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After collecting solar-wind samples for more than two years while orbiting the Sun-Earth Libration point, the Genesis spacecraft released its Sample Return Capsule (SRC) containing the science samples on September 8, 2004. The final location of the landed SRC, which was well within the allowed recovery area in the Utah Test and Training Range, showed that the operation of the Genesis spacecraft, including the navigation, leading up to the SRC's atmospheric entry, was successful, and the navigation was accurate. This paper describes Genesis orbit determination activities during the final-approach and atmospheric-entry phases, covering from the end of the science phase through the SRC release, in more detail.

INTRODUCTION

After collecting solar-wind samples for more than two years while orbiting the Sun-Earth libration point (L1), the Genesis spacecraft released its Sample Return Capsule (SRC) containing the solar-wind samples on September 8, 2004. Due to the failure of the drogue chute and the parafoil deployment (because the g-sensors were installed backwards), the originally planned mid-air recovery did not occur, and the SRC hard-landed in the targeted area of the Utah Test and Training Range (UTTR). Fortunately, most of the science samples were recovered from the SRC and show good signs of meeting most of the science objectives of the mission.

The final location of the landed SRC, which was well within the allowed recovery area, shows that the operation of the Genesis spacecraft, including the navigation, leading up to the SRC's atmospheric entry, was successful and accurate. Genesis hit the target—albeit, a bit too hard.

MISSION OVERVIEW: RETURN TO EARTH

The Genesis spacecraft was launched on a Delta II rocket from Cape Canaveral in August of 2001. After a four-month trip to L1, 1.5-million kilometers from Earth, it began its 28-month science phase, where it basked in the Sun's radiant glow and collected particles of solar wind. During this time, the spacecraft's attitude was tweaked one degree

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per day so that it could maintain an attitude approximately 4° ahead of the solar wind (the relative velocity of the solar wind was then normal to the collection apparatus). Fifteen station-keeping maneuvers (SKMs) were performed while in the science phase to keep the spacecraft on its Lissajous orbit. These SKMs included a deterministic bias in addition to a statistical component. A typical implementation involved a spin correction to 1.6 rpm, precession to attitude (PTA), spin change from 1.6 rpm to 2.65 rpm, main burn, spin change back to 1.6 rpm, and a PTA to final attitude. An SKM usually included the daily correction, so a separate daily precession was not needed around the time of the SKM (about every 60 days).

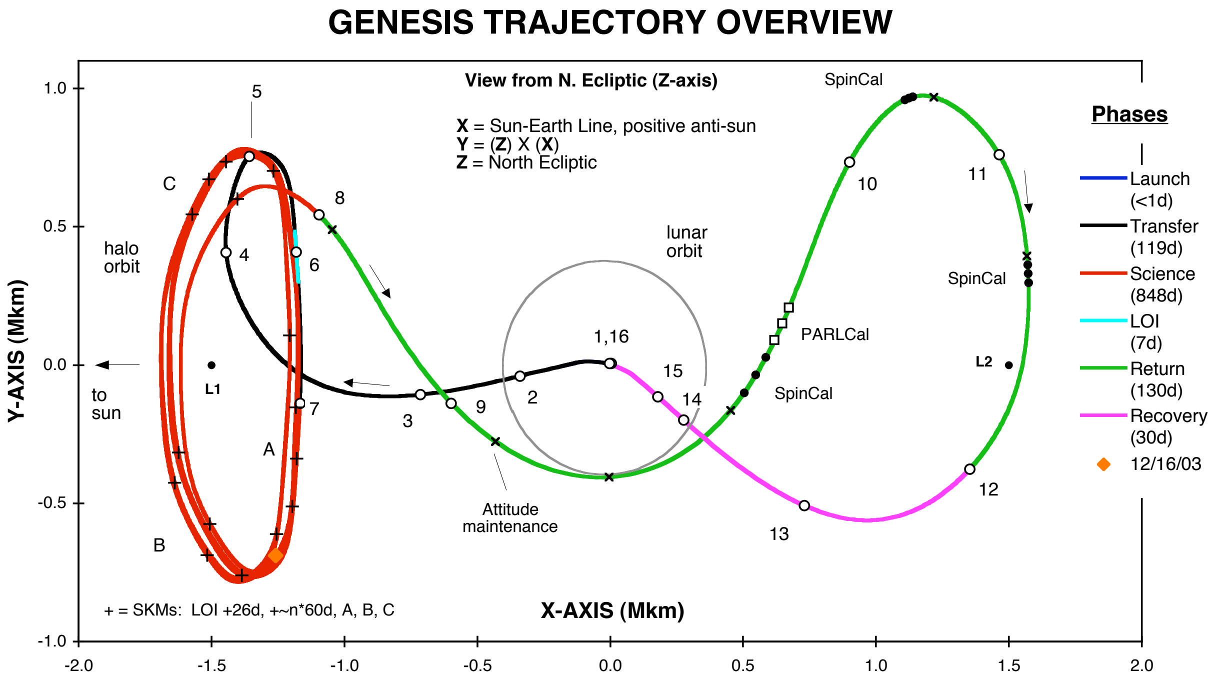
All nominal maneuvers on Genesis from Lissajous orbit injection (LOI) through the end of the mission were deterministically biased as part of the maneuver strategy, so no nominal maneuver could really be cancelled in the same sense as on other missions. Each maneuver was targeted to the next maneuver; no maneuvers were purely statistical. However, during the initial transfer phase of the mission, TCM-2, -3, and -4 were cancelled, partly due to the excellent injection accuracy and partly in response to the paint contamination problem, which caused excessive heating of the SRC battery. The trajectory from LOI through the early science phase was re-optimized several times to accommodate this cancellation and to improve the visibility of LOI along the Earth LOS.

After completing a series of five Lissajous orbits around L1, on April 1, 2004, the Genesis science phase ended. The concentrator was turned off; the solar-wind-particle-collection arrays were stowed and the canister was closed; the SRC backshell was closed the next day. Figure 1 shows the spacecraft trajectory as viewed from ecliptic north. The green line indicates the return phase. Attitude maintenance went from daily to occasional (events marked by "x"'s in Figure 1) to maintain sufficient power. On the return to Earth, a sixth TCM was performed; TCM-7 was made optional by a mission change, but remained in the schedule as a placeholder in the event it was required after a series of calibrations.

After passing to the other side of Earth, the first of three spin calibrations was performed, followed by a PARL (Precession Along Rhumb Line, a type of attitude turn relying on dead reckoning) calibration. These calibrations were required because the spacecraft's thrusters were not balanced, meaning that any change in attitude or spin rate resulted in a ΔV. They were also used to accurately model the final TCMs and SRC-release events.

The ΔV as a result of these events had to be well known in order to accurately target the entry corridor at Earth. Each spin calibration was carried out over three days, so that the spin-up of the spacecraft was from its nominal 1.6 rpm to 5 rpm the first day, 10 rpm the second, and 15 rpm the third. The maximum spin rate during the final months of the mission, 15 rpm, was experienced during the SRC-release events. Correlation between the achieved ΔV and the spin rate change was obtained during three separate calibration campaigns. These calibration results were used during the final maneuver design process and resulted in excellent executions of the final two maneuvers, which were performed with less than 0.2% (1σ) difference from the design.[*]

[*] The authors intend to submit a future paper discussing these spin calibrations and maneuver reconstructions in detail.



Key Events

1. Launch 08aug01/000	6. LOI (TCM-5) 16nov01/100	11. TCM-8 30jun04/1057	16. Entry 08sep04/1127
2. TCM-1 10aug01/002	7. Start Science 05dec01/119	12. TCM-9 09aug04/1097	Divert 08sep04/1127
(~~3. TCM-2 15aug01/007~~)	8. End Science 01apr04/967	13. TCM-10 29aug04/1117	
(~~4. TCM-3 18sep01/041~~)	9. TCM-6 22apr04/988	14. TCM-11 06sep04/1125	
(~~5. TCM-4 03oct01/065~~)	10. TCM-7 25may04/1021	15. TCM-12 07sep04/1126	

Figure 1. Genesis trajectory with key events, their dates, and days since launch.

TCMs-1 through -9 involved turning the spacecraft, which introduced large uncertainties. Fortunately, the last two TCMs, TCM-10 and TCM-11, were achieved by adjusting the spacecraft spin rate up and down, resulting in the desired ΔV without changing the attitude. TCM-9 targeted the spacecraft to a 250 km altitude flyby on August 9, thirty days before entry (E–30 days). TCM-10 occurred at E–10 days and targeted the range. TCM-11, scheduled at E2 days, was targeted to northeastern Nevada, because the subsequent SRC-release sequence would result in additional ΔV, targeting the SRC back to the UTTR. An optional TCM-12 was scheduled at E–1 day as a backup to TCM-11 and was designed using the same OD as TCM-11. TCM-12 was canceled after TCM-11 executed nominally.

The OD team monitored the SRC-release events, but performed no actual orbit determination reconstruction for the event. For each type of ΔV-inducing event (spin calibrations, maneuvers, and the SRC release) the OD team monitored the real-time Doppler display in the mission support area (MSA). The team performed quick-look assessments based on the Doppler shift resulting from the thruster firings. For the SRC-release events, the OD team developed a process to remove the spin signature from the Doppler data in real time and convert the Doppler shift to ΔV. Based on a set of pre-determined criteria, the OD team contributed their assessment of the trajectory based on the Doppler shifts to regular go/no-go polls. At E–5.12 hours, the spacecraft was spun up from 1.6 to 10 rpm, imparting 0.62-m/s ΔV. A half hour later, the spacecraft turned to the release attitude, doing an about-face with respect to the Earth and imparting 1.54-m/s ΔV. Since the spacecraft pointed in the opposite direction, the line-of-sight ΔV changed direction. The spacecraft then spun up to 15 rpm, followed by the release of the SRC at E–4 hours. After the release, the bus went into a divert sequence to flyby the Earth.

ORBIT-DETERMINATION PROCESS

Prior to April 2004, the OD team had one person doing day-to-day operational analysis and another doing covariance studies. Reconstructions and predictions involved a simple set of assumptions, one filter strategy, and one attitude adjustment per day. By the beginning of July, just over two months before entry, the operations OD team added four people. The team also started looking at the OD process systematically. This process was similar to the OD process used on the Mars Exploration Rovers (MER), in that the OD team incorporated a semi-automated filter variation process (known as "filter_loop" in JPL-navigation parlance) to test variations in the data weights, data types, dynamic models, and a priori uncertainties of estimated and considered parameters.[1,2]

Three beam-waveguide, 34-meter DSN antennas (DSS-24, -34, and -54) performed primary navigation-tracking-data collection. Three 26-meter antennas (DSS-16, -46, and -66) were intended as backups, but their tracking data were considerably noisier than the 34-meter antennas' data, and the 26-meter antennas played only a supplemental role in the tracking data acquisition. Prior to TCM-9, tracking was one pass every other day. Between TCM-9 and TCM-10, tracking was one pass per day or on pass every other day. Tracking was continuous after TCM-10.

After the tracking data were collected by the DSN, the radiometric data-conditioning group (RMDC) at JPL delivered the pre-processed data to the OD team. The OD team proceeded to "despin" the data using a process that estimated the spin rate, amplitude, phase, and bias and subtracted the spin signature from the Doppler and range data based on Doppler residuals from a prior, but accurate, trajectory.[*] Changes in spin rate and attitude of the spacecraft affected the spin signature. The team was able to despin the data during these changes and during ΔV events.

The orbit-determination process then involved modeling the system and fitting the data. The baseline filter (estimation) assumptions are shown in Table 1. Compared to other missions, Genesis had a smaller set of estimated and considered parameters. Solar radiation pressure (SRP) on the spacecraft was modeled as a flat plate, and specular and diffuse reflectivities were estimated. Navigators attempted to model the SRP with higher fidelity, but no improvement in the estimate was apparent in the predicted residuals. Specular reflectivity was estimated to be 1.24e–3, which is quite low, and the diffuse reflectivity was estimated to be 7.8e–1, which is a bit high.[†] The OD team suspected that the filter was accounting for the shape of the SRC, the crinkles and folds in the multi-layer insulation (the gold-colored, Kapton foil), and other surface features as diffuse reflectivity. The team also estimated constant-acceleration biases in the radial and along-

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[*] MER navigators used the same technique for removing the spin signature from the MER navigation-tracking data taken during maneuvers. A similar technique was used for all other MER tracking data.[1]

[†] Specular and diffuse reflectivity plus the fraction of absorbed energy equal unity.

track directions to better help the data fit. These constant biases were restarted after maneuvers.

Table 1
Genesis OD Baseline Assumptions

Error Source	Est/ Con	A Priori Uncertainty (1σ)	Corr. Time	Update Time	Comments/References
2-way Doppler (mm/s)	–	0.30	–	–	0.0045 Hz
Range (m)	–	1.0 (34-m BWG)	–	–	6.89 RU
	–	3.05 (26-m DSS)	–	–	21.0 RU
Epoch State					
Position (km)	E	1,000	–	–	Effectively Infinite
Velocity (km/s)	E	1.0	–	–	Effectively Infinite
Solar Pressure					
Specular Coefficients	E	3.0E-04	–	–	9e–4 in normal units
Diffuse Coefficients	E	0.1	–	–	0.3 in normal units
TCM-9 (long arc only)					
Magnitude	E	50.00%	–	–	0.127 Newton
Pointing (degrees)		1	–	–	1° for both cone & clock
Timing (s)	E	5	–	–	
Nongrav Accels (km/s^2)	E	1.00e–11	–	–	Constant bias parameter
Range Bias (m)	E	14 (34-m BWGs)	0	per pass	Estimated per pass
		100 (26-m stations)	0	per pass	Estimated per pass
Station Locations	C	per covariance	–	–	Using latest station location updates and covariance
Pole X, Y (cm)	C	20	–	–	
UT1 (cm)	C	35	–	–	
Ionosphere – day (cm)	C	75	–	–	S band units
Ionosphere – night (cm)	C	15	–	–	
Troposphere – wet (cm)	C	4	–	–	
Troposphere – dry (cm)	C	1	–	–	

Genesis's transponder operated on an S-band frequency (2060.825 MHz uplink, 2238.00 MHz downlink). This band is more susceptible to ionospheric noise than the higher frequency X-band, which is used on most other JPL missions. Late in the mission, the team supplemented predicted media delays (part of the ionospheric and tropospheric calibration process) by using a process similar to differenced range versus integrated Doppler (DRVID).[3] Since charged-particle media affect range and Doppler by the same amount, but with opposite signs (group advance and phase delay), the effect is easy to calibrate when it is so apparent, as it is in S-band.

The team also required small-forces files for orbit determination, which contain times, modes, and directions of all thruster firings, except for main-ΔV-mode thrusters. During the OD process, the small-forces files were used to create inputs for the models, estimate list, and data cuts during times of thruster firings.

Similar to MER, the Genesis OD analysts employed a filter_loop process, where multiple estimation strategies were tested. As mentioned previously, this tested different arc lengths (the class)—the long arc started after TCM-9, the short arc after TCM-10, and a tiny arc after TCM-11, different data combinations (the series), and filter and data weight assumptions. Table 2 is a matrix showing these combinations. To determine the filter_loop case number, add the series to the class number. Green-cell cases were run for each data-cutoff time; yellow-cell cases were run when time permitted. F2 is two-way Doppler data and SRA is range.

Table 2
The filter_loop case list

Data Series	Class:	+01	+02	+03	+04	+05	+06
	Filter Setup:	Baseline	Tight Doppler	Loose F2&SRA	Baseline with 15° elev. cutoff	Baseline with 20° elev. cutoff	Extremely Loose F2&SRA
	Data Weighting:	F2: 0.3 mm/s 34m SRA: 1.0 m 26m SRA: 3.0 m	F2: 0.15 mm/s 34m SRA: 0.5 m 26m SRA: 1.5 m	F2: 1 mm/s 34m SRA: 5 m 26m SRA: 15 m	F2: 0.3 mm/s 34m SRA: 1.0 m 26m SRA: 3.0 m	F2: 0.3 mm/s 34m SRA: 1.0 m 26m SRA: 3.0 m	F2: 10 mm/s 34m SRA: 30 m 26m SRA: 30 m
100	F2, SRA	1	1	1	1	1	1
200	F2 only	1	1	1	1	1	0
300	SRA only	1	1	1	1	1	0

Data Series	Class:	+07	+08	+09	+10	+11
	Filter Setup:	Pass-thru of last several days	Extremely Loose F2	Extremely Loose SRA	No 26-m stations	Open Stoch SRA Biases; 1 batch/pass, 0 day corr.
	Data Weighting:	F2: 0.3 mm/s 34m SRA: 1.0 m 26m SRA: 3.0 m	F2: 10 mm/s 34m SRA: 1m 26m SRA: 3m	F2: 0.3 mm/s 34m SRA: 30m 26m SRA: 30m	F2: 0.3 mm/s 34m SRA: 1.0 m	F2: 0.3 mm/s 34m SRA: 1.0 m 26m SRA: 3.0 m
100	F2, SRA	0	1	1	1	1
200	F2 only	1	0	0	1	0
300	SRA only	1	0	0	1	1

Data Series	Class:	+21	+22	+23	+24	+25
	Filter Setup:	Loose SRP, Diffuse coef.	Tight SRP, Diffuse coef.	Stoch SRP, DIFF01; 1 batch/day, 5 day corr.	Stoch ATAR,X,Y; 1 batch/day, 0 day corr.	Stoch ATAR,X,Y; 1 batch/day, 5 day corr.
	Data Weighting:	F2: 0.3 mm/s 34m SRA: 1.0 m 26m SRA: 3.0 m	F2: 0.3 mm/s 34m SRA: 1.0 m 26m SRA: 3.0 m	F2: 0.3 mm/s 34m SRA: 1.0 m 26m SRA: 3.0 m	F2: 0.3 mm/s 34m SRA: 1.0 m 26m SRA: 3.0 m	F2: 0.3 mm/s 34m SRA: 1.0 m 26m SRA: 3.0 m
100	F2, SRA	1	1	1	1	1
200	F2 only	1	1	1	1	1
300	SRA only	1	1	1	1	1

Using filter_loop, the team also tested stochastic-acceleration assumptions that were not a part of the baseline. The objective of these variations was to demonstrate consistency of the solution. The OD team was testing the robustness of the modeling in the filter. After analyzing the output from a post-TCM-10 filter_loop solution, the team noticed that there should be a break in the constant-bias acceleration at the TCM; without the break, it appeared that the different filter_loop solutions did not agree very well. Afterwards, the different filter_loop solutions showed excellent agreement and this experience was remembered for TCM-11.

ORBIT-DETERMINATION SCHEDULE

Like all of the other sub-teams on the Genesis flight team, the OD team was busy during the last few months. TCM-6 occurred on April 22. The first spin calibration and PARL calibration occurred during the second week in May, as did the first Operational Readiness Test (ORT) to practice the activities of the final days before re-entry. June contained another spin calibration, another ORT, TCM-8, and a major risk review. A Mission-Design-and-Navigation (MDNAV) peer review was scheduled for July, as were another ORT and the third spin calibration. Fortunately, all reviews and major ORTs had already occurred, prior to TCM-9, 30 days before entry.

The final week of operations was the busiest for the OD team. Navigation Advisory Group (NAG) meetings were scheduled to provide a peer review of delivered products. Four days before entry, the OD team went on a 24-hour rotation with three shifts each day. Figure 2 shows the schedule of deliveries, shifts, and meetings required of the OD team. The figure also shows major spacecraft events and tracking schedules during the last week.

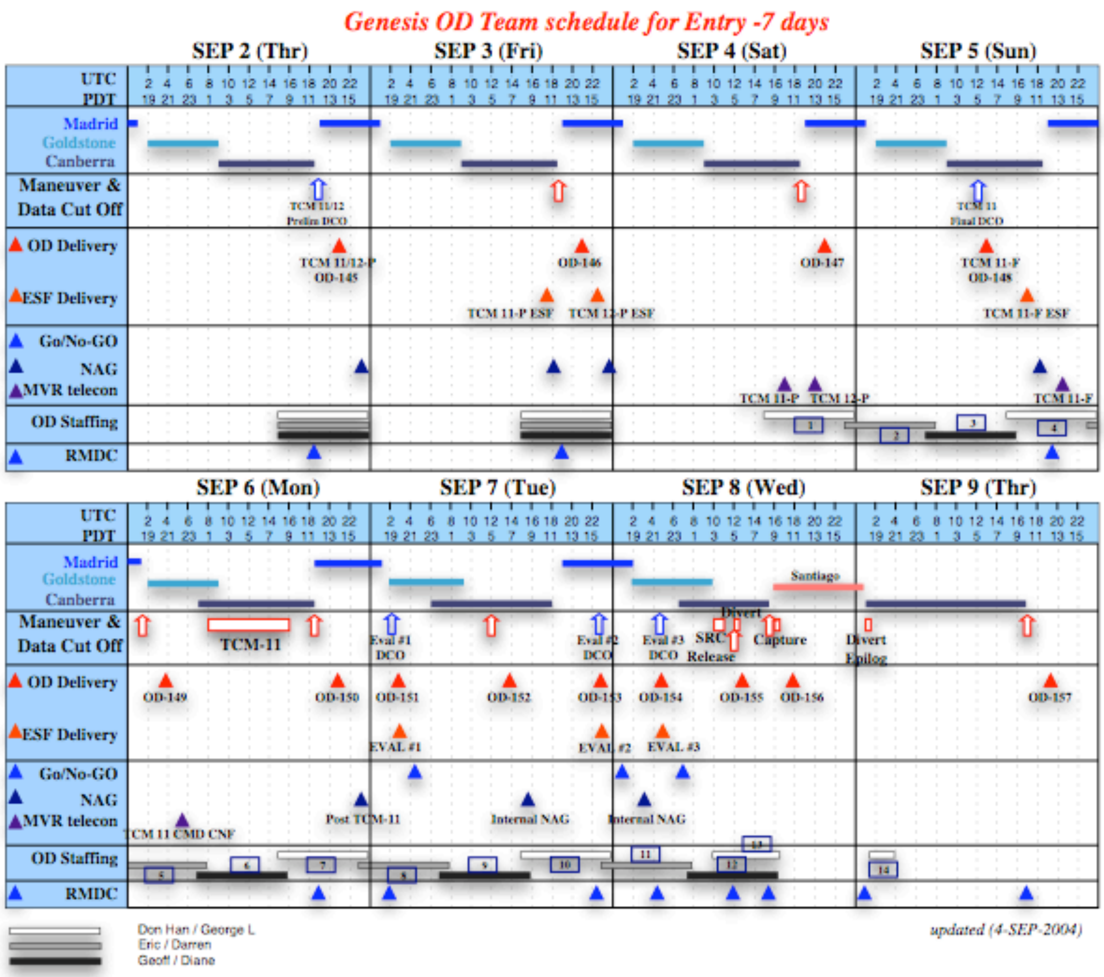

Figure 2. Genesis OD-team schedule for the final week before atmospheric entry.

ORBIT-DETERMINATION RESULTS

The navigation requirements for the Genesis mission were driven by the maneuvers.[4] For the entry phase of the mission, the spacecraft needed to enter Earth's atmosphere (defined at an altitude of 125 km above the ellipsoid, or radius of 6503.13 km) with a flight-path angle of –8.00° ± 0.08° and enter a "keyhole" ellipse 33 by 10 km at 125-km altitude in order to land on the Utah Test and Training Range (UTTR). Project focus on human-safety requirements based on a study by Wawrzyniak and Wahl rendered these requirements obsolete.[5] The results from orbit determination, maneuver design and implementation, and entry-descent-and-landing analysis—the complete navigation process—were summarized by where the SRC would impact the ground.[4,6]

OD capabilities were re-assessed in a series of covariance analyses that were performed in the year prior to the Earth-return phase of the mission. For each case, nominal filter assumptions were used in combination with a simulated tracking data arc, which represented a segment of the planned tracking pass schedule through the end of mission. Spacecraft state covariances were generated for use in planning the return phase TCMs. As part of the covariance analysis, the sensitivity to data arc lengths was assessed for the TCM-10, -11 and -12 designs and for determining the SRC atmospheric-entry state. The results showed that for TCMs 10 through 12 the OD could, if necessary, be re-started after each maneuver with no degradation to the design of the maneuver to follow, or, in the case of TCM-11 and TCM-12, to the estimate of the SRC-entry state. For instance, if it had been necessary to use TCM-12 to target to entry, and if the TCM-12 tracking pass had been lost, thereby preventing reconstruction of TCM-12, the SRC entry state could have been determined using only post-TCM-12 data and have no degradation in the result. The strength of the OD solutions put Genesis OD in the enviable position of being immune to almost any conceivable loss of tracking data.

For example, the OD was subsequently updated using the final planned final data cutoff for TCM-11 design, but the results did not change significantly so the preliminary TCM-11 design was uplinked to the spacecraft. This was a final demonstration of the very robust OD capability, which contributed to the accurate delivery of the SRC to the desired atmospheric entry target.

Nevertheless, the OD team tested for consistency within the filter_loop sets. Figure 3 is an example of the consistency of a filter_loop set (from the last solution before entry using a data starting after TCM-11). The figure is zoomed into the cluster of filter_loop ellipsoids. The largest ellipsoid and flight-path angle (both in black) represent a Doppler-data-only case with extra-loose stochastics (filter_loop case 206). All of the ellipsoids are mapped to the start of the SRC-release events, September 8, 2004, at 10:45 (ET). The flight-path angle (FPA) is mapped to entry; it does not include the ΔV from the SRC-release events (which is why the mean FPA is –8.77° and not –8.00°).

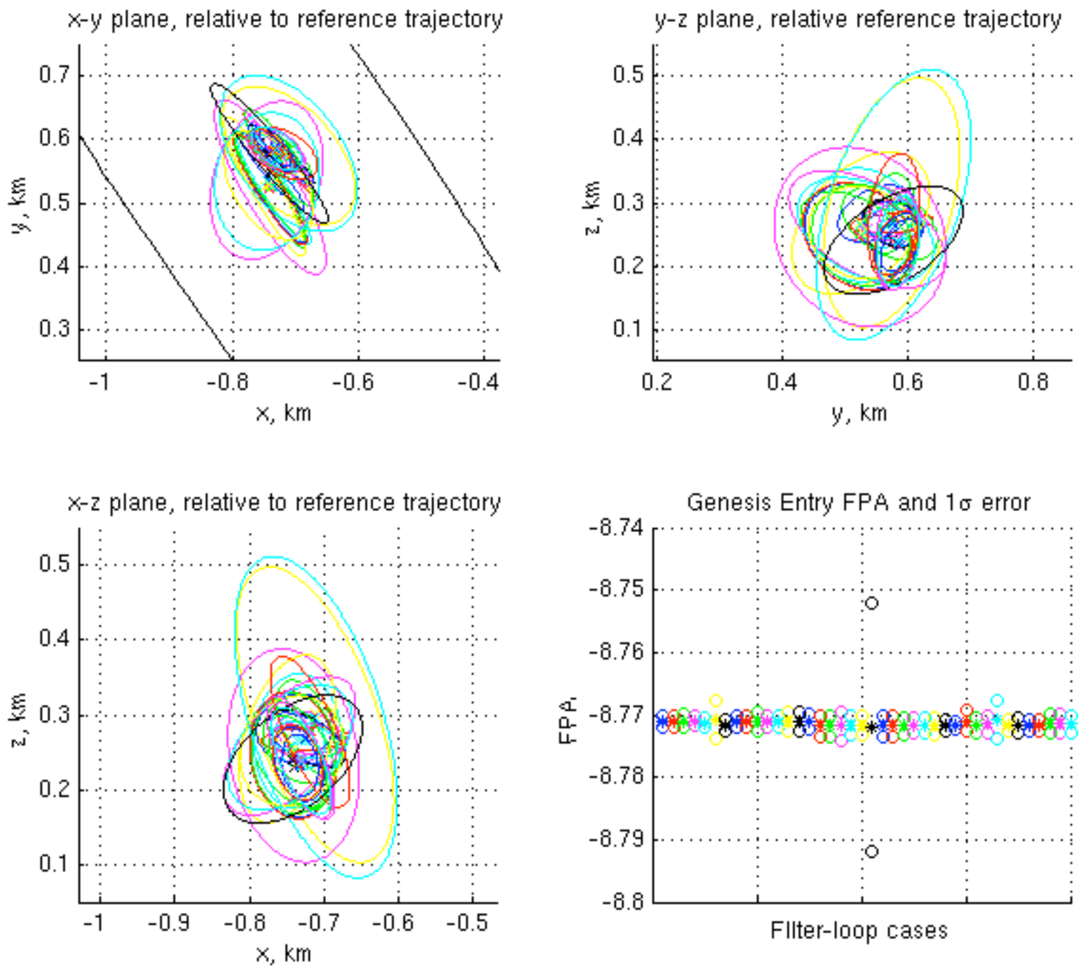

Figure 3. Ellipsoids mapped to 08-SEP-2004 10:45 (ET) and FPAs mapped to entry for the last set of filter_loop runs.

The OD was also stable between solutions. The nominal solution did not change much from day to day, indicating that the OD was reliable and the spacecraft was dynamically quiet. Figure 4 illustrates the stability from solutions mapped to entry for last five OD deliveries. It should be noted that the semi-minor axis of each ellipse in this figure has been scaled up by a factor of five to show the details of each ellipse. This figure contains all delivered solutions after TCM-11 and before the SRC-release events. Other OD deliveries showed day-to-day consistency. The table in the Appendix shows the OD performance of each delivery from the end of the science phase to the SRC release.

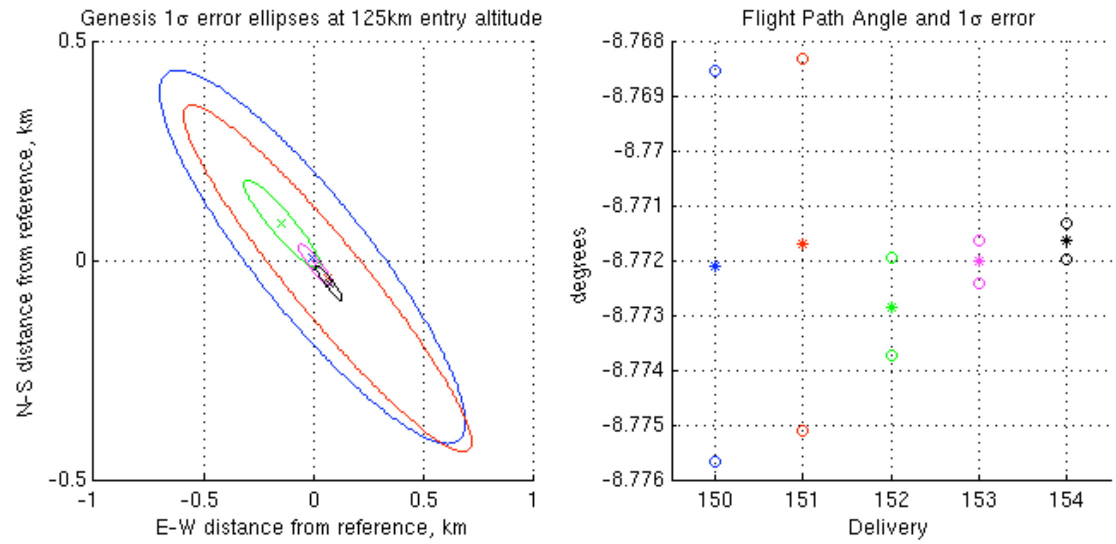

Figure 4. Consistency plots for the last five deliveries, each mapped to the entry altitude. The semi-minor axis of each ellipse has been scaled up by a factor of five.

The OD team also played a vital role in the go/no-go assessment of the SRC-release events. Even though they were not able to reconstruct each of the SRC-release events in real time, the team was assigned to observe the real-time, line-of-sight, Doppler-data display and determine whether the SRC-release events were executing correctly.

Using a JPL real-time navigation-data-display tool, known as Xardvarc, the team observed real-time-Doppler residuals (which can be converted to velocity residuals) based on trajectories with and without the SRC-release events modeled. Xardvarc has a method to calculate and remove spin signature from data, thereby allowing analysts to see how much ΔV is imparted by an event (if the event is not modeled) or what the difference between the predicted and actual ΔV is (if the event is modeled). One member of the OD team was assigned to calculate the line-of-sight ΔV using Xardvarc and its spin-signature-assessment feature. That analyst also had to factor in the bias in the Doppler data due to spin, which, for Genesis, is expressed as:

$$bias = \left(1 + \frac{240}{221}\right)\frac{rpm}{60} \qquad (1)$$

This provided a check to a Kalman-filter process that calculated and removed the spin signature and spin bias from velocity residuals (Xardvarc has the ability to log residuals) and displayed those residuals automatically. The Kalman-filter process logged the spin-free residuals, and those residuals were read and displayed by a Matlab function. From that display, analysts recorded the change in line-of sight velocity and the estimated spin rate after an event. Figure 5 shows the line-of-sight ΔV from the SRC-release sequence for the entire SRC-release sequence of events.

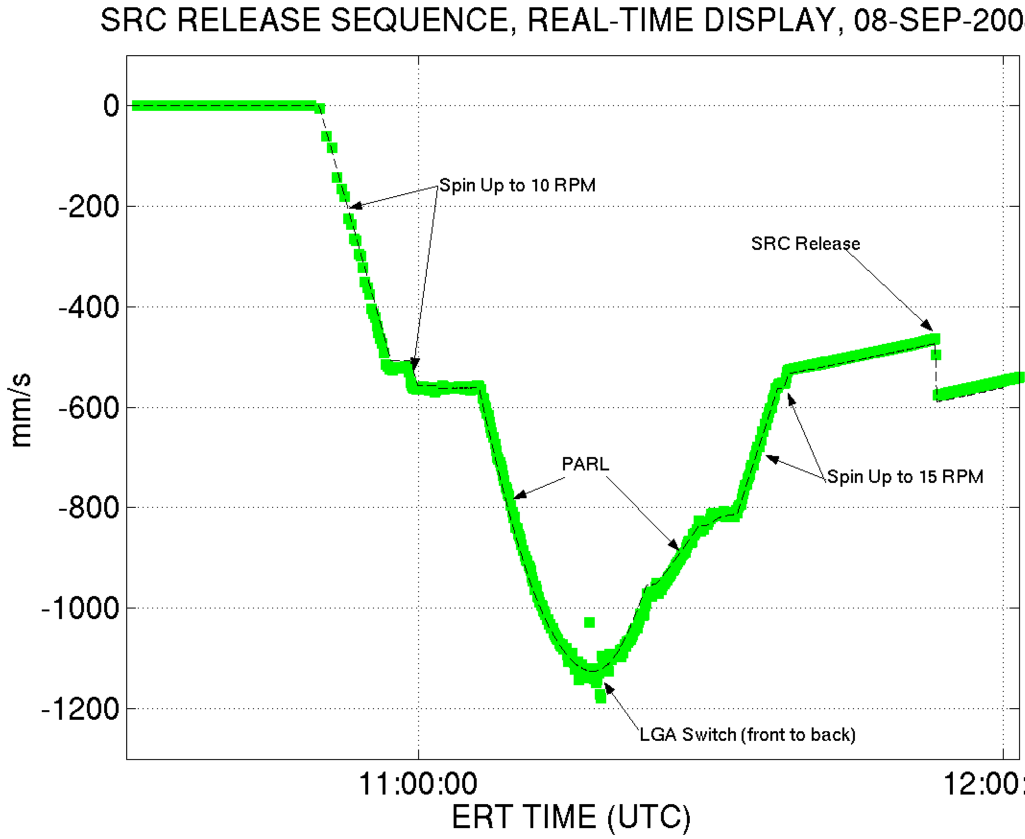

Figure 5: The green squares are the estimated line-of-sight ΔV based on the Doppler data during the SRC-release events. The dashed line is the predicted ΔV.

The line-of-sight ΔV and spin rate after each event (spin up to 10 rpm, 117° PARL, spin up to 15 rpm, and the release) was reported to the MDNAV-team chief. A poll was taken of the MDNAV and spacecraft team after each event. At the end of the first three polls, the mission manager integrated the results into a recommendation to the project manager. If the mission manager determined that entry was not going to be safe or successful, he could "push the red button" which sent a command to the spacecraft to not release the SRC. The divert maneuver—which was scheduled for the bus after the SRC release—would have occurred with the SRC still attached.

For each event, if the MDNAV team's result for a particular event was "green", the team chief reported green to the mission manager at the poll following that event. If the measurement was "yellow" or "red", the team chief reported that to the mission manager and then worked with the project engineer to determine the validity, severity, and consequence of the off-nominal condition. The project engineer, in turn, would report the results of that discussion to the mission manager. Table 3 shows MDNAV results from the SRC-release events and the acceptable ranges of those results.

The mission manager also had an option of a "purple button", which would have been pressed if the spacecraft divert maneuver was deemed unsafe because of an inadequate separation. This was defined either as the two spacecraft remaining tethered or by a weak separation velocity, potentially resulting in re-contact. The purple button would have canceled the divert maneuver and the SRC and bus would have burned up over an unpopulated area. Fortunately, everything about the SRC-release events was nominal. Unfortunately, the drogue parachute release was not.

Table 3
MDNAV Table for Genesis Re-entry Criteria

	Observed Values	**Red-Button Criteria**						
	Poll #1: Spin up to 10 RPM	Red	Yellow	Green	Nominal	Green	Yellow	Red
Spin (RPM)	9.95	< 9.2	9.2	9.6	10	10.4	10.8	> 10.8
ΔV (mm/s)	-561.90	> -503	-503	-533	-563	-593	-623	< -623
	Poll#2: PARL	Red	Yellow	Green	Nominal	Green	Yellow	Red
Spin (RPM)	N/A	N/A						
ΔV (mm/s)	-255.47	> -164	-164	-206	-256	-306	-348	< -348
	Poll #3: Spin up to 15 RPM	Red	Yellow	Green	Nominal	Green	Yellow	Red
Spin (RPM)	15.0	< 14.15	14.15	14.75	15	15.25	15.85	> 15.85
ΔV (mm/s)	287.67	< 235	235	259	279	299	323	> 323
	Poll #4: SRC release	No-GO	GO	Nominal				
Spin (RPM)	N/A	N/A						
ΔV (mm/s)	111.00	< 20	> 20	117				

CONCLUSION

The overall mission operations of the Genesis spacecraft, including the orbit determination, was a success. Using S-band Doppler and range data, the orbit-determination team proved that navigating a spacecraft back to Earth from deep space—and to enter Earth's atmosphere so that a sample could be delivered to the UTTR—could be done. This ability will be demonstrated again for the Stardust spacecraft in January 2006 and for other unmanned sample return missions, such as Mars Sample Return in the next decade. As for the samples returned in this mission, scientists expect most of them to be useful in the effort to increase understanding of the early Solar System.

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APPENDIX

Table A.1
OD Performance from the End of Science to SRC Release

Delivery	Days Of Data	Data Cutoff (ERT-UTC)	Next Event	Evaluation Time (ET)	Pos. Diff From Ref (km)	Vel. Diff From Ref (cm/s)	Pos. Pnorm[*] (km, 1σ)	Vel. Pnorm (cm/s, 1σ)	Inert EFPA[†] (deg)	Inert EFPA Unc (deg, 1σ)
OD096	26.1	04/06/04 01:09	TCM-06	04/22/04 19:00	27.155	3.551	n/a	n/a	DNE	DNE[‡]
OD097	28.1	04/08/04 01:49	TCM-06	04/22/04 19:00	37.734	5.360	18.715	0.3380	DNE	DNE
OD098	32.9	04/12/04 21:23	TCM-06	04/22/04 19:00	40.904	5.599	8.395	0.1984	DNE	DNE
OD102	20.2	04/26/04 02:15	update	04/05/04 21:00	n/a	n/a	0.283	0.0041	DNE	DNE
OD103	23.4	04/29/04 06:04	update	04/05/04 21:00	n/a	n/a	0.296	0.0038	DNE	DNE
OD104	14.8	05/07/04 18:09	update	04/23/04 00:00	n/a	n/a	0.191	0.0071	DNE	DNE
OD105	9.9	05/24/04 12:03	update	05/14/04 15:00	n/a	n/a	0.295	0.0123	DNE	DNE
OD106	16.6	05/31/04 05:48	update	05/14/04 15:00	n/a	n/a	0.227	0.0064	DNE	DNE
OD107	29.6	05/31/04 05:49	update	05/01/04 15:00	n/a	n/a	0.073	0.0024	DNE	DNE
OD108	33.9	06/17/04 12:54	update	05/14/04 15:00	n/a	n/a	0.174	0.0022	DNE	DNE
OD110	37.3	06/20/04 21:39	TCM-08	06/30/04 12:00	79.865	3.849	0.613	0.0046	DNE	DNE
OD111	40.5	06/24/04 03:54	TCM-08	06/30/04 12:00	79.710	3.852	0.294	0.0022	DNE	DNE
OD112	27.1	07/12/04 13:54	TCM-08	06/30/04 12:00	79.111	3.762	0.162	0.0025	DNE	DNE
OD113	12.7	07/13/04 16:23	TCM-09	08/09/04 12:00	79.360	5.331	2.560	0.0166	DNE	DNE
OD115	21.8	07/22/04 18:53	TCM-09	08/09/04 12:00	87.583	6.273	1.367	0.0073	DNE	DNE
OD117	29.1	07/30/04 01:25	TCM-09	08/09/04 12:00	87.625	6.242	0.387	0.0036	DNE	DNE
OD121	24.1	08/10/04 19:44	TCM-10	08/29/04 12:00	24.243	3.675	2.009	0.0081	n/a	n/a
OD124	2.4	08/12/04 01:29	TCM-10	08/29/04 12:00	28.000	3.711	15.294	0.1706	n/a	n/a
OD125	28.7	08/15/04 09:09	TCM-10	08/29/04 12:00	26.870	3.693	0.617	0.0031	n/a	n/a
OD128	8.1	08/17/04 17:49	TCM-10	08/29/04 12:00	26.848	3.673	1.825	0.0249	n/a	n/a
OD129	31.0	08/17/04 17:49	TCM-10	08/29/04 12:00	26.222	3.647	0.290	0.0019	n/a	n/a
OD134	11.1	08/20/04 16:54	TCM-10	08/29/04 12:00	25.890	3.627	0.868	0.0130	n/a	n/a
OD139	17.0	08/26/04 15:09	TCM-10	08/29/04 12:00	26.478	3.656	0.213	0.0041	n/a	n/a
OD141	20.1	08/29/04 18:24	TCM-11	09/06/04 12:00	24.317	3.280	1.883	0.0136	n/a	n/a[§]
OD143	22.1	08/31/04 18:12	TCM-11	09/06/04 10:00	17.943	3.550	0.290	0.0028	-8.00	0.0117
OD144	23.1	09/01/04 18:13	TCM-11	09/06/04 10:00	17.912	3.550	0.161	0.0019	-8.00	0.0115
OD145	24.1	09/02/04 18:09	TCM-11	09/06/04 10:00	17.848	3.549	0.106	0.0015	-8.00	0.0115
OD146	25.1	09/03/04 18:03	TCM-11	09/06/04 10:00	17.813	3.545	0.075	0.0013	-8.00	0.0126
OD147	26.1	09/04/04 18:03	TCM-11	09/06/04 10:00	17.742	3.548	0.057	0.0011	-8.00	0.0126
OD148	26.9	09/05/04 11:40	TCM-11	09/06/04 10:00	17.523	3.593	0.057	0.0019	-8.00	0.0126
OD149	27.4	09/06/04 00:49	TCM-11	09/06/04 10:00	17.543	3.584	0.051	0.0015	-8.00	0.0126
OD150[**]	8.3	09/06/04 21:25	Release	09/06/04 10:00	17.550	3.589	0.049	0.0020	-8.00	0.0099
OD151	8.5	09/07/04 01:03	Release	09/08/04 10:45	5.951	15.413	0.313	0.0231	-8.00	0.0099
OD152	8.9	09/07/04 11:42	Release	09/08/04 10:45	5.917	15.385	0.084	0.0062	-8.00	0.0092
OD153	9.3	09/07/04 21:21	Release	09/08/04 10:45	5.930	15.408	0.040	0.0040	-8.00	0.0091
OD154	9.6	09/08/04 03:15	Release	09/08/04 10:45	5.923	15.416	0.037	0.0038	-8.00	0.0091

[*] Pnorm is the covariance norm.

[†] All future events (TCMs, SRC-release sequence) were modeled in the trajectory runout.

[‡] DNE: Did not enter the atmosphere

[§] TCM-11 was not yet designed, so the reference TCM-11 was used in the ESF, making it incomparable to other EFPAs with the SRC-release events modeled.

[**] This delivery's mappings were not updated to entry, so the evaluation time is still at TCM-11.