Genesis – The Middle Years *

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Abstract – Genesis is the fifth mission of the Discovery program sponsored by NASA. The objective of Genesis is the return of pristine solar wind samples to Earth to expand the understanding of how planets, asteroids, and comets were formed from our original solar nebula. Genesis was launched August 2001 and will return September 2004. After an initial checkout of the spacecraft and instruments, Genesis is well into the solar wind collection phase, the middle years, of the mission. Performance of the operations team and the flight system has been exceptional to date. Completion of solar wind sample collection and return to Earth is planned in 2004.

TABLE OF CONTENTS

1. MISSION AND SCIENCE OVERVIEW

Introduction: Genesis is the fifth mission in the NASA Discovery program series of dedicated science investigations. The Genesis spacecraft was launched on August 8, 2001 from Kennedy Space Center aboard a Delta 7326 launch vehicle. After a period of spacecraft and payload checkout, sample collectors were exposed to the sun on December 3, 2001. After approximately two years of solar wind sample collection, the collectors will be stowed and the samples will be returned to Earth on September 8, 2004. Upon return to Earth, Genesis scientists will perform a preliminary analysis of a small portion of the samples. Using a competitive process, additional samples will be provided to scientists throughout the world. The samples from Genesis are expected to provide a reservoir for experimentation that will lead to scientific discovery well into the twenty-first century.

The Genesis team is led by Principal Investigator Dr. Donald Burnett of the California Institute of Technology. Other Genesis team members include: the Jet Propulsion Laboratory – project, payload/mechanisms, and mission management, navigation and mission planning and sequencing; Los Alamos National Laboratory – science instrument development and operations; Lockheed Martin Astronautics – spacecraft development and operations; and Johnson Space Center – contamination control and sample curation.

Mission Description: The Genesis mission design[1,4] was driven by the requirement to collect solar wind samples outside the Earth's magnetosphere for at least 22 months and the requirement to provide a daytime return of those samples to the Utah Test and Training Range (UTTR). The Genesis mission design was essentially based on a combination of two trajectories linked by a deterministic maneuver, designed using dynamical systems theory[3]. The Genesis mission trajectory, shown in Figure 1, was designed to depart from the Earth toward the sun, perform five orbits about the sun-Earth L1 libration point, transition from the L1 libration point to the L2 libration point, and finally return to the dayside of Earth. Although updated several times since its original inception[4,5,6] to accommodate revised launch periods[8], the basic mission characteristics still apply[11]. The first part was required for transfer of the spacecraft from launch in July-August

* [0-7803-7651-X/03/$17.00©2003 IEEE]

2001 to the vicinity of the Earth-sun L1 point approximately three months later. The second entails five halo orbits about L1, each approximately six months in duration, where the bulk of the solar wind collection occurs. The solar wind collection duration was needed to provide sufficient sample to precisely measure most elements of the periodic table. The daytime return to Earth was needed to support a mid-air capture of the sample by helicopter over UTTR. Although based in part on previous libration-point orbiting missions flown over the past twenty years[7], a unique trajectory was designed to meet the Genesis requirements. This trajectory was designed with a single deterministic orbit insertion maneuver. Additionally, small station-keeping maneuvers were designed to periodically maintain the Genesis mission trajectory.

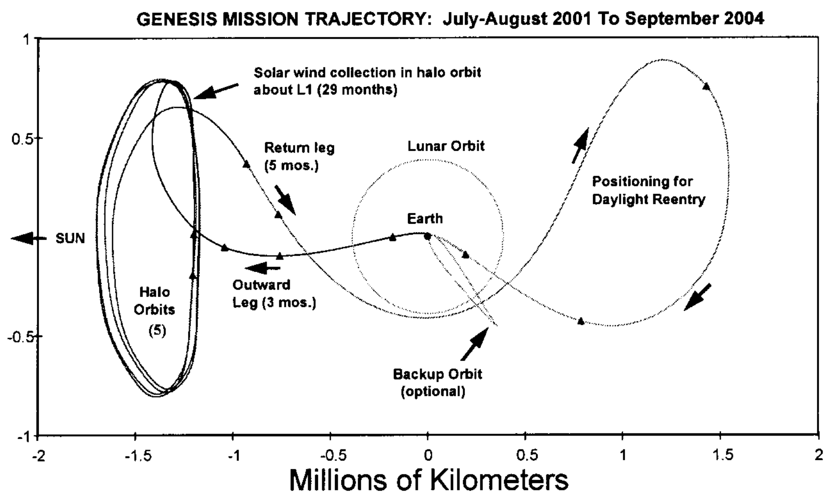


Figure 1. Genesis Mission Trajectory

Science and Payload Description: The objective of the Genesis mission is the precise characterization of elemental and isotopic composition of the solar wind, which is thought to be isotopically representative of the solar photosphere. The photosphere in turn is considered to have the same composition as the solar nebula from which the solar system was formed. Thus by measuring the solar wind isotopic composition scientists hope to gain insight into the process of solar system evolution. Apollo astronauts first collected solar wind on the moon, undisturbed by the Earth's magnetic field, using a foil made from ultra-pure aluminum. Despite the short duration, approximately 2 days, the experiment successfully demonstrated the process of collecting a solar wind sample. After Apollo the Genesis mission concept of a dedicated, long duration sample return mission was born.

Three different types, or regimes, of solar wind are widely recognized from in-situ spacecraft observations: the "Fast" regime from coronal holes, the "Slow" regime from coronal boundary regions, and the "CME" regime from coronal mass ejections. These regimes have different elemental compositions due to different acceleration mechanisms near the surface of the sun. To filter out the effects of solar-wind acceleration, Genesis will collect separate samples of all three of these solar-wind regimes.

Genesis uses an ion monitor and an electron monitor to determine the current solar wind regime. Raw data from these instruments are processed on board to continuously check the state of the solar wind and deploy one of three collector arrays corresponding to the correct solar-wind regime. The three regime-specific collectors ("E", "H", and "L" for CME, coronal Hole, and Low-speed) reside inside the science canister along with two continuously-exposed collector arrays, one located above the three-regime specific arrays and one in the open lid of the canister. In addition to passive collection, one electrostatically active instrument, the solar-wind concentrator, focuses a high fluence of solar-wind ions onto a small target. The concentrator was also designed

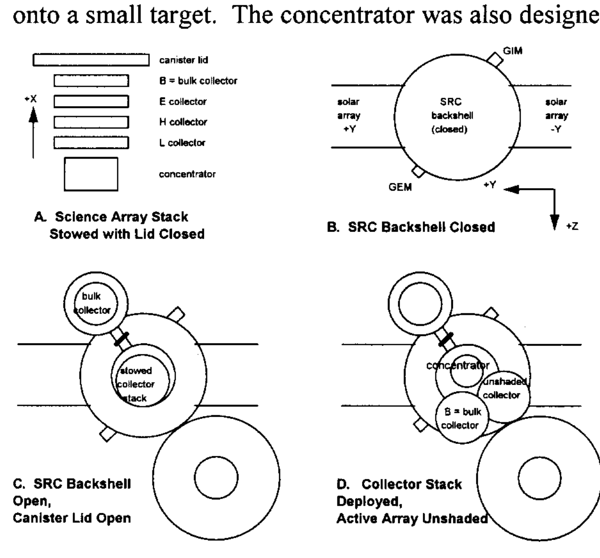


Figure 2. Science Canister

to rely on information from the ion and electron monitors, in order to select voltage levels to optimize collection of C, N, and O ions. Figure 2 illustrates the science canister, including the concentrator, the collectors, and the process for deploying the collectors.

2. SPACECRAFT OVERVIEW

The Genesis spacecraft was designed to meet critical science objectives while minimizing modification to elements inherited from previously flown Lockheed Martin spacecraft. As a sample return mission with a spacecraft bus and an entry capsule, the primary heritage for Genesis came from STARDUST. Unique science objectives drove several spacecraft configuration differences for Genesis. First, the tight contamination restrictions for solar wind collection led to an independent science canister within the sample return capsule (SRC) for Genesis instead of the combined canister / SRC designed for STARDUST. Second, Genesis ion and electron monitors require a continuous 360 deg rotational sweep in order to determine solar wind regime. This led to a spin-stabilized spacecraft for Genesis instead of the three-axis stabilization for STARDUST. Finally, the combination of contamination and spin-stabilization requirements led to a Genesis-unique thruster configuration.

Spacecraft: The basic Genesis spacecraft configuration is shown in Figure 3. The Genesis spacecraft is configured like a pancake to provide the inertia properties needed for a major axis spinner. The bus is comprised of a single equipment deck with two solar array wings and two hydrazine propellant tanks. The SRC is attached to the sunward side of the equipment deck. The launch vehicle adapter ring and thrusters are attached to the anti-sunward side of the equipment deck. Operationally, the spacecraft spin axis is pointed toward the sun for solar array power and for solar wind sample collection.

and tracking aids to support SRC recovery. The event sequencer deploys the drogue and main parachutes, and initiates the tracking aids. Tracking aids include a global positioning system transceiver and an emergency locator transmitter.

Structures: The requirement for an independent science canister is also accommodated by the structural design. Launch vehicle loads are supported through the launch vehicle adapter ring to struts that support the SRC. The struts external to the SRC are aligned with struts within the SRC that support the science canister. The equipment deck structure is an aluminum honeycomb core with composite facesheets. Additional struts from the base of the launch vehicle adapter ring to the equipment deck provide support for the propellant tanks.

Attitude Control: The requirement for spin stabilization is accommodated primarily by the attitude control subsystem (ACS). Spinning sun sensors (SSS) and two-axis digital sun sensors (DSS) provide sun-relative attitude knowledge. The spinning sun sensors provide off-sun angle and spin rate. The two-axis sun sensors provide sun location in two axes while the sun is within 28 deg of the spacecraft X-axis. Data from the star trackers in conjunction with the two-axis sun sensors yield an attitude quaternion while the sun is within 28 deg of the spacecraft X-axis and the spin rate is less than 2 rpm. The nominal spin rate during science is 1.6 rpm, although for brief periods during other parts of the mission the spin rate exceeds 2 rpm and can reach 15 rpm. Passive nutation dampers, mounted near the propellant tanks, dissipate energy through viscous fluid motion within sealed tubes.

Propulsion: Genesis utilizes a straightforward, blowdown hydrazine propulsion subsystem design. Contamination and spinner requirements are accommodated through a Genesis-unique thruster configuration. All thrusters are mounted on the anti-sunward side of the equipment deck

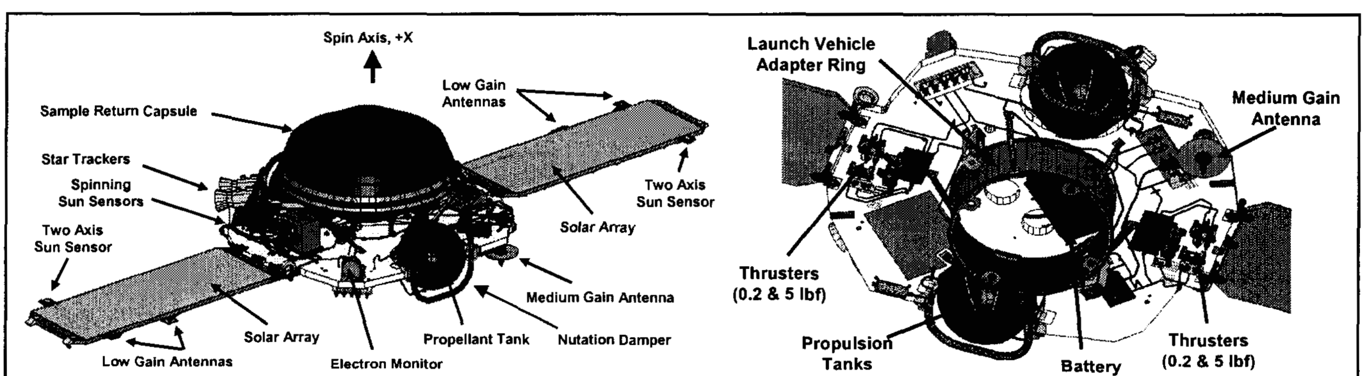


Figure 3. Spacecraft Configuration

Sample Return Capsule: The requirement for an independent science canister is accommodated by the SRC design. In addition to housing the canister, the SRC contains the entry event sequencer, the parachute system,

to ensure no direct line of sight to the collectors. Two 22N thrusters provide axial delta V control for large trajectory correction maneuvers, and precession attitude control when the spacecraft spin rate is greater than 2 rpm. Eight 0.9N thrusters provide axial delta V control for small maneuvers, precession attitude control when the spacecraft spin rate is less than 2 rpm, and spin rate control. Two tanks provide the hydrazine to support the required thruster firings.

Mechanical: The thermal control subsystem and mechanisms utilize straightforward designs. Multi-layer insulation, thermal coatings, thermal tape, and heaters provide control of component temperatures. Retention, release, and gimbal devices provide solar array retention for launch, solar array release for post-launch deployment, SRC opening and closing for science collection, and SRC release for entry.

Telecom: The telecom subsystem utilizes a near-Earth standard S-band transponder. A medium gain antenna, mounted on the anti-sunward side of the equipment deck, provides a 47.4 kbps downlink during science collection. Low gain antennas on the front and back of the solar arrays provide coverage during brief off-sun attitude excursions and during the L2 part of the trajectory.

Avionics: The command and data handling (C&DH) and the electrical power subsystem (EPS) utilize straightforward designs. The C&DH is based on a RAD6000 flight processor unit with ample throughput and storage to support flight software, fault protection, and science collection requirements. The EPS consists of a power control assembly, a pyro initiation unit, two solar arrays, and a 16 Ahr Nickel Hydrogen rechargeable battery. The power control assembly performs load switching functions and controls battery discharge / recharge. The solar arrays are populated with Silicon cells and provide ample power during the life of the Genesis mission.

For more information on the spacecraft and mission design, refer to Hong et. al., 2002[11].

3. Initial Checkout Operations

After launch Genesis completed mission activities such as trajectory correction maneuvers, navigation, and reassessment of the trajectory. The payload and spacecraft also completed initial checkout. The team encountered several challenges that were addressed and overcome, enabling transition to the science collection phase of the mission.

Mission Checkout: As previously discussed, Genesis utilizes a combination of two trajectories. The first part or transfer trajectory culminated in the Lissajous Orbit Insertion (LOI) maneuver required to initiate the second part of the Genesis trajectory. The launch period for Genesis opened on July 30, 2001 and extended through August 14. Each launch date assumed a direct ascent trajectory leading to the same LOI point on November 16, 2001 in all cases. The LOI target, as well as collision avoidance requirements, limited the length of each launch opportunity to no more than 2 minutes on each launch date. For convenience, a common trajectory could be assumed for 2-3 day periods, known as launch blocks, centered on July 30, August 2, August 5, August 8, August 11 and August 14, respectively. Because of several delays, the actual launch occurred on August 8. Injection into the transfer orbit was achieved with a Delta II launch vehicle with a Star 37 third stage.

The Navigation Plan[9] called for five trajectory correction maneuver (TCM) opportunities, scheduled between launch and LOI, to correct transfer orbit injection errors and set up the proper conditions for performing the LOI maneuver. The first TCM was needed primarily to correct the launch energy, ideally in the direction of, or opposite to, the spacecraft velocity, and as soon as possible after launch to avoid exorbitant delta V or fuel costs. The first TCM (designated TCM-1) was scheduled to be performed nominally at 48 hours after surpassing the post-injection target interface point (TIP), which occurred about 40 minutes after launch. If launch errors had been extremely large, owing to about a 1% probability of early shutdown of the second stage of the launch vehicle, the first TCM could have been executed at 24 hours past TIP. This contingency TCM (designated TCM-0) would have replaced TCM-1 in such an event.

Because TCM-0 or TCM-1 were required to occur so soon after launch, instead of weeks after launch as is the case with most deep space missions, these maneuvers were designed to use only the sun sensors for attitude determination[12]. Since TCM-0 and TCM-1 were designed primarily to correct the launch energy, a strategy was devised where pre-planned, fixed pointing directions could be assumed for the burn. This strategy avoided the need to bring the star trackers on-line and calibrate them prior to the first maneuver. These burn directions were selected to lie in a plane which included the injection attitude and the sun. Two burn directions particular to each launch block were chosen, one sunward to compensate for an injection underburn, the other anti-sunward in the event of an injection overburn. The sun sensors, primarily the spinning sun sensors operating at post-injection spin rates of 9.5 RPM and higher, impose constraints on spacecraft attitude relative to sunward and anti-sunward directions. These constraints, known as keep-out zones (KOZ) were designed to prevent a situation where the attitude control system (ACS) cannot determine spin rate due to false sun crossing indications in the presence of nutation and allowing for the possibility of single thruster failures. Consequently, the sunward and anti-sunward directions selected for various launch blocks were at the edge or beyond the KOZ, albeit as close to the ideal velocity or anti-velocity direction as allowed operationally.

Following the aforementioned launch energy correction, a TCM at 35 days after launch (designated TCM-3) was scheduled to correct pointing errors arising from injection and earlier TCMs. Further TCMs were included for contingency purposes only, at seven days after launch (TCM-2) and 65 days after launch (TCM-4). These TCMs would only be needed in the event of severe spacecraft anomalies associated with abort or delay of TCM-0/1 and/or TCM-3.

In reality, the injection provided by the Delta Star 37 third stage was so accurate that only a small anti-sunward burn of about 5 m/s was needed to correct a slight injection overburn. Combined with other attitude control events, involving precession to the burn attitude and spin up to 15 rpm, the overall net delta V became about 8 m/s. Had the required TCM-1 burn been any smaller, the TCM-1 burn might have been canceled in favor of a maneuver at a later epoch after the star tracker had been brought on line and fully checked out.

During the period leading up to the scheduled TCM-3 on September 12, the temperatures of several SRC components increased above predicted levels. This necessitated that scheduled activities be delayed or postponed to allow further investigation. Fortunately, it was determined that the direction of the LOI maneuver could be improved, from the standpoint of Earth visibility, by canceling TCM-3 and other transfer TCMs altogether. Re-optimization of the post-LOI trajectory was also needed to ameliorate severe delta V penalties, which could arise in the event of an LOI delay. Results proved quite favorable in terms of simplifying operations for the subsequent halo station-keeping maneuvers (SKMs).

Science and Payload Checkout: The ion and electron monitors were powered on shortly after launch. Both monitors performed as expected and were used to checkout the algorithm for determining solar wind regime prior to deploying the collector arrays on December 3, 2001. The concentrator turn-on took place on December 4. Plans called for raising high-voltage elements to their maximum levels before allowing the on-board software to begin commanding the elements to the levels required based on solar-wind speed. However, during the initial voltage ramp-up, carried out at 500 V increments, the hydrogen rejection grid would not go above 1500 V. Its intended maximum range was 3500 V, though the upper end of this range was only to be used during less frequent high-speed solar-wind streams. It appeared that when commanded above 1500 V the power supply became current-limited and could only output a relatively constant voltage below that requested. This voltage level has varied since turn-on, but was initially between 1400 and 1700 V. At the time of turn-on, a software voltage limit of 1500 V on the rejection grid was implemented, and the concentrator was allowed to begin operation. One month after turn-on the rejection grid demonstrated operation to levels slightly in excess of 2000 V if the voltage increments were limited to ~60 V. When the requested voltage went too high, the current-limiting condition occurred, dropping the output voltage to the 1400-1700 V range. The present hypothesis is that electrostatic attraction causes a loose end of a grid wire to bend slightly to the point where field emission occurs across the several mm gap to the ground grid. To improve autonomous performance a software patch was implemented that requires voltage increases above 1500 V to be limited to the capabilities previously demonstrated. With this new mode of operation, 2060 V is the current software limit to the rejection grid voltage.

The concentrator operates nominally during periods of normal solar wind. During periods of high-speed wind (e.g., above ~600 km/s, about 20% of the time) the rejection of hydrogen ions is less efficient because the rejection grid voltage no longer tracks the wind speed. The rejection of solar-wind hydrogen minimizes radiation damage to the concentrator target. Because hydrogen ions are far more abundant in the solar wind than the heavy ions the instrument was designed to concentrate (oxygen, nitrogen), a concentrated flux of hydrogen to the target would result in ion-induced blistering and peeling of the target surface. The rejection grid was designed to reduce hydrogen fluences to levels acceptable to the target. The design goal for hydrogen rejection was 90%, averaged over the course of the mission. Current operation is projected to result in 86% hydrogen rejection. Tests on target materials suggest that the higher hydrogen fluence to the target will still be below the threshold for target damage.

Spacecraft Checkout: The Genesis spacecraft was launched in a minimal power mode to conserve battery energy. The majority of the spacecraft hardware was checked out shortly after launch. Approximately 45 minutes after launch, the solar arrays were deployed following the third stage separation. A sunward precession utilizing the spinning sun sensors and the reaction control subsystem (RCS) thrusters was then performed. Downlink and uplink were subsequently established. The initial thermal control subsystem checkout showed nominal telemetry and nominal heater operation. Within about one hour from launch, the basic attitude control functions, the propulsion subsystem, the battery and power control subsystem, the telecom subsystem, and the solar array deployment mechanism were all verified. The command and data handling system (C&DH) was operational since pre-launch.

The first trajectory correction maneuver (TCM) exercised the larger TCM thrusters. Following this TCM, the star tracker was checked out. Good star tracker performance was a key milestone because of the importance of accurate pointing for science collection and subsequent maneuvers. To allow for outgassing prior to science canister deployment, the SRC backshell was opened 9 days after launch. In order to limit wobble, opening the backshell was designed to take approximately 30 minutes.

One of the first in-flight challenges to impact the Genesis team was the increase in several SRC component temperatures above the predicted levels, shown in Figure 4. After a thorough investigation, these increases were concluded to be most likely due to the degradation of a thermal coating inside the SRC. To counteract the high absorption to emissivity ratio of collector surfaces, most temperatures at the updated temperature predictions for end-of-mission conditions. A second action was to perform a canister re-qualification at its higher predicted temperature. This re-qualification was performed with the flight-like engineering model.

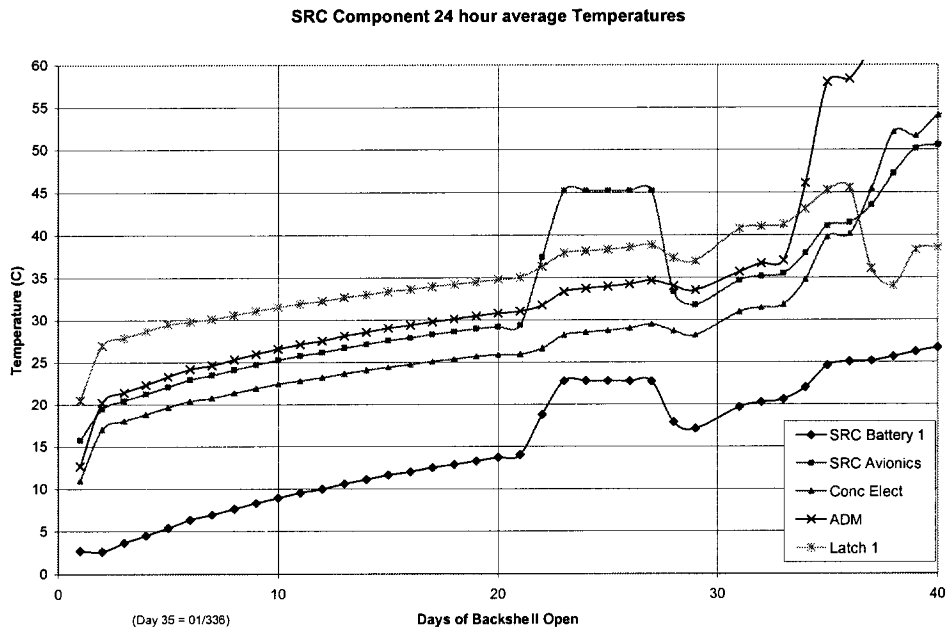


Figure 4. SRC Component Temperatures

non-collecting areas were covered with a conductive coating. This coating had exceptional low solar absorptance beginning-of-life thermo-optical properties. Previous thermal vacuum testing had shown the SRC interior would reach thermal equilibrium within about a day of exposure to a new environment. Upon opening the SRC backshell, it was noticed that the SRC component temperatures did not stabilize within this timeframe. In fact, the temperatures continued to rise. Components inside the SRC that were affected included a primary battery used to power the SRC post-spacecraft separation, the canister mechanisms, and the concentrator. The battery was identified as the component most at-risk.

Faced with a 10 C battery temperature rise in the first two weeks of sun exposure, the project made attempts to mitigate the problem. During the investigation, the backshell was partially closed. After LOI, the backshell was reopened and the temperatures continued to increase To mitigate this condition, two major actions were undertaken. The first was to start a battery ground test program. Many hundreds of battery cells were placed in temperature-controlled chambers at the actual flight temperature plus margin. Some of these cells have been periodically removed from the chamber and expended in a flight-like load profile. Extrapolation of the results of the testing has shown that the cell performance and capacity will meet mission requirements, with margin, with cell

4. Performance During Science Collection

Genesis performance during science collection has been excellent to date. The mission trajectory stability and the navigation performance have been quite good. The science payload has performed all necessary functions. The spacecraft has met or bettered all operational requirements.

Mission Performance: Navigation accuracies achieved to date[13], in concert with re-optimization of the Genesis reference trajectory both prior to and subsequent to the LOI maneuver, have helped to maintain the overall integrity of the Genesis mission thus far. Table 1 provides an overview of execution performance for propulsive maneuvers performed as of this writing. In all cases the demonstrated performance is well within specified execution errors, which are generally around 6%, 3-Sigma. This applies to maneuvers where larger (22N) thrusters were employed for TCM-1 and LOI, and to the halo SKMs on smaller (0.9N) thrusters. TCM-1 execution errors were slightly higher than the other maneuvers because it was performed without the star trackers, which would normally provide more accurate attitude information for both execution and reconstruction. Also, unlike other maneuvers targeted to a specific location in space, TCM-1 was targeted to a specific energy within the Earth's gravitational sphere of influence, defined in terms of C3 (kinetic plus potential energy per unit mass). Nevertheless, TCM-1, in concert

Table 1. Maneuver Reconstruction Performance

Maneuver	Epoch	Overall Magnitude Error	Overall Direction Error (deg)	Reconstructed Net ΔV (m/s)	Reconstruction Report Date**
TCM-1*	8/10/01	~+4%	---	~8	8/30/01
LOI	11/16/01	-1.20%	0.78	25.065	11/28/01
SKM-1A	12/12/01	2.30%	0.53	1.115	12/19/01
SKM-1B	1/16/02	1.44%	0.17	1.328	1/30/02
SKM-1C	3/20/02	0.79%	0.63	1.549	4/1/02
SKM-2A	5/22/02	-0.07%	0.9	0.793	6/3/02
SKM-2B	7/24/02	0.30%	0.23	1.465	8/6/02
SKM-2C	9/25/02	0.26%	0.23	1.453	10/3/02
*Reconstruction precision limited by data availability					
**Maneuver reconstruction reports by Don Han (Reference 12)					

with the excellent injection afforded by the Delta II launch vehicle, performed well enough to deliver the spacecraft to a location on November 16 where the LOI maneuver could be performed. Only about 8 m/s net delta V was required from TCM-1 to attain the LOI target.

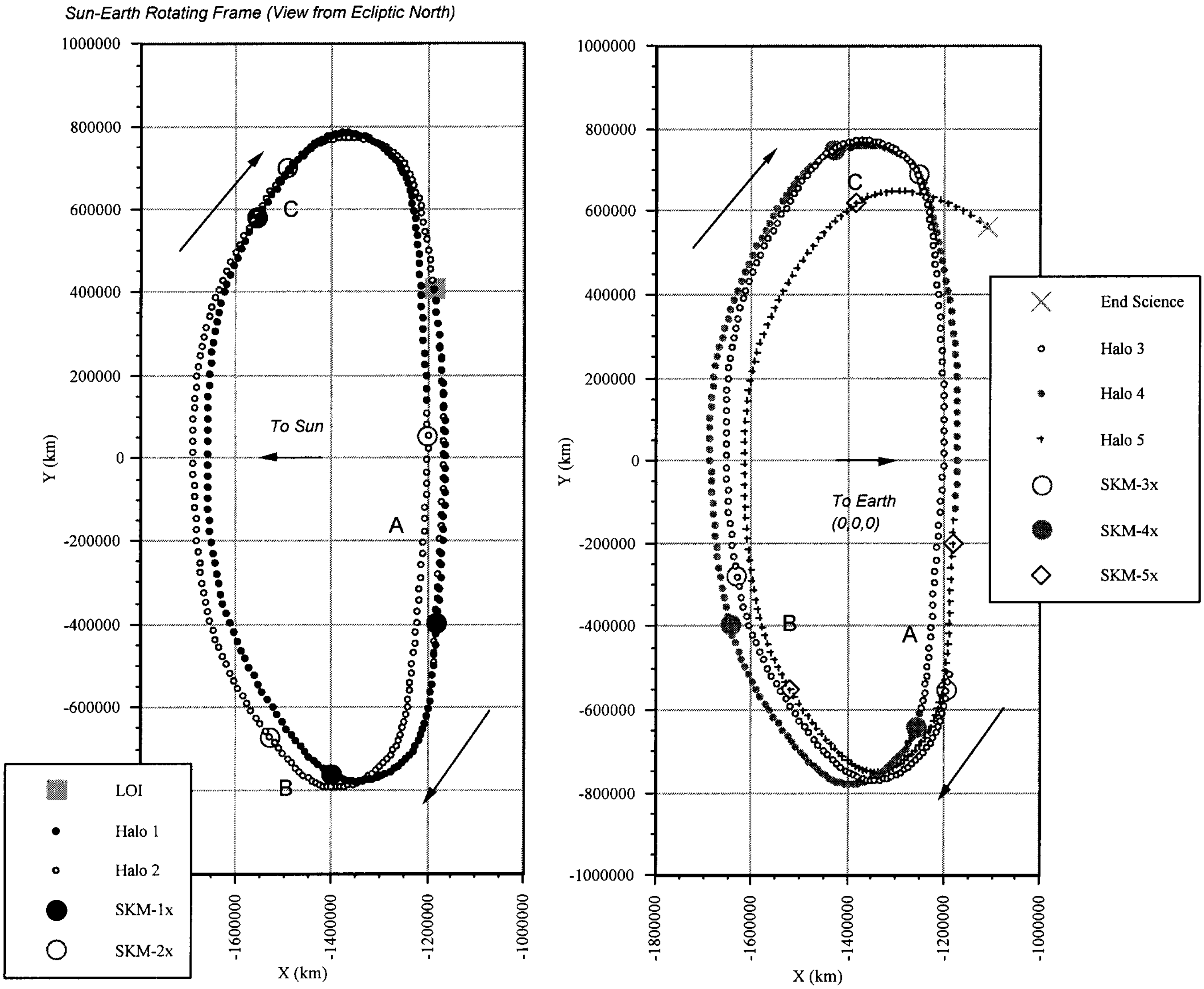
The LOI maneuver and all but one of the remaining maneuvers to date have been within 2%. LOI is the only maneuver performed so far which utilized both large thrusters and the star tracker. The star trackers and DSS are used to provide ACS with a 3-axis attitude solution, in a mode of attitude determination known as spin track. The DSS field of view is limited to a 28 deg off-sun angle. Precessions to off-sun angles in excess of 28 deg require the SSS for attitude determination and control. Off-sun precessions can best be performed by first changing the sun-relative clock angle to the desired longitude using the star tracker / DSS and then changing the off-sun angle or sun-relative cone angle using the SSS. LOI is the most recent maneuver to be performed in the cruise configuration to date, where all science collection instruments were stowed and the SRC backshell closed. After collection is completed, performance of the spacecraft in cruise configuration will be re-verified.

Fifteen halo SKMs are scheduled covering five halo orbits through the end of science collection in April 2004. The maneuvers are designated according to the nomenclature SKM-nX where n is the orbit number (1-5) and X is the first, second, or third (A, B, or C) maneuver in the orbit. Except for the first two SKMs which are intended to provide cleanup for the LOI maneuver, SKMs will occur generally about 60 days apart, as shown in Figure 5. This interval was determined to be optimal, based on earlier studies[7,8]. Note that halo orbits are demarcated here by LOI for the first halo orbit, the first SKM for each subsequent orbit and the point at which science collection ends. Such maneuvers are always targeted to the reference trajectory location at the next maneuver epoch. Halo SKMs expel sufficiently small quantities of proprellant exhaust constituents to satisfy mission contamination requirements, which allow the spacecraft to remain in science configuration with the SRC backshell open. Unlike earlier TCMs, the SKMs have been biased generally at 1.5 m/s in a near-sunward direction about halfway between the sunward KOZ for science configuration (12.5 deg off sun) and the limit of reliable star tracker performance (28 deg off sun). This assures use of the star tracker for all precessions with attendant pointing accuracy and greatly simplifies the maneuver sequence. Moreover, since the same basic sequence has been used numerous times for all SKMs thus far, it has been possible to improve proficiency and to establish important trends in spacecraft performance. The improvement in maneuver accuracy evident after SKM-1B may be due partially to a correction to mass properties and thruster characteristics assumed for planning SKMs, which was made possible by such trending. SKM targeting accuracies relative to the current reference trajectory[7], shown in Table 2, have been sufficient to support mission needs. The capability to characterize and improve performance shown thus far portends well for successful execution of critical maneuvers and associated activities later in the mission.

Table 2. Navigation Performance

Maneuver	Target	Position Error at Target after Reconstruction (km)	Velocity Error at Target after Reconstruction (m/s)
SKM-1C	SKM-2A	7	0.004
SKM-2A	SKM-2B	44	0.01
SKM-2B	SKM-2C	144	0.05
SKM-2C	SKM-3A	190	0.3

Science and Payload Performance: The Genesis payload components are highly interdependent. Collection of the samples by both the collector arrays and the concentrator requires proper operation of the Genesis ion and electron monitors (GIM & GEM). These are required to determine the solar-wind regime and to provide solar-wind velocity information to which the concentrator voltages are adjusted at any given instant. The GEM and GIM have so far operated flawlessly since their initial turn-on August 23 and 24, 2001, respectively. Their raw data are fed into a moments extractor code (MEC) in the computer. The MEC determines solar wind proton velocity, temperature, density, and helium-hydrogen ratio from GIM raw data, and determines the presence of counter-streaming electrons (electrons coming from two opposing directions) from GEM data. These moments are input to an algorithm that determines the solar-wind regime, selecting between slow and fast wind based on speed, and selecting CMEs based on the presence of one or more of: counter-streaming electrons, low temperature/velocity ratio, or high helium/hydrogen. The period between GIM and GEM turn-on in August, 2001 and the array deployment in December, 2001 was intended to be a check-out period for the monitors and the science algorithm. Extensive ground testing of the science algorithm was intended to lessen the need for major revisions to the on-board software during the checkout period. After turn-on in space, one error was found in early September that affected detection of CMEs.



Maneuver	Delta-V (m/s)	Sun Angle (deg)	Representative Epoch (UTC)
LOI*	25.065	116.6	2001 NOV 16 19:00
SKM-1A*	1.115	24.7	2001 DEC 12 20:15
SKM-1B*	1.328	21.4	2002 JAN 16 19:00
SKM-1C*	1.549	22.1	2002 MAR 20 19:00
SKM-2A*	0.793	21.3	2002 MAY 22 19:00
SKM-2B*	1.465	21.3	2002 JUL 24 17:00
SKM-2C†	1.452	22.0	2002 SEP 25 17:00
SKM-3A†	1.485	11.8	2002 DEC 11 23:00
SKM-3B†	1.534	21.5	2003 FEB 05 19:00
SKM-3C	1.509	21.3	2003 APR 16 19:00
SKM-4A	1.508	21.9	2003 JUN 11 19:00
SKM-4B	1.509	18.8	2003 JUL 30 19:00
SKM-4C	1.508	19.4	2003 SEP 24 19:00
SKM-5A	1.510	17.8	2003 NOV 19 19:00
SKM-5B	1.510	18.4	2004 JAN 14 19:00
SKM-5C	1.504	17.6	2004 MAR 10 19:00

* Reconstructed values shown.
† Estimate just prior to SKM-2C; re-optimization likely prior to SKM-3A.

Figure 5. Overview of Genesis Science Phase Trajectory

Subsequent to this initial correction, the algorithm has worked very well, with only a couple of minor adjustments to parameters to optimize the distinctions among regimes.

The arrays have been collecting solar wind continuously since deployment on December 3, 2001. A solar-wind collection statistics webpage found under http://genesis.lanl.gov/plots/index.html keeps up-to-date information on the collection of solar wind by the bulk collectors and by the regime-specific collectors. Figure 6 shows the proportions of the three different solar-wind regimes collected as of September 15, 2002. Genesis is collecting wind in the declining phase of the 11-year solar cycle (the peak occurred around June, 2000). As the mission proceeds, the fraction of solar-wind occurring in CMEs is expected to decline, while the fraction of fast solar-wind is expected to increase. Collection of solar-wind is expected to continue until the SRC is closed for the return phase of the mission.

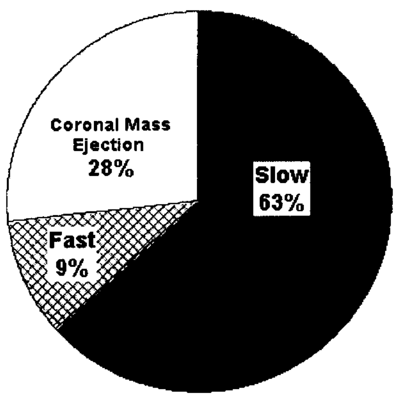


Figure 6. Solar Wind Regime Occurrences 12/01 - 9/02

Spacecraft Performance: Thus far, the spacecraft has performed well throughout the mission. The performance of each subsystem is summarized below.

The attitude control subsystem has met all requirements, including pointing accuracy, nutation, and wobble. Each daily precession maneuver has resulted in a slight decrease in the spin rate. The spin rate has been adjusted back to a nominal 1.6 rpm during each stationkeeping maneuver. The star tracker has been producing over 40 quaternions per spin and rarely loses track (only during high proton solar events). Sun sensors have been performing nominally.

The propulsion subsystem has also met all requirements. Thruster performance has been within 1% of the specification value and is now characterized even finer, based on maneuver reconstruction analyses. Due to the accurate launch vehicle orbit injection, there is a large percentage of hydrazine fuel remaining.

The C&DH has performed nominally with the exception of corrupted EEPROM bits. This problem was identified when performing CRC checks of EEPROM. It was found that these cells had lost charge and changed state. A patch to overwrite each bad bit before its use in bootable code was successfully implemented.

The solar array performance has been close to expected. In the early part of the mission, there were numerous solar energetic particle events. The arrays now produce slightly less power than at launch, but more than 25% power margin remains. Due to the maneuver biasing, the spacecraft NiH2 battery has only been used twice, during launch and TCM-1. All power switching has been nominal.

The mechanisms to deploy the solar arrays and articulate the backshell have been successfully operated. The solar wind collectors have been deployed and have responded to software commanded wind regime selections.

The thermal control subsystem has performed close to pre-flight predictions with the exception of the SRC components previously discussed. There have been no failures in any of the temperature sensors, nor in any of the heaters.

Throughout most of the mission, communication data rates have been at 47400 bps for downlink and 2000 bps for uplink. Genesis utilizes both 26-m and 34-m DSN antennas. Since off-pointing from Earth has been kept to a minimum, the medium gain antenna has been used for the primary link, with the low gain antennas briefly employed during off-sun maneuvers.

5. PRELUDE TO RETURN

Benefit from Expected Margins: The performance of the Genesis mission to date bodes well for the successful return of solar wind samples. Genesis was launched with a delta V budget of 480 m/s, including a 45 m/s margin. Because of the small magnitude of TCM-1 and the relatively smaller deterministic LOI associated with the August 8 launch, the delta V margin has increased to 144 m/s. This margin can be exploited in several ways.

The additional delta V provides operational flexibility and robustness for both the Return Phase and Backup Orbit. Although larger maneuvers are not anticipated nominally during Return, the added fuel reserve provides a hedge against catastrophic events. At this point in the mission, with entry approaching, a more thorough re-optimization of the trajectory is no longer an option. Since all TCMs are biased at levels in the range 1-1.5 m/s, any planned maneuver delayed beyond a few days would grow larger with at least one maneuver and possibly more needed to correct both position and velocity and get back on the original course. The increased delta V margin provides protection in this unlikely event.

The backup orbit, planned as an alternative to the nominal entry, is in the process of being analyzed. The preliminary baseline, a 24-day orbit, involves several large maneuvers. Among these is an initial maneuver prior to the primary entry epoch on September 8, as well as maneuvers at apogee and perigee required to achieve backup entry conditions similar to the primary entry. Challenges with achieving the backup entry requirements have necessitated further assessment of the backup orbit design. With the increased delta V margin available, a redesign can be considered which would allow for more maneuvers to reduce delivery errors or non-optimal maneuvers to increase orbit determination tracking times and enhance downstream maneuver accuracy.

Finally, even if the additional delta V margin is not expended, more fuel provides increased moments of inertia, which ameliorates nutation and enhances overall stability of the spacecraft.

Trajectory Activities Planned: Additional halo SKMs (through SKM-5C) are scheduled about every 60 days through the end of the collection period in April 2004, as previously shown in Figure 5. These maneuvers are biased generally at 1.5 m/s in a near-sun direction about halfway between the sunward KOZ for science configuration (12.5 deg off sun) and the limit of reliable star tracker performance (28 deg off sun). If necessary, the trajectory can be re-optimized to ensure that remaining SKMs fall within a range of off-sun angles where the maneuver sequence is simplified as much as possible (i.e., a single leg maneuver is sufficient to avoid the KOZ). As a footnote, any re-optimization must guarantee that the spacecraft returns to Earth in September 2004, and that both the spacecraft bus and SRC still satisfy requirements for entry and recovery.

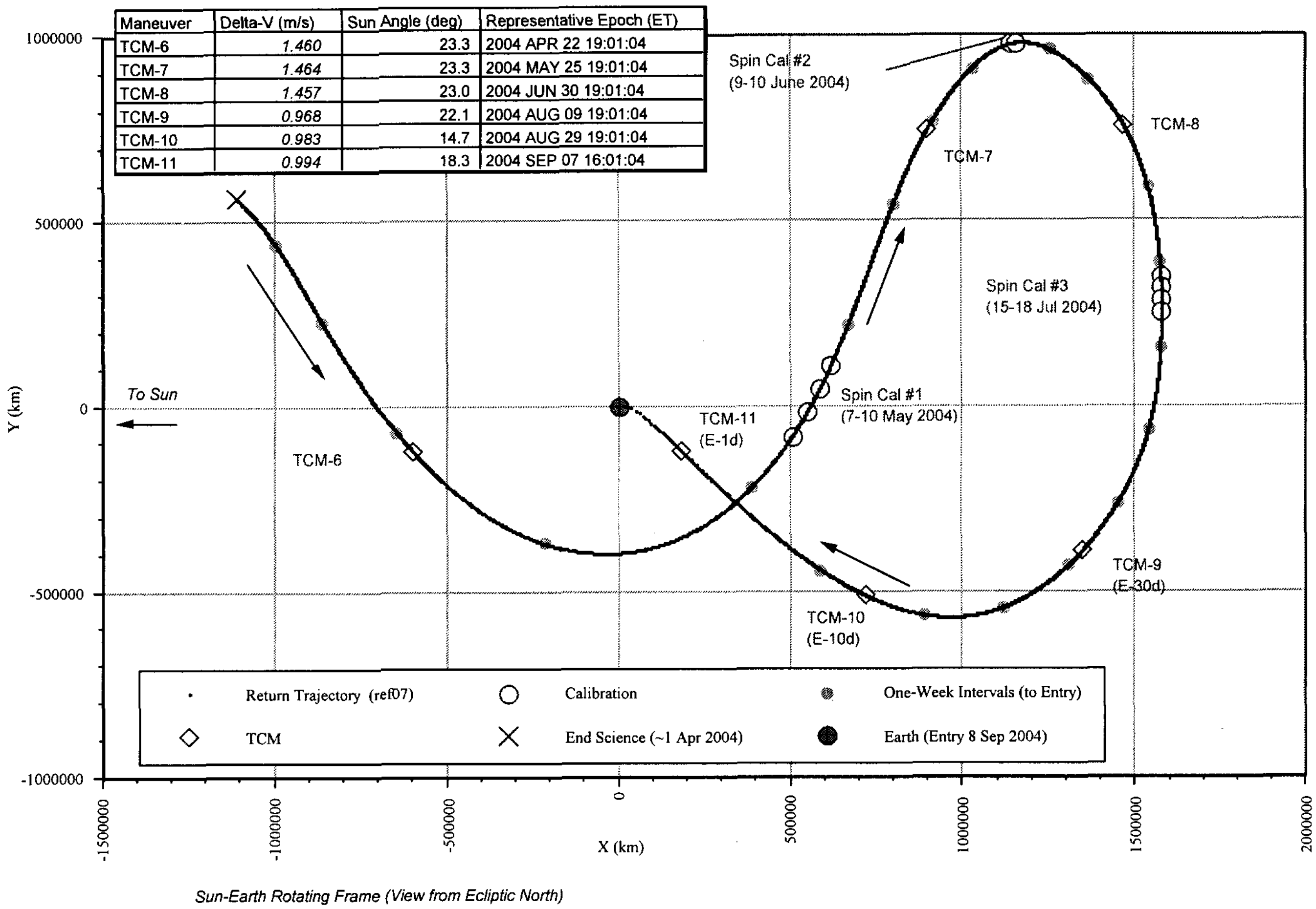
After science collection is completed in April, 2004, the collection instruments will be stowed and the SRC backshell closed, leaving the spacecraft in its original cruise configuration. Several more TCMs, all of which are biased at either 1 m/s or 1.5 m/s near-sunward, must be executed during the Return Phase of the mission, as shown in Figure 7.

Performance of maneuvers executed thus far has been excellent. Nevertheless, the spacecraft will have to be re-characterized during Return when in a different configuration. This will have an impact on both spacecraft and orbit determination performance (e.g., different solar radiation pressure cross-section). Also, a contributor to the recent SKM performance is the relative simplicity driven by controlling the off-sun direction of these burns. It will be more difficult to re-optimize the trajectory to guarantee favorable off-sun direction early in the Return Phase. Although biased relatively sunward in the current trajectory design, the early return TCMs (6-9) may need to be directed at larger off-sun angles and result in less accurate maneuvers than have been experienced recently. Like earlier SKMs, these TCMs are targeted to the reference trajectory location at the next maneuver epoch.

In order to successfully complete the mission, the final TCMs (10-11) will be constrained more tightly than previous TCMs. These TCMs will be targeted directly to inertial flight path angle, latitude and longitude at the entry interface (125 km geocentric altitude above Earth). In order to fulfill entry requirements, Monte-Carlo studies have demonstrated that execution errors must be in the 1-2% range, 3-Sigma for the final TCMs leading to entry. An alternative spin control maneuver was designed to provide this accuracy without accelerometers for these TCMs biased in a near-sunward direction. The sunward direction permits use of spin track to establish accurate attitude and eliminates concerns about battery depletion over longer durations, which might be required to carry out such activities. The spin control maneuver takes advantage of the linear relationship between delta V imparted and spin rate change as well as vehicle properties. Vehicle properties such as spin moment of inertia, total mass, and thruster lever arm will be characterized prior to entry through ground calibration of spin rate change events. Provided there are no large maneuvers after such a calibration and the spacecraft is in the closed cruise configuration, the delta V proportionality relationship should remain accurate enough to support a quasi-closed loop "burn" composed of a series of spin rate changes.

To establish a high degree of accuracy in characterizing the proportionality during the calibration event, the spacecraft spin axis must be along the line of sight (LOS) to the Earth. This geometry affords direct observation of the event on the ground through radiometric tracking. Doppler measurements with 1-3 mm/sec accuracy are achievable in S-Band if the spacecraft spin axis is within 1-2 deg of the Earth LOS for a tracking duration of 2-4 hours. Power and telecommunication constraints allow such alignment during certain portions of the mission when the Earth-spacecraft-sun geometry is favorable.

Three calibrations have been scheduled to support planning of spin control TCMs. These activities derive from the original calibration plan[2], which has undergone considerable evolution over the past three years. These include two near Earth-sun line crossings on 7-10 May (SC-1) and 15-18 July 2004 (SC-3). SC-1 will test a series of spin change events designed to cover the range 0.5-1.5 m/s effective delta V. SC-3 will provide backup or verification for SC-1 activities. An intermediate calibration (SC-2) on 9-10 June 2004 is also scheduled. The purpose of this calibration, directed about 50 deg away from the Earth LOS, will be to verify that there are no significant off-axis components which could impact the accuracy of the spin control TCMs.



Maneuver	Delta-V (m/s)	Sun Angle (deg)	Representative Epoch (ET)
TCM-6	1.460	23.3	2004 APR 22 19:01:04
TCM-7	1.464	23.3	2004 MAY 25 19:01:04
TCM-8	1.457	23.0	2004 JUN 30 19:01:04
TCM-9	0.968	22.1	2004 AUG 09 19:01:04
TCM-10	0.983	14.7	2004 AUG 29 19:01:04
TCM-11	0.994	18.3	2004 SEP 07 16:01:04

Figure 7. Overview of Genesis Return Trajectory

In addition to the spin control calibrations, activities are being considered to calibrate precession maneuvers to be used prior to SRC release. The best opportunity to perform these precession calibration activities would be during the period 10-12 May 2004, just after SC-1. With the maneuver performance achieved to date, the deletion of TCM-7 is being considered to ease the schedule in the timeframe of the proposed precession calibrations.

In short, flight performance has resulted in increased margins available to further enhance the return to Earth. The trajectory activities needed to support return to Earth are well understood. The return plan will be refined as necessary to ensure a successful completion to the Genesis mission.

6. SUMMARY

Thus far the Genesis team has achieved excellent performance in operating the mission. Initial checkout was completed and several operational challenges overcome. The transition to the science configuration was performed smoothly with more than one year of solar wind samples collected. Based on the excellent performance of the Genesis mission to date, preparations are ongoing for the completion of science collection and the return of samples in September 2004.

7. ACKNOWLEDGEMENTS

The list of contributors to the ideas and content of this paper is longer than all the members of the Genesis team. The authors would like to mention a few, with apologies to those whose names are not specifically included: Bruce Barraclough, Julia Bell, Richard Bennett, Gene Bollman, Don Burnett, George Carlisle, Jennifer Delavan, Don Gray, Don Han, Ed Hirst, Phil Hong, Tim Linn, Martin Lo, Greg McAllister, Angus McMechen, Don Mietz, Lloyd Oldham, Chet Sasaki, Don Sevilla, Eileen Stansbery, Kenny Starnes, Don Sweetnam, Chris Voth, Bobby Williams, Roby Wilson.

This work was performed by Lockheed Martin under contract to JPL, and by JPL under contract with the National Aeronautics and Space Administration.

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BIOGRAPHIES

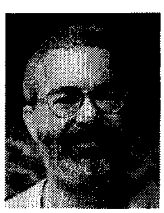
Nick Smith has a B.S. in Math and an M.S. in Aerospace Engineering, with over 18 years of aerospace experience in mission analysis and systems engineering. Flight programs have included the Space Shuttle Solid Booster Parachute System, Mars Global Surveyor, Stardust, and Genesis. Advanced studies have included Lunar Resource Mapper, Solar Probe, Saturn Miniprobe, and Mars Sample Return. Nick is the Chief Engineer for the Genesis spacecraft.

Kenneth Williams received a B.S. in Physics and Mathematics in 1977 and an M.A. degree in Physics in 1980 from Indiana State University. He has been involved in space exploration work for 13 years, beginning with such projects as the Midcourse Space Experiment (MSX) and Near Earth Asteroid Rendezvous (NEAR) at the Applied Physics Laboratory (APL). In 1996, Mr. Williams joined the staff at JPL as a mission planner for the Cassini project. For the last four years, he has been in the Navigation and Mission Design Section and has served as the principal maneuver analyst for the Genesis mission.

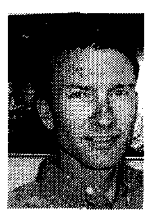
Roger C. Wiens has B.S. and PhD degrees in Physics. He carried out his dissertation research at the University of Minnesota and Johnson Space Center on Martian meteorites and the composition of the Mars atmosphere. He started working on the scientific research of the Genesis mission over twelve years ago and is currently the payload manager. Other mission involvement includes science roles in STARDUST, Deep Space-1, and Lunar Prospector.

Chuck Rasbach has B.S. and M.S. degrees in Mechanical Engineering and an MBA degree, with over 20 years aerospace experience in thermal design, systems engineering, and test. Flight programs include Hubble Space Telescope, Cassini, Stardust, and Genesis. He was the System Design Lead for the Genesis spacecraft prior to launch and is currently the Genesis spacecraft engineer during operations.

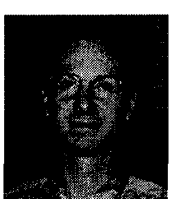
Nick Smith



Kenneth Williams



Roger C. Wiens



Chuck Rasbach