On-Orbit Maneuver Calibrations for the Stardust Spacecraft

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The Stardust spacecraft, launched February 7, 1999, successfully delivered its sample return capsule to the Utah Test and Training Range on January 15, 2006. The entry maneuver strategy included a trajectory correction at entry minus 10 days (TCM18) targeted to entry with the inclusion of a final biased fixed direction maneuver at entry minus 29 hours (TCM19). To meet the stringent entry targeting requirements necessary for human safety and capsule integrity, a campaign of maneuver calibrations were undertaken in summers of 2003 and 2005 to improve performance for both maneuvers. The results of the calibration program are reported here. The in-flight calibrations included a series of several turns to various final attitudes via deadband walks about each of the three spacecraft axes, as well as 12 in-place burns with magnitudes between 0.5 and 1.0 m/s, the range initially expected for TCM19. The turn and burn calibrations as well as the performance of TCM 17, 18 and 19 are discussed.

I. Introduction

After a seven year cruise, the Stardust spacecraft successfully delivered its sample return capsule to the Utah Test and Training Range on January 15, 2006. To meet requirements for both capsule integrity and human safety, an entry flight path angle error of less than 0.08 degrees was desired. In order to to meet this stringent requirement while meeting operations feasibility constraints, the final fixed direction maneuver (TCM 19) correcting only flight path angle was executed at entry minus 29 hours (E-29h). Targeting for the remaining position components was accomplished using a full vector trajectory correction (TCM 18) at entry minus 10 days (E-10d).[1] Since it had been observed during previous maneuvers that the maneuver magnitude was biased by thruster activity during turns associated with a maneuver and return to normal attitude, two campaigns of maneuver calibrations were undertaken in summer of 2003 and 2005 to improve the design and error assessment for the final two maneuvers.[2] This paper reports on the results of the 2005 campaign along with a reanalysis of some measurements taken during the 2003 campaign.

Stardust is a 3 axis stabilized spacecraft designed operate during a cruise which brings it up to 3.6 AU from Earth and 2.7 AU from the sun and support a prime mission to collect dust samples at Comet Wild-2 while 2.6 AU from Earth and 1.9 AU from the sun.[3] Propulsive maneuvers are performed using a hydrazine propulsion system comprised of a propellant tank and two strings of eight thrusters. The thrusters are mounted in four clusters on the lower deck of the spacecraft, opposite the sample collector and solar panels (Fig 1). Each cluster consists of one primary and one redundant 0.2-lb thruster for attitude control (RCS) and one primary and one redundant 1.0-lb thruster used for propulsive maneuvers (TCM). The unbalanced mounting configuration of the thrusters, designed that way to reduce contamination of the sample collector, results in a net impulse during any spacecraft turn or attitude control activity. The in-flight calibrations included a series of several turns to various final attitudes via deadband walks to better characterize the magnitude and repeatability of the resulting impulse. In addition, a set of 12 in-place burns were performed to characterize the impulse associated with maintaining attitude control during a burn and regaining attitude control afterwards. The burns had magnitudes between 0.5 and 1.0 m/s, the range initially expected for TCM19. Results from the calibration maneuvers were extrapolated and applied to TCMs 17, 18 and 19, which were all larger than the calibration maneuvers (see Table 3).

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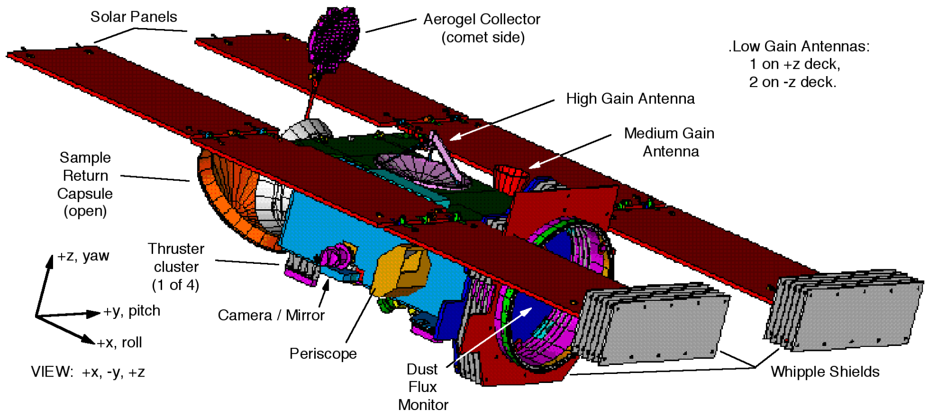

Figure1. Stardust Spacecraft in sample collection configuration.

II. Analysis

A. Turn Calibrations

Spacecraft turns can be achieved using the RCS thrusters either by quick slews or slower deadband walks. Due to the unbalanced configuration of the RCS thrusters, all turns result in a net delta-v directed approximately midway between the start and stop direction of the turn. Since the slower deadband walks have smaller and more predicFig associated delta-v, the Earth return navigation strategy included use of this type of turn during the critical last two maneuvers, and this is the type of turn that was studied during in-flight calibrations. These calibration values were used to bias the commanded values of the last few TCMs. A set of several calibration walks at several turn angles about the pitch (y) and roll (x) axes were conducted in June 2003 and their range was extended to in August 2005, to obtain a bias delta-v associated with a walk and characterize the expected dispersion. Due to spacecraft geometry and mass configuration asymmetry, turns about each axis were characterized separately. Table 1 lists the specific turns that comprise the data set for the turn calibrations. Note that each sample consists of a paired set of turns to a commanded attitude and then back to the initial attitude.

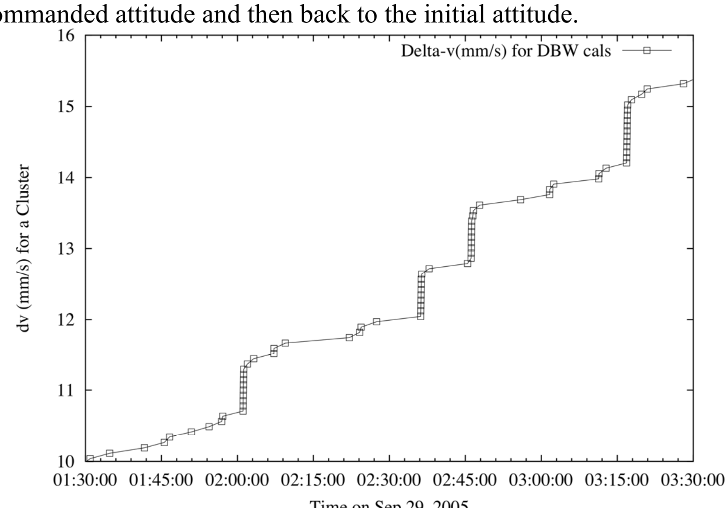

Figure 2. Time series of impulses associated with a pair of deadband walk turns

Spacecraft telemetry during each turn gave a time history of thruster firings that could be correlated with the commanded time of each turn maneuver. Figure 2 shows a time series of impulses associated with RCS thruster firings during a typical pair of turns. Each turn is characterized by a set of thruster firings to initiate the turn, another set to end the turn and a few firings during the coast to the new attitude. Firing statistics for these three periods were tabulated for each turn in the data set and then averages and standard deviations calculated for each type magnitude and axis of turn. Finally, the absolute magnitude of the total impulse for the turn was calibrated using an empirical value derived from fitting thruster impulses as part of orbit determination. The fit periods used for the orbit determination process ranged from a week to several months and consistent behavior was seen for the scaling parameter.

B. Maneuver Magnitude Calibrations

While the main impulse for a TCM on Stardust comes from the larger TCM thrusters, the execution sequence of a propulsive maneuver includes a set of attitude corrections involving firings of the RCS thrusters. Due to the unbalanced RCS thruster configuration, these attitude corrections produce a velocity increment above and beyond the desired burn. These corrections include a correction to the burn attitude at the start of the maneuver, and both attitude rate correction and a final attitude correction post maneuver. To calibrate these effects and characterize the variation with respect to changes in burn magnitude, a set of 12 in-place maneuvers with three at each of 0.5 m/s, 0.75 m/s and 1.0 m/s were performed in August and September 2005. Operational feasibility concerns necessitated that only a small set of data of this sort could be gathered.

RCS thruster telemetry and attitude telemetry was examined during each portion of the pre-burn and post-burn activities to evaluate contributions attributable to each. Thruster firing counts were scaled with a value determined from orbit determination fits over a long period. The main burn magnitude was determined by fitting radiometric data, both Doppler and range collected before, after and during the burns, and accounting for pre and post burn activity. A variation associated with burn duration (and therefore magnitude) was expected associated with RCS firing to maintain attitude during the burn. It was observed that all burns required a post-burn attitude correction about the pitch axis, as expected based on the spacecraft geometry. However, three burns required a correction about the roll axis as well and one required a correction in all three axes. The conditions resulting in the extra axes correction were not predictable based on this small dataset. However, this resulted in some samples that were outliers in calculating mean biases as a function of burn magnitude. All samples were including in the final statistics shown below in Fig 3.

III. Results

A. Turn Calibrations

The deadband walk calibration turns showed very consistent behavior over the set of data collected. In both axes, the walks show a slow variation with increased turn angle, associated with the length of the coast phase of each turn (Fig. 3). The total impulse imparted during a turn is dominated by the start and stop thrust behavior which is largely independent of the target turn angle. The errors shown are simply the standard deviation seen in the set of calibrations and don't reflect any additional systematic errors. One possible source of such an error is the renormalization of the magnitude of the impulses using outside (orbit fit) analysis. The magnitude of the error accruing from this correction is small compared to the sampling error for such small data sets. Some 5-deg turns were performed during the 2003 campaign and were not analyzed in the same fashion as the larger angle turn samples, and so are not included in the final results herein. However, the behavior of the 5-deg turns is consistent with the larger turns. The same data in Fig.3 is shown in Table 1.

Table 1. Turn Calibration Data Set and Results

Turn Axis	Turn Magnitude (deg)	Number of Samples (Out and Back)	Mean Impulse (mm/s)	Std. of Impulse (mm/s)
Roll	15	10	5.22	0.30
	60	4	7.79	0.67
Pitch	15	10	3.35	0.24
	40	4	4.54	0.83
	60	4	4.64	0.56

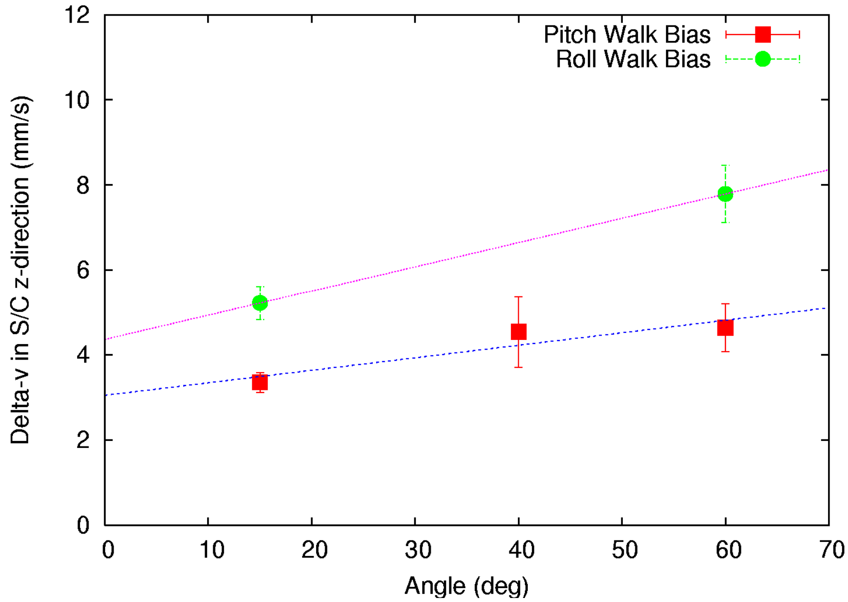

Figure 3. Delta-v contribution from deadband walks as a function of turn angle.

B. Maneuver Magnitude Calibrations

Table 2 shows average biases for each effect averaged over the samples of a given magnitude with 1s errors. Expectations for biases from these effects could be extrapolated with some confidence to larger burn magnitudes based on analysis of spacecraft attitude telemetry. For a large burn, with accompanying longer burn duration, minimal and predictable biases could be expected due to post burn attitude rate settling and attitude correction walks. The burn magnitude bias was extrapolated to have the same slope outside the calibrated range. Extrapolation to smaller magnitudes was more problematic, and the entry maneuver design strategy sought to avoid small maneuvers.[1] The maneuver bias equations derived from the data in Table 2 for burns in the calibrated range (0.5-1.0 m/s) was *Bias* = 7.6 mm/s – 2.4 mm/s per m/s x *Burn magnitude* in m/s. For burns above 1.0 m/s, the bias value used was *Bias* = 3.6 mm/s – 1.6 mm/s per m/s x *Burn magnitude* in m/s.

Table 2. Result of Entry Maneuver Demonstration Maneuvers.

Nominal Magnitude (m/s)	Delta-Burn (mm/s)	Settling (mm/s)	Attitude Correction (mm/s)	Total Bias (mm/s)
0.5	2.4±1.3	2.9±0.6	1.5±0.8	6.8±2.2
0.75	2.8±1.0	1.2±0.1	1.2±0.2	5.3±0.7
1.0	3.1±1.0	1.6±0.2	0.5±0.1	5.1±2.1
totals	2.8±1.1	1.9±0.8	1.1±0.6	5.8±2.1

C. Trajectory Correction Maneuver Performance

The final maneuvers prior to Earth entry, TCM17, TCM18 and TCM19 were designed to account for the delta-v bias resulting from RCS activity during and after the burn. Two of them, TCM 17 and TCM 18 also included biases associated with the turns to and from maneuver attitude accounted for (TCM19 was a fixed attitude burn). Final execution performance for the three maneuvers is shown in Fig 2.

Table 3. Maneuver Performance for Post Calibration Maneuvers

	Time	Desired Magnitude (m/s)	Commanded Bias (mm/s)	Expected Execution Error (mm/s) 1 sigma	Difference from Commanded (mm/s)
TCM17	E-60 day	4.1700	10.3	6.0	4.0
TCM18	E-10 day	2.3945	5.4	4.0	4.0
TCM19	E-29 hr	1.3004	5.7	2.0	1.3

IV. Conclusions

A set of several small maneuvers and turns were executed with Stardust. The additional delta-v resulting from RCS thrusting before, during and after a maneuver was extensively characterized. Performance during the last three TCMs was in family with the maneuver and turn calibrations. Execution error TCM 18 largely affected the crosstrack component of ground targeting whose error was largely dominated by atmospheric disturbance. However, For TCM 19, each millimeter per second of execution error would accrue 10 km of uprange or downrange position error from the final ground target. The entry requirement to have a 90% probability to be within the Utah Test and Training Range, given the location of the target, required an execution error of less than 5 mm/s for TCM 19. Given that a nearly 6 mm/s additional delta-v was expected to be associated with TCM 19, it was very valuable to have measured and included the expected bias in the maneuver design. TCM 18 resulted in a 4 mm/s overburn, causing a negligible contribution to the final crossrange error. TCM 19 resulted in a 1.3 mm/s overburn, resulting in an acceptable contribution to uprange error associated with the maneuver. Both maneuvers were biased based on the calibrations presented here, and performed as could be expected based on computed errors.

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