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GENESIS EARTH RETURN: REFINED STRATEGIES AND FLIGHT EXPERIENCE

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Genesis Earth Return: Refined Strategies and Flight Experience

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As part of NASA's Discovery Program, Genesis is the first NASA mission since the Apollo Program to return samples collected in deep space. Launched in August 2001, Genesis collected solar wind constituents near the Earth-Sun L1 point over a period of about 29 months through March 2004, with an a subsequent five months required for Earth return. The original strategy for Earth approach was revised to maximize the safety of people and property on the ground in light of possible anomalies and contingencies, while preserving the capability to meet nominal entry requirements. A series of Earth approach maneuvers was performed successfully, resulting in delivery of the sample return capsule to within 2 km of the targeted position at the entry altitude of 125 km. Unfortunately, because of a failure in deployment of the drogue and parafoil, mid-air recovery was not performed and the sample return capsule subsequently crashed on the Utah Test and Training Range (UTTR) on September 8, 2004. Nevertheless, solar wind samples were still recovered and nearly all of the science objectives of the mission were met. This paper describes refinements to trajectory correction maneuvers, including contingency plans for addressing potential operational anomalies, as well as actual spacecraft flight performance during Earth approach.

BACKGROUND

Genesis is the fifth mission selected as part of NASA's Discovery Program. After collecting solar wind samples for a period of approximately two and a half years around the Earth-Sun L1 point, Genesis followed a free-return trajectory back to Earth, arriving at the Utah Test and Training Range (UTTR) on September 8, 2004. The samples were intended for retrieval via mid-air capture of the Sample Return Capsule (SRC) after deployment of a parafoil. Requirements for recovery of the samples were unprecedented and presented a formidable challenge in terms of both mission design and navigation. An overview of the Earth-return portion of the Genesis trajectory is shown in Figure 1.

The design of the Genesis spacecraft is illustrated in Figure 2. Spin stabilization was chosen for attitude control, with a star scanner and two types of sun sensors (near-Sun digital and spinning). Propulsive maneuvers were always performed open loop. All thrusters are located on the opposite side of the space vehicle from sample collectors to minimize contamination of samples. These include two redundant pairs of 5 lbf thrusters (T) aligned with the spacecraft principal axis (x) and two redundant strings of 0.2 lbf thrusters (R), canted at 45° in the spacecraft xz-plane. Since thrusters so positioned do not produce balanced torques, all attitude control maneuvers contribute a translational delta-velocity (delta-v or Δv) in addition to intended propulsive maneuvers. These must be accounted for orbit determination purposes and in terms of designing propulsive maneuvers. Also, power is provided by solar arrays with a battery in reserve, limiting time at which the spacecraft can point far off Sun. As a primary means of avoiding excessive turns away from the Sun, trajectory correction maneuvers (TCMs) during Earth return were biased near the Sun; that is, the maneuvers contained a deterministic component of about 1 or 1.5 m/s, included in the reference trajectory design. Thus, all TCMs must be utilized.

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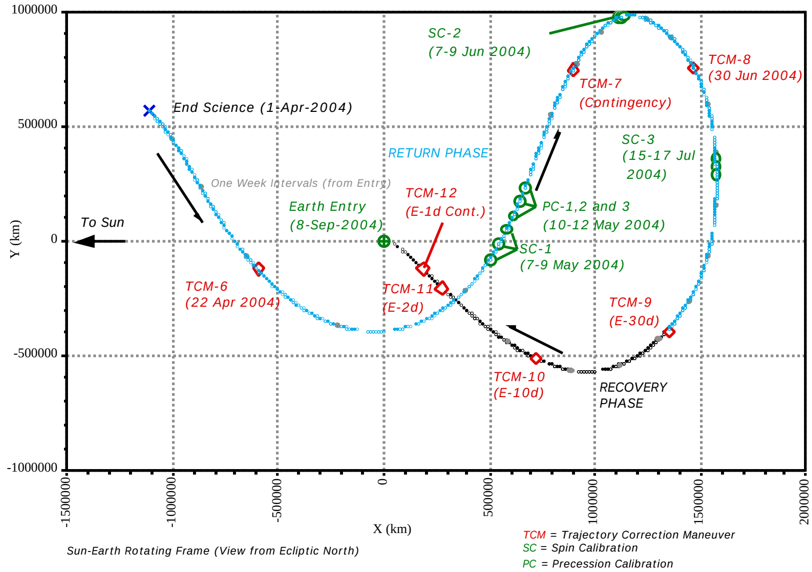
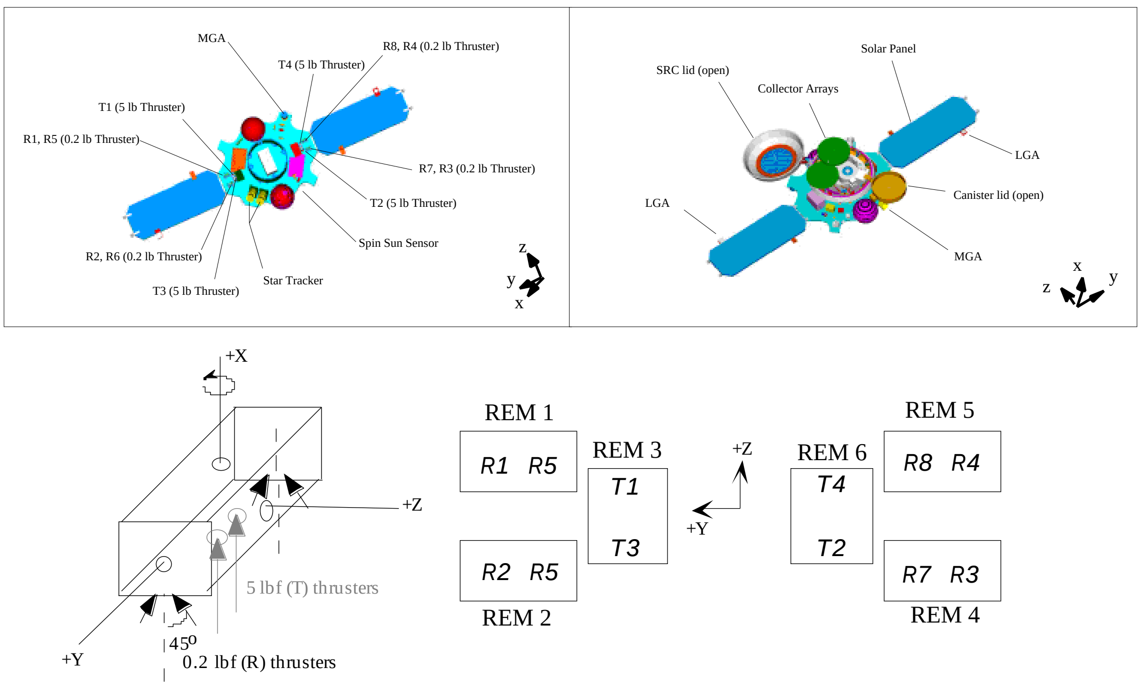


Figure 1. Genesis Earth Return Trajectory



String 1 (Primary)	String 2 (Redundant)	Maneuver Usage
R1+R2 and R3+R4	R5+R6 and R7+R8	Precession (alternating pairs each half spin cycle)
R2+R4	R6+R8	+X spin up
R1+R3	R5+R7	+X spin down
R1+R2+R3+R4	R5+R6+R7+R8	Δv < 2.5 m/s
T1+T2	T3+T4	Δv > 2.5 m/s
T1 and T2	T3 and T4	Rapid Precession (alternating each half spin cycle)

Figure 2. Genesis Spacecraft - Rear and Forward Deck Views and Thruster Configuration

During development, additional limitations arose from star scanner performance tests, which led to a design workaround. The star scanner can only guarantee identification of one star per spacecraft rotation. As a result, the star scanner must be used in combination with the digital sun sensor (DSS) to obtain a three-axis attitude fix. Because the DSS was designed for use only when near the Sun, this effectively limited the use of the star scanner to attitudes within about 28° of the Sun. In addition, when at a higher spin rate, required for propulsive maneuvers to guard against consequences of a failed thruster, star scanners cannot reliably identify even one star. When off Sun or at higher spin rates, only the spinning sun sensor (SSS) can provide attitude information in the form of sun angle and sun crossing time, the latter of which provides the basis for estimating the spacecraft spin rate. Any attitude maneuvers beyond 28° off Sun entail motion directly away from or towards the Sun, with attitude quaternions estimated via dead reckoning. Moreover, because of the presence of wobble and nutation, which is exacerbated by any maneuvers, keep-out zones must be observed for spinning sun sensors at attitudes near the sunward and anti-sunward directions, to ensure that sun crossing times are accurately measured and spin rate knowledge is maintained. As a consequence of these considerations, maneuver errors are minimized only by remaining in an annular region between 7.5° and 28° off Sun.

Because Δv cannot be determined by on-board ACS software directly, the most accurate maneuver implementation possible for a spinning spacecraft makes use of the following relationship for spin rate changes $\Delta\omega$ along the spacecraft spin (+x) axis:

$$\Delta v_{spin} \cong \frac{I\Delta\omega}{mr} = k\Delta\omega \tag{1}$$

Here I (or I_{xx}) is the moment of inertia about the principal or spin axis, m is the mass, and r is the thruster moment arm. All of these quantities can be characterized as a single proportionality constant k. Spin changes can only be performed with selected pairs of the canted 0.2-lbf thrusters. The constant k may be determined via independent ground-based Doppler observations coupled with spin rate telemetry during calibration events near Sun-Earth line crossings, as indicated in Figure 1.

SRC delivery requirements are paraphrased as follows:

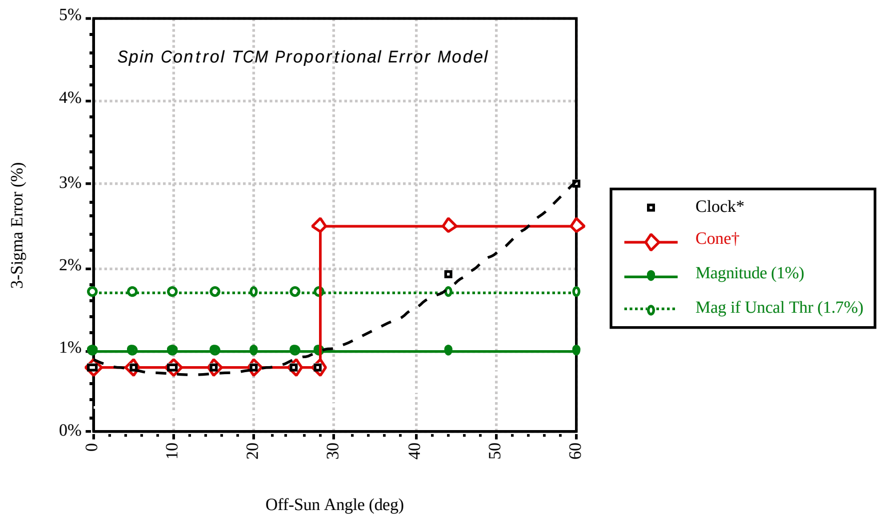
- The Genesis SRC must pass through the entry interface (125 km) at -8.0° ± 0.08° (3-sigma) flight path angle to achieve nominal aerodynamic and thermal conditions for atmospheric entry.
- The Genesis SRC must achieve a specified latitude and longitude at the entry interface to within an elliptical "keyhole" sized to ensure recovery within UTTR airspace; for analysis purposes, the acceptable tolerance at altitude is represented by an ellipse 33 km long and 10 km wide.

After calibration, quasi-closed-loop burns are possible with 3σ fixed errors within ~3 mm/s and proportional errors within ~1% to meet these entry requirements. The predominant worst-case execution errors assumed for spin control maneuvers after calibration are shown in Figure 3.

Additional background information on the Genesis mission and spacecraft design is provided in previous technical publications [1,2,3,4].

REFINEMENTS TO NOMINAL MISSION

Delivery accuracy was re-evaluated in light of improved orbit determination performance and modeling of non-gravitational forces acting on the spacecraft, derived as a consequence of radiometric tracking during a “quiet period” following completion of science collection in April 2004. Further refinements to the mission were examined around this time, which led to re-optimization of the reference trajectory, using techniques developed previously [4]. These modifications were intended to minimize adverse effects arising from possible spacecraft failures. These included changes to the SRC release sequence (Option A) and modified maneuver biases to reduce the odds of potential ground impact of the Genesis spacecraft at locations outside of UTTR (Option B). Such changes were examined in light of possible contingencies, such as delayed or partial maneuvers, and diversion into a backup orbit for deferred return of samples to the Earth. Minor adjustments to spin calibrations were also implemented as part of these mission refinements.



* Approx 1-sigma error = $-4.2600E{-}09*\theta^3 + 3.7703E{-}06*\theta^2 - 9.0567E{-}05*\theta + 2.9009E{-}03$

† 0.7947% within 28 deg of Sun; 2.5% elsewhere (on SSS)

Figure 3. Off-Sun Angle Effect on Spin Control Maneuver Execution Errors

New Baseline: Updated Reference Trajectory for Earth Return

After completion of the Science phase of the mission, the Earth return trajectory was re-optimized. The baseline maneuver strategy was adjusted as shown in Table 1. As mentioned previously, all of the TCMs shown in Figure 1 were biased to point near the Sun, primarily to minimize the chances of turning away from the Sun, resulting in increased execution errors as indicated in Figure 3. The bias directions chosen for the TCMs were originally somewhat arbitrary, coinciding with the planned attitude of the spacecraft at the time of each TCM. However, as a consequence of less conservative modeling of execution errors and reduced orbit determination (OD) errors due to a better characterization of non-gravitational forces, improved entry performance was predicted relative to previous results [5], as indicated in Figure 4 (Note that the ellipse shown provides an approximation of the allowable entry region or “keyhole” at the 125 km entry interface). Improvements to OD performance were evident from covariance studies based on post-science flight experience; this will be discussed briefly in a later section.

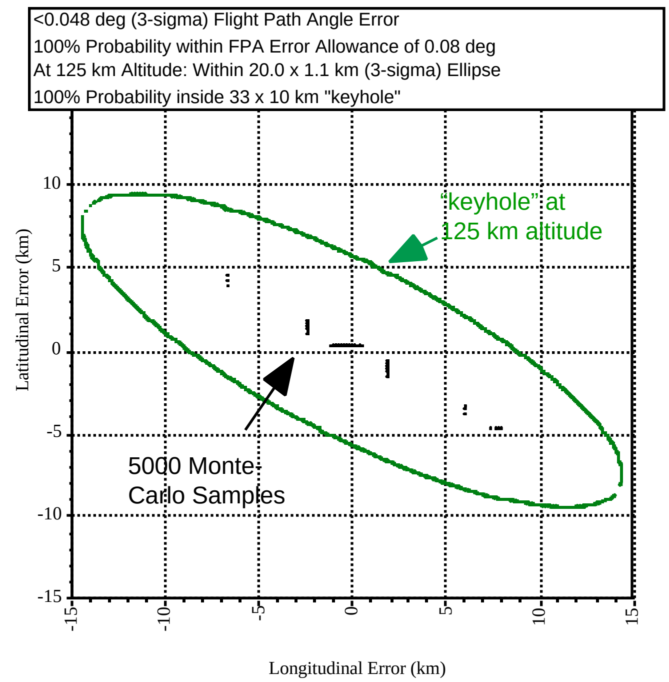


Figure 4. Predicted Delivery Errors for New Baseline

Table 1. Baseline Maneuver Plan for Earth Return

Maneuver	*Nominal Epoch*	*Previous Bias (m/s) and Sun Angle (deg)**	*Revised Bias (m/s) and Sun Angle (deg)†*	*Primary Backup*	*Backup Epoch*
TCM-6	*22-Apr-04*	*1.47 \ 20.4*	*0.97 \ 19.2*	*TCM-7*	*25-May-04*
TCM-8	*30-Jun-04*	*1.45 \ 22.4*	*1.81 \ 38.5*	*TCM-8a*	*7-Jul-04*
TCM-9	*9-Aug-04*	*0.97 \ 22.2*	*0.97 \ 22.5*	*TCM-9a*	*16-Aug-04*
TCM-10	*29-Aug-04*	*0.98 \ 9.5*	*0.98 \ 9.5*	*TCM-10a*	*3-Sep-04*
TCM-11	*6-Sep-04*	*0.96 \ 15.2*	*0.96 \ 15.3*	*TCM-12*	*7-Sep-04*

** Based on previous reference trajectory (ref08).*

† Based on post-Science re-optimized reference trajectory (ref09).

Option A: SRC Release Sequence Changes

The SRC release sequence consists of a number of separate activities, beginning from an attitude around 28° off Sun. Depassivation of batteries, required to provide power for the SRC separation, is performed prior to hinge separation with a cable cut to isolate the SRC electronically. This is followed by a series of attitude maneuvers, the first of which involves an increase in spin rate from 1.6 to 10 RPM. This is followed by a rapid precession along a rhumb line (PARL) directly away from the Sun to the SRC release attitude, performed on 5 lbf thrusters and supported by spinning sun sensors. The size of this turn is about 117° directly away from the Sun. A final spin change from 10 to 15 RPM occurs prior to the actual separation event, preformed via pyrotechnic release of eight mechanical springs.

The original mission design provided for a backup orbit, in the event that the SRC release could not be completed or previous maneuvers failed to deliver the SRC within the requirements for successful Earth entry. However, the hinge separation and cable cut can never be repeated in flight. Thus, one big drawback to exercising the backup orbit option would be loss of battery power needed later for the second SRC delivery attempt. To improve robustness in light of a possible sequence abort, an alternate sequence was considered in which the second spin-up event would be removed, and the entire sequence shifted two hours closer to entry with battery depassivation, hinge separation and cable cut inserted just prior to SRC separation.

Execution errors associated with the SRC release sequence were estimated to increase for 10 RPM versus 15 RPM, as shown in Table 2. Note that cone and clock angles are based on the orientation of the spacecraft +x axis relative to the Sun, cone being in the direction directly away from the Sun and clock being in the direction orthogonal to both cone and magnitude.

Table 2. SRC Release Sequence Execution Errors for Baseline and Option A

Activity	*Nominal Delta-V (m/s)*	*Execution Errors (mm/sec, 3-sigma)... Baseline \ Option A*		
		Magnitude	*Cone*	*Clock*
1.6-->10 RPM	*0.623*	*29.9*	*0.1*	*0.1*
PARL	*1.540*	*62.1 \ 69.8*	*15.1 \ 21.3*	*28.4 \ 28.4*
10-->15 RPM	*0.371 \ 0*	*18.1 \ 0*	*9.4 \ 0*	*9.4 \ 0*
Separation	*0.314*	*20 \ 20*	*48.4 \ 65.2*	*48.4 \ 65.2*

The resulting entry performance is shown in Figure 5. In comparison to the baseline performance in Figure 4, some degradation is evident. This would have been acceptable operationally. Nevertheless, Option A was rejected by the Genesis Project for another, more significant reason. The existing SRC release sequence had already been tested extensively by the Spacecraft Team, utilizing Lockheed Martin Astronautic's (LMA's) Spacecraft Test Laboratory (STL) which also supports a number of other missions in flight, such as Mars Global Surveyor and Mars Odyssey. With only a few months remaining until actual Earth entry, the scarcity of STL resources to support a sequence redesign was considered a greater risk than a potential sequence failure after battery depassivation [1].

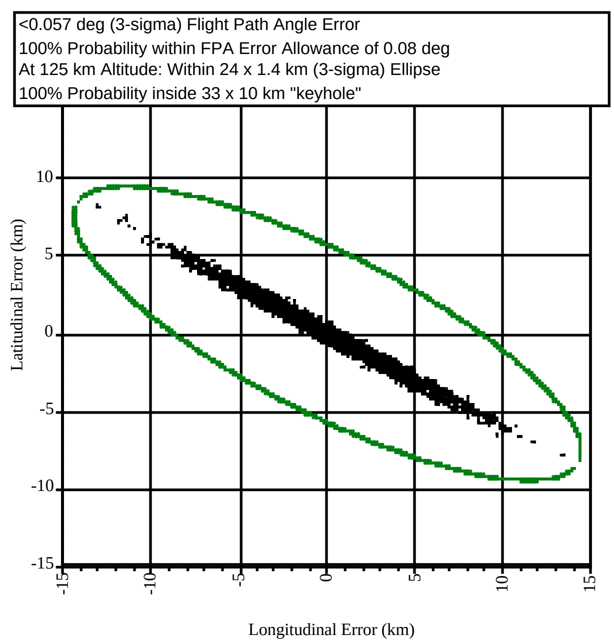


Figure 5. Predicted Delivery Errors with Option A (SRC Sequence Re-Design)

Option B: Approach Maneuver Biasing Adjustments

A review of the TCM biasing strategy uncovered concerns about risks to people and property on the ground, in the unlikely event of total spacecraft failure before or during some of the final TCMs prior to Earth return. Consequently, additional requirements were considered for TCM-9, at thirty days prior to entry, and for TCM-10, about ten days before entry:

- TCM-9 must be targeted effectively off Earth to achieve a geocentric altitude of no less than 200 km at perigee in the absence of subsequent maneuvers.
- TCM-10 must have an effective impact target within UTTR in the event that TCM-11 and SRC release are not executed.

Operationally, all TCMs through TCM-9 were actually targeted to a waypoint coinciding with the nominal location of the next TCM, while TCM-10 and TCM-11/12 were targeted directly to the Earth entry interface. The foregoing new requirements could be implemented via selection of appropriate bias directions for TCM-9 and 10, transparent to these operational procedures. Since these changes were considered late in the mission, it was important to make sure that such changes could be accommodated without adversely affecting the SRC delivery requirements mentioned previously.

A potential drawback to Option B was that, in order to meet the additional ground safety requirements above, both TCM-8 and TCM-9 were required to be biased off Sun, outside the ideal region for spin control maneuvers, as shown in Figure 6. Fortunately, TCM-10 and TCM-11 remain well within this region and, consequently, entry performance realized for Option B was virtually identical to that shown in Figure 4 for the baseline. Consequently, Option B was adopted as the revised baseline for the remainder of the Genesis mission, beginning with TCM-8, as shown in Table 3.

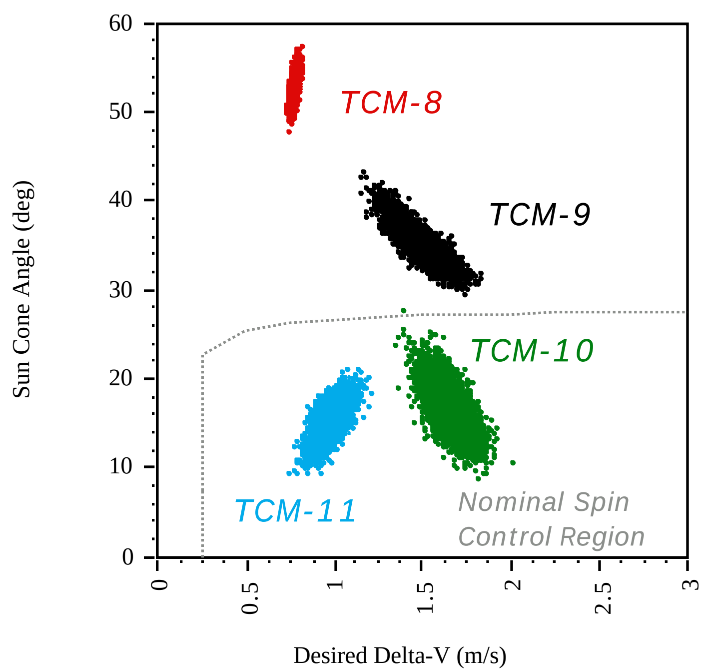


Figure 6. Monte-Carlo Results for Option B (TCM Bias Re-Design) Based on 5000 Samples

Table 3. Updated Maneuver Plan for Earth Return after Adoption of Option B

Maneuver	Nominal Epoch	Bias (m/s) and Sun Angle (deg)*	Primary Backup	Backup Epoch
TCM-8	30-Jun-04	0.77 \ 52.9	TCM-8a	7-Jul-04
TCM-9	9-Aug-04	1.50 \ 35.0	TCM-9a	16-Aug-04
TCM-10	29-Aug-04	1.66 \ 16.5	TCM-10a	2-Sep-04
TCM-11	6-Sep-04	0.98 \ 15.6	TCM-12	7-Sep-04

** Based on re-optimized reference trajectory for Option B (ref10).*

Adjustments to Calibrations

As part of the overall calibration plan, minor adjustments to spin calibrations were also implemented, after re-evaluation of spacecraft mass properties after closure of the SRC, as indicated in Table 4. The original plan [5] called for three sets of three specific spin calibrations with equivalent delta-v of 0.5, 1.0 and 1.5 m/s, respectively, achieved by increasing the spacecraft spin rate from 1.6 RPM to a higher value, then spinning back down to 1.6 RPM. However, as a consequence of a near perfect spacecraft injection early in the mission, less fuel was used than originally expected with a relative increase to I/m at the end of science collection. It was determined that spin changes to and from a maximum prescribed spin rate of 15 RPM would yield a higher effective delta-v (close to 2 m/s). However, it was desirable to induce about the same overall delta-v to the reference trajectory to preserve the integrity of the mission plan based on Option B. Therefore, the minimum spin change delta-v was lowered to about 0.3 m/s (between the one-way turn circle diameter of $2I\omega/mr \sim 0.24$ m/s and two-way turn circle diameter of $4I\omega/mr \sim 0.47$ m/s). An intermediate delta-v of 0.8 m/s was also selected. These changes allowed exploration of the full range of spin change capability, which might be particularly useful in the event of contingencies (to be discussed in the next section).

Table 4. Updated Genesis Earth Return Calibration Activities

Calibration	Nominal Epoch(s)	Purpose/Description
OD Quiet Period	5-21 Apr '04	Characterize solar radiation pressure cross-section while in cruise configuration (SRC backshell closed); reduce unmodeled non-gravs.
Spin Cal (SC)-1	7-9 May '04	Determine proportionality or function between spin rate change and delta-v while at Earth point via three 3 spin control maneuvers (0.3, 0.8 and 2.0 m/s).
PARL Cal	10-12 May '04	Verify delta-v model for precession to attitude using rhumb line, to be used during SRC release sequence; precess across Earth point 7.5 to 25 deg from Sun while at 10 RPM.
SC-2	7-9 Jun '04	Verify previous spin control maneuver results while off Earth point.
SC-3	15-17 Jul '04	Verify previous spin control maneuver results at Earth point.

UPDATES TO CONTINGENCY PLANS

Contingency plans were devised for maneuvers and other events during Earth approach and return. These include backup maneuvers, as indicated in Tables 1 and 3, which must be implemented in response to delayed or aborted maneuvers. Earlier plans [5] for implementation of a biasing turn after TCM-10 in the event of an off-sun TCM-11/12 were discarded based on the improved performance of off-sun maneuvers (see later section). Delays in SRC release activities can be tolerated to a limited extent. In the event of a failure or significant performance shortfall during SRC release, either the spacecraft could be diverted into a backup orbit for a later SRC delivery attempt, or continue on a UTTR impact trajectory, in the event of a failure of the SRC to successfully separate from the spacecraft bus. Certain contingency plans dealing with SRC release are discussed in related papers [6,7]. In preparation for actual operations, contingency plans were carefully reviewed in terms of risk and readiness to undertake return to Earth.

Considerations for Backup Maneuvers

As mentioned previously, since all TCMs are biased, they must be executed to keep the spacecraft on course for Earth return. Hence, if a maneuver is delayed, or aborted at some point during execution, the missing delta-v must be made up at the designated backup maneuver and/or at later maneuvers. In most cases, two corrective maneuvers must be applied, each addressing three of the six degrees of freedom encompassing position and velocity. However, near Earth entry, flight path angle, latitude and longitude are strongly correlated and can be corrected largely via adjustments to arrival time; this will be addressed further in a later section. Examples of how deterministic delta-v varies, as a function of nominal maneuver completion, are shown in Figures 7, 8 and 9.

Figure 7 addresses TCM-9, the maneuver 30 days prior to Earth entry. In all but about 10% of cases shown, the missing delta-v is made up by a combination of TCM-9a (23 days from entry) and TCM-10 (10 days from entry). For the remaining cases, TCM-9a becomes too small to execute (e.g., inside turn circle or outside spin calibration range); in these cases, re-optimization of remaining TCMs would be needed. If TCM-9 is delayed or aborted when less than about 54% complete, the required direction for TCM-10 is forced off Sun or outside the nominal spin control region. However, even in the worst case, entry performance equivalent to the nominal (Figure 4) is still realized.

Figure 8 shows the effects of incomplete TCM-10 and TCM-11, the final nominal maneuver at two days prior to SRC release and Earth entry. As shown in Figure 8, if TCM-10 is aborted or delayed, one of two corrective actions must be taken:

- Backup maneuver TCM-10a (at six days prior to entry) must be implemented with the nominal TCM-11, or
- In at least 10% of cases shown, where TCM-10a would be too small, TCM-11 must be augmented in both magnitude and off-sun angle to compensate for an anomalous TCM-10.

Note that the off-sun angle for TCM-10a is small enough to lie within a keep-out zone, requiring a “dogleg” implementation in which the maneuver is effectively split into two parts, lying about 7.5° from the sun on opposite sides of the spacecraft-Sun line. Finally, Figure 9 indicates the effects of an anomalous TCM-11. If TCM-11 is delayed or aborted, there remains only one opportunity to make up the delta-v at TCM-12, or about one day prior to entry, short of diverting into the backup orbit. As expected, TCM-12 would become a multiple spin control maneuver, about twice the size of TCM-11, if the latter were delayed altogether. Also, in about 15% of cases shown, TCM-12 would be too small to execute accurately, possibly requiring diversion into the backup orbit.

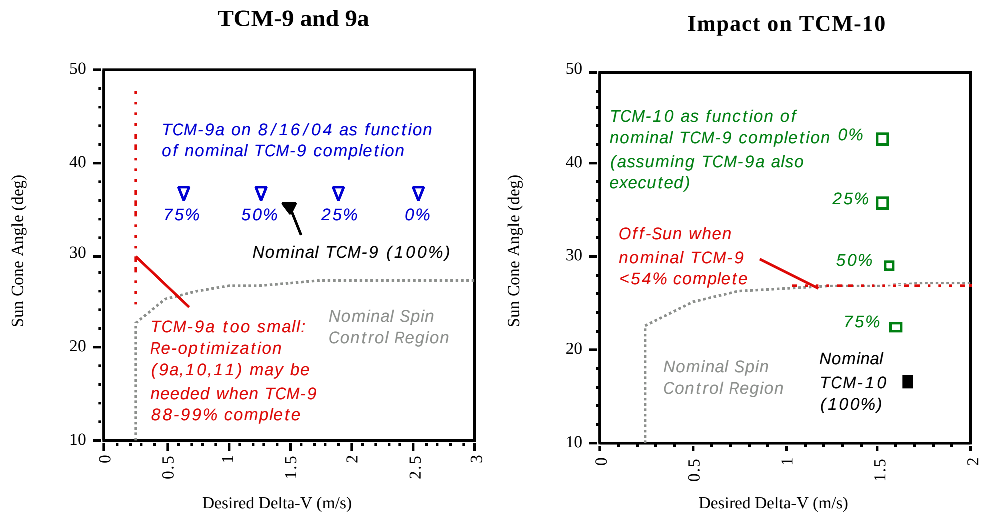


Figure 7. Effects of Delayed or Aborted TCM-9

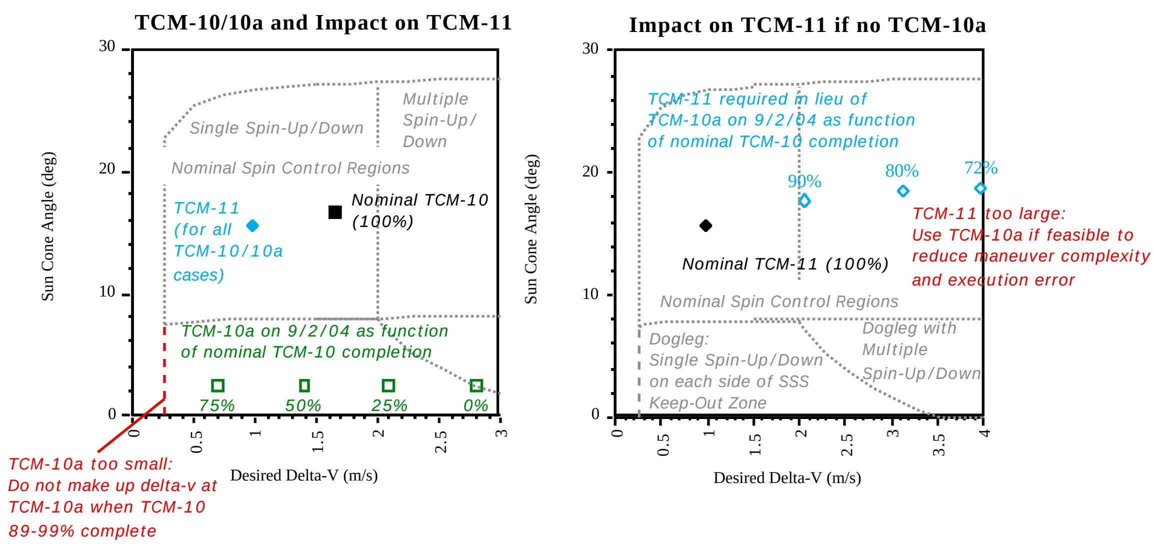


Figure 8. Effects of Delayed or Aborted TCM-10

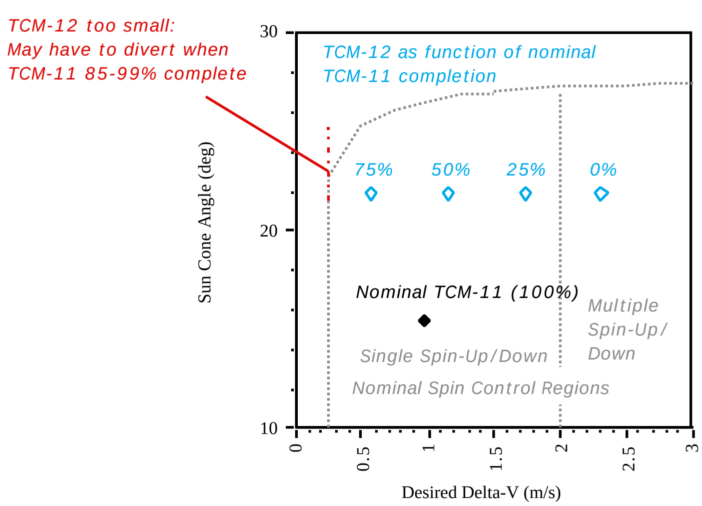


Figure 9. Effects of Delayed or Aborted TCM-11

SRC Release Delays

Another type of contingency to consider is the possibility of delayed execution of SRC release activities. The Spacecraft Team developed a specific set of fault protection (FP) responses on board which generally allowed for possible processor and thruster string swaps and permitted at least two attempts to perform each SRC release activity before aborting the sequence and preparing to divert the spacecraft into the backup orbit. Since each activity imparts delta-v to the spacecraft as it plunges further into Earth's gravity well, such delays could have a significant effect on delivery accuracy, as indicated in Figure 10. As shown, most delays are tolerable with respect to entry requirements.

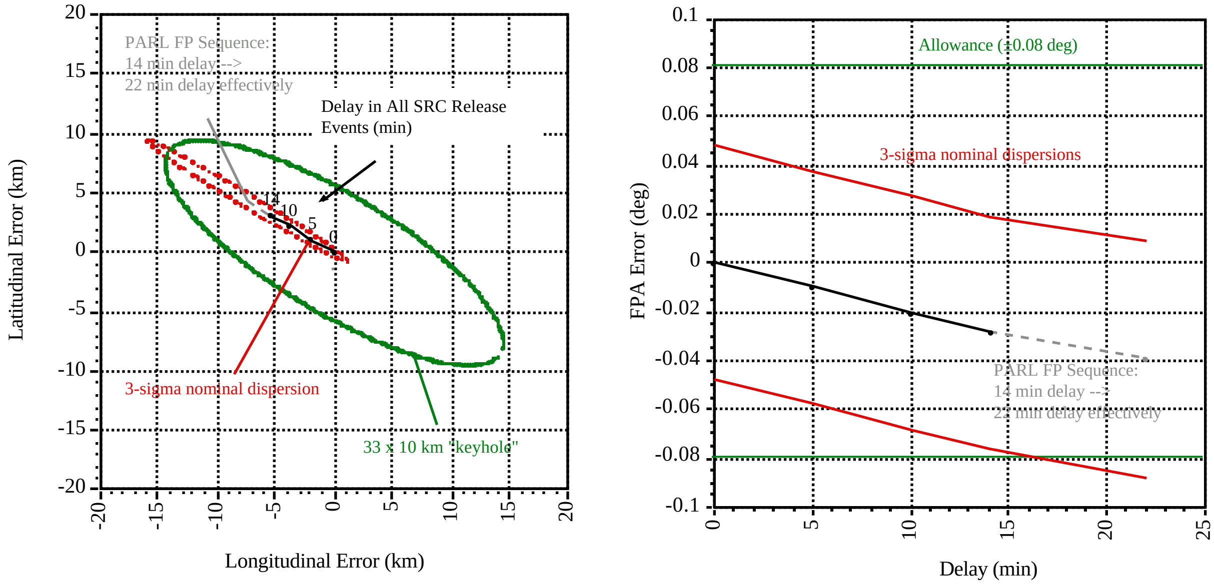


Figure 10. Effects of Delays in SRC Release Sequence

Risk Review and Readiness Assessment

As part of an overall risk review and readiness assessment of the final phase of the Genesis mission, three areas of residual risk were identified for maneuver planning:

- Execution accuracy
- Anomalous execution
- Design and implementation

Execution accuracy could be worse than expected. In particular, experience with large-angle off-sun maneuvers was limited to relatively large maneuvers performed early in the mission, including TCM-1 (48 hours post-launch) and Lissajous Orbit Insertion (LOI). These maneuvers were also the only experience with the PARL at 10 RPM, later to be used for SRC release. Also, although the relatively accurate spin control maneuvers had been tested during the aforementioned calibration activities, there was the possibility that the primary thruster string would fail prior to entry. Although mass properties were the dominant factor in these calibrations, thruster alignment errors associated with the backup string could result in increased magnitude execution error, as indicated in Figure 3.

To address these concerns, Monte-Carlo analyses were performed in which modeled execution errors were increased and the impact on entry delivery accuracy gauged. For example, Figure 11 reveals that, even when all execution errors are arbitrarily doubled, the resulting entry performance is still well within requirements.

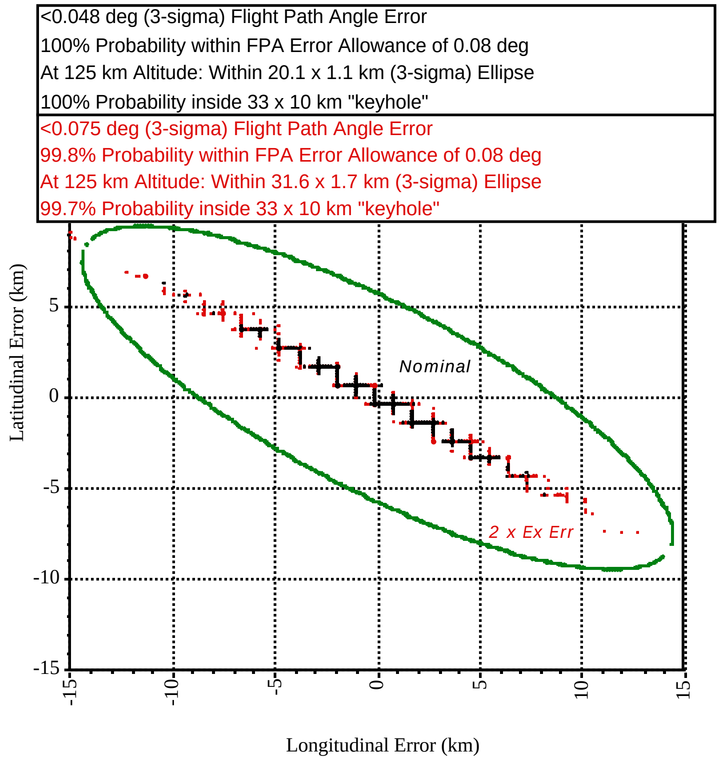


Figure 11. Impact on Entry Performance of Arbitrary Doubling of Maneuver Execution Error

So, calibration of backup thrusters was deemed unnecessary and residual risks associated with execution errors were judged to be low, because of such demonstrated robustness.

Anomalous execution encompasses issues discussed in previous sections, including possible delays and partial maneuver execution. Maneuver overburn is also possible, but extremely unlikely due to the way that maneuvers are sequenced. Precessions and spin changes are typically divided into progressively smaller segments; for instance, for a three-segment spin change, 90% of the delta-v is experienced in the first segment, followed by 9% and then the final 1%. The latter is executed, only if the targeted spin rate has not been achieved within an acceptable tolerance (e.g., 0.14 RPM) [8].

Design and implementation risks were also identified, but judged to be very low, because of in-flight experience. The vast majority of maneuvers performed during the science collection phase were relatively benign, near-sun station-keeping maneuvers (SKMs); most of the maneuver modes planned for prior to launch had not been exercised in flight. However, as a risk mitigation measure, the project developed and tested a new maneuver mode, utilizing spin control for sun angles beyond the nominal spin control regions. This mode was successfully implemented for TCM-9 (see later section). Moreover, concerns about uploading erroneous parameters were assuaged by the extensive and thorough maneuver design process, culminating in STL ground verification; this process is described in the next section.

In summary, residual risks were identified and judged to be low at most and Genesis was deemed ready to support Earth return and recovery operations.

FLIGHT EXPERIENCE

The operational planning process for TCMs, as described below, entails close cooperation between the Navigation (JPL) and Spacecraft (LMA) teams. This begins with an OD solution from which the pre-TCM state is derived [9]. This encompasses targeting and total delta-v search, decomposition of the delta-v into precession, spin change and burn blocks, segmentation of blocks to derive uploadable configuration files with command parameters, and independent design verification via sanity checks and STL runs. Additional processes in support of Genesis return, SRC recovery and bus disposal are described in related papers. Operational readiness tests (ORTs) were conducted to test and refine critical processes. Finally, actual flight performance associated with TCMs 8 through 11 is examined, as well as actual delivery accuracy, which was still quite excellent, in spite of the drogue chute deployment failure.

Maneuver Planning Process

An overview of the process employed for planning TCMs is shown in Figure 12.

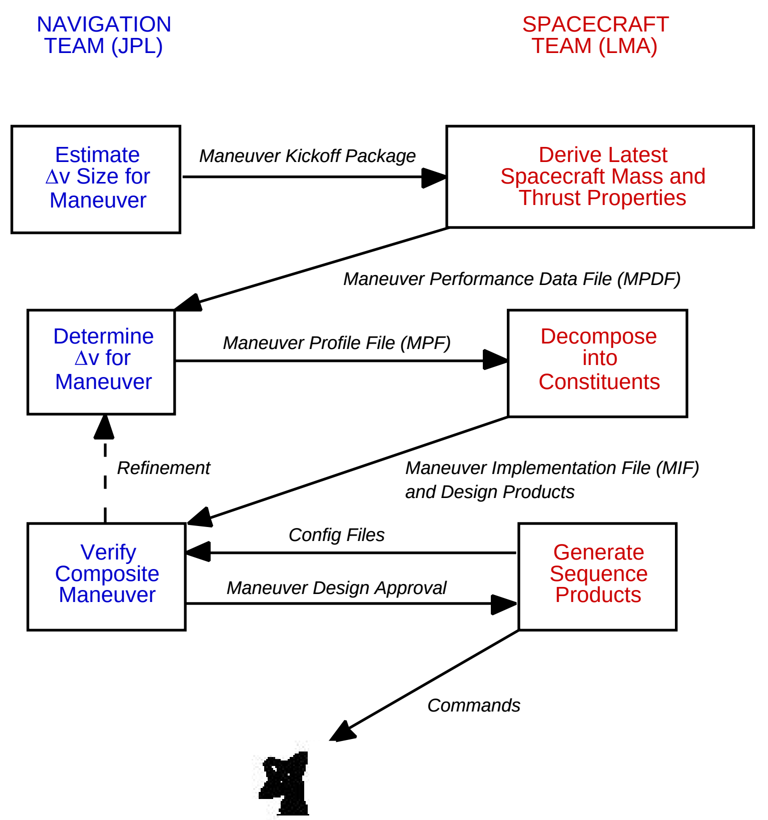


Figure 12. Overview of Maneuver Planning Process

The process begins with an initial determination of delta-v size, based on an OD solution [9] and instantaneous total delta-v search by the Navigation Team. This information is presented at a teleconference to kick off the maneuver design process; the maneuver type and design constraints are also determined as part of this kickoff discussion. The delta-v sizing information is used by the Spacecraft Team to estimate updated mass properties and thrust characteristics. These properties are sent back to the Navigation Team in the Maneuver

Performance Data File (MPDF) to support a finite burn search. This search accounts for total delta-v imposed over a representative duration, which is supplied to the Spacecraft Team in the Maneuver Profile File (MPF). The Spacecraft Team then decomposes the delta-v geometrically, in accordance with the pre-selected maneuver type, into spin change, precession and burn constituents. These constituents are supplied to the Navigation Team as separate blocks in the Maneuver Implementation File (MIF). Each block can be represented as one or more segments, which can be used to develop a more detailed version of the MIF, known as the segmented MIF. The MIF and/or segmented MIF are used by the Navigation Team to verify the design, along with ancillary design information. In the vast majority of cases, the detailed design will achieve a state close enough to the desired target that the Spacecraft Team can proceed with generation of sequence products, including STL runs for final verification. The Navigation Team also performs a spot check of key parameters within these sequence products prior to final approval of the maneuver design. After final approval at a command teleconference, the sequence products are uploaded to the spacecraft via the Deep Space Network (DSN) prior to maneuver execution.

Usually, one design cycle, also known as the preliminary design, is sufficient. However, if an unsatisfactory design is apparent, the Navigation Team can refine the required delta-v based on updated OD data and begin a final design cycle with an updated MPF in order to achieve an acceptable TCM design. Refinement via a final design cycle becomes more critical in the design of TCM-11/12, where Earth's gravity field varies significantly over the course of a few hours.

Targeting Variations

For TCM-9 and all earlier maneuvers, the target selected by the Navigation Team was the location at the next maneuver epoch as derived from the reference trajectory. Such waypoint targeting was employed to keep the spacecraft within tens to a few hundred kilometers of the reference trajectory until the last ten days of the mission. At this point, beginning with TCM-10, more precise entry targeting was necessary to support SRC recovery and spacecraft bus disposal.

As mentioned previously, additional ground safety constraints were factored into the reference trajectory itself, such that they were transparent in terms of the operational planning process. However, for the entry targeting to be successful, a detailed representation of the delta-v incurred during SRC release was critical to the targeting process for TCM-11/12. Moreover, the nominal TCM-11 delta-v needed to be included with the trajectory, in order to correctly target TCM-10. Targeting to waypoints involved three components of position at a fixed epoch. On the other hand, targeting to entry entailed four parameters, including flight path angle, latitude, longitude and geocentric altitude or radius from the center of the Earth at a given time. Alternatively, the targeting could be tied to a particular event, such as crossing the 125 km entry interface altitude; however, determination of longitude would still be linked to a particular arrival time via the Greenwich hour angle (GHA), so four targeting parameters would still be involved, either directly or indirectly.

For operational robustness, it was convenient to use inertial flight path angle, altitude and latitude or declination at a fixed time as the basis for the entry-targeting search. Once these target parameters were satisfied within acceptable criteria (e.g., usually 0.001° for angles and 1 m for distance), a determination of right ascension could be made and a longitude derived using the GHA. If the longitude estimate was too far off from the required position, arrival time was adjusted accordingly and the search process repeated until the longitude requirement was met within similar error criteria. This process usually required only a single iteration in order to converge to the correct target conditions, in part because the spacecraft never drifted far from the reference trajectory. The robustness of this process also arises from the strong correlation among flight path angle, latitude and longitude errors, as evident in Figure 13.

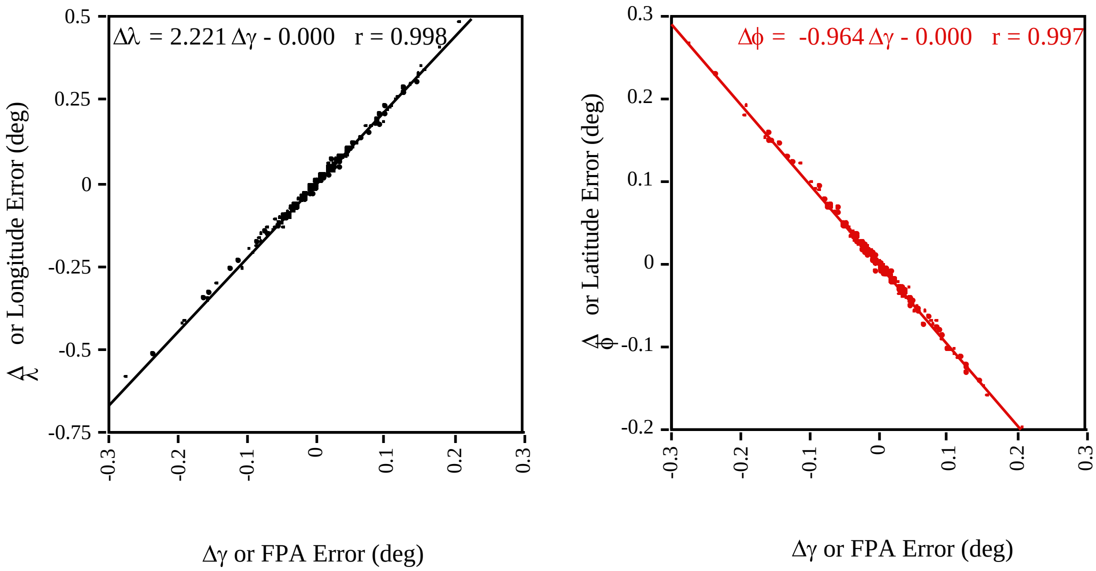


Figure 13. Correlation of Entry Targeting Parameters (Based on 5000 Monte-Carlo Samples)

Maneuver Types and Decomposition

Maneuver types used during flight are shown in Table 5. As stated previously, delta-v events include various combinations of precessions, spin changes and translational delta-v's or burns. Precessions outside of the region within 28° of the Sun must follow a rhumb line, usually directly away from or towards the Sun, instead of a great circle across the celestial sphere. Keep-out zones must be observed to guarantee that knowledge of spin rate is preserved in the presence of nutation, wobble and potential thruster failures. To meet these and other constraints, a number of maneuver types were developed and tested [8], such as those indicated in Table 5. The maneuver decomposition process, performed operationally by LMA's Spacecraft Performance Analysis System (SPAS), was able to accommodate all such types [8].

For most maneuvers, the impact of maneuver decomposition on targeting performance was insignificant, so that only one design cycle, as outlined in Figure 12, was required. However, for maneuvers targeting the entry interface near Earth, additional iterations were thought to be required in order to minimize targeting error. For instance, TCM-11 was implemented as a spin control TCM, requiring decomposition into a great circle precession to attitude (PTA), followed by a spin-up, a spin-down, then another PTA to the planned post-maneuver attitude. To achieve the designated entry target within a specific design cycle required first deriving a total delta-v, decomposing the delta-v into an initial maneuver implementation, and calculating the error in FPA, latitude and longitude due to decomposition. These errors were then used to derive a target offset, or "windage" correction. The entire design process could then be repeated with the offset target, as indicated by the modified process in Figure 14.

However, the timeline for design and execution of final TCMs was restricted to only 24 hours, beginning with delivery of the OD solution. After the modified process was tested during an early operations readiness test (ORT), it became apparent that there was little or no schedule margin to accommodate this "windage" correction. Also, the correlation evident in Figure 13 suggests a simpler approach in which the impact of decomposition can be minimized by merely adjusting a single parameter. This parameter was usually the timing of the decomposed

Table 5. Maneuver Types Used for Trajectory Correction During Flight

Time-line	Description	Flight Usage	Config†	Thruster(s) Used††	Off-Sun Angles (deg)	Off-Sun Time (min)*	Keep-Out Zone(s) **	ΔV Limits, (m/s)
2	TCM-1 on SSS	TCM-1	C	T,R	30 or 150	68	AS, S or SM	2.5<ΔV<110
4	LOI or Large TCM	LOI, Divert	C	T,R	12.5 - 150	84	AS, S or SM	1.0<ΔV<57
5	Small TCM (Off-Sun)	TCM-8	C	R,T	28 - 150	85	AS, S	0.05<ΔV< 1.5
7	Near-Sun ΔV (SKM/TCM)	SKM-1A thru 5C (15), TCM-6	S for SKM, C for TCM	R	<28	0	SM	0.05<ΔV< 6
11	Spin Control ΔV (Spin-Up/Down)	Spin Cals (9), TCM-10/11	C	R	7.5 - 28	0	SC	0.5<ΔV<1.5
11b	Spin Control ΔV (Off-Sun Variant)	TCM-9	C	R	28 - 60	85	n/a	0.5<ΔV<1.5
19	PARL (at 10 RPM)	PARL Cals (3)	C	T,R	<28	0	SC	n/a

† C = Cruise or SRC Closed, S = Science or SRC Open (with collectors deployed).
†† R = Reaction Control Subsystem (RCS) or 0.2lbf thrusters, T = TCM or 5lbf thrusters; if multiple, first is primary thruster used, second is support for certain precessions or spin adjustments.
* Maximum time allowed when >35° off Sun.
** SC = 7.5° Sunward
SM = 12.5° Sunward (17.5° for timeline 7 TCM)
S = 25° Sunward (after Return from Off-Sun)
AS = 30° Anti-Sunward (when Off-Sun Delta-V)

sequence, but could also be the intermediate spin rate achieved after the spin-up. The mid-time of the decomposed sequence could be made to coincide with the time associated with the initial delta-v search. If additional adjustment was needed, the sequence start time or intermediate spin rate could be changed without requiring a full design iteration. This abbreviated process was verified during ORTs, including a stress test in which TCM-11 was aborted and a quick turn-around design of TCM-12 was required to recover from this anomalous situation.

Maneuver and Entry Targeting Performance

Actual performance for SKMs and return TCMs consistently met or exceeded expectations [10]. This is shown in Table 6 for all smaller maneuvers through TCM-10 (TCM-11 was never fully reconstructed); note that the best performance was realized for maneuvers using spin control, beginning at TCM-9. Figure 15 indicates the actual TCM-11, as designed in flight. This is well within the possible dispersion predicted from earlier Monte-Carlo analyses, as shown in Figure 15. Finally, Figure 16 provides the final (post-TCM-11) targeting performance projected down to UTTR. This ground prediction was performed by our colleagues at NASA's Langley Research Center (LaRC) using the 6-Degree-of-Freedom (6-DOF) Program for Optimization of Simulated Trajectory (POST). This prediction utilized the entry interface target state used by Navigation and provided via an Entry State File. Details regarding the entry state propagation down to the ground are discussed in a related paper [11].

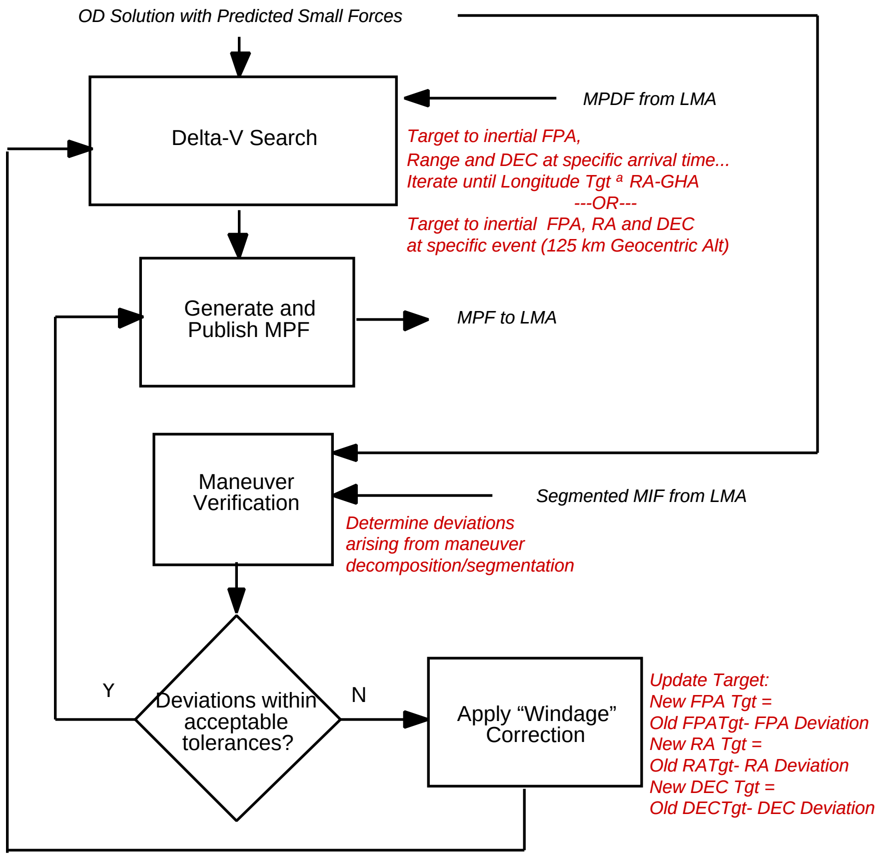


Figure 14. Entry Targeting Process Utilizing “Windage” Correction

Table 6. Reconstructed Performance for TCMs during Earth Return

Maneuver	Epoch	Overall Magnitude Error	Overall Direction Error (deg)	Reconstructed Net Δv (m/s)
SKM-1A	12/12/01	+2.30%	0.53	1.115
SKM-1B	1/16/02	+1.44%	0.17	1.328
SKM-1C	3/20/02	+0.79%	0.63	1.549
SKM-2A	5/22/02	-0.07%	0.90	0.793
SKM-2B	7/24/02	+0.30%	0.23	1.465
SKM-2C	9/25/02	+0.26%	0.23	1.453
SKM-3A	12/11/02	+0.53%	0.64	1.276
SKM-3B	2/6/03	+0.68%	0.73	1.256
SKM-3C	4/16/03	+0.38%	0.57	1.233
SKM-4A	6/11/03	+0.37%	0.16	1.274
SKM-4B	7/30/03	+0.71%	0.23	1.478
SKM-4C	9/24/03	+0.63%	0.16	1.350
SKM-5A	11/19/03	+0.30%	0.18	1.112
SKM-5B	1/14/04	+0.26%	0.38	1.460
SKM-5C	3/10/04	+0.34%	0.14	1.327
TCM-6	4/22/04	+0.67%	0.12	0.896
TCM-8	6/30/04	+2.39%	0.35	0.723
TCM-9	8/9/04	+0.19%	0.30	1.343
TCM-10	8/29/04	+0.15%	0.12	1.634
MEAN:		0.66%	6.22 mrad	
STD DEV*:		0.67%	4.15 mrad	
3σ*:		2.02%	12.46 mrad (1.25%)	
zero-mean STD DEV†:		0.96%	7.62 mrad	
zero-mean 3σ†:		2.88%	22.86 mrad (2.29%)	
MEAN#:		0.17%	3.67 mrad	
spin control STD DEV†:		0.06%	1.33 mrad	
spin control 3σ†:		0.17%	3.99 mrad (0.4%)	

* NOTE: These errors assume mean can be extracted (compensated for) as a systematic error with high confidence

† These numbers assume no systematic error (i.e., low confidence)

TCM-9 and 10 only (spin control maneuvers)

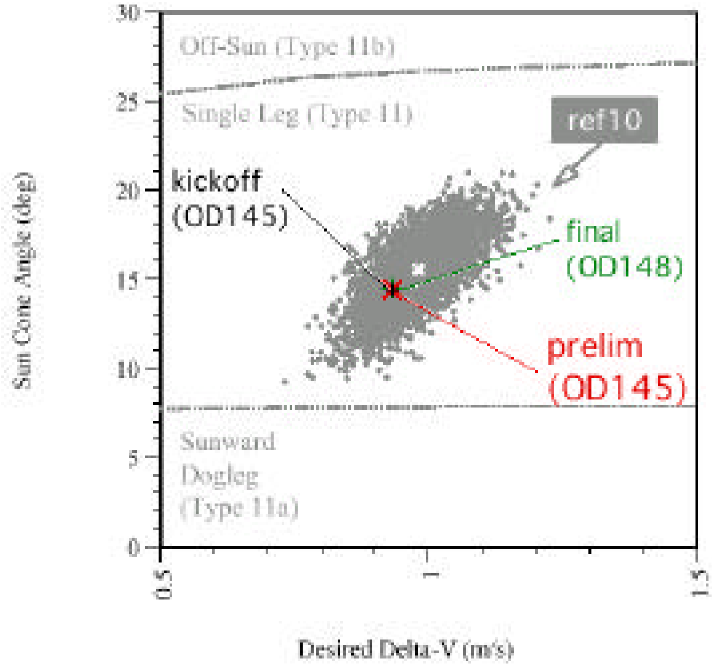


Figure 15. TCM-11 Design Compared to Monte-Carlo Prediction

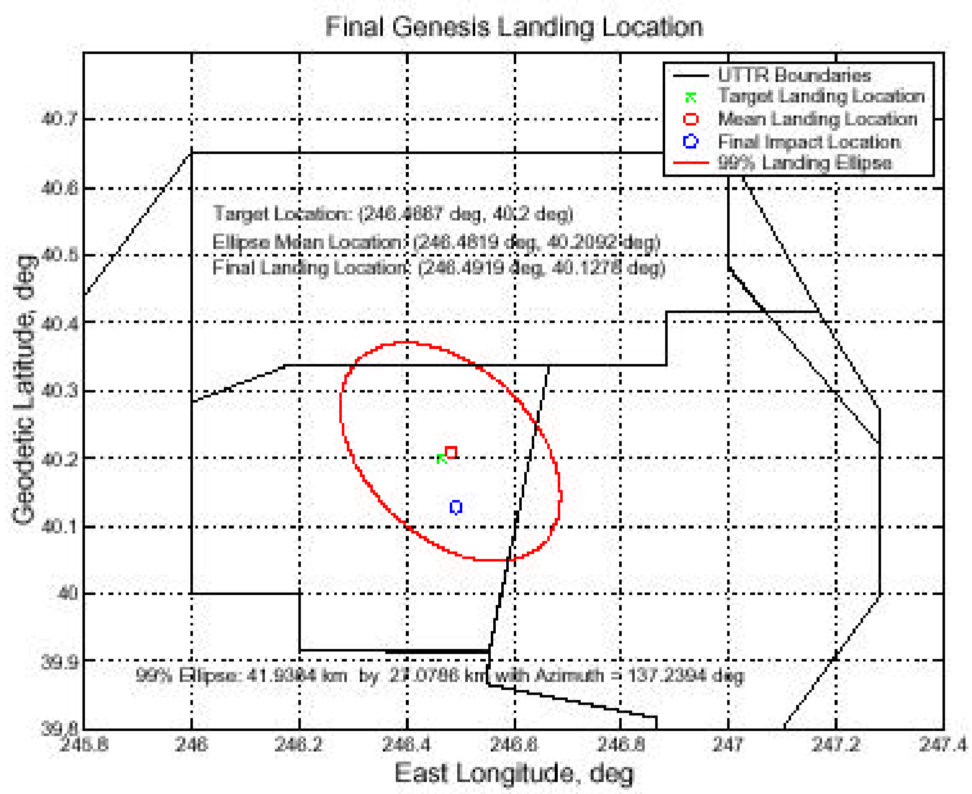


Figure 16. Final (Post-TCM-11) Ground Targeting Performance

Supplementary Notes on OD Performance

OD covariance analyses supported the foregoing maneuver analyses and were performed with two main objectives:

- Generate a set of realistic delivery covariances on the spacecraft state at the maneuver execution epochs for use in TCM design.
- Explore variations in data arc lengths and other OD parameters to identify any vulnerability that might exist, and similarly to identify OD capabilities, which might be required in non-nominal conditions, such as losing a tracking pass during a TCM, thereby preventing reconstruction.

In general the results showed that OD capabilities were extremely robust due to several factors, including the lack of delta-v between TCMs (no daily precession maneuvers as during the Science phase). Also, the spacecraft was spin stabilized, thereby eliminating any thrusting activity to maintain spacecraft stabilization. Finally, the accuracy of the tracking data enabling the use of data weights of one meter in range and 0.3 mm/s in Doppler (after spin signature removal). In conclusion, if necessary, the reconstruction of TCMs could be dispensed with altogether in flight operations (should the tracking pass be lost) by beginning a new data arc after each TCM. This produced spacecraft state uncertainties at the next TCM, virtually identical to those, which estimated the TCM just executed using a longer data arc. This high degree of robustness made the OD process immune to any conceivable data arc outage.

LESSONS LEARNED FOR FUTURE MISSIONS

The next sample return mission is Stardust, also a part of NASA's Discovery Program [5]. The objective of Stardust is to collect interstellar and comet dust particles, the latter from an encounter with the comet Wild 2 in January 2004. After re-entry at Earth, a parachute landing and recovery on the ground is planned for the Stardust SRC in January 2006. Unlike Genesis, Stardust utilizes three-axis attitude control, but, like Genesis, has unbalanced thrusters. In the case of Stardust, these are used both for propulsive maneuvers and to maintain attitude control within specific pitch, roll and yaw deadbands. The strategy for dealing with Stardust return and entry has a number of similarities to Genesis, as well, including calibration of specific thruster modes, maneuver decomposition, and TCM biasing near the Sun. Contingency plans for Stardust will incorporate refinements similar to those discussed for Genesis, including backup maneuvers, recovery from aborted maneuvers, special fault protection measures for SRC release, and provisions for diversion of the SRC and TCM biasing adjustments, both driven by ground safety considerations.

For other missions, not yet fully developed nor in flight, there are perhaps deeper lessons to absorb. Although many difficulties were successfully surmounted for Genesis, attendant operational complexities were overlooked or even ignored in development, solely on the basis of launch cost. Complexities, such as maneuver decomposition, sunward biasing impacts on backup maneuvers, and SRC release fault protection strategy, had the potential to overwhelm the ground team in the final days of the mission. Additional fuel had been added to the spacecraft prior to launch as an attempt at a relatively inexpensive mitigation for design shortfalls, such as that described earlier for the star tracker. However, other enhancements, such as balanced thrusters or additional solar cells on different sides of spacecraft, were rejected summarily, without a comprehensive trade study to gauge the impact on the mission as a whole.

Future missions should undertake extensive trade studies during Phase A/B to avoid such problems. A more systematic, end-to-end assessment of mission requirements and capabilities is called for to avoid merely passing on problems to Phase E, which may require a tremendous, possibly unsupportable, influx of resources to resolve.

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