Design and Navigation Section, JPL, Caltech, Pasadena, CA.
‡‡ Stardust-NExT Deputy Principal Investigator, JPL, Caltech, Pasadena, CA.
§§ Stardust Spacecraft Team Manager, Lockheed Martin, Denver, CO.

Science objectives

The proposed baseline mission objectives were:

1. Document the style and amount of sublimational erosion and other surface changes occurring between successive perihelion passages of a comet.

2. Extend the geologic mapping of the nucleus of Tempel 1 to elucidate the extent and nature of layering and help constrain models of the formation and structure of comet nuclei.

3. Extend the study of smooth flow deposits, active areas, and known exposures of water ice.

4. If possible, determine the size and depth of the crater formed by Deep Impact (DI) and map any evidence of crater ejecta to provide constraints on models of crater formation and to derive further information on the structural properties of the nucleus of Tempel 1. (The DI impact produced so much ejecta that DI did not succeed in imaging the crater.)

The performance floor objective (required by NASA as part of the proposal) was to return at least one stereo image pair at a resolution of 20 m/pixel or better with a stereo separation angle between 10 and 30°, and to image at least 25% of the hemisphere seen by Deep Impact at 80 m/pixel or better.

Imaging of the DI crater, while not a stated criterion for mission success, was a goal of great interest. Imaging the crater required controlling the encounter time so as to arrive at the point in the comet's rotational period that would place the crater underneath the S/C with the desired geometry and lighting conditions. Achieving this geometry could have required changing the time of arrival (TOA) by up to ~20 hours (half of the comet's 40.7-hr rotational period). Analysis found that the most fuel-efficient point in the trajectory to adjust TOA was roughly a year before encounter (requiring ~2.9 m/s ΔV per hour of TOA change). A maneuver at this time was included in the mission plan as TCM-28. A 20-hour change in TOA at one year before encounter would have required ~7.2 kg of propellant, which was over 40% of the estimated propellant quantity onboard at the time the Stardust-NExT mission was proposed. The estimated propellant quantity at proposal time was sufficient to accommodate a 20-hour change with some margin. TOA adjustments made closer to encounter would have required significantly more fuel to accomplish (e.g., 15 m/s per hour at E-30 days, increasing closer to encounter) and could not be accommodated with the propellant onboard. This constraint required the important decision of how much to adjust arrival time to be made a year prior to encounter.

SPACECRAFT DESCRIPTION AND STATUS AT START OF MISSION

The Stardust spacecraft is illustrated in Figure 1. The spacecraft bus measures 1.7-meters in length and 0.66-meters in width. Power is provided by two solar arrays, protected from damage due to dust impacts during a comet encounter by Whipple shields.

At the start of the Stardust-NExT mission in the fall of 2007, all subsystems were healthy; the spacecraft had operated on only one of its two redundant sets of electronics during the prime mission and had not yet used the other set. Margin still remained on all components in the set used during the prime mission. Detailed status of selected subsystems is discussed below.

Attitude control

The spacecraft is three-axis stabilized with thrusters mounted in four groups of 4 (each group consisting of two 1-N RCS and two 5-N TCM thrusters). All thrusters are mounted on the lower deck of the spacecraft (opposite the high-gain antenna and solar panels), firing nearly in the same direction but canted to provide control authority about all three axes. This unbalanced thruster configuration produced a nonzero net ΔV whenever thrusters were fired. Thrusters provided the sole means of attitude control. Frequent pulsing was required to maintain pointing within a desired deadband.

Propulsion

Most of the 85 kg of propellant onboard at launch was expended during the prime mission. The spacecraft was contacted several times in late January / early February of 2007 after slightly over a year of dormancy since the end of the prime mission. At that time, the remaining fuel was estimated to be approximately 17.1 kg.

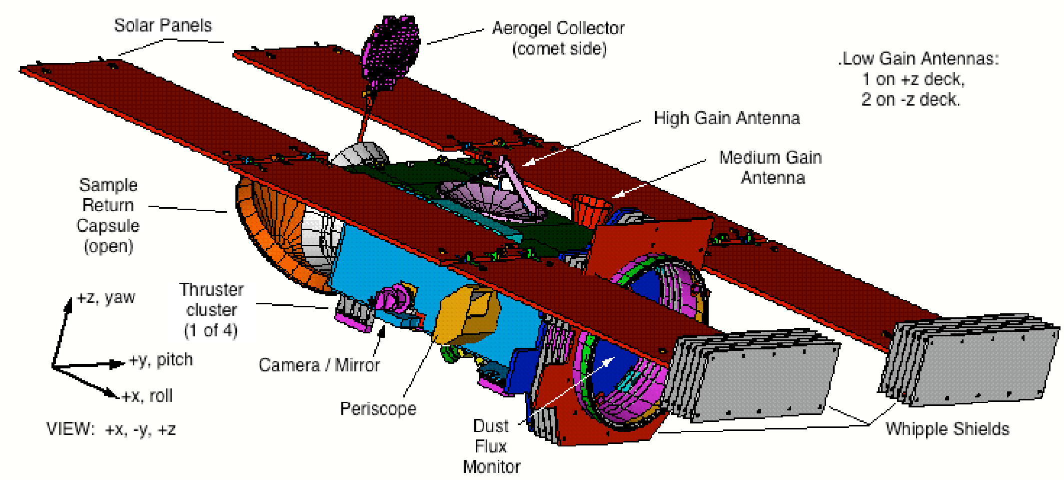

Figure 1. Stardust spacecraft configuration. Sample return capsule was jettisoned prior to the start of the Stardust-NExT mission.

Science payload

The Stardust-NExT science payload included the following instruments:

Navigation camera (NAVCAM). The NAVCAM utilized the flight spare optics from the Voyager wide-angle camera. The camera is hard-mounted on the spacecraft bus, with its boresight aimed at a scanning mirror that rotates about the Y-axis (see Figure 1). The mirror is steerable through 180° so the comet can be imaged on approach to an encounter, near closest approach, and on departure as the spacecraft passes by the comet on the Sunlit side while the spacecraft holds attitude to present the Whipple shields to the incoming particle flow. A periscope allows the camera to look forward into the cometary dust stream on approach so that the camera rotating mirror and 200-mm optics are not impacted by dust particles. The camera looks through the periscope when the mirror is aimed within 16° of the spacecraft's X-axis.

During the Stardust prime mission, contamination of the camera was observed when the first images were taken in late 1999 and during the two subsequent 1-AU trajectory passes, as well as prior to the Annefrank encounter and on approach to Wild 2. The source of the contamination remains unknown. A procedure was developed that was successful in removing most of the contamination. This process involved turning on the CCD heater to raise the CCD temperature to 0–10°C and then performing a "bake maneuver," slewing the spacecraft to place the Sun on the radiator on the –Z side of the spacecraft to raise the CCD temperature to 20–25°C. Camera bakes were planned periodically during the Stardust-NExT mission, including four in the last 60 days prior to encounter, to mitigate the risk of image degradation due to contamination.

Also observed during the prime mission was a fixed pattern of noisy pixels that reduced the sensitivity of the NAVCAM when it had been powered on for longer than a few hours or when substantial background scattered light was present. Power-cycling the camera (turning it off and back on again) greatly reduced the density and amplitude of the pattern noise. However, there was concern that the NAVCAM would fail to turn on again after being turned off. Consequently, the Stardust-NExT project decided not to power-cycle it more often than absolutely necessary, allocating twelve power-cycles to support the most important images for ground-based optical navigation (those immediately preceding maneuver data cutoffs plus the image used to initialize the Autonav system described below prior to encounter).

Dust Flux Monitor Instrument (DFMI). This instrument provides data on the flux and size distribution of particles in the cometary environment. Electric pulses are generated as a special polarized plastic sensor is struck by high-energy particles as small as a few micrometers in diameter. The DFMI was activated shortly after launch to monitor interplanetary dust particles. After several months of operation, the instrument started to experience thermal problems and became noisy if left on for long periods. Consequently, the decision was taken to operate DFMI for only 30 minutes at a time. This method of operation was used successfully many times during the Stardust mission. The instrument performed nominally during the Wild 2 encounter.

Cometary and Interstellar Dust Analyzer (CIDA). CIDA is a mass spectrometer providing detection and analysis of certain compounds and elements. Particles impact a silver foil target at high velocities, emitting ions that travel down a tube to a detector. The detector measures the time of flight for each ion to travel through the instrument, which is a direct indication of mass.

Experiences with the NAVCAM during the prime mission showed that ***development in an environment of restricted funding can lead to insufficient attention to design and quality control leading to operational issues*** and that ***better testing before launch can prevent problems during operations.*** In our case, testing and more complete bakeout of volatiles could have identified and solved the NAVCAM contamination issue before launch. Also, power-cycle lifetime testing could have removed any concerns about how many times the camera could be power-cycled. Specific design recommendations for future cameras include lowering read noise and elimination of coherent noise sources, active control of detector temperature, automatic pre-exposure flushes of the detector, and ensuring adequate engineering telemetry to support instrument calibration.

Stardust Autonav system

The Stardust spacecraft is equipped with an autonomous navigation (Autonav) system that enables closed-loop tracking of a comet nucleus near closest approach, designed for the Wild 2 encounter during the prime mission. The predicted delivery uncertainty for ground-in-the-loop navigation at encounter with Tempel 1 was roughly 30 km in the crosstrack directions and about 90 seconds in downtrack (all 1 sigma). These accuracies are not sufficient to maintain visual lock on the comet through closest approach (where the highest imaging resolution is obtained) with the scan mirror operating in open-loop mode. In particular, the crosstrack uncertainty is too large to determine the flyby plane in which the scan mirror needs to sweep, and the downtrack uncertainty is too large to determine the mirror angles vs. time through the encounter. For this reason, onboard closed-loop tracking is essential (as it was for the primary mission). This capability is provided by the autonomous navigation (Autonav) system [1].

Autonav is seeded with the best ground-based ephemeris knowledge, and Autonav operations are initiated at E-24 min. At 30-second intervals, comet images are taken and centroided, then used to perform a least-squares solution of the spacecraft state relative to the comet. The updated state is passed on to the Attitude Control System to compute the correct attitude for aligning the scan mirror plane and to the mirror controller to point the mirror. The first update occurs at E-10 min; subsequent updates occur after every image. At E-5 min, the spacecraft performs a roll maneuver to put the nucleus in the scan mirror plane. The encounter imaging sequence of 72 images is initiated at E-4 min, with images taken every 6 or every 8 seconds, with every second or every third image used by Autonav. Autonav terminates 90 seconds past the nominal encounter time.

BASELINE MISSION PLAN (AKA "WHAT WE THOUGHT WOULD HAPPEN")

Figure 2 shows a north trajectory pole view of the interplanetary trajectory flown by the spacecraft from its Earth flyby in January, 2006 through the encounter with Tempel 1 in February, 2011. After the 2006 Earth flyby (during which the Wild 2 coma sample was returned to Earth in the sample return capsule), the spacecraft was placed into the heliocentric orbit labeled "Loops 1 & 2", returning to Earth three years later (after two revolutions about the Sun) in January, 2009 for an Earth gravity assist that placed it into the orbit labeled "Loops 3 & 4".

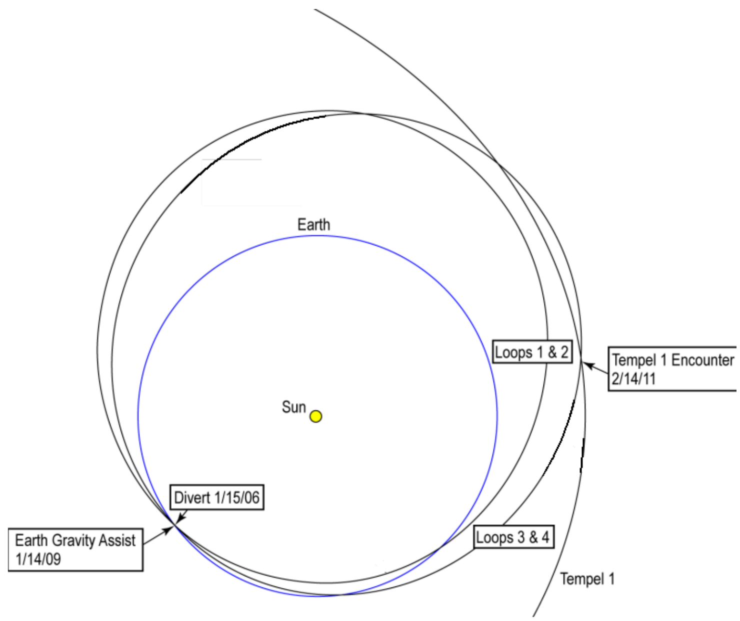

Figure 2. Stardust-NExT cruise trajectory. An Earth gravity assist in January, 2009 targeted the Stardust S/C to an encounter with comet Tempel 1. ΔV cost to move the encounter position was high due to the ~10.5° inclination of the orbit of Tempel 1 to the ecliptic plane.

Imaging schedule

An early science analysis predicted that the comet could be detectable 60 days before encounter. Consequently, science imaging at 2-hr intervals (with "sets" of 8 images shuttered at a time to gather a time history enabling construction of a light curve of the comet on approach) was planned to begin at E-60 days, requiring continuous operation in 0.25° deadbands until encounter. The available data rate was insufficient to downlink an entire set of 8 complete images in a 2-hour period, so the data volume was reduced by downlinking only a "window" of 200x200 pixels in the center of each image. The 0.25° deadband subtends ~±75 pixels in the NAVCAM field of view, so windows of 200x200 pixels are wide enough to capture the comet with some margin. For ground-based optical navigation (OPNAV), the plan was to add up to 3 additional windows for stars in selected images, to locate the comet against a star field. Two sets of OPNAV images were planned during the interval between E-60 and E-30 days, 1 set per day between E-30 and E-10 days, and 2 sets per day from E-10 days to E-42 hours.

Maneuver plan

The schedule of planned maneuvers during the last few months prior to encounter is shown in Table 1. As the table shows, several changes were made to this schedule – these changes are explained in the following sections.

Table 1. Schedule of Planned and Actual Maneuver Dates

	Plan as of Oct. 2010		Final executed maneuver	
Maneuver	Date	Mnvr time wrt flyby	Date	Mnvr time wrt flyby
TCM-30	10/13/10	E-125d	11/20/10	E-87d
TCM-31	1/14/11	E-32d	1/31/11	E-14d
TCM-32	2/4/11	E-10d	2/7/11	E-7d
TCM-33	2/13/11	E-2d	2/13/11	E-2d
TCM-34	2/14/11	E-18h	n/a	n/a

The data cutoff for the E-2 day maneuver (TCM-33) was set at E-78 hours, after a detailed reexamination of the entire Stardust-NExT maneuver design process in the months before encounter showed that the minimum time to design this maneuver was 30 hours.

The maneuver at E-18 hours (TCM-34) was a planned contingency maneuver, to be used only to move the encounter aimpoint further from the comet if needed. Since the time available was insufficient to accommodate the full 30-hour maneuver design process, exercising this contingency would have amounted to selecting one of three maneuver designs that had been “pre-canned” (including testing of S/C sequences) weeks in advance for uplink to the S/C. These maneuvers were designed to move the aimpoint 35, 70, and 150 km radially away from the comet along a line from the nucleus to the nominal aimpoint in the B-plane (see also Figure 5).

Attitude profile on approach

The attitude profile from E-60 days to encounter was largely driven by the plans for imaging the comet on approach discussed above, the desire to point the high-gain antenna (HGA) at Earth for tracking and communication unless otherwise necessary, and the geometry of the NAVCAM and periscope on the spacecraft (both of which are mounted on the –Z side of the S/C, opposite the HGA which is fixed and points along the +Z axis as shown in Figure 1).

The Earth-S/C-comet angle (between the S/C-Earth and S/C-comet vectors) along the trajectory from E-60 days to encounter is plotted in Figure 3. Recall that a mirror angle of > 16° is needed to avoid imaging through the periscope (and to avoid the associated signal attenuation). With the HGA pointed to Earth and the +X axis “flying forward,” pointing generally toward the comet, the comet can be imaged without changing the spacecraft’s attitude (simply by steering the mirror) whenever the Earth-S/C-comet angle is >106° (90 + 16). When the Earth-S/C-comet angle is <106°, the S/C must be pitched (turned about the Y axis), and the HGA turned away from Earth, to image the comet “off the periscope.” Figure 3 shows that on the Stardust-NExT trajectory, the Earth-S/C-comet angle is below 106° from E-47 days to encounter.

However, if the S/C is flown “backward” (HGA to Earth and the –X axis generally toward the comet), the comet can be imaged using only mirror steering as long as the Earth-S/C-comet angle is >94° At an Earth-S/C-comet angle of 94°, the mirror angle is 176°, the largest mirror angle tested for scattered light issues. The choice was made to fly “backward” starting at E-60 days, since comet imaging could be accomplished with mirror steering alone for a longer time (until E-

21 days) in this attitude. After E-21 days, pitch walks were needed (turning the HGA away from Earth) for comet imaging while flying "backward."

To accommodate plans for comet imaging every two hours, a repetitive 2-hour block of activities was designed for use after E-21 days in which 10 minutes were allocated for comet imaging, 20 minutes to walk to point the HGA to Earth, 70 minutes for tracking and downlinking of images, and 20 minutes to walk back to imaging attitude for the next set of images.

An attitude "flip" (180° yaw about the Z-axis) was planned at E-3 days to allow viewing of the comet while "flying forward," to minimize the number of attitude changes needed close to the encounter. Near closest approach, flight with Whipple shields pointing along the velocity vector was required to protect the spacecraft.

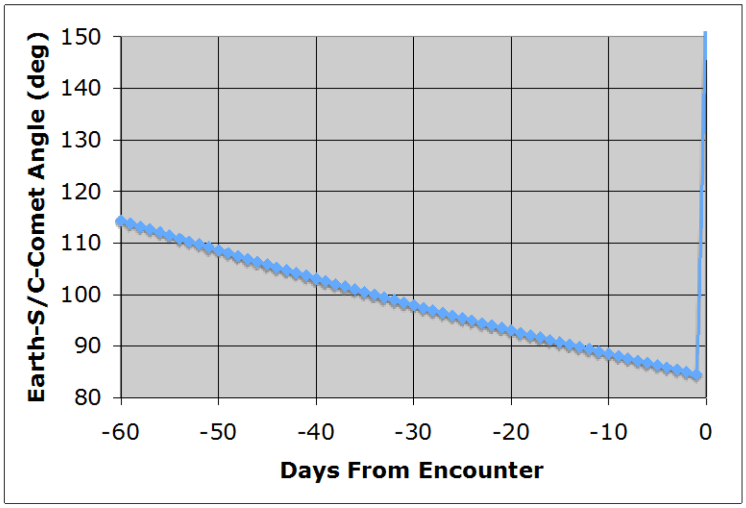

Figure 3. Earth-S/C-Comet angle from E-60 days to encounter

OPERATIONAL ISSUES AND RESPONSES (AKA "WHAT ACTUALLY HAPPENED")

Things did not always go as planned on Stardust-NExT, providing ample opportunities to show that ***an experienced team able to respond with flexibility can be critical to mission success.*** The value of this lesson was driven home repeatedly in different ways and at different times during the Stardust-NExT mission.

Effects of unbalanced thrusters

One important lesson learned repeatedly on Stardust-NExT was that ***the use of unbalanced thrusters has numerous undesirable ramifications and should be avoided on future missions.*** The unbalanced thruster configuration was adopted in the design stage of the Stardust spacecraft as the lowest-cost solution (in a cost-constrained environment) to minimize contamination of samples of comet and interstellar dust collected in aerogel. However, the unbalanced configuration made it necessary to model ΔV due to both ACS deadbanding and planned attitude changes (slews or walks) to accurately propagate the trajectory and ensure successful targeting. The frequent pulsing of the unbalanced thrusters, which was required to maintain pointing within a desired deadband, produced non-gravitational accelerations that over time had the largest effect on the trajectory other than gravity.[2] In addition to ACS deadbanding, propellant was expended for slews and walks to change attitude and TCMs (using TCM thrusters). Any changes to the mission plan that added or deleted attitude changes caused errors in the predicted trajectory. This effect changed the standard mission paradigm in which instrument calibrations and other spacecraft activities have no effect on navigation. In addition, unplanned events that caused thruster firings (e.g. safings) caused the trajectory to diverge from predictions.

The order of magnitude of ΔV due to attitude changes was roughly the same as the ΔVs of many TCMs. Consequently, the B-plane corrections at TCMs were dominated by non-random events; at every maneuver on Stardust-NExT, the design B-plane correction was greater than the 1-sigma relative orbit determination error. As a result, the TCM ΔV allocation was not well predicted by traditional tools using formal statistics. Another undesirable side effect of the unbalanced thruster configuration was that cancellation of fuel-consuming activities to save propellant moved the predicted trajectory in the B-plane, which could increase the ΔV required at the upcoming maneuver and prevent realization of all the expected propellant savings. The impact of the above factors over the course of the Stardust-NExT mission was magnified because of the propellant situation, discussed below.

Another consequence of the use of attitude deadbanding was smearing of images on approach to the comet. Image smear of up to twenty-five pixels was observed due to S/C attitude motion within the 0.25° deadband. Attempts were made to recover useful images from smeared ones by characterizing the stellar point-spreads in each picture and sharpening them and the comet images with deconvolution techniques. These attempts were unsuccessful due to high background noise and low comet signal. We relied instead on taking enough pictures so that we could reject those with smear greater than ten pixels. Only during the last week of approach was the comet bright enough to allow reducing OPNAV exposures to five seconds to minimize smear. ***Use of reaction wheels to improve pointing stability and eliminate deadbanding provides substantially improved imaging performance.***

Changes to propellant budget

When the Stardust-NExT mission was proposed, the mission was planned using an estimate of remaining fuel onboard that was based on two methods: bookkeeping of thruster-on times since launch; and calculation from tank pressure, volume, and temperature (the "PVT" method). Later measurements using a third "Propellant Gauging System" (PGS) method yielded a substantially lower estimate of onboard propellant.

The PGS method relies on measuring the thermal response of the tank to heating and comparing the observed temperature rise to simulation results obtained from a thermal model of the tank.[3] Previous experience with Earth-orbiting spacecraft had shown that when the remaining propellant quantity is low, PGS is more accurate than PVT (because the sensitivity of the estimate to pressure changes decreases as propellant is depleted) or bookkeeping of thruster pulses (due to uncertainty in I_{sp} and the amount of propellant expended per pulse). The accuracy of the PGS estimate is, however, heavily dependent on the fidelity of the thermal model of the tank.

PGS testing was performed on three occasions during the Stardust-NExT mission: October 2008, May 2009, and November 2010. The onboard propellant estimates from these tests were ~3 kg lower than the estimates obtained from PVT and bookkeeping. The accuracy of the PGS estimate was confirmed at the end of the mission on 3/24/11 when a decommissioning burn exhausted all remaining propellant, at which time the PGS-based prediction was found to have been within ~0.2 kg of the actual propellant quantity. For Stardust-NExT, ***the PGS method did prove to be a significantly more accurate method of measuring propellant quantity in a near-empty tank, even in the absence of dedicated thermal sensors for high-fidelity thermal modeling of the tank. Future missions should add thermal sensors to ensure the accuracy of PGS measurements.***

Due mainly to the significant reduction in the estimated onboard propellant quantity discussed above, by the time a decision on arrival time adjustment had to be made in January, 2010, the maximum possible arrival time change at TCM-28 (the arrival time adjustment maneuver) was reduced to 7.75 hr.. At that time, the science team reported the results of an intensive, 2-year effort to predict the comet's rotation state at arrival and to recommend an arrival time adjustment if needed.[4, 5] This effort concluded that without an arrival time adjustment, the mission would not satisfy its performance floor objective of imaging 25% of terrain imaged by DI, and that a delay of 8 hr. would be necessary to meet the performance floor (and would also result in Sunlit viewing of the DI crater site, but on the approach asymptote instead of at closest approach as originally planned). As a result, the project made the decision to delay arrival time by 8 hr at TCM-28, with the knowledge that close monitoring of propellant consumption and predictions would be necessary for the remainder of the mission as a consequence.[6]

Subsequently, it was found that the propellant cost of continuous operation of the spacecraft in 0.25° deadbanding (needed for science imaging at 2-hr intervals as planned for the last 60d before encounter) was higher than predicted. An early estimate put the number of pulses per day during 0.25° deadbanding at 400, for a total consumption of ~390 g at 18 mg/pulse for 65 days (E-60 days to E+5 days, allowing 5 days after encounter for transmission of science data). No extended period in 0.25° operation was planned to allow checking this estimate until a NAVCAM bake and calibration in August, 2010 (several months after TCM-28 in February, 2010), at which time the S/C was operated for ~4 days in 0.25° deadbands. This experience, acquired in an attitude different than the attitude in which the S/C would fly on approach, yielded ~630 pulses per day on average, an increase of ~50% over the earlier prediction. This result prompted an intensive effort over several weeks to reevaluate the estimated consumption in tight deadbanding during the 60 days prior to encounter. This effort resulted in an even higher estimate of 675 ± 75 pulses per day, totaling ~790 ± 87 g from E-60 days to E+5 days.[7] In response to this "hit" to the propellant budget, the project deleted a planned NAVCAM calibration and delayed the start of science imaging and associated 0.25° deadbanding until E-40 days to save propellant. In addition, TCM-30 was delayed from 10/13 until 11/20 to be able to incorporate the results of the above effort into the design of the maneuver.

The spacecraft experienced three safe mode entries in a period of roughly three weeks in late fall of 2010. A safe mode entry on 10/28/10 was caused by an unrequested reboot, believed to be a single event upset. Another safing on 11/11/10 was caused by a false IMU failure indication. The last of the trio of safings was on 12/10/10, due to a MEEB (memory error external bus) upset, which required a cold reboot of the S/C. This was accomplished on 1/4/10. These, like all safe mode entries, expended propellant and imparted ΔV that altered the trajectory (which had to be compensated for at the next maneuver).

The delay in detection of the comet (discussed below) also adversely impacted the propellant budget. A B-plane correction of up to several thousand km was anticipated to correct comet ephemeris error at the first maneuver after measurements from OPNAV images became available to augment radio data. The original plan assumed TCM-31 on 1/14 (E-32 days) would be the first maneuver after OPNAV became available. In early January when the comet had not yet been detected, TCM-31 was delayed to 1/31 (E-14 days) and TCM-32 was delayed from 2/4 (E-10 days) to 2/7 (E-7 days), as shown in Table 1. Due to the decreased time to go to encounter, these delays necessitated an increase in propellant allocated for these maneuvers. To accommodate this increase, the start of science imaging and 0.25° deadbanding was delayed further to E-7 days.

Delayed comet detection

As discussed above, twice-weekly OPNAV imaging was begun at E-60 days. Initial OPNAV images did not reveal the comet, even with extensive image processing (co-adding and filtering of images, with software developed during operations). Failure to detect the comet in early images prompted a reexamination of the early prediction of comet detection, during which comparisons with the Wild 2 approach imaging helped uncover that the previous analysis had incorrectly used the total unresolved nucleus signal rather than the peak-pixel signal in computing the predicted signal-to-noise ratio. This discovery forced a revision of previous assumptions relating to comet brightness, resulting in a revised prediction of comet detection at ~E-20 days. This teaches us to ***check and recheck assumptions that form the basis for mission planning*** (in this case, comet brightness calculations).

Complicating factors impacting optical navigation were NAVCAM pattern noise and image smear due to deadbanding (both of which rendered some images unusable as discussed above). Stray light contamination arose as an additional factor, rendering more images unusable.

During the prime mission, it was observed that at some S/C attitudes and scan mirror angles, stray light scattered into the camera from undetermined spacecraft structures and produced increased background noise in images that sometimes varied in a complex way over timescales of several minutes. A calibration had been done at an attitude believed to be representative of the attitude that would be used on approach (flying "forward") - this showed no stray light at a mirror angle of 176°. However, the attitude flown on approach ("backward") was not the same as the one flown during the calibration. A significant increase in background noise was noted in images taken between 1/8 and 1/17 at mirror angles greater than 168° that made those images unusable. A test confirmed that a scan mirror angle of 160° produced acceptable levels of background noise, following which the attitude profile was changed starting 1/18 (E-27 days) to fix the mirror angle at 160° and initiate spacecraft pitch walks, producing usable images again. This experience reinforces the credo of ***"test as you fly" (the specific corollaries of which here are "fully characterize scattered light in all important S/C attitudes" and "don't skimp on critical calibrations in flight").*** Subsequently, a background estimation technique was developed in which the median value of each pixel across a set of 8 images shuttered close together in time was determined, and that median subtracted from each of the images (made possible by the deadband motion moving the comet image locations from frame to frame so they generally did not overlap). This virtually eliminated the scattered light pattern and also completely removed the pattern noise spikes, providing another illustration of the value of an experienced team capable of flexible response to issues on the fly, and also teaching us to ***have a wide variety of tools and algorithms developed and available whether you think they'll be needed or not.***

Detection of the comet was reported on 1/20 (E-25 days), after changing the attitude profile to fix the scan mirror angle at 160°. However, by 1/31 (E-14 days), stray light contamination reappeared in images. On 2/1/11, the project decided to execute the attitude "flip" several days earlier than planned, on E-8 days instead of E-3 days, to be able to image the comet at well-characterized attitudes and mirror angles at which stray light contamination would not be an issue.

Adjustment of image window sizes

In mid-January, operating at a mirror angle of 160°, differences of ~50-60 pixels were noted between actual and predicted positions of the comet in images. These differences, in addition to the ~75 pixel uncertainty in the position of the comet due to 0.25° deadbanding, caused concern about the possibility of missing the comet in images. Camera–mirror misalignment was investigated as an error source. This misalignment is a function of mirror angle and was calibrated during the prime mission; however, the calibration was poor beyond mirror angles of ~130° due to stray light contamination of calibration images. In the process of revisiting this calibration, an apparent error was found in the code used on the ground to calculate the predicted position of objects in the camera FOV, and the code was changed. However, the first set of images using predictions made with the revised code (shuttered on 1/24) missed the comet. Upon again rechecking the code, the original code was found to be correct, and its use was restored for subsequent images. This reinforces that ***deliberation and thorough testing are essential before making any code change***.

In order to assure that future images would contain the comet with adequate margins, the decision was made on 1/27 (E-18 days) to change the windowing scheme to use one window of 351x351 pixels (with no additional windows for stars in OPNAV images, since the larger 351x351 window was large enough to include stars). The larger window required increased data downlink time, but the increase could be accommodated even within the 2-hr. interval between imaging sets after the start of science imaging on 2/8. Additionally, this change significantly increased the number of images usable for OPNAV in the last week (to 96 images a day instead of 16), yielding a bounty of data but also imposing a much heavier workload on the team of OPNAV analysts processing the images. The week of imaging at 2-hr. intervals required the efforts of four OPNAV team members staffing 2-1/2 shifts per day.

Co-adding of images was required to detect the comet until E-7 days. The delay of the start of science imaging until E-7 days discussed above, which was decided on for reasons related to propellant budgeting, ultimately had little effect on science return since the images up to E-7 days produced little information of use to science. In total, 638 pictures were received during the approach to Tempel 1 (18 more were not down-linked) and 552 of them were used. The remaining 86 were unusable due to the variety of causes discussed above.

Bulb mode problem

On 2/6/11 (E-8 days, the day before the scheduled execution of TCM-32), downlinked images were damaged, with a fragment of the last previously shuttered image repeated multiple times in all the downlinked images. As part of investigating the cause, the camera was power-cycled (powered off and back on) after which an image was successfully taken and downlinked. Conclusions of a team formed to diagnose the problem concluded that Bulb mode had inadvertently been left ON on the NAVCAM. The CCD cannot be read out in Bulb mode.

Bulb mode holds the camera shutter open, permitting very long exposures. Bulb mode was also used between imaging activities early in the mission in conjunction with a narrow-band filter to protect the shutter from thermal distortion (warping of the thin shutter blades) if the camera is pointed toward the Sun during a safing event.

The decision to move the spacecraft "flip" from E-3 days to E-8 days was made on 2/1/11 (E-13 days) following the completion of TCM 32. Shortly after the completion of the "flip," science imaging every 2 hours was started. In the original "flip" sequence designed for execution at E-3 days, no "Bulb mode OFF" command was included, because in the original plan science imaging at 2-hr. intervals would have already been in progress, with the camera operational and Bulb mode already OFF. Moving the "flip" to E-8 days (before the start of science imaging at E-7 days) created a situation in which Bulb mode was ON at the start of science imaging. The "flip" sequence had already been tested in the Spacecraft Test Lab (STL) before the project decided to move the "flip" earlier, and with the tempo of operations activities already quite high, the value of retesting this sequence in the STL appeared low and the sequence was not retested. This experience shows that it is important to ***ensure the state of components (in this case the NAVCAM) is understood before commanding.***

Final maneuver decisions

In the final imaging schedule, images were taken at 2-hr intervals prior to E-106 hours, after which imaging was halted for 24 hours to accommodate a camera bake (the last one prior to encounter). Imaging resumed at E-82 hours and continued at 2-hr intervals until E-52 hours. Imaging was then halted for the execution of TCM-33 at E-48 hours, with one final image set shuttered at E-42 hours. The data cutoff for TCM-33 was set at E-78 hours, to allow the required 30 hours for the design and uplink of the maneuver.

As shown in Figure 4, optical navigation residuals over the last several days had developed a shape that some observers suggested was roughly sinusoidal, which was interpreted as evidence that we were seeing an offset between the center of brightness and center of mass as the comet rotated [8]. However, the three image sets shuttered at E-82, E-80, and E-78 hours aroused a great deal of interest in the possibility that this pattern had been broken, possibly an indication of "seeing the nucleus" clearly through the coma. The decision meeting to select a TCM-33 design occurred at E-71 hours. Although the data cutoff had already passed and the last orbit determination solution before the decision meeting had already been designed, a special effort was made to process the next few imaging sets as quickly as possible to gather all available data before the decision meeting to see if the apparent trend continued. The next several points did indeed confirm the results of the E-82, E-80, and E-78 hour images (including an indication of "flattening out" of the previous sinusoidal trend seen by some observers), After some discussion, the decision was made to design TCM-33 based on the assumption that the E-82, E-80, and E-78 hour data points were giving reliable information. Consequently, a new orbit determination solution was produced after the meeting, with these three points weighted heavily; this was used for the design of TCM-33.

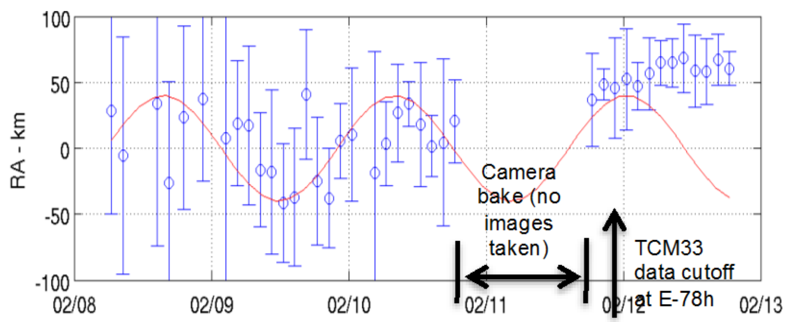

Figure 4. Optical navigation residuals in right ascension over last several days before encounter.

The B-plane targeting "wedge plot" shown in Figure 5 was devised to illustrate the decision criteria adopted by the project for exercising the option to execute the TCM-34 contingency maneuver. If the best orbit determination solution after TCM-33 indicated the flyby would occur in the green region in the B-plane, no contingency maneuver would be executed; in the yellow region, the project's decision would depend on the specifics of the situation; in the red region, one of the three contingency maneuvers would be chosen and executed to best satisfy the science requirements of the mission. The lower altitude limit of the yellow region was driven by the 3.6 deg/sec angular rate limit of the scanning mirror. At our flyby speed of 10.9 km/s, this limit was reached at an altitude of 174 km. The science team set the lower altitude limit at 155 km, accepting a low probability of image smear to get a high probability of images at or near the highest possible resolution. The upper altitude limit of the yellow region was set by the requirement to obtain one stereo image pair at 320 km altitude or less (20 m/pixel or better resolution). The angular limits of the yellow region were driven by the desire to keep the solar phase angle at closest approach between 0 and 40° for proper exposures with the sequenced integration times, with the nominal trajectory targeted to 20°. As Figure 5 shows, the nominal aimpoint ("target" in the figure) coincidentally lay within ~0.1° of the comet equator in the B-plane.

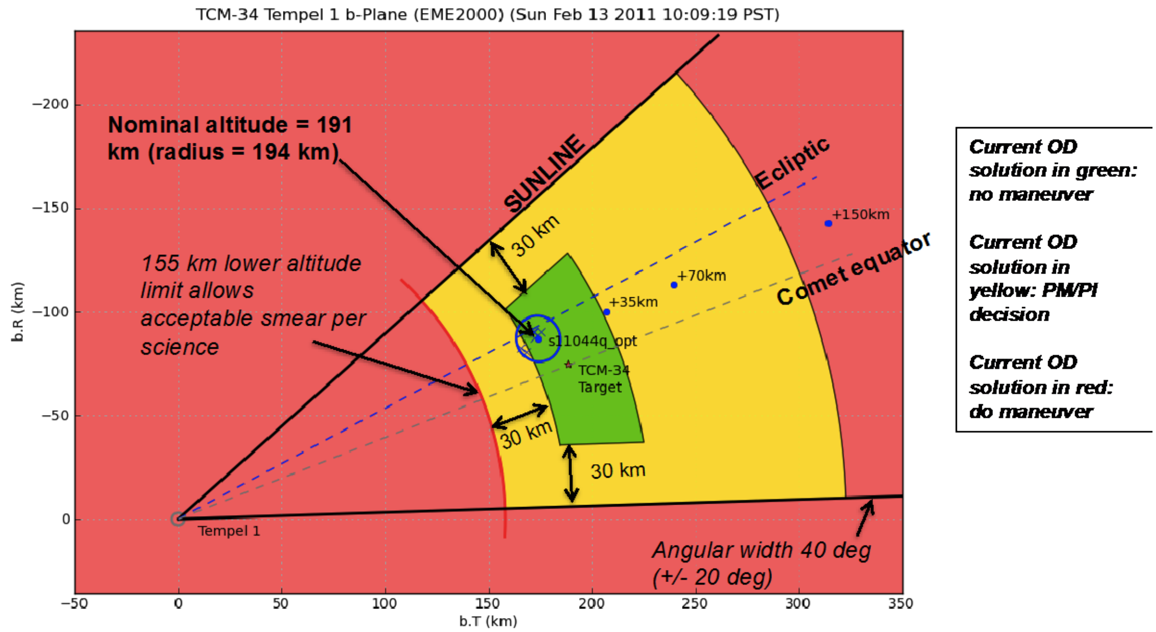

Figure 5. "Wedge plot" showing decision criteria for TCM-34 contingency maneuver.

Figure 5 also shows the post-TCM-33 orbit determination solution (the point labeled s11044q_opt, surrounded by a nearly-circular blue ellipse which shows the 1-sigma B-plane uncertainty). Since this point was in the green region, no contingency maneuver was necessary. This result confirmed that the decision to base the design of TCM-33 on the assessment that the sinusoidal pattern had disappeared in the E-82, E-80, and E-78 hour images was indeed the correct decision (with high-fives exchanged all around). This experience shows us to ***use as much data as practicable to inform decision making,*** including available data not included in original planning. In addition, ***projects that have dynamic events (such as late-breaking target ephemeris knowledge) should have a flexible, portable, and quick-turnaround process for conducting TCMs.***

Autonav and operations during encounter

The Autonav system successfully tracked the comet through closest approach, capturing the nucleus in the camera field-of-view in all 72 planned images. Post-encounter analysis showed that Autonav performed as expected, with the final state correction amounting to about 13 km cross-track and 16 seconds in the encounter time. The crosstrack correction was almost entirely along the radial direction to the comet such that the mirror alignment attitude adjustment was less than 0.5°. Post-flyby reconstruction put the final estimate of the flyby altitude at 178 km (radius 181 km), yielding nearly the best imaging resolution possible without incurring image smear (see Figure 6). The S/C team confirmed that telemetry showed that the scanning mirror was driven right up to its angular rate limit but did not exceed the limit. In addition, comet rotation predictions turned out to be quite accurate, and we were able to image the DI impact site.

The uncertainty in the *a priori* predicted time of closest approach of several tens of seconds (1-sigma) and the lack of capability to autonomously shift sequenced event times based on the Autonav-computed actual time of closest approach made science observation sequence optimization difficult. This limitation will affect any mission with a fast flyby of a target with significant ephemeris uncertainties. For future missions, ***projects should implement an onboard autonomous sequence start time adjustment capability based on Autonav ephemeris solutions for such missions.***

CONCLUSION

The stunning success of Stardust-NExT, which met all of its science objectives including imaging the Deep Impact crater region, provides an outstanding example of how much "bang for the buck" can be derived from extended missions using existing assets. However, the story of Stardust-NExT is also a cautionary tale providing a reminder (if any was needed) of the value of robust resources and margins, and above all an experienced team capable of responding with flexibility and ingenuity (as this team did with replans of activities at an accelerating pace all the way to encounter, responding to multiple issues while operating with thin propellant margins, and implementing innovative image processing techniques on the fly), working together and backed by institutions with long experience in planetary missions.

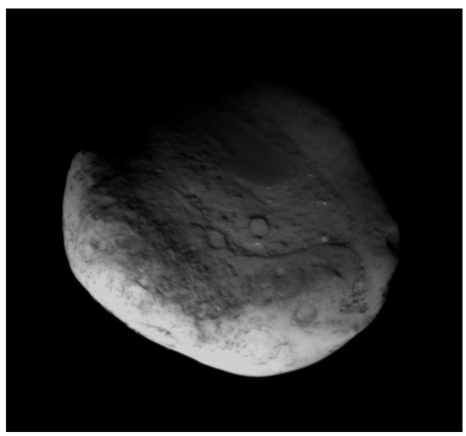

Figure 6. Stardust-NExT image of comet Tempel 1 near closest approach.

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REFERENCES

[1] S. Bhaskaran, J. E. Riedel, and S.P. Synnott, "Autonomous Target Tracking of Small Bodies During Flybys", Paper AAS-04-236, AAS/AIAA Astrodynamics Specialist Conference, Maui, Hawaii, February 2004.

[2] T. McElrath, "Stardust Spacecraft Design Implications for Mission Operations Cost and Risk," JPL Interoffice Memorandum 3430-11-v18, 16 May, 2011

[3] B. Yendler, "Results of PGS Fuel Estimation #3 for Stardust Spacecraft," Lockheed Martin internal memorandum, December 20, 2010

[4] M. J. S. Belton, "STARDUST-NExT Encounter Time-of-Arrival Determination and Adjustment Strategy", presentation to JPL management, January 20, 2010

[5] Belton, Michael J. S., Meech, Karen J., Chesley, Steven, et al, Deep Impact, Stardust-NExT and the accelerating spin of 9P/Tempel 1, *Icarus,* Volume 213, Issue 1, p. 345-368 (2011)

[6] T. Larson, , "Time of Arrival Decision Briefing," presentation to JPL management, January 20, 2010

[7] S. Ardalan, T. McElrath, P. Thompson, and B. Young, "Tight Deadbanding Predictions,", presentation, November 3, 2010

[8] S. Gillam, J.E. Riedel, W.M. Owen, T-C. Wang, R.A. Werner, S. Bhaskaran, S. Chesley, P. Thompson, A. Wolf, "Ground Optical Navigation for the Stardust-NExT Mission to Comet 9P Tempel 1," Paper AAS-11-483, AAS/AIAA Astrodynamics Specialist Conference, Girdwood, Alaska, August, 2011