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Stardust is a 3-axis stabilized spacecraft that maintains its attitude by firing a pair of its one-sided thrusters. This thruster arrangement causes Stardust to produce unbalanced torques at each thruster firing, which yields an undesired perturbing force and makes navigation a challenge. In addition to this perturbing force, Stardust Navigation contended with the problems caused by the contamination of the Navigation Camera and the experience of flying through 2 solar conjunctions during Stardust's inbound leg to the Wild 2 encounter. Both the contamination and the solar conjunctions were major challenges Navigation had to overcome. Descriptions of the Stardust mission, the spacecraft trajectory and discussion of the navigation challenges will be provided, as well as discussion of the orbit determination estimation procedure, models and performance accuracies.

INTRODUCTION

Stardust, the fourth mission flown under the National Aeronautics and Space Administration's Discovery Program, was launched on February 7, 1999 from Cape Canaveral, Florida. The primary objective of the Stardust mission is to collect comet dust particles during encounter with the comet Wild 2 in January 2004, and return these samples to Earth in January 2006. Stardust performed additional science measurements during the comet fly-by, which included composition analysis of the comet particles in real-time, kept count of the number of particles the spacecraft encounters, and took pictures of the comet nucleus throughout the encounter. The instruments used to perform all of these tasks include the Aerogel Collector Grid, the Comet and Interstellar

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Dust Analyzer (CIDA), the Dust Flux Monitor (DFM), and the Navigation Camera (NavCam), respectively. After executing a successful fly-by of the asteroid Annefrank in November 2002, Stardust was 7 months from completing its second orbit around the Sun (at 2.3 AU away from the Sun), heading for its main science mission target Wild 2. Spacecraft attitude-maintenance thruster firings, contamination of the NavCam, and 2 solar conjunctions during this part of the trajectory introduced three navigation challenges to the orbit determination task. A more detailed description of these navigation challenges and their resolution will be provided in the paper, as well as a discussion of the orbit determination estimation procedure, models and performance assessment.

TRAJECTORY AND SPACECRAFT DESCRIPTIONS

Lift-off of the Stardust spacecraft occurred on February 7, 1999 at 14:04 EST aboard a three-stage Delta II launch vehicle and was placed directly into an interplanetary orbit about the Sun. The spacecraft trajectory was designed to make 3 orbits around the Sun before it returns to Earth (see Fig. 1): 1) During the first orbit, the spacecraft began its first of two campaigns (spanning 2 months) of collecting interstellar dust on February 22, 2000, and made a 6,000 km altitude fly-by of the Earth on January 15, 2001 to adjust its orbit inclination to intercept the target comet; 2) During the second orbit, the spacecraft began its second campaign (spanning 4 months) of collecting interstellar dust on August 5, 2002, flew by the asteroid Annefrank within 3,300 km on November 2, 2002 as a preparation test for the comet fly-by, and ended with the 1-AU tests[1]; 3) Shortly after the start of the third orbit, Stardust made its rendezvous with the target comet Wild 2 with a fly-by distance of about 236 km on January 2, 2004 and is on its way out to aphelion before completing its final orbit to head back to Earth for reentry in January 2006.

Stardust was designed, built, and is operated by Lockheed Martin Astronautics (LMA), Denver, CO. The California Institute of Technology's Jet Propulsion Laboratory (JPL) is responsible for mission management and spacecraft navigation. The Deep Space Network (DSN), also managed by JPL, provides spacecraft telecommunication support. The spacecraft was built in the shape of a "rectangular box", with the approximate dimensions of 1.7 m x 0.7 m x 0.7 m (see Fig. 2 for multiple views of Stardust). This "box" is Stardust's main bus, on which all of the science instruments, telecommunication systems, the Sample Return Capsule (SRC) and other components are housed/mounted. On either side of the bus are two flat, fixed solar array panels, which have a combined approximate area of 7 square meters and is the primary source of spacecraft power. Mounted on the front edges of the solar array panels and the front side of the bus are whipple shields, which protect the panels and the spacecraft from particle impacts during particle collection periods. Stardust has five X-band antennas, which it can use for telecommunication; the high gain antenna (used for transmit only), the medium gain antenna (used to receive and transmit) and one of the low gain antennas (for receive only)

are used for comm. in the +Z direction, and two low gain antennas are used for comm. in the –Z direction (one to receive and the other transmit only). The Navigation Camera, the Periscope (a pair of mirrors used by the NavCam to look over the bus whipple shield) and the Rocket Engine Modules are three other components, which are of particular importance to Navigation, and are discussed in the following section.

NAVIGATION CHALLENGES

Stardust is a 3-axis stabilized spacecraft and maintains its attitude by firing its 0.2 lbf Reaction Control System thrusters (RCS thrusters) or by firing its 1.0 lbf trajectory Correction Maneuver thrusters (TCM thrusters). The type of thruster that is used to maintain attitude, depends on the type of attitude controller that is being used during flight; e.g., during nominal cruise, the RCS thrusters are used to maintain attitude, however, during a maneuver, the TCM thrusters are used to supply the desired delta V, as well as to maintain the desired attitude. The spacecraft has eight of each type of thruster and all are mounted on its bottom side, in four sets of clusters, which are referred to as Rocket Engine Modules (REMs), as seen in Fig. 2b. Each REM contains two RCS thrusters and two TCM thrusters; one thruster of each type serves as the primary thruster and the other serves as the backup. This arrangement of having all thrusters on one side of the spacecraft causes Stardust to create unbalanced torques each time a pair of thrusters fire to maintain attitude (dead-band activity), change attitude (slew or walk transitions), change method by which attitude is maintained (dead-band mode change), or perform TCMs. Further descriptions of each of these activities can be found in [Kennedy[1]]. The spacecraft experiences a perturbing acceleration when any of these activities are conducted, and the perturbing force cannot easily be cancelled in the spacecraft Z-axis direction. The cumulative effect of these small forces is non-negligible and must therefore be predicted, modeled, and estimated. This acceleration is non-deterministic and is difficult to predict accurately given the dead-band mode that is used; i.e., the mode depends on which type of thrusters are firing, the duration of the pulses, and the degree tolerance to which attitude is to be maintained. All the small force thrusting events are computed and reported by the spacecraft using an on-board thruster model, combined with knowledge of the spacecraft inertial attitude, and are then telemetered to the DSN.

The second challenge, which must be overcome for a successful fly-by of Wild 2, is the contamination of the NavCam and the stray light in & low throughput of the Periscope. The contamination resulted from spacecraft out gassing, when Stardust flew past perihelion in late July 2003. This contamination degraded the quality of images taken by the NavCam by 2.5 magnitudes and was first noticed in the images taken on Oct 8; the potential for contamination of the NavCam was expected due to perihelion passage. The NavCam images are essential to Stardust Navigation because they are optical data of the comet-spacecraft relative position; therefore, efforts were made to clean the camera.

Additional contamination occurred when the NavCam was left powered on in early December. The problems of the Periscope were detected when calibration images were taken on Dec 4; the stray light increased the overall amount of light that is reflected by the Periscope, thus drowns out the detection of stars and comet in the images taken by the NavCam, and the low throughput decreased the level of detect ability by the NavCam. The source of the stray light is not known; however, calibrations performed on Dec 18 indicated that the problems could cause a problem for the planned images of Wild 2 from ten days out to the day of the encounter. The NavCam must look through the Periscope if the spacecraft was to remain in it's planned "ram" orientation; i.e., the attitude in which Stardust has its whipple shields facing the direction of flight.

The third challenge, which must be overcome during this inbound leg to the comet Wild 2, is the 2 solar conjunctions of Stardust with respect to the Earth. During the 14-month period from the asteroid Annefrank fly-by to the comet encounter, Stardust has a Sun-Earth-Probe (SEP) angle of less than 10 deg for over 56% of the time; i.e., the spacecraft is within 10 deg of the Sun as viewed from the Earth over a consecutive 240 days out of 426 days. Having an SEP angle of less than 10 deg causes the radiometric data to be noisier than usual, thus degrading the accuracy of the data. During the periods when the SEP angle is less than 3 deg, the solar conjunction prevents playback of the telemetry data, which contains the spacecraft attitude-maintenance thruster firings. This occurrence of 2 solar conjunctions within a 1-year span is due to the orbit geometry of the spacecraft with respect to the Earth. The first solar conjunction maximum occurred on April 9, 2003 with an SEP angle less than 2.2 deg and the second solar conjunction maximum occurred on August 17, 2003 with an SEP angle less than 1.0 deg.

ORBIT DETERMINATION MODELING

The Orbit Determination (OD) of Stardust was performed using X-band 2-way coherent Doppler data, 2-way coherent ranging data, differenced Doppler data (2-way Doppler minus 3-way Doppler), and during the encounter phase, optical data, as well. All of the radiometric data was collected through the DSN; the 2-way Doppler and the differenced Doppler data were collected at 1 minute sample rates, while the ranging data was collected at 10 minutes sample rates. After the Annefrank asteroid fly-by in early November 2002, Stardust went into 2 solar conjunctions in 2003 before it encountered Wild 2. During these conjunctions periods, the Doppler data was loosely weighted between 2 to 15 mm/sec and the ranging data was weighted between 3 to 14 meters. By mid November 2003, the SEP angle became greater than 10 degrees and the radiometric data noise level began to decrease, as seen in Figure 3 of the Doppler residuals; Figures 4 and 5 are plots of the differenced Doppler and range residuals, respectively. During the encounter period, the Doppler data was weighted from 0.8 to less than 0.1 mm/sec, while the range data was weighted at less than 3 meters. Additionally, the star optical data was weighted at 0.2 pixels and the comet optical data was weighted from 2.0 to 0.5 pixels on approach

and 150 pixels for the closest approach images. Invalid radiometric data was removed and valid data was calibrated for media effects (troposphere, ionosphere) and the differenced Doppler was also calibrated for station clock offsets.

The radiometric data was processed using JPL's Orbit Determination Program (ODP[2]), while the optical data was processed using JPL's Optical Navigation Program (ONP[3]). The ODP solves for the spacecraft position, velocity and other requested parameters using a square root information (SRIF) weighted least squares filter[4,5]. The OD processing is performed on an HP-C3700 workstation running HP-UX B.11.11. The dynamic models used in the orbit fits are the Newtonian point-mass model, the relativity model, the solar radiation pressure model, the impulsive maneuver model, the finite maneuver model, and the small forces model. The Newtonian point-mass model computes the gravitational acceleration of the spacecraft due to the nine planets, the Sun and the comet Wild 2 by treating the bodies as point-masses. The relativity model computes the relativistic perturbative acceleration caused by the Sun and Jupiter. The solar radiation pressure model determines the acceleration due to solar radiation on the spacecraft; the spacecraft is simply modeled by four components: 3 flat plates for the bus and 1 flat plate for the solar array panels. The impulsive maneuver model is used to model the predicted translation delta Vs imparted on the spacecraft when Stardust turns in orientation to perform a TCM. The finite maneuver model is used to model predicted and reconstructed TCMs. The small forces model is used to model predicted and reconstructed delta Vs associated with spacecraft attitude changes and attitude maintenance thruster firings.

Several other models used in the OD process include, but are not limited to, the solid Earth tide correction model, the continental plate motion and ocean loading models, the Earth precession model, the relativistic light time correction model, the Earth and Moon's direct and indirect oblateness models, and the quadratic and exponential gas leak models. The precession model uses the Universal Time and Polar Motion data as determined by JPL's UTPM-STOIC 2000 file[6]. The quadratic and exponential gas leak models are used for predict covariance purposes. The *a priori* sigma for each model used in the filter runs is listed in Table 1, along with other estimated parameters and consider parameters. A detailed discussion on the filter strategy can be found in a paper entitled *1-AU Calibration Activities For Stardust Earth Return*[1]. In particular, the *a priori* sigma for each of the spacecraft's position components is 10,000 km and is 1 km/sec for each of the spacecraft's velocity components. The Earth-fixed coordinate system used in the ODP was consistent with International Earth Rotation Service (IERS) terrestrial reference frame labeled ITRF93[7]. The locations of the DSN tracking stations are consistent with the ITRF93 reference frame[8,9]. The ephemerides of the Sun, Moon and the nine planets are defined by the JPL DE405 planetary ephemeris[10,11]. An internal office memo released by Dr. Steve Chesley defines the comet Wild 2 ephemeris[12], with updates occurring during

encounter. The inertial coordinate system used for orbit integration was Sun centered, Earth mean equator and vernal equinox system at J2000.

ORBIT DETERMINATION RESULTS

The strategy for overcoming the challenge of small force prediction required a large amount of work and was difficult to implement, in part due to a small Navigation team. During the last two months prior to encounter, the behavior of the small forces was closely monitored. Updates to the predictions were made when OD-updated small force trends significantly differed from predicted trends, when new OpNav related calibration tests were added to the flight plan, and whenever the schedule for taking OpNav images changed. It was difficult to determine long, OD-updated small force trends because the spacecraft performed many activities in these last two months; the on-board small force data was used in and was scaled by the OD process via scale factors to yield OD-updated small force data. These spacecraft activities included turns required to take OpNav images, turns required to conduct OpNav calibration tests, turns required to perform TCMs and clamps required to tighten down the dead-band box. All these activities resulted in dynamic changes to the spacecraft velocity; these changes corrupted efforts to determine a long-term trend of the small forces, thus made it difficult to establish an accurate predictable trend. Instead, short-term trends were studied. Due to the nature of the encounter maneuver strategy, which is discussed in a paper entitled, *Wild 2 Approach Maneuver Strategy Used For Stardust Spacecraft*[13], small short-term trend errors were tolerable. This was possible because Stardust had 4 maneuvers scheduled in the last 30 days before comet fly-by that could correct problems encountered, and 1 contingency maneuver 6 hours prior to fly-by in case the mapped closest approach was believed to be too close to the comet. During actual OD reconstruction of the trajectory, all small thrust activity is modeled via the discrete reporting of the on-board small forces. This on-board modeling does not take into account the approximate 30% uncertainty of the delta V of each thruster firing. With this record of small force events, the filter is configured to apply stochastic scale factors (see Table 1 for filter set up) to solve for the thruster firing uncertainty. When tracking data (direct observations of the spacecraft Doppler signature) are available, small stochastic batch sizes are used. This effectively allows a scale factor to be determined for each individual thruster firing. During off-track periods, large (three-hour) batch sizes are required, allowing for a single scale factor to be computed in place of a large number of small force events. *A priori* uncertainties of these stochastic scale factors are set to 30%, with larger numbers being used for particularly energetic events (such as slews and clamps).

Figure 6 contains a plot of small force events over a two-day period during the approach to Comet Wild 2 and it shows two OpNav activities: one at 1100 on December 20th and one at 1100 on December 21st. This figure is a plot of accumulated delta V over time, based on predicted activities, reported events and OD-updates made to the reported small

force events. Seen in this figure are example signatures of attitude maintenance through three-axis dead-band control, two clamp events (in which the dead-band control was tightened from +/- 2 deg to +/- 0.25 deg) and attitude transitions between Earth point and Comet point. Note: Leading up to the Wild 2 encounter, OpNav activities (two of which are seen in Figure 6) required that pointing control of the spacecraft be accurate to within 0.25 deg. As can be seen by the trends in the figure, reporting and prediction of the small force events due to spacecraft dead-band are fairly accurate (less than 1 cm/sec difference), based on their agreement with the OD-updated trend. The dead-band clamps, on the other hand, are over-predicted and underreported. When possible, comparisons such as this are used to tune the prediction files used for future trajectory propagation. Figure 7 shows the computed scale factors that are applied to the reported small force events during OD reconstruction. As one can see, the individual scale factors of thruster events seen during a tracking period are in line with the 30% *a priori* uncertainty.

The schedule for taking OpNav images changed frequently in the last month before encounter. In late November, NavCam engineers recommended to leave the Navigation Camera on and cease to power cycle the camera, as done in previous imaging procedures. The recommendation resulted from a flight directive, which states not to power cycle spacecraft components numerous times. This flight directive conflicted another flight directive, which states not to perform any untested procedures during critical flight periods. Prior to comet encounter, the NavCam was power cycled because time between imaging sessions was on the order of weeks to months; it was not practical to have the camera on over these long periods. For this encounter period, image sessions were occurring very frequently from days to several hours; see Table 2 for a summary of the OpNav images taken for encounter. The camera engineers conducted tests of leaving the NavCam powered on and these tests yielded a camera temperature increase of 1-2 degrees C, which is an acceptable side effect. In practice, what resulted was not expected. The camera was left on during the Dec 4 geometric calibration test and the camera temperature rose 12-13 degrees C. This rise in temperature caused the camera to produce images with noisy backgrounds, due to contamination, and the noisy level was noticed to increase over the course of days. Similar to the decontamination efforts made in October 2003, Stardust was commanded to use its internal NavCam heater numerous times to boil off the contamination in the remaining weeks before comet encounter and the spacecraft was rolled 180 degrees, such that the Sun could bake off the contamination during TCM-11 (Dec 23) and once more five days from Wild 2 encounter. (Note: Stardust conducted two bake sessions in late October in an effort to decontaminate the NavCam post perihelion passage. The bakes were successful, however, a solar flare caused the spacecraft to go into safe mode and caused the NavCam to have hot pixels in the CCD shortly after the first bake session. Also, none of the small force events related to the bakes nor the safe mode were predicted in the small force predicts; therefore, the expected map fly-by distance and time of closest approach changed after each event but this was factored into the design of the next maneuver to correct any undesired changes.) The December

decontamination effort was successful in reducing the noisy background level to yield an image quality comparable to quality prior to perihelion passage and it helped reduce the hot pixel problem caused by the October solar flare.

Early detection of the stray-light problem in the Periscope allowed engineers enough time to formulate a new strategy for imaging Wild 2 from 10 days to 14 hours before comet encounter. The new strategy implemented was to use the NavCam to image Wild 2 by turning the spacecraft no more than 25 degrees from the "ram" direction, to allow the NavCam to have an unobstructed view of the comet. There was not a great concern for using the Periscope during the last 30 minutes to encounter, when the auto-nucleus tracking occurred. This was because during this short but critical time, the comet nucleus was expected to be bright enough to stand out from the stray-light and have relatively low loss of throughput light. The exact brightness was difficult to predict, therefore, the images exposure setting alternated between two pre-selected lengths: 100 millisecond and 10 millisecond exposures. As a result of the new strategy, the auto-nucleus tracking was successful in taking images through the Periscope, from 30 minutes to 5 minutes before encounter. Figure 8 shows the pixel and line residuals during the fly-by.

The strategy for overcoming the challenge of the 2 conjunction periods was fairly simple. It involved loosening the 1 sigma radiometric data weights in the OD process to 2.5 sigma of the observed noise during the conjunction periods. Once the observed noise level decreased significantly in the 2-way Doppler in mid November, then the 1.5 sigma observed noise level was used. Solution epochs during conjunction ranged from early March to early July, while solution epochs for the encounter ranged from early October to late December. Solutions of multiple data arc lengths, with multiple weighting schemes and multiple combinations of data types were used to verify that there were no hidden problems with the primary strategy and that the differing strategies were all consistent with each other. Several b-plane results of the Wild 2 fly-by are listed in Table 3. Although TCM-10 was targeted to a fly-by distance of 150 km and was executed nominally, initial post TCM-10 solutions showed that the mapped fly-by distance was on the order of 2,600 km. This was a result of not modeling the small forces relating to the geometric calibration tests performed on Dec 4 (the day after TCM-10); upon further study, Navigation identified that the small forces relating to both the encounter demonstration tests (performed on Dec 11) and the photometric calibration tests (performed on Dec 18) were also not modeled into the TCM-10 design. However, due to the fluid nature of these tests and after the TCM-10 design was finalized, further adjustments were made to these calibration tests, which required updating of the small force predicts. Stardust's flexible maneuver strategy allowed the opportunity to correct these miss modeling errors in the small forces with TCM-11 on Dec 23, which performed nominally. (Table 4 lists the reconstructed estimates of the TCMs 8-12; TCM-9 is not included in this table, although it is discussed in the 1-AU test results[1].) TCM-11 was designed using noisy optical data, which was caused by leaving the NavCam powered on.

Post TCM-11 optical data was much cleaner because it was data that was acquired after power-cycling of the NavCam was resumed. Post TCM-11 solutions indicated that the spacecraft was approximately 500 km below the desired aim point and this was attributed to the comet being 500 km above its estimated location, which was solved for with the noisy optical data. Pre TCM-12 solutions showed the aim point was dropping further below the desired location (see Fig. 9), but analysis of the optical data resulted in the finding of two optical data points on Dec 24, which was causing the solutions to walk towards a 500 km B dot R value and a –20 B dot T value. Confirmation that the optical data was the cause came when radiometric data only solutions showed no walking in the aim point. Using post TCM-12 / pre TCM-13 solutions within 2 days from fly-by, Navigation determined that TCM-13 and contingency maneuver TCM-14 were not necessary because trajectory mappings showed Stardust would fly by Wild 2 within the desired area, as specified by the Project requirements (see wedge in Fig. 10). The current reconstruction solution, s04005mC, shows Stardust flew by comet Wild 2 at –66.2 km in B dot R, 226.6 km in B dot T, at a radial distance of 236.1 km and a time of closest approach of 19:22:36 ET (see Table 3 for 1 sigma values and Fig. 11 for the b-plane location with respect to the target marked as an X).

CONCLUSIONS

Navigating the Stardust spacecraft by the comet Wild 2 at a fly-by distance of 236 km was a difficult task to achieve. Navigators faced three main challenges in accomplishing this task and these challenges had to be overcome in order to ensure a successful fly-by. The first challenge to overcome was the difficult task of accurately predicting the small force thrusting events, which are caused by Stardust's unbalanced thrusters that consequently impart an undesired perturbing acceleration on the spacecraft that cannot be easily cancelled in the +Z-direction. The resolution to this problem was to closely monitor the small force short-term trend (comparing it to the predicted trend) and update the small force predict, whenever differences between the trends were significant or changes were made to the spacecraft attitude plan. Short-term trend errors were tolerable because Stardust had four maneuvers scheduled in the last 30 days before encounter (plus 1 contingency maneuver), which could correct them in the event that the errors were unfavorable.

The second challenge to overcome was the contamination of the Navigation Camera. Further more, the problems of stray-light and low throughput of the Periscope added to the concerns of the ability to image Wild 2 with high accuracy in the last several days before encounter to yield a delivery accuracy of 16 km 1 sigma. Decontamination of the NavCam was achieved by turning on the NavCam internal heaters numerous times during the last three months before encounter and rolling the spacecraft 180 deg a few times to allow the Sun the opportunity to bake off the contamination. The NavCam was used, in place of the Periscope, to image Wild 2 throughout the approach to encounter, until the

14 hours out; this was done to avoid the Periscope problems of stray-light and low throughput. In the last 30 minutes before the comet fly-by, the NavCam was required to use the Periscope to image Wild 2. The stray-light and low throughput problems were not a concern during this period because the comet nucleus was expected to be very bright. However, because of this expectation two exposure lengths were used (100 milliseconds and 10 milliseconds) to ensure a high probability of imaging the comet at an acceptable image quality level. This strategy yielded successful results.

The third challenge, which was overcome during the inbound leg to the comet Wild 2, was the 2 solar conjunctions of Stardust encountered with respect to the Earth. The first solar conjunction maximum occurred on April 9, 2003 with an SEP angle less than 2.2 deg and the second solar conjunction maximum occurred on August 17, 2003 with an SEP angle less than 1.0 deg. These conjunctions made the approach to Wild 2 difficult in that determination of the spacecraft trajectory was not as accurate while in conjunction and the second conjunction postponed the playback of the small force thruster events data. The resolution to the solar conjunction challenge was to de-weight the radiometric data during the conjunction periods and move up the solution epoch when enough data had accumulated post conjunction.

Despite the miss modeling of the small force predicts associated with calibration tests in December for TCM-10, all of the challenges were overcome and Stardust successfully flew by comet Wild 2. OD reconstruction solution s04005mC shows Stardust flew by the comet at –66.2 km in B dot R, 226.6 km in B dot T, at a radial distance of 236.1 km and a time of closest approach of 19:22:36 ET.

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REFERENCES

1. Kennedy, B., E. Carranza, and K. E. Williams, *1-AU Calibration Activities For Stardust Earth Return*, AIAA/AAS Astrodynamics Specialist Conference, Maui, HI, February 8-12, 2004.

2. Moyer, T. D., Mathematical formulation of the Double-Precision Orbit Determination Program, *Technical Report 32-1527*, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA, 1971.

3. Owen, W. M. and R. M. Vaughan, *Optical Navigation Program User's Guide*, Engineering Memorandum 314-152, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA, August 9, 1991.

4. Lawson, C. L., and R. J. Hanson, *Solving Least Squares Problem*, Society for Industrial and Applied Mathematics, Philadelphia, PA, 1995.

5. Bierman, G. J., *Factorization Methods for Discrete Sequential Estimation*, Academic Press, New York, 1977.

6. TRK-2-21, DSN Tracking System Earth Orientation Parameter Data Interface, DSN Systems Requirements Detailed Interface Design internal document, 820-13; Rev A.

7. Boucher C., Z. Altamimi, and L. Duhem, Results and analysis of the ITRF93, *IERS Tech. Note 18*, Obs. de Paris, 1994.

8. Folkner, W. M., DSN station locations and uncertainties, *Progress Rep. 42-128*, pp. 1-34 Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA, 1996.

9. Folkner, W. M., DSN Station Location Update for MER, *Internal Office Memorandum*, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA, November 4, 2003.

10. Standish, E. M., and Newhall, X X, New accuracy levels for solar system ephemerides, in *IAU Symp. 172: Dynamics, Ephemerides and Astrometry of the Solar System*, edited by S. Ferraz-Mello et al., pp. 29-36, IAU, Paris, 1996.

11. Newhall, X X, J. G. Williams, and E. M. Standish, Planetary and Lunar Ephemerides, Lunar laser ranging, and Lunar physical librations, in *IAU Symp. 172: Dynamics, Ephemerides and Astrometry of the Solar System*, edited by S. Ferraz-Mello et al., pp. 37-44, IAU, Paris, 1996.

12. Chesley, Steve R., A. B. Chamberlin, D.K. Yeomans, M. S. Keesey, P. W. Chodas, Comet 81P/Wild 2: updated orbit, ephemeris files, and uncertainty analysis, *Internal Office Memorandum IOM 312.N-03-012,* Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA, June 6, 2003.

13. Bhat, R. and K. E. Williams, C. E. Helfrich, B. M. Kennedy, E. Carranza, *Wild 2 Approach Maneuver Strategy Used For Stardust Spacecraft*, AIAA/AAS Astrodynamics Specialist Conference, Providence, Rhode Island, August 16-19, 2004.

14. Web site for the Stardust mission, http://stardust.jpl.nasa.gov/

Table 1: Filter Parameters

Parameters	A Priori Uncertanty (1-sigma)	Comments
Estimated as bias:		
Epoch state (6)	10,000 km, 1 km/sec	
Solar pressure acceleration (solar panel)	5% of a prior value	Scale factor for flat plate. (A Prior Value = 1)
Diffusivity coefficient (solar panel)	6.85E-03	(A Prior Value = 6.61E-02)

Finite Burn Right Ascension	0.5 deg	
Finite Burn Declination	0.5 deg	
Finite Burn Magnitude	1% of delta V	
Wild 2 Set III		Correlated Cov.
Estimated as stochastic:		
Range bias (stochastic part)	100 RU	
DV Scale Factors	30% of small force	3 minute interval for Comm 3 hour interval for Non-Comm
Quadratic Gas Leak (3)	0.00E+00	For 2x2x10 Mapping: 5E-11, 2*5E-12 km/s^2
	0.00E+00	For tight DB Mapping: 3.7E-10, 2*3.7E-11 km/s^2
Exponential Gas Leak (3)	0.00E+00	For 2x2x10 Mapping: 2E-11, 2*2E-11 km/s^2
	0.00E+00	For tight DB Mapping: 1.4E-10, 2*1.4E-11 km/s^2
Considered:		
Impulsive events (3)	5 cm/sec	
Station Location	50 cm, 50 cm, 5^-6 deg	
Diffusivity coefficients (3)		
Specular coefficients (4)		
Earth ephemeris		
Polar motion		
UT1		
Troposphere Dry		
Troposphere Wet		
Ionosphere Day		
Ionosphere Night		
Center Finding L&P	50% of radius	

Table 2: Summary of Optical Navigation Images

Date	OpNavs Planned	Data Weight** (pixels)	Comments
13-Nov	3 images		Not used in solution
17-Nov thru 04-Dec	2 sets/wk*	1.5	1 set = 25 images
08-Dec thru 14-Dec	1 set/day*	1.5,2.0	1 set = 25 images
15-Dec thru 22-Dec	1 set/day*	0.75,1.0,2.0	1 set = 3 images
24-Dec thru 31-Dec	9 sets*	0.5	1 set = 18 images
31-Dec thru 02-Jan	8 sets*	0.5	1 set = 8 images

Fly-by images	26 images	150	# of Images used for Encounter Reconstruction

* Not all images taken were used in the Orbit Determination Solutions
** Data weight same for pixel and line directions

Table 3: Wild 2 Fly-by B-Plane Results

Stage	*OD Solution*	*Wild 2 Ephemeris*	*Targeted Range from Wild 2 (km)*	*B.R (km)*	*B.T (km)*	*CLTOF (ET on 02-JAN-2004)*	$\sigma_{B.R}$ *(km)*	$\sigma_{B.T}$ *(km)*	σ_{LTOF} *(sec)*
Pre-	s03325m	sb_81p_sd1	150*	-671.5	1437	19:09:28	321.9	600.2	177.4
TCM-10	s03325m_opt1	(OD updated)		-1309	3705	18:57:02	493.6	549.7	357.5
	W-42dAmR	sb_81p_sd8		-1037	2964	19:02:24	289.6	432.4	175.0
Pre-	W22dDmO	(OD updated)		-1017	2470	19:23:32	199.1	224.7	129.5
TCM-11	W18dBmO			-879.5	2540	19:23:31	200.3	212.5	127.5
	W18dCmO			-806.6	2524	19:23:33	200.2	211.7	127.5
Pre-	W10dAmO		300	-4.83	-10.60	19:19:35	135.6	156.3	122.1
TCM-12	W09dAmO			318.2	19.18	19:18:15	77.17	106.2	119.4
	W08dAmO			378.9	-3.85	19:18:00	64.40	91.36	119.2
	W07dAmO			440.4	-28.39	19:17:45	49.66	72.41	118.3
	W06dAmO			464.7	-27.26	19:17:49	42.82	62.01	117.1
	W05dAmO			483.4	-14.59	19:18:19	34.96	46.22	113.7
	W04dAmO			421.9	-29.45	19:18:19	42.71	42.06	113.5
	W99hAmO	sb_81p_sd28	250	424.8	79.08	19:24:14	39.59	32.79	43.68
	W78hAmO	(OD updated)		459.2	57.32	19:24:16	22.85	22.11	43.23
	W63hB1O			462.8	74.28	19:24:03	18.11	17.07	42.85
	THY_4xs			502.2	41.14	19:24:03	11.13	11.10	124.7
	W61hAmO			474.4	76.48	19:24:06	15.09	15.37	42.61
Post-	W45hAmO			-85.34	230.8	19:24:03	15.42	13.27	42.61
TCM-12	W45hBmO	sb_81p_sd31		-82.62	226.0	19:23:50	15.41	13.37	42.09
	W27hAmO	(OD Updated)		-59.10	217.9	19:23:47	5.81	5.08	41.24
Post-Encounter	s04005mC			-66.17	226.6	19:22:36	0.93	1.27	0.20

* θ = 2.31 deg; TCMs 10 and 11 targeted to LTOF of 02-JAN-2004 19:20 UTC as well.

Table 4: Estimated TCMs

TCM:	Nominal RA (deg)	RA (deg)	1-sigma (deg)	Nominal Dec (deg)	Dec (deg)	1-sigma (deg)	Nominal Mag (m/sec)	Mag (m/sec)	1-sigma (m/sec)
8A	-0.55	-0.12	0.18	10.09	10.35	0.41	36.137	36.178	0.076
8B	-0.50	-0.13	0.20	10.08	10.26	0.43	34.391	34.455	0.075

10	-48.23	-48.24	0.50	-14.96	-14.95	0.52	2.602	2.602	0.026
11	-138.37	-138.43	0.47	-12.39	-12.45	0.50	3.229	3.230	0.029
12	49.71	49.73	0.49	73.63	73.64	0.44	3.229	3.227	0.030

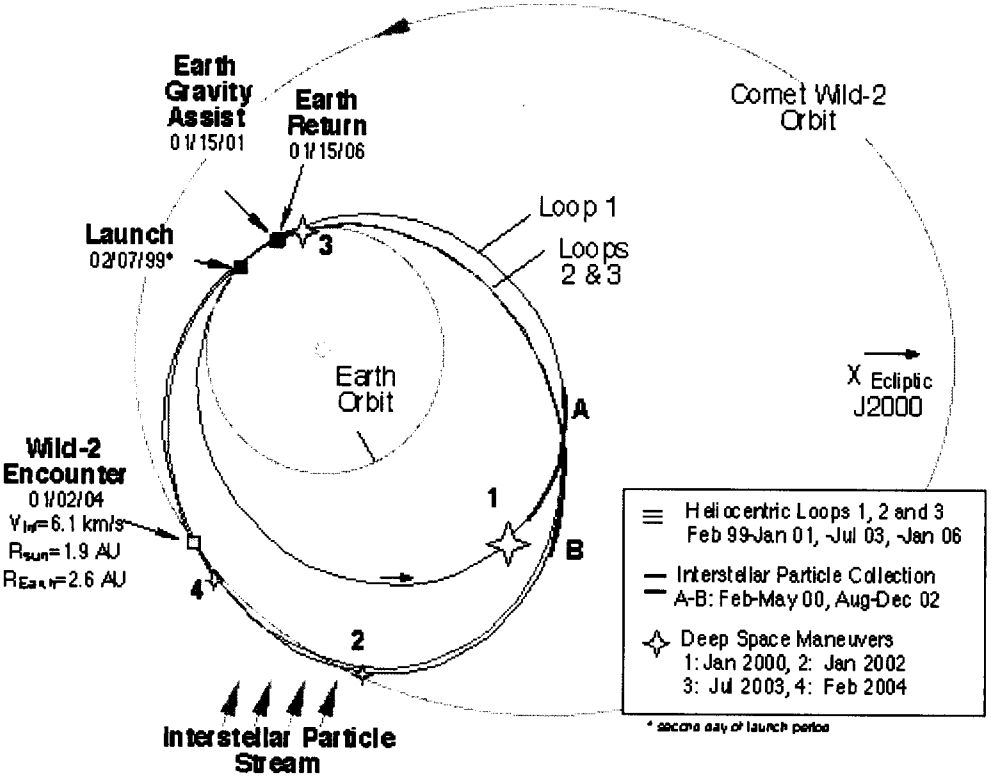


Figure 1: Stardust Mission Trajectory (1999-2006)

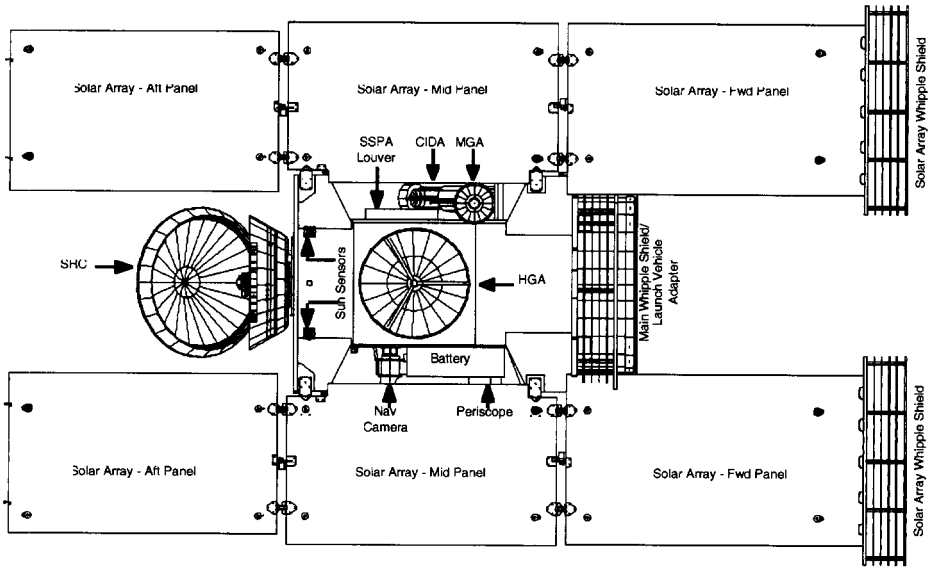


Figure 2a: Spacecraft +Z-Axis View

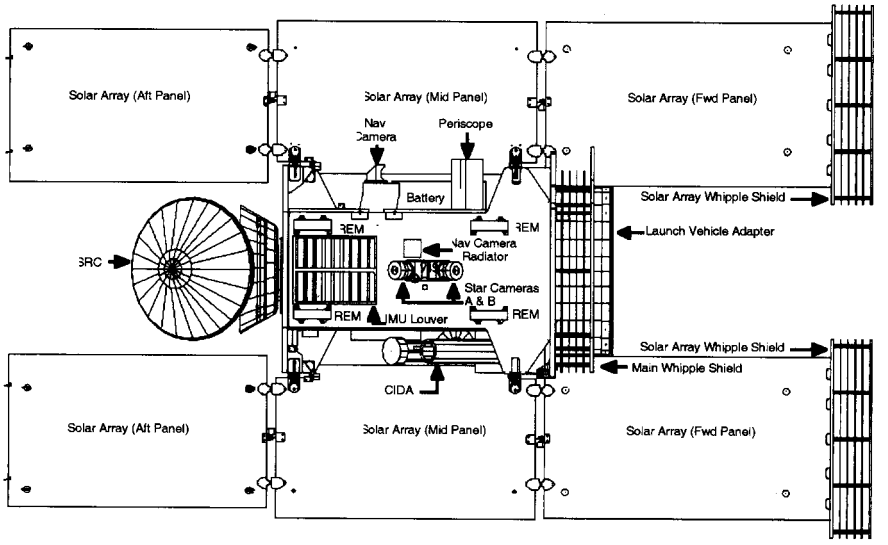


Figure 2b: Spacecraft –Z-Axis View

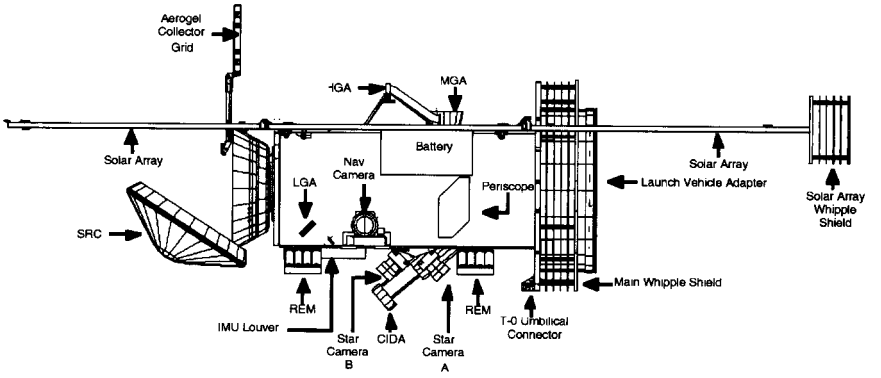


Figure 2d: Spacecraft –Y-Axis View

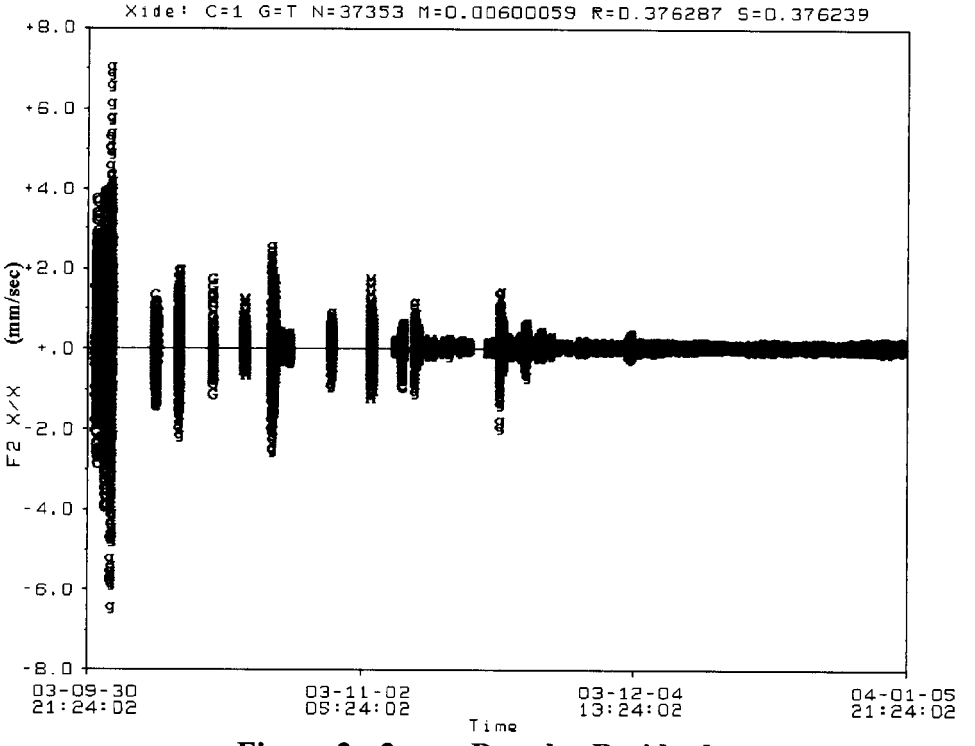


Figure 3: 2-way Doppler Residuals

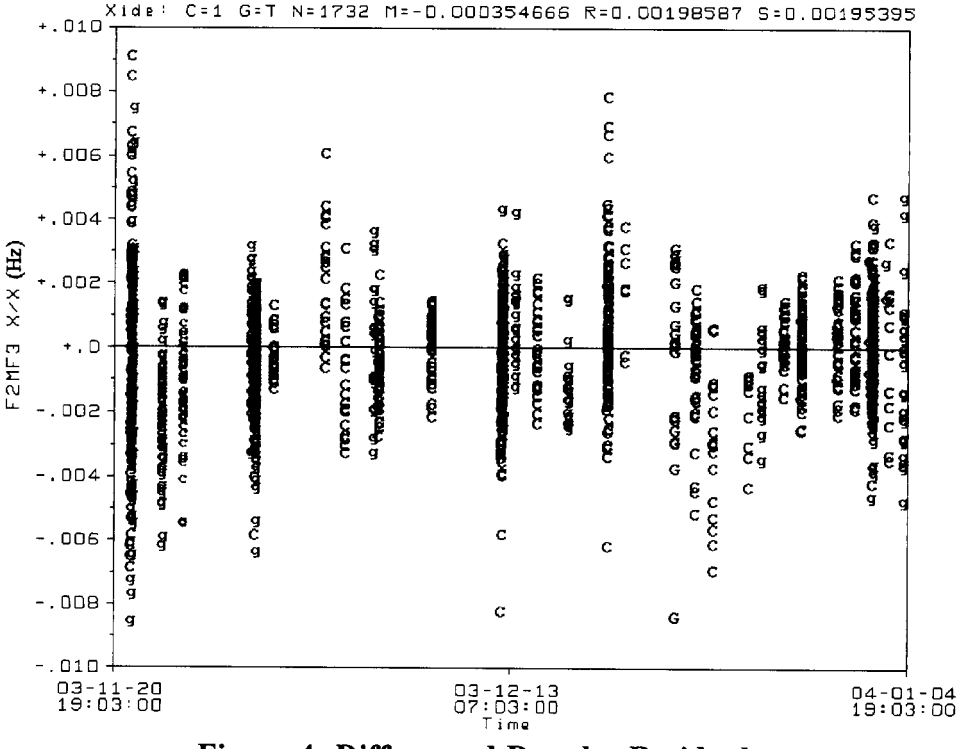


Figure 4: Differenced Doppler Residuals

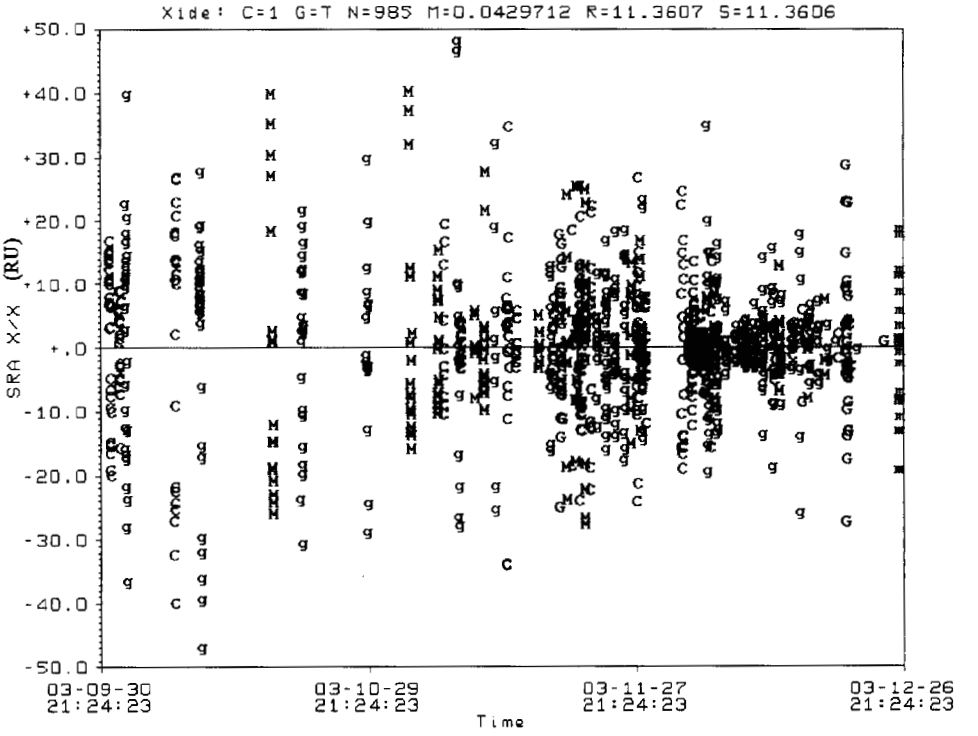


Figure 5: Range Residuals

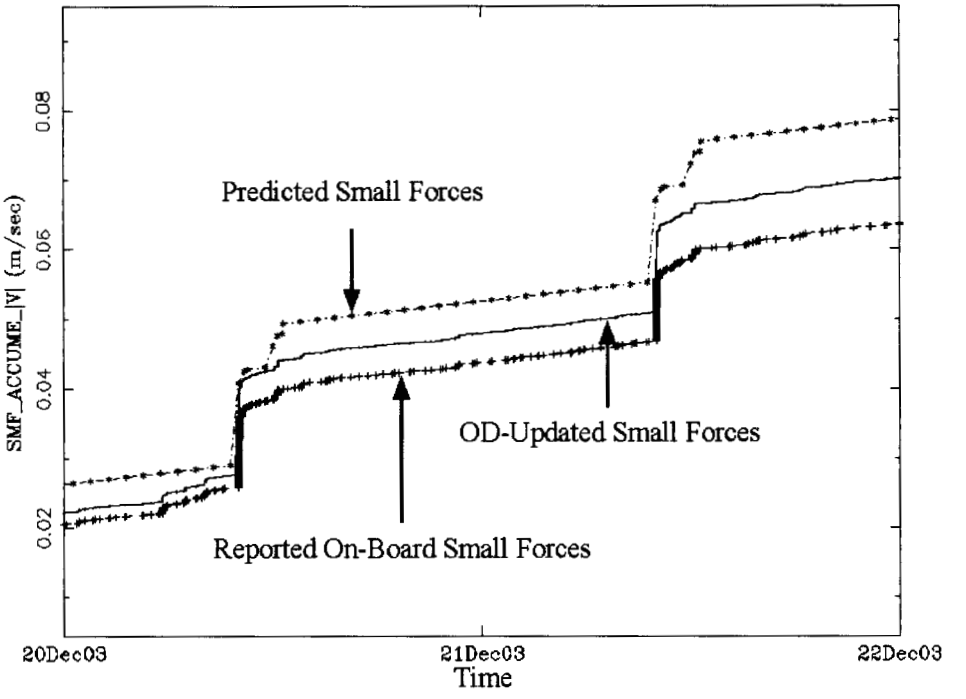


Figure 6: Comparison of accumulated delta V based on small force predictions, reported events and OD-updated small forces

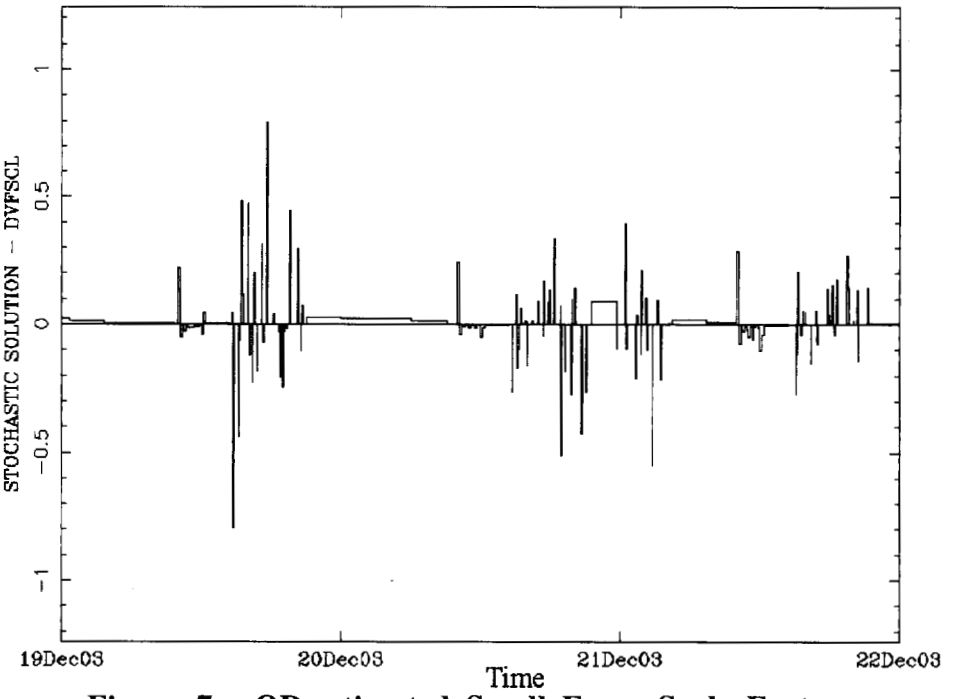


Figure 7: OD-estimated Small Force Scale Factors

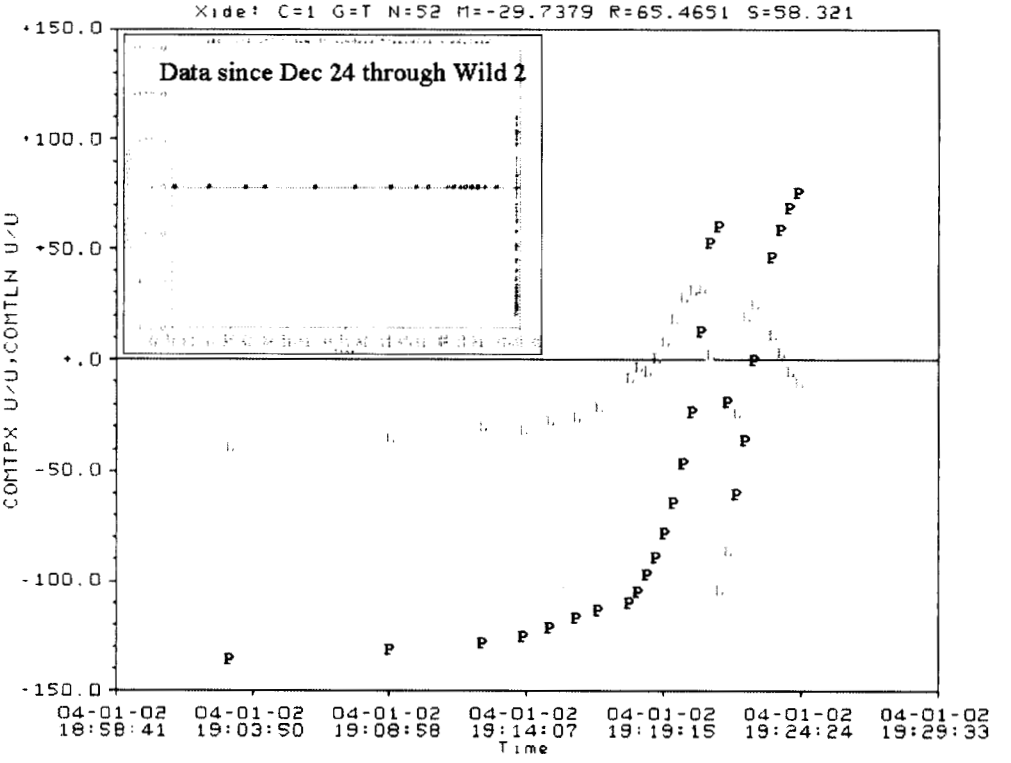
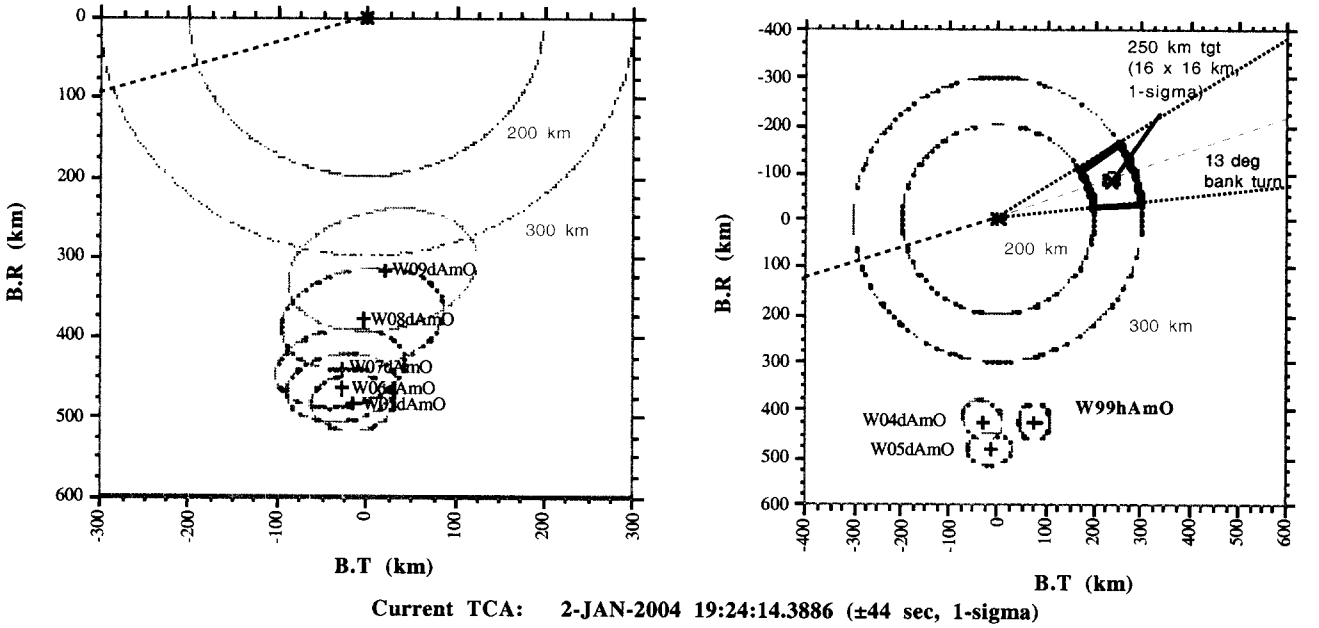


Figure 8: Optical Pixel and Line Residuals

Pre-TCM-12 Target and OD Estimates

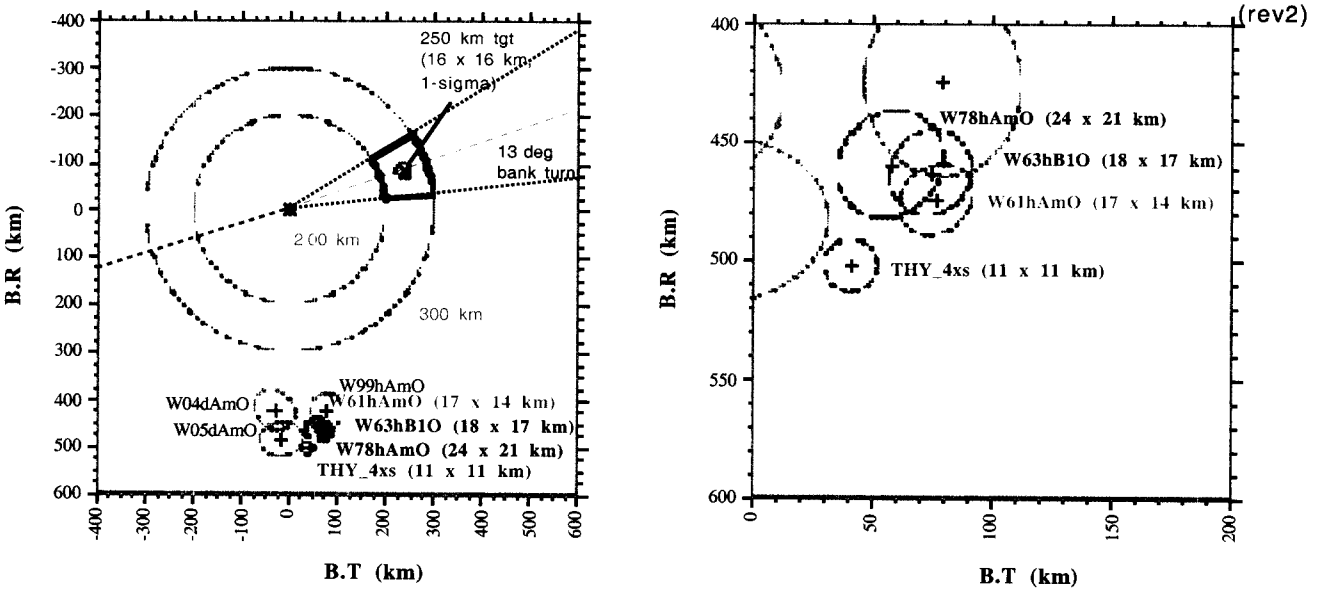


Current TCA: 2-JAN-2004 19:24:14.3886 (±44 sec, 1-sigma)

Current OD Accuracy (1-sigma): 40 x 33 km

Pre-TCM-12 Target and OD Estimates

12/29/03
(rev2)

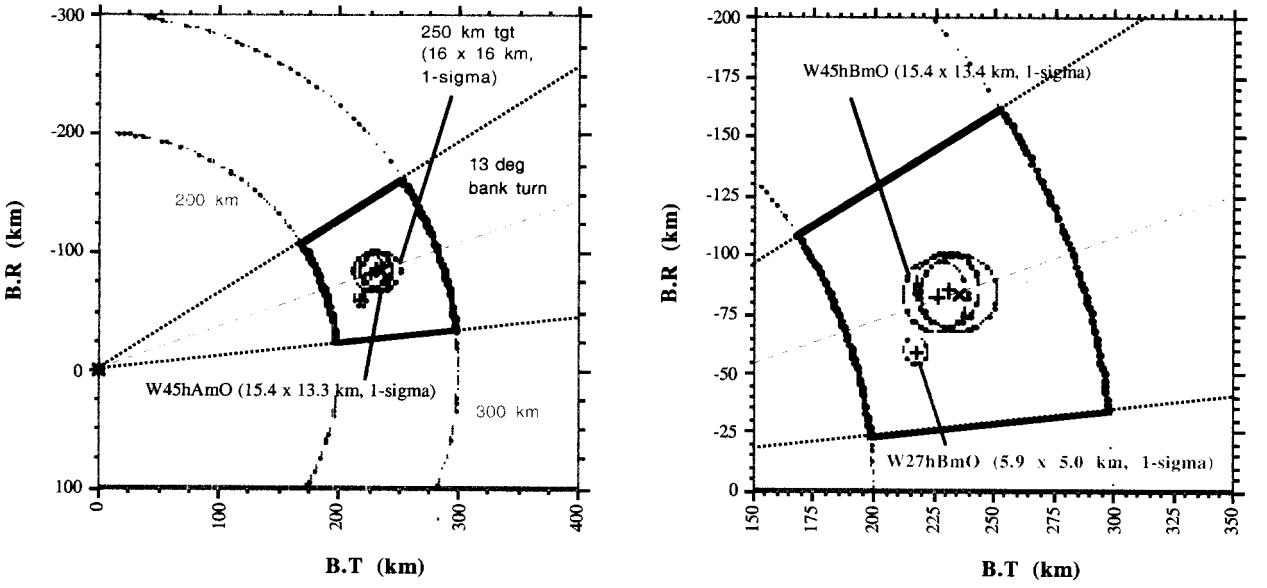


Current TCA: 2-JAN-2004 19:24:05.5123 (±43 sec, 1-sigma)

Figure 9: Pre TCM-12 Target and OD Estimates

12/31/03

Pre-TCM-13 Target and OD Estimates

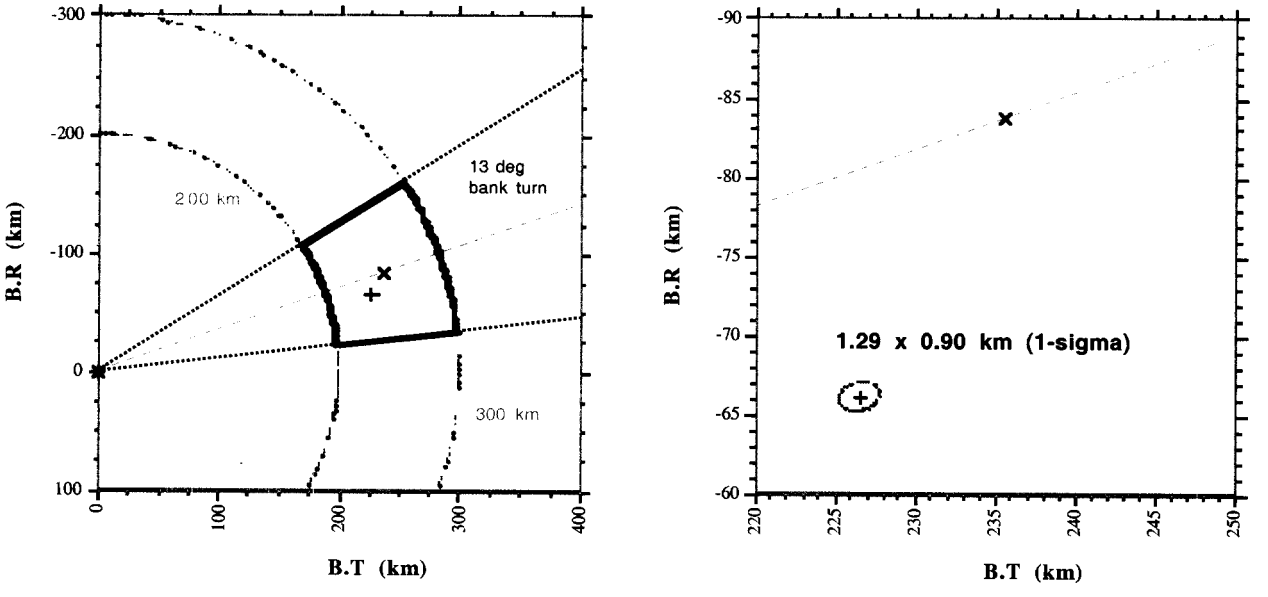


Current TCA: 2-JAN-2004 19:23:47.0014 (±41.2 sec, 1-sigma)

Figure 10: Pre TCM 13 Target and OD Estimates

Post-Encounter Reconstruction

1/1/04



TCA: 2-JAN-2004 19:22:36.2466 ET (±0.2 sec, 1-sigma)

Figure 11: Post Wild 2 Fly-by Reconstruction