Modeling of Deadbanding DV for the Stardust Earth Return: Calibration, Analysis, Prediction and Performance

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On January 15th, 2006, 0556 UTC, the Stardust spacecraft released a 42-kg Sample Return Canister (SRC) along a trajectory intended to impact a target on the Air Force Utah Test and Training Range (UTTR), near Dugway, Utah. Assurances of a successful SRC delivery to UTTR depended on identifying (and mitigating, if possible) a myriad of error sources. These sources included atmospheric effects, maneuver execution, Orbit Determination (OD) uncertainties and ΔV induced by the firing of the unbalanced Reaction Control System (RCS) thrusters needed for deadband attitude control. Every mm/s in prediction error at the TCM-19 epoch would amount to missing the target by approximately one kilometer[1]. This paper will describe the work performed in analyzing and predicting the levels of ΔV caused by the attitude deadbanding, as well as prediction performance.

I. Mission Background

During its 7-year interplanetary mission, the Stardust Spacecraft collected samples of particles from the interstellar dust stream, as well as samples of dust and particles that made up the coma of Comet Wild-2. This latter collection took place on January 2nd, 2004, during a highly successful flyby of the comet, with a closest approach distance of less than 200 miles. Once collected, these samples were stored within a Sample Return Capsule (SRC) for delivery to Earth in mid-January, 2006.

For most of 2005 and 2006, the spacecraft was in the final deep cruise portion of the mission trajectory, with ground teams (including Navigation) preparing for the final events leading up to the delivery of the SRC. For the Navigation team, these preparations included routine orbit determination[1] and maneuver planning[2], as well as participation in project-wide rehearsals and readiness tests. Also, a great deal of technical work remained, including refinement of the final maneuver plans and continued study of the spacecraft attitude control performance. In the case of the latter, the predicted behaviors of the attitude controller during nominal stationkeeping, attitude changes and maneuver execution would need to be verified. Appropriate consideration of all these effects within nominal entry scenarios could then show that the Stardust spacecraft would be able to successfully deliver the SRC to the Air Force Utah Test and Training Range (UTTR), near Dugway, Utah.

This paper will discuss the calibration, analysis and prediction of the ΔV incurred during periods of nominal stationkeeping. The application of these predictions to operations maneuver design is also discussed.

II. Spacecraft Attitude and Trajectory Control

The Stardust spacecraft (Fig. 1 and 2) utilizes a three-axis stabilized Attitude Control System (ACS). Since the spacecraft is not equipped with reaction wheels, control is asserted entirely by the hydrazine thrusters of the Reaction Control System (RCS). This attitude actuation is primarily driven by the use of a deadband controller, designed to keep each axis of the spacecraft within a specified range (in degrees) about a specified reference attitude.

The RCS thrusters are located on the opposite side of the vehicle from the deployed position of the sample collector in order to minimize hydrazine contamination of the samples. The thruster subsystem includes two strings (prime and backup) of four main thrusters (1 lbf each) used for TCMs and four reaction control subsystem (RCS)

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thrusters (0.2 lbf each). Since such thruster placement and orientation does not produce balanced torques, all attitude control activities contribute a translational ΔV that lies nominally in the direction of the spacecraft +Z-axis. These RCS thruster events must be accounted for in orbit determination (OD) and prediction processes. The idealized expectations of ΔV in the spacecraft frame are shown in Table 1.

For the final months of the cruise portion of the mission, the use of relatively loose deadbands was in effect, primarily to maintain pointing of the non-steerable high-gain antenna during communication and tracking periods. For the month prior to Earth return, the controller was changed to use much tighter deadband constraints, primarily to give the Navigation team stable periods in which to observe long-term controller performance. The driving need for these tight deadbands was to provide accurate attitude control during the SRC-release event.

The RCS response in the context of deadband control is deterministically predictable, but such predictions are subject to error because of variances in pulse-to-pulse thruster performance, solar distance (which causes variations in torque produced by solar radiation pressure) and changes in the Sun-relative spacecraft attitude (which affects solar-induced torque).

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TIFF (LZW) decompressor
are needed to see this picture.

Figure 1. Spacecraft Configuration (Thrusters)

A. Attitude Profile

Over the course the mission, the attitude profile underwent many changes. As flown, the attitude profiles preceding Earth return are shown in Table 2.

B. Maneuver Plan

Over the course the mission, the maneuver profile underwent numerous changes. The final timing and deterministic biasing of the maneuver plan during the return phase is shown in Table 3. These maneuvers were intended to deliver the Spacecraft on an Earth-impacting trajectory, but were also designed to account for execution errors of past maneuvers. As a matter of principle, the design of TCM-18 was desired to be close Sun-pointed as possible (to minimize power issues) and the design of TCM-19 was desired to be in the same inertial attitude as the SRC release event.

For each maneuver design cycle, an update to the predicted inertial ΔV due to RCS thruster events incurred during the future attitude profiles was required to assure maneuver effectiveness.

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Figure 2. Spacecraft Configuration (major components)

Table 1. Idealized ΔV per pulse, in spacecraft body frame.

Controlled Axis	X-axis ΔV (mm/s)	Y-axis ΔV (mm/s)	Z-axis ΔV (mm/s)
+X (pos. roll)	0.0	-0.02	0.073
-X (neg. roll)	0.0	0.02	0.073
+Y (pos. pitch)	0.0	0.00	0.073
-Y (neg. pitch)	0.0	0.00	0.073
+Z (pos. yaw)	0.0	0.00	0.073
-Z (neg. yaw)	0.0	0.00	0.073

Table 2. Attitude profiles for Earth Return phase of mission.

Time Ranges	Deadband Tolerances	Reference Attitude
07/11/05-12/27/05	2º about X- and Y-axes, 10º about Z-axis	Earth-pointing of Z-axis (High-Gain Antenna (HGA) boresight)
12/27/05-01/05/06	0.25º about all axes	29º pitch, 0º roll, 11º yaw (All Sun-relative)
01/05/06-01/14/06	0.25º about all axes	29º pitch, 20º roll, 11º yaw (All Sun-relative)
01/14/06-01/15/06	0.25º about all axes	Identical to previous, but with transition to inertial hold from Sun-relative pointing.

Table 3. Earth-targeting Maneuvers

Maneuver	Date	Deterministic Component
TCM-17	November 17th, 2005 (E-6 days)	None.
TCM-18	January 5th, 2006 (E-10 days)	1.4 m/s, sun-pointed
TCM-19	January 14th, 2006 (E-29 hours)	1.0 m/s, release attitude

C. Calibration Periods

To best predict the inertial ΔV incurred during the attitude profiles noted in Table 2, selected periods of time in which the spacecraft was operating in similar conditions were observed and the behavior was quantified. These periods are listed in Table 4. The first and second items in Table 4 were previously analyzed[4], and those data were re-analyzed during the Earth return phase. The first, second and fifth periods described in Table 4 were carefully planned calibration activities designed to emulate the end of mission attitude profile conditions. The third, fourth, sixth and seventh periods were observations of nominal spacecraft performance during cruise and approach. The latter periods provided long baselines over which the effects of torque from solar radiation pressure could be observed.

III. Application of Calibration Data and Flight Data

Predicting future deadband activities required characterizing the behaviors of the attitude regimes described in Table 4. The spacecraft thruster telemetry was processed and categorized into 6 quantities: one-sided deadbanding pulses about roll, pitch and yaw, as well as two-sided deadbanding pulses about roll, pitch and yaw. Two-sides pulses were considered to be any pairing of a positive-axis and negative-axis thruster firing within a given time sample. One-sided pulses were considered to be any residual thruster firings within the same time sample. The solar torque effects were directly observable in the residual thruster firings about a given axis.

Once quantified, correlations between pulse frequency, solar distance and Sun-relative attitude angle were identified, and these correlations were extrapolated in order to fit models to the Earth Return conditions. For attitudes in which solar torque was present, the behavior of the data indicated that the torque response was independent of off-Sun angle, and showed an inverse-R^2 dependence. This was most readily observable during long-term periods of flight data (items 3 and 4 in table 4.) From the data observed in each calibration period, a model of pulse frequencies at 1-AU was generated. This model was fed into a tool that generated predicted ΔV based on expected pulse frequencies at 1-AU, distances to the Sun and nominal ΔV per thruster pulse. Once the pulse frequencies for each family of attitudes were determined, appropriate generation of predictions for expected ΔV could commence.

Table 4. Calibration periods (1, 2 and 5) and samples of flight performance (3, 4, 6 and 7)

	Date (approx.)	Deadbands	Attitude (Off-Sun angle)	Sun Distance (AU)	Observed Z-axis ΔV (cm/s/day)
1	Summer, '03	0.25º	26º pitch	1.00	3.3
2	Summer, '03	0.25º	26º pitch, 18º roll	1.00	4.4
3	Spring/Fall, '03	2º/10º	Z-axis on Earth, variable pitch, no roll	1.00 to 2.00	3.0 to 2.0
4	Summer/Fall, '05	2º/10º	Z-axis on Earth, variable pitch, no roll	1.00 to 2.00	3.0 to 2.0
5	November, '05	0.25º	29º pitch, 20º roll	1.15	5.5
6	December, '05	0.25º	29º pitch, 11º yaw	1.05	3.5
7	January, '05	0.25º	29º pitch, 11º yaw, 20º roll	1.00	4.5

A. Predictions for TCM-17 Design

The design of TCM-17 (item 1, Table 3) required construction of predictions based on the calibrations taken during the summer of 2003, and observed flight performance from 2003 and 2005 (items 1, 2, 3 and 4 from Table 4). Since the final calibration of deadbanding (item 5, Table 4) was not scheduled until after TCM-17, these data could not be used to construct the predictions. Due to other uncertainties about the spacecraft performance[3,4], these predictions were intended to be accurate enough to deliver the spacecraft on a trajectory that would allow the (then upcoming) TCM-18 burn direction to be within 60º of the Sun, and the burn magnitude to be greater than 1.4 m/s[§].

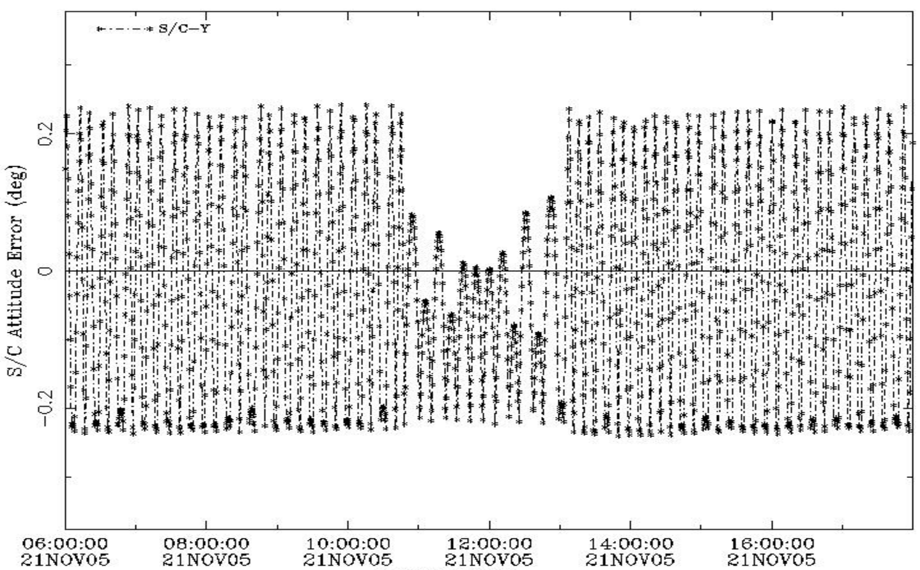

Figure 3. Anomalous pitch deadbanding behavior observed during November calibrations.

[§] The need to bias maneuvers sunward was project requirement to maintain positive power from the solar panels during the long transitions to and from the burn attitude.

B. Predictions for TCM-18 Design

The design of TCM-18 (item 2, Table 3) required construction of predictions based on the calibrations taken during the summer of 2003 and November of 2005 (items 2, 5 and 6 from Table 4). Since the actual flight performance of last deadbanding regime (item 7, Table 4) would not be seen until after TCM-18, this prediction was based on combinations of the yaw and roll performance observed during the November calibration (item 5, Table 4) as well as the pitch performance observed during the Summer, 2003, calibrations (item 2, Table 4). The need to deliver a hybrid model for this critical prediction was based on the observations of bimodal behaviors in the pitch performance during the November calibrations. This bimodal behavior can be seen in Fig. 3 as a temporary decrease in pitch activity. These bimodal pitch behaviors were not observed in the 20003 calibration data, and it was concluded that this particular signature of deadbanding behavior is very sensitive to Sun distance. Due to other uncertainties about the spacecraft performance[3,4], these predictions were intended to be accurate enough to deliver the spacecraft on a trajectory that would allow the (then upcoming) TCM-19 to be > 1.0 m/s, and executed as a fixed-direction maneuver, performed in the inertial release attitude. This would allow the TCM-19 to solely control flight path angle at the atmospheric entry interface[1], and consequently affect the alongtrack delivery errors to the UTTR. This also meant that TCM-18 (at E-10 days) would be the last nominal maneuver to control crosstrack delivery to the UTTR.

Making the prediction for the post-TCM-18 ΔV more difficult was the direct effect that one-sided roll deadbanding had in the spacecraft Y-direction (see Table 1). The nature of the inbound trajectory was such that unmodeled ΔV in the spacecraft Y-axis directly mapped into a cross track delivery error. Errors in the prediction of the pitch and yaw controlling pulses could be accounted for by a fixed-direction TCM-19, but a large error in the prediction of the one-sided (unbalanced) roll pulses might have required the design of a full maneuver for TCM-19.

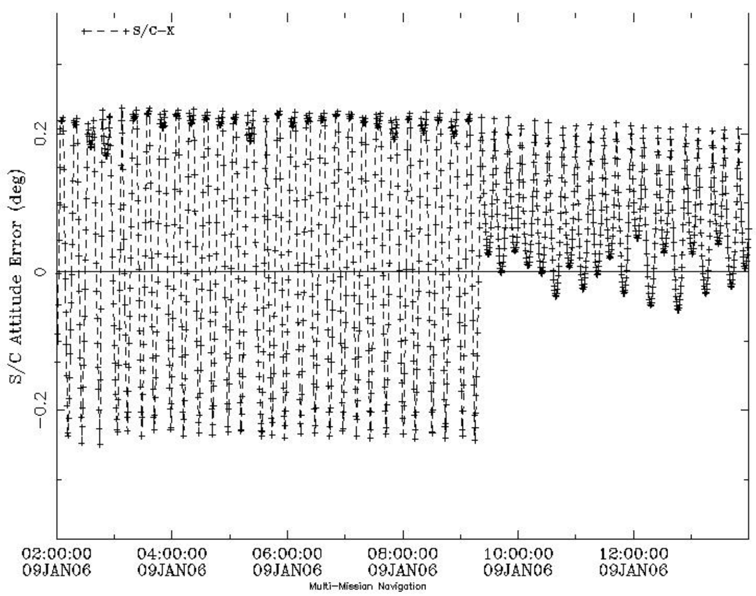

Figure 4. Anomalous roll deadbanding behavior observed during flight, in early January, 2006

This was an undesirable contingency, given that this would have required the spacecraft to transition out of (and back into) the release attitude. These attitude transitions would have added additional uncertainty to the prediction process. Reference 2 describes the prediction selection matrix trade study in greater detail.

C. Predictions for TCM-19 Design

The design of TCM-19 (item 3, Table 3) required construction of RCS thruster event predictions based on observed flight performance from early January 2006 (item 7 from Table 4). At the time of this delivery, it was observed that the roll performance was showing the same bimodal behavior at 1-AU distance that the pitch performance was showing during the previous November calibrations. This can be seen in Fig. 4 as a decrease in activity about the roll axis. This can also be seen quantitatively in Fig. 5, as periods of two-sided roll activity (10 pulses/hr) are interspersed with periods of completely one-sided activity (0 two-sided pulses/hr). Although this variance in performance was qualifiable and the mode transition signatures were quantifiable, the times at which

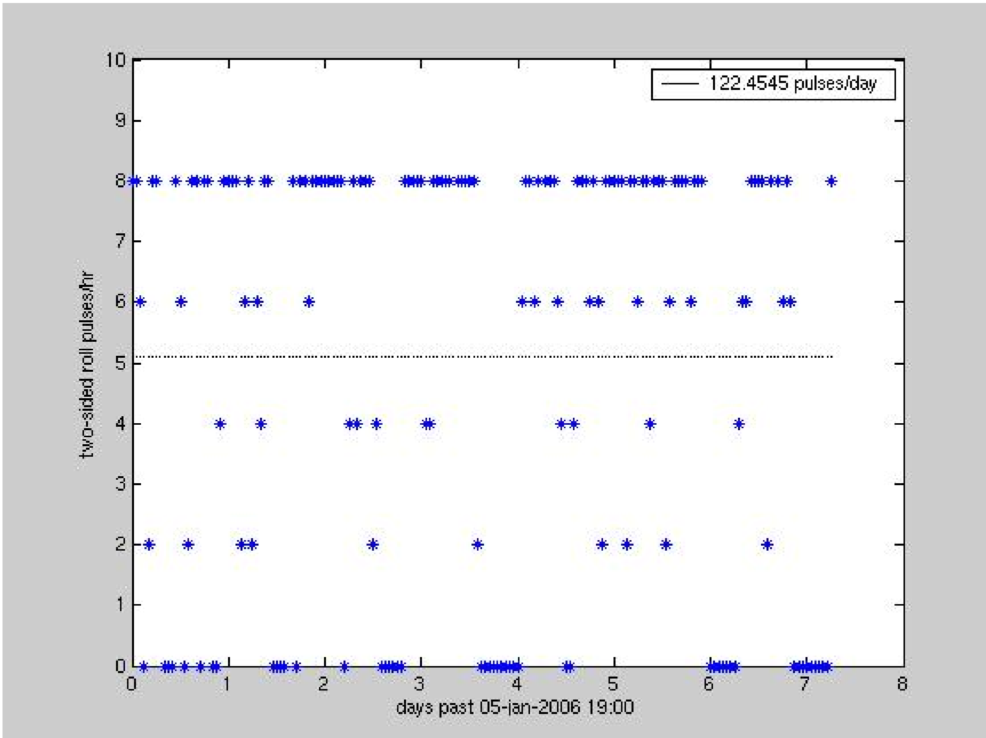

Figure 5. Two-sided (balanced) pulse counts per hour, for the period between TCM-18 execution and TCM-19 design.

these mode transitions would occur were not predictable[**]. No assumptions were made that would model the transition times, so a model containing pulse frequencies that reflected the relative contributions from the two modes was delivered for the TCM-19 design.

IV. Navigation Performance

TCM-18 and -19 were executed within the specifications required for a nominal Earth return. The final design and execution of TCM-18 was 2.4 m/s, and was within 18º of the sun. The desired conditions for TCM-18 were that it be > 1.4 m/s, and that the burn direction be within 60º of the sun. The final design and execution of TCM-19 was 1.3 m/s, and performed at the release attitude. The desired conditions for TCM-19 were that it be > 1.0 m/s, and performed at the release attitude. A minimization of delivery error to UTTR was also desired, and this was met, with the final crosstrack and alongtrack delivery errors being 3 km and 6 km, respectively. These delivery numbers are with respect to the targeted landing point within UTTR, and do not account for weather dispersions after entering the atmosphere.

V. Conclusion

The Stardust Earth Return was an unqualified success. The predictions of deadbanding behavior were accurate enough to meet requirements for the design of TCMs -18 and -19. The SRC was also delivered to the atmospheric

[**] It is hypothesized that the pitch transition from two-sided deadbanding to solely one-sided pitch deadbanding is a result of two items: the implementation of an attitude error minimization algorithm in the Flight Software (FSW), and the cross-axis torque caused by the impulse differential between frequently-used and infrequently-used thrusters.

entry interface with a predicted UTTR delivery error of 6 km alongtrack (NW), and 3 km crosstrack (SW) from the nominal target.

The frequencies of the thruster firings during Earth Return were definitively bimodal. Future Earth Return Missions (should they be delivered by unwheeled spacecraft equipped with unbalanced RCS thrusters) will need to contend with mitigating this behavior as a source of error. At distances of 1-AU, the effects of solar torque on controller dynamics increase the uncertainties of the predicted rate of thruster firings. Conversely, these close solar distance increase power margins, which for some missions would allow the spacecraft to remain stationed in off-Sun attitudes for long periods, resulting in efficient and predictable monomodal deadbanding.

For future sample return missions, tight deadbands should not be chosen solely on the considerations of delivery error during the sample delivery event. Opening a trade space to include better predictability of the deadband performance is worth considering. In the case of Stardust, it can be hypothesized that opening up the deadbands from 0.25º to 0.30º could have made the spacecraft behavior much more predictable during the past 10 days. This conjecture is based on the performance observed within the nominal deadbanding signatures seen on the left half of figure 4. Also, disabling of the FSW error minimization algorithm (previously alluded to in footnote) would need to be considered.

Calibrations are important, and the timing and duration of calibration periods should be given careful consideration. This need is even more critical when bimodal behaviors are hypothetically possible. In the interest of identifying hypothetical bimodal behavior, tools that model spacecraft attitude dynamics, thruster temperature variances and solar torque effects have proven to be very useful. If calibrations are not feasible, the attitude and maneuver plan should be constructed to take advantage of observed deadbanding behavior so that post-maneuver DV predictions can be generated with a high degree of confidence.

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