Lessons Learned in the Decommissioning of the Stardust Spacecraft

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The Stardust spacecraft completed its prime mission in 2006, returning samples from the coma of comet Wild 2 to earth in the sample return capsule. Still healthy, and in a heliocentric orbit, the Stardust spacecraft was repurposed for a new mission – Stardust NExT. This new mission would take the veteran spacecraft to a 2011 encounter with comet Tempel 1, providing a new look at the comet visited in 2005 by the Deep Impact mission. This extended mission for Stardust would push it to the limits of its fuel reserves, prompting several studies aimed at determining the actual remaining fuel on board. The results were used to plan mission events within the constraints of this dwindling resource. The team tracked fuel consumption and adjusted the mission plans to stay within the fuel budget. This effort intensified toward the end of the mission, when a final assessment showed even less remaining fuel than previously predicted, triggering a delay in the start of comet imaging during the approach phase. The flyby of comet Tempel 1 produced spectacular up close views of this comet, imaging previously seen areas as well as new territory, and providing clear views of the location of the 2005 impact. The spacecraft was decommissioned about a month after the flyby, revealing that the fuel tank was now empty after having flown successfully for 12 years, returned comet dust samples to earth, and flown by an asteroid and two comets.

I. Introduction

THe Stardust spacecraft was launched on February 7, 1999 as NASA's fourth Discovery mission. Its mission was to collect particles from the coma of comet Wild 2 and return these samples to earth. Upon completion of its primary mission, the spacecraft was still healthy and continued in its heliocentric orbit. In 2006 an announcement was issued for missions of opportunity utilizing this spacecraft. A new mission was proposed that would adjust the trajectory to fly by comet 9P/Tempel 1 in 2011 to follow up on the previous Deep Impact investigation in 2005. This new flyby of the comet would provide an unprecedented opportunity to examine the comet nucleus on two consecutive perihelion passes to study the changes in the surface, expand the extent of the imaged area, and if possible, to image the crater resulting from the 2005 Deep Impact mission. The new mission, Stardust NExT (New Exploration of Tempel 1), was selected in 2007, leading to a successful flyby of the comet on February 14, 2011. Accomplishing this extended mission with an aging spacecraft posed several challenges for the team, particularly in managing the remaining fuel on a spacecraft that accomplished all its attitude control with thrusters.

II. Managing an Aging Spacecraft

The Stardust spacecraft, shown in Figure 1, had been flying for eight years at the time of the extended mission selection, after ejecting the sample return capsule and having exceeded its planned mission life. At the time of the proposed second flyby, the spacecraft would be 12 years old, requiring the team to carefully assess any potential life-limiting factors on the spacecraft.

The first issue to be considered was the life of the reaction control thrusters. The Stardust spacecraft had been designed as a thruster control only system. All daily attitude control dead-banding, spacecraft turns, slews, and walks, essentially anything that involved attitude control required a thruster firing. Thus, the primary thruster string had accumulated over twice the number of firing cycles than had been demonstrated in life tests. Although the

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thrusters showed no measurable degradation, a risk assessment led to the decision to switch to the back-up thruster string, providing ample thruster life to complete the extended mission and preserving the original string as a back-up in case of unexpected failure. This was easily accomplished since the thrusters were fully cross-strapped in the system.

The next aging piece of hardware was the IMU (Inertial Measurement Unit). This ring laser gyro was nearing the end of its operating life and was showing signs of laser degradation in one axis. A careful assessment of the data and discussions with the manufacturer indicated that the project could not count on more than an additional month of operation of this device. Although the spacecraft spent most of its cruise time in stellar only mode, where the attitude was calculated solely on the output of the Star Camera, use of the IMU was essential for any activities that required finer pointing control. Use of the IMU was necessary when pointing the high gain antenna at earth for communications sessions to maintain as high a data rate as possible, and when performing imaging activities. The baseline mission plan called for more operating time than remained in the IMU. A trade study looked at ways of reducing the IMU usage during the comet approach phase by delaying the start of imaging operations as late as 10 days before arrival. This approach would significantly increase the navigation uncertainties due to the reduced number of optical navigation images and would result in fewer overall observations of the comet on approach, limiting the science collection. The alternative was to switch to the back-up IMU. The spacecraft avionics were block redundant, so switching to the back-up IMU would require a full side swap of the spacecraft. Since this set of equipment had not been operated since before launch, a thorough assessment of the risks involved was undertaken. The project ultimately decided that a side swap to enable completion of the mission using the 'fresh' back-up IMU was the preferred approach, and after a risk review with senior management, this was undertaken. The first attempt at swapping sides in April 2010 was unsuccessful due to pre-existing software error. This error only manifested itself upon a cold boot of the command and data handling system. After implementing appropriate corrective measures, the side swap was successfully executed a month later, and the remainder of the mission was flown with the IMU on. This proved to be a benefit to the fuel conservation efforts described in the following sections.

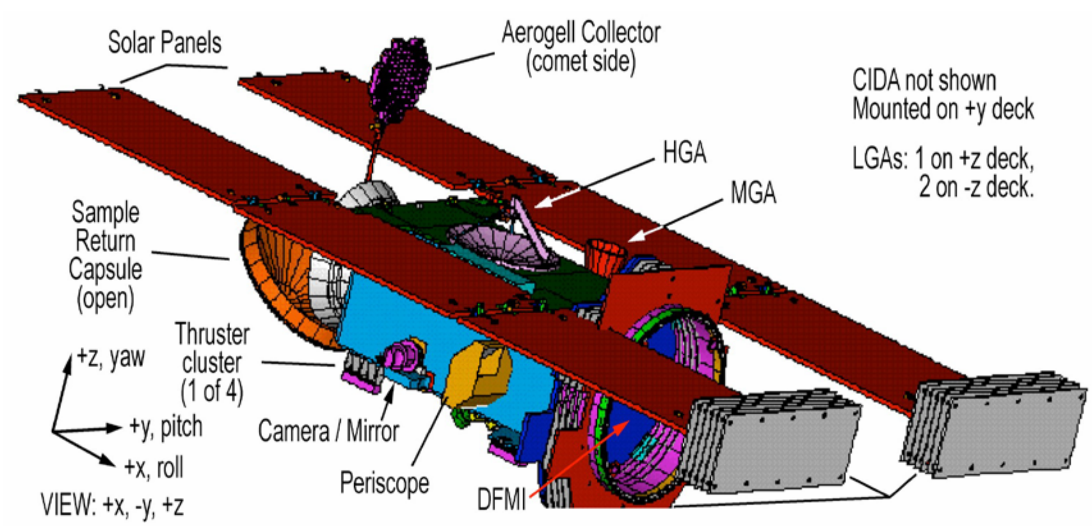

Figure 1 - Stardust spacecraft configuration at launch.

III. Fuel Management

Fuel conservation was central to mission management and operations from the outset of the extended mission. The mission plan, shown in Figure 2, required a combination of deep space maneuvers (DSM) and an Earth Gravity Assist (EGA) to adjust the spacecraft's trajectory to intersect with the comet's path. In addition to these maneuvers, every action with the spacecraft used fuel. Navigating to the comet rendezvous required an allocation of sufficient fuel to accommodate the various uncertainties, as well as sufficient fuel to perform a maneuver a full year before arriving at the comet to adjust the arrival time to maximize the opportunity to view the Deep Impact crater. As mentioned above, the daily pointing control of the spacecraft was accomplished with the RCS (reaction control subsystem) thrusters. Since the spacecraft was configured with all the RCS thrusters on the lower deck, opposite the solar arrays and high gain antenna, every thruster actuation used for spacecraft pointing control produced a small velocity change. This behavior, if not accounted for in the navigation solutions for each TCM would result in additional fuel usage at the following TCM to correct the built up error. This necessitated careful modeling of the daily fuel use, adjusting the models to observed behavior. It also required the navigation team to predict future behavior based on the solar pressure on the spacecraft at the comet imaging attitudes to account for the resulting thruster use. During long, quiescent cruise periods the spacecraft communicated with earth every two to three weeks. These communication sessions provided the accumulated engineering telemetry that showed the pointing performance and the associated thruster firings. These data were fed into the navigation models and the navigation predicts were adjusted accordingly. In order to understand the solar torques that would act on the spacecraft during the comet-imaging period, a test was carried out on board the spacecraft to generate attitude control data at similar spacecraft attitudes. The data generated by this test were used to refine solar torque models that were then applied to the predictions of fuel consumption during the comet approach and flyby phases.

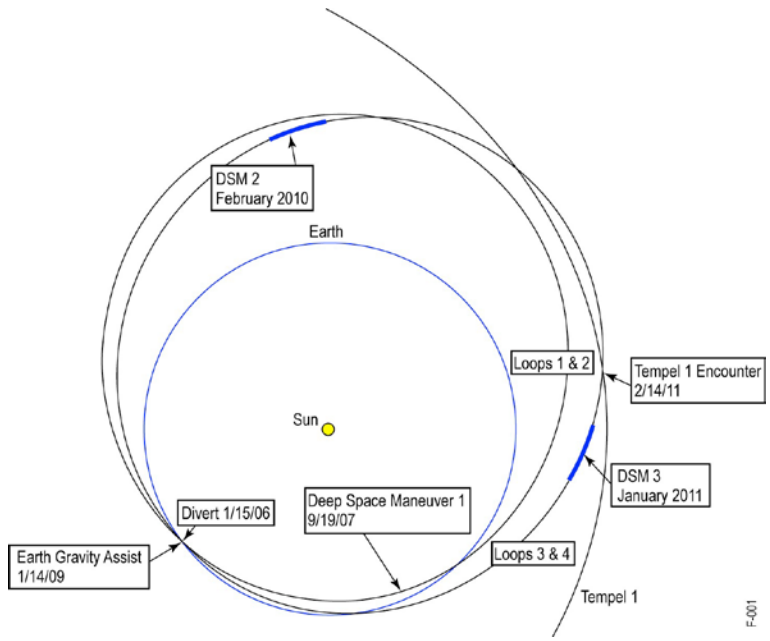

Figure 2 - Stardust NExT mission trajectory.

Because of the coupling between spacecraft control and orbital delta V, any change to the planned activities on board the spacecraft, whether adding spacecraft turns or deleting planned turns, would result in trajectory errors that would have to be corrected at the next planned TCM. For example, every TCM was designed with the future delta V prior to the next TCM factored in. If a camera calibration was added to the plan, the effect of this unplanned delta V would result in larger than planned trajectory errors that would have to be corrected at the next TCM. Therefore, every proposed change in mission activity had to be evaluated not only for the immediate fuel consumption to accomplish the activity, but also for the downstream cost to correct the resulting trajectory error. [3] The impact of this was not as great during the prime mission because there were ample fuel margins available to correct the trajectory. However, this concern was magnified during the extended mission because the spacecraft was nearing the end of its fuel supply and fuel budgets were being tracked to the grams of fuel needed for operations.

The spacecraft was launched with 87 kg of hydrazine fuel on board. Fuel consumption was tracked by accounting for all the thruster pulses reported in the engineering telemetry and adding up the fuel used with each pulse based on the thruster specific impulse (Isp). The estimate was based on pre-launch thruster performance tests coupled with the state of the tank temperature and pressure during the mission. This estimate was periodically tested against the pressure, volume, temperature state of the tanks. This was a standard method for tracking fuel use on spacecraft. The error in this estimate was estimated to be ±1.0 kg, primarily based on an error analysis that accounted for sensor performance. At the beginning of the extended mission, the estimate of remaining fuel was 17.1 ±1.0 kg.

One feature of the flyby mission was the desire to fly by the comet at the optimum time for viewing the impact site from 2005. Since fuel consumption was a prime consideration, the optimum time to perform the maneuver that would adjust the time of arrival at the comet with minimum fuel use was a full year before arrival. This would result in the lowest fuel cost for this maneuver. While the science team undertook the challenge of estimating the rotational phase of the comet at the arrival time based on the observed phase and rotational rate during the 2005 Deep Impact encounter and subsequent ground and spaced based comet observations, the operations team looked for additional ways of estimating the remaining fuel. An alternate method had been developed and utilized on several earth orbiting missions. The PGS (Propellant Gauging System) methodology [1] relies on building a detailed thermal model of the fuel tank and its interaction with the spacecraft and any other thermal boundaries. This model is then correlated to thermal transient data obtained by heating and cooling the spacecraft fuel tank, thus calculating the contribution of the thermal mass of the fuel to the transient thermal behavior. Such heating tests were implemented on the Stardust spacecraft in 2008 and 2009 the data was incorporated in the PGS model. This yielded a prediction of 10.8±0.4 kg remaining fuel, compared to the 12.9±1.0 kg predicted by the 'book-keeping' system at this stage of the mission.

This significantly lower result, combined with the sensitivity of the fuel needed for trajectory corrections based on mission activities, prompted an early effort to plan all the comet approach and flyby activities in detail quite early in the mission in order to understand the fuel budget with enough resolution to support the project's decision on how much fuel to allocate to the time of arrival maneuver. This fuel budget accounted for details such as how many grams per day would be used for spacecraft pointing, the exact number of turns that the spacecraft would execute on its way to the comet, whether the turns were slow walks or fast slews, the spacecraft orientation, the number and content of all camera calibrations, camera bake-outs, number of images taken on comet approach and the uncertainty in the magnitude of the final course corrections necessary for the desired flyby location relative to the comet. The fuel budget also had to account for unforeseen events such as spacecraft safe mode entries. All this planning was completed 14 months before arrival at the comet in order to support the decision on the magnitude of the time of arrival maneuver to be executed in February 2010.

In January of 2010 the final results predicting the comet phase at the time of arrival were reviewed and the decision was made to adjust the time of arrival 8.5 hours earlier. Upon execution of the maneuver, this decision irrevocably committed the mission to its arrival time as well as the fuel available to get there. Fuel management would become a key theme in all upcoming risk reviews. The only choice available to the project to reduce fuel use from then on would be to eliminate science imaging and the associated slews, reduce the number of camera bake-outs, or reduce the number and content of calibrations prior to the flyby. The consequence of running out of fuel before arriving at the comet would be loss of the mission due to the resulting inability to control the spacecraft pointing.

In order to continually understand whether the fuel usage was proceeding as planned, a chart was created that showed all the planned fuel consumption through the end of the flyby. Each time new telemetry was received from the spacecraft, the actual fuel use was plotted against this plan, giving a running view of how the plan was unfolding.

The PGS exercises carried out in 2008 and 2009 predicted the remaining fuel between 2.1 and 2.5 kg lower than the bookkeeping method. One last PGS exercise was performed in the Fall of 2010 to obtain a final fuel estimate comparison prior to beginning the comet approach period. This time the PGS result predicted an additional 0.65 kg lower than the previous iterations [2]. Late in the mission, this prompted several decisions to reduce the planned fuel consumption even further to maintain a small but positive fuel margin. A few factors worked in the project's favor to reduce the impact of this new result.

Sequencing of commands is a key feature of all deep space missions since the round trip light time for commands makes it impossible to do any real time commanding during critical events. At this point in the mission, the round trip light time between Earth and the spacecraft was approximately 38 minutes. Because of this, all activities on board the spacecraft were controlled by on board sequences that were uploaded in advance, controlling the spacecraft turns, imaging, and downlinks for a week at a time during approach. Having an experienced team that had built the sequences with reusable blocks enabled the project to quickly adapt to mission changes with minimal risk. This ability was exercised several times on approach as the project dealt with changes in the imaging plans due to electronic noise in the imager, stray light at some attitudes, and smear due to the thruster-based dead-banding. The team was able to modify the exposure frame sizes, exposure times, and spacecraft re-orientation quickly by making limited changes to parameter tables used by the on board sequences resulting in operational agility without significantly increasing the chance of making errors.

Another factor that worked in the project's favor was that as the spacecraft got closer to its target, the effect of delta V on the spacecraft trajectory continued to diminish. So, even though trajectory changes cost more fuel, changes to the planned activities had correspondingly smaller impact on the total fuel expenditure.

The last reduction in predicted available fuel was unwelcome news at a critical time in the mission. The plan had been to begin a campaign of daily comet imaging for both science and optical navigation purposes 60 days before arrival. The project had the choice of ignoring this new, worse case prediction with the risk of prematurely exhausting the ful supply or changing the plan to accommodate it. The only choice left to reduce fuel consumption was to delay the start of daily science imaging by a month until E-30 days. This decision saved all the spacecraft turns necessary to point the imager at the comet. A weekly optical imaging set was retained in the plan for navigation purposes. Since the comet was too dim to detect with the camera at this time, this resulted in no net reduction in science. Additionally, the comet ephemeris calculations during the approach phase resulted in approach maneuvers that were smaller than the worse case estimates that had been used for planning purposes.

All this effort culminated in a February 14, 2011 flyby of comet Tempel 1. The estimated flyby altitude was 178 km above the surface of the comet, the optimum point to maximize the image resolution, allowing the scan mirror to keep up with the comet movement in the field of view without any smearing. The time of arrival also proved to provide ideal viewing conditions of the location where Deep Impact delivered the Impactor in July 2005. The arrival time also enabled the spacecraft to obtain the desired balance of images of terrain previously observed by Deep Impact and new terrain never before imaged.

After transmitting all the images stored in the computer memory to Earth and verifying that all had been received uncorrupted on the ground, the memory was erased and the spacecraft resumed imaging of the comet as it receded, providing additional light curve data upon departure.

IV. Decommissioning

The project plan called for departure imaging as long as the comet was detectable by the camera, followed by preparations for decommissioning the spacecraft in March 2011. Since the post-mission orbit of the spacecraft was shown to be safe at the time of the proposal, and there was not enough fuel on board to make any meaningful change to this orbit, the only requirement for a decommissioning activity was to ensure that the spacecraft was placed into a known state, with the transmitter turned off. The latter was to ensure there would be no possible frequency interference with other spacecraft using the same X-band communication frequencies. However, since fuel management had been such a central theme in the last part of the mission, the decommissioning provided a rare opportunity to determine how much fuel actually remained on board.

The decommissioning activity was thus designed with a final thruster burn to be executed at a spacecraft orientation that maintained real time telemetry throughout the burn. The sequence was built to command a burn many times larger than the fuel predicts would support, with the thought that it would allow the ground to see the entirety of the remaining fuel consumed before the sequence commanded the transmitter off. After consuming all its remaining fuel, the spacecraft would no longer be able to control its attitude, it would gradually drift so that the sun would no longer illuminate the solar arrays, the battery would drain, and the spacecraft would turn off and remain inert in its heliocentric obit.

The spacecraft signaled its readiness to retire a few days before decommissioning, when the telemetry showed a small step change in the tank pressure. The propulsion subsystem engineers reviewing the data concluded that this was a sign of pressurant gas being ingested into the screen of the propellant management device, indicating an empty tank. The decommissioning burn a few days later, on March 24, 2011, showed that the first thruster indicated signs of processing both gas and fuel 30 seconds into the burn, indicating that the tank indeed was empty at the start of the burn.

The decommissioning burn showed that the PGS methodology had provided the most accurate estimate of remaining fuel for this particular situation. There had been many discussions within the operations and science teams about the conservatism of these results and the impact it was having on the mission planning. However, had the project not adjusted its mission plan to account for this worst case prediction, the spacecraft would not have had enough fuel to complete its mission, and would not have captured the images the comet shown below. Figure 3 shows four close up views of 9P/Tempel 1 during the flyby. Figure 4 shows a side-by-side comparison of the impact site. The image on the left was taken by the Impactor on its way in to the comet in 2005. The center image was taken by Stardust in 2011. The arrows in the image on the right show the location of the impact. The changes n the comet surface due to the impact are surprisingly subtle, revealing that the surface material has the consistency and strength of loosely packed dry snow. [4]

One key lesson from this experience is that risk and resource management remain critical until the very end of the mission. Had the team not pursued an alternate approach to estimating remaining fuel, the fuel would have been exhausted prior to reaching the target and obtaining the high value science. Effective risk management relies on good data, and thus the team should continually assess whether there are other approaches to analyzing a problem or gathering data to evaluate an issue. The mission planning must always adapt to the latest understanding of the worse case conditions in order to ensure that the goals of the mission are protected. This requires the various teams to work cooperatively to adapt to changing situations while understanding each other's needs. The final year of the Stardust mission required constant balancing of the science, navigation, and operations team efforts to ensure success. Frequent communications and open discussion of difficult issues were of utmost importance, and all the project teams showed outstanding skill and cooperation. The success of this mission is directly attributable to these teams and the way they worked together to evaluate, adjust, and conquere these challenges.

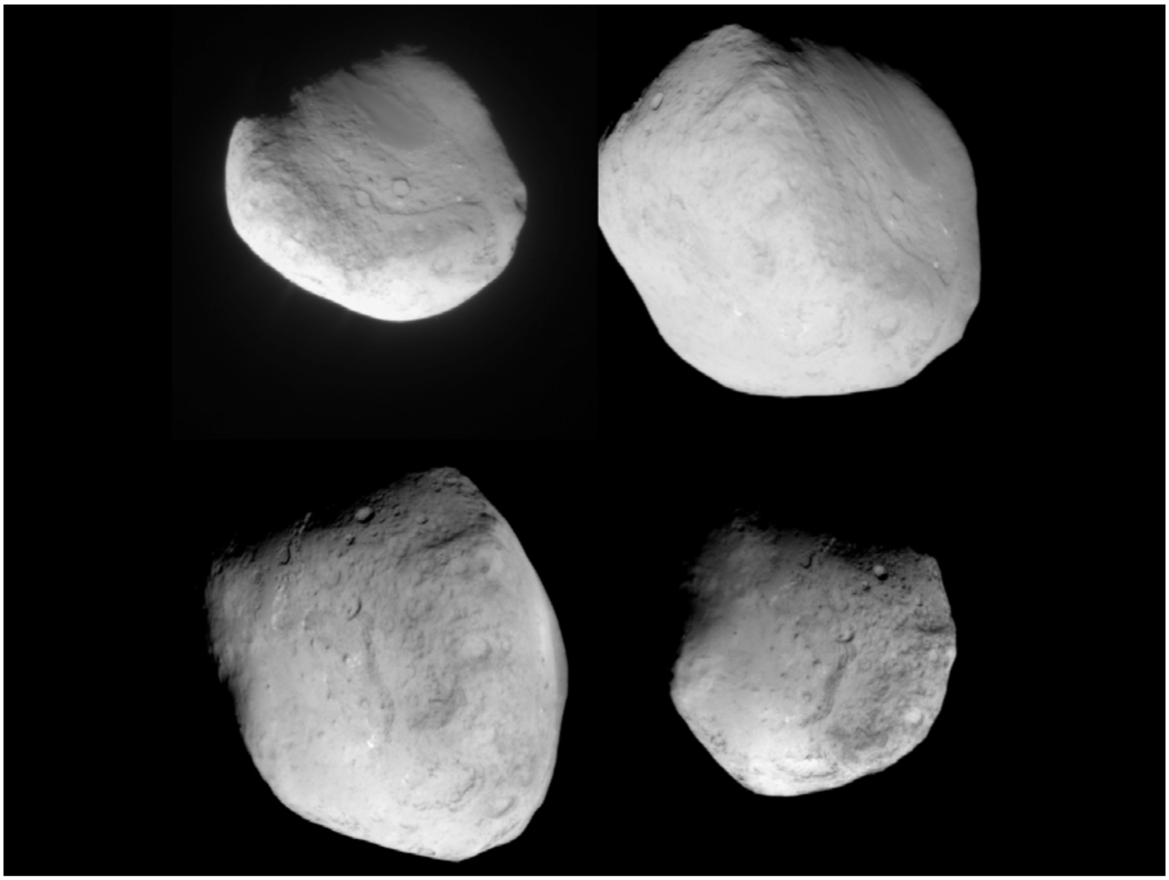

Figure 3 - Views of Tempel 1 nucleus around closest approach.

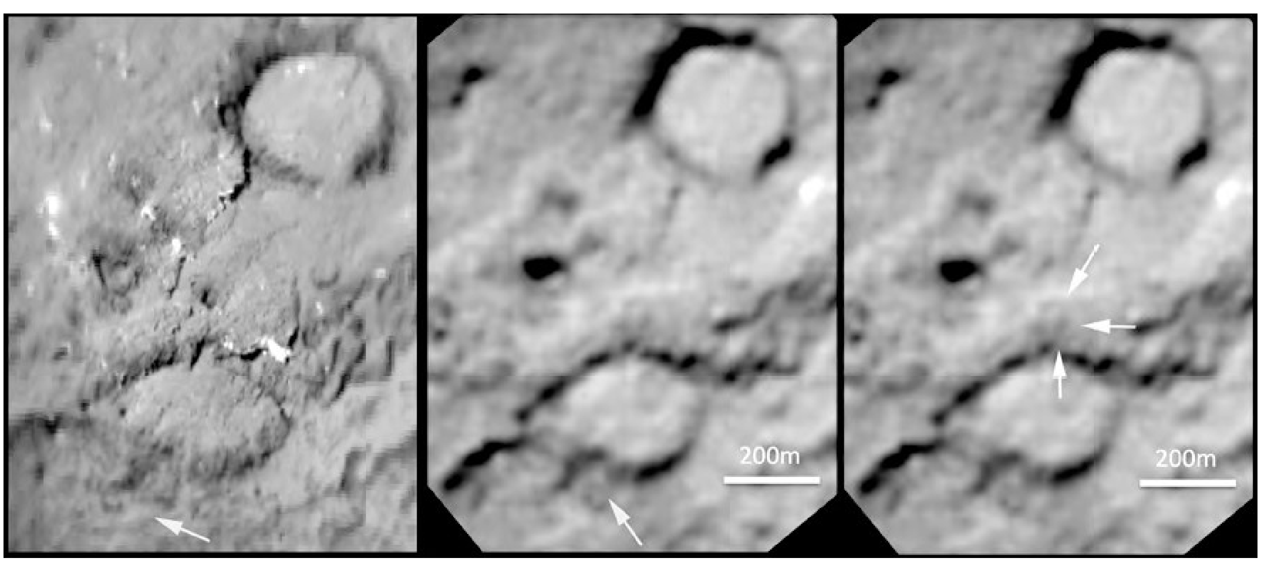

Figure 4 - DI Impact site. Pre-impact (left) and post-impact (center and right). Arrows at bottom show direction of incident sunlight in DI and SN views. Cluster of arrows in rightmost image point to the impact site.

V. Conclusion

The success of the Stardust NExt mission depended on having enough fuel to reach its target and maintain attitude control during the imaging campaign and subsequent downlink. The ability to effectively manage fuel consumption in the last year of the mission required a new approach to estimating the remaining fuel, close coordination between the operations, navigation, and science teams, and the flexibility to adapt to changing circumstances. Doing this required frequent communication, awareness of the needs and challenges of other team members, and willingness to adjust the mission plan. Early agreement on the science content, implementation approaches, and operational constraints provided the project with a sound baseline for planning. As late developments provided new challenges, the dedication, skill, and collaborative nature of the teams provided the tools for mission success.

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