MANEUVER DECOMPOSITION ALGORITHM FOR THE GENESIS SPACECRAFT

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ABSTRACT

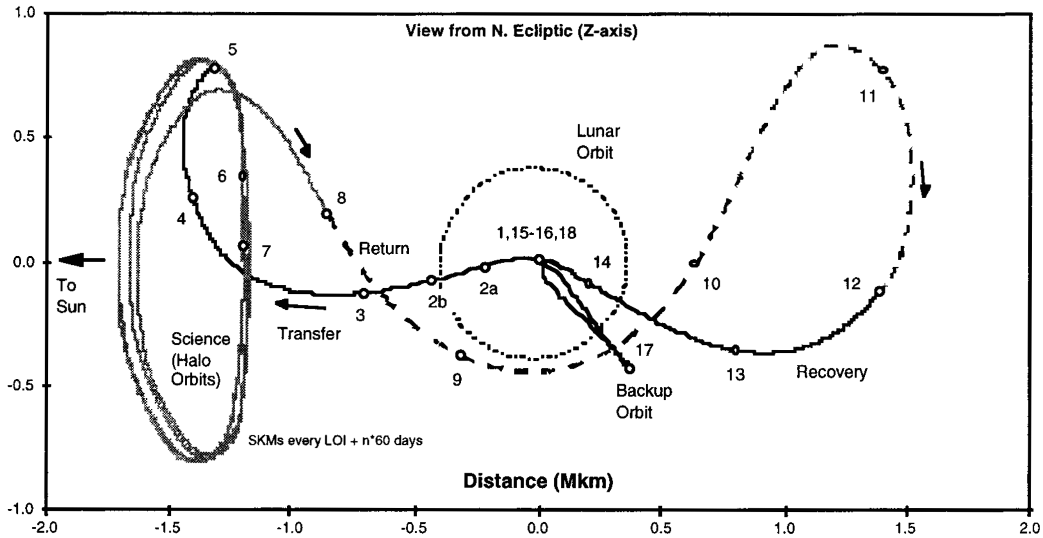
The Genesis is the fifth mission selected as part of NASA's Discovery Program. Genesis will collect solar wind samples for a period of approximately two years while in orbit about the Earth-Sun L1 point. This paper addresses a maneuver decomposition algorithm which will support design and refinement of propulsive maneuvers for the Genesis spacecraft by the Navigation Team at JPL. The basic algorithm is applicable to any spin-stabilized spacecraft with axisymmetric thrusters. *The following is an extended abstract. The final version of this paper will also address tailoring of the algorithm to specific operational scenarios with incorporation of empirical performance parameters to be obtained via in-flight calibrations.*

MISSION OVERVIEW AND SPACECRAFT CHARACTERISTICS

The Genesis mission[1] is designed to deliver the spacecraft and its instruments into a series of four halo orbits about the Sun-Earth collinear libration point, L1, located between the Sun and Earth. The prime mission is scheduled for launch in January 2000, using a Delta II launch vehicle. Genesis will spend a minimum of 22 months collecting samples of the solar wind and taking science data, mostly during the halo orbits. At the end of the collection period, the spacecraft will follow a free-return trajectory to a specific target that results in a parachute recovery at the Utah Test and Training Range (UTTR) outside Salt Lake City, Utah. Sample return to Earth from L1 has never been attempted before and presents a formidable challenge in terms of mission design and operations, particularly with regard to planning and execution of propulsive maneuvers.

An overview of the Genesis trajectory[2] is provided in Figure 1, including various mission phases and locations for expected trajectory correction maneuvers (TCMs). In addition to maneuvers indicated in Figure 1, there are 13 halo station keeping maneuvers (SKMs), three per halo orbit plus with an additional cleanup burn after Lissajous Orbit Insertion (LOI). Moreover, a deboost maneuver will be performed on the spacecraft bus after release of the Sample Return Capsule (SRC) to enable descent over the Pacific Ocean and prevent entry over a populated area. However, in the event of adverse conditions at UTTR, the spacecraft will be diverted to backup orbit for entry 19 days later, as shown. Also, there are opportunities for special calibration maneuvers[3] during return in preparation for more precise TCMs during recovery.

The spacecraft design for Genesis is shown from two perspectives in Figure 2, with solar arrays and collectors on the front and thrusters on the aft side of the spacecraft. After initial maneuvers and spacecraft checkouts are performed, the SRC backshell and collection canister lid will be open as shown in Figure 2 until completion of science collection. However, for large maneuvers during collection, such as LOI, the SRC backshell and canister lids will be closed and latched, then reopened after the maneuver is completed. Except when maneuvers are required, solar arrays are usually pointed to within 10° of the sun to avoid battery power depletion. However, over science collection and checkout, collectors need to be pointed in the prevailing solar wind direction or between 4° and 5° ahead of the sun near the ecliptic plane.



Key Events (by Earliest Date/Mission Day)

1. Launch	07jan01/000	5. Start Science	20mar01/072	10. TCM-7	24apr03/837	15. Entry	16aug03/951		
2a. TCM-1a	08jan01/001	6. TCM-4	20apr01/103	11. TCM-8	10jun03/884	or			
2b. TCM-1b	10jan01/003	7. LOI (TCM-5)	30apr01/113	12. TCM-9	17jul03/921	16. Divert	16aug03/951		
3. TCM-2	14jan01/007	8. End Science	28mar03/810	13. TCM-10	06aug03/941	17. Apogee	26aug03/961		
4. TCM-3	11feb01/035	9. TCM-6	10apr03/823	14. TCM-11	15aug03/950	18. B. Entry	04sep03/971		

Figure 1. Genesis Mission Trajectory

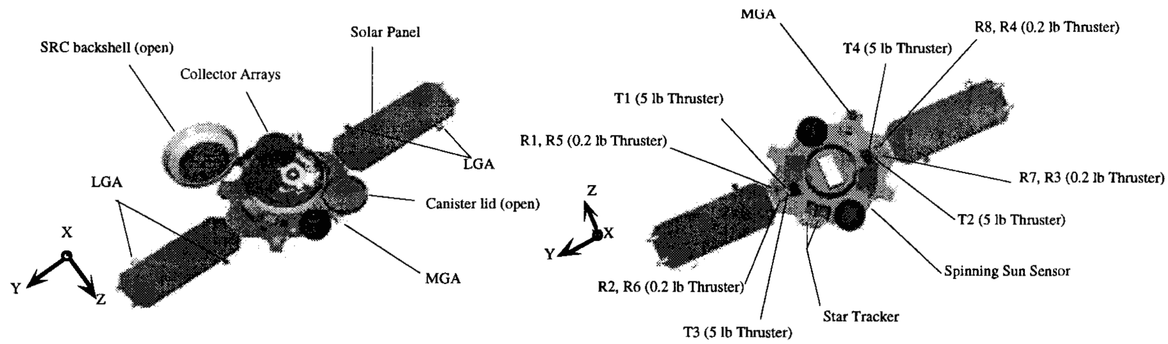


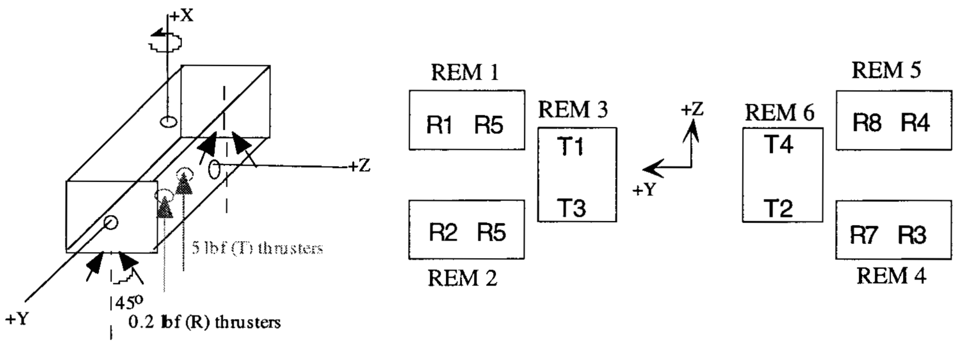
Figure 2. Forward Deck View (Normally Pointing Toward Sun) and Rear Deck View

All maneuvers, including both translational maneuvers and attitude control, will be performed using a hydrazine fueled blowdown system. To minimize contamination risk to the samples collected for maneuvers other than LOI, all thrusters have been placed in an axisymmetric configuration on the side opposite the sample collection canister. For trajectory corrections more than 30° off sun, a Δv limit for each propulsive maneuver is imposed, driven by a maximum battery depletion time.

Spin stabilization was chosen as a simple means of attitude control, in lieu of three-axis stabilization. No reaction wheels, gyros or accelerometers are included in the attitude control subsystem (ACS). The space vehicle normally spins at 1.6 revolutions per minute (rpm). Star trackers and sun sensors support attitude determination, but only the latter are effective when spinning at greater than 2 rpm. Any attitude changes, including spin changes and precessions, must be performed open loop with thrusters. Because the thrusters do not produce balanced torques, all attitude control maneuvers result in a translational Δv, affecting the spacecraft trajectory. Thruster activity, asymmetric mass properties and misalignments also induce oscillations in the spin vector, such as nutation and wobble.

The orientation and characteristics of thrusters needed for guidance and navigation are indicated in Figure 3 and Table 1. There are two separate thruster strings, a primary and redundant. For large maneuvers (Δv > 2.5 m/s), two 5 lbf thrusters will be used for the burn or translational maneuver, with an initial precession to the burn attitude using alternating pairs of 0.2 lbf, followed by spin up from 1.6 to 10 rpm with 0.2 lbf thrusters before the burn. The higher spin rate increases stability during large maneuvers and reduces execution errors. Following the burn itself, the space vehicle will precess back towards the initial near-sun pointing attitude. Spin down to 1.6 occurs after precession-induced nutation has damped out. For small maneuvers (Δv < 2.5 m/s), no spin changes are needed and four 0.2 lbf thrusters are used for the burn. 360° precession changes may be required to remove undesired components introduced by the precession itself. The most recent estimate of execution errors for most maneuvers without calibration are indicated in Table 2. Another maneuver mode, which will be employed prior to recovery, involves use of spin changes in lieu of previously described translational maneuvers to achieve higher delivery accuracy via calibration[3].

The Genesis spacecraft is also equipped with nutation dampers (not shown in Figure 2). Depending on the size and direction of the maneuver required, nutation could grow as large as 20°. As much as 6 hours could be required to allow damping to less than 0.5° of nutation, as well as full recharge of batteries. Therefore, a period of at least 12 hours for interruption of science collection will be reserved for execution of TCMs and SKMs. Maneuver design will be performed jointly by the Navigation Team at the Jet Propulsion Laboratory (JPL) and the Spacecraft Team at Lockheed-Martin Astronautics (LMA) in Denver, CO, in light of spacecraft constraints[3].



Notes:
All thrusters are located on aft (-X) side, which usually face away from sun and toward s Earth.
T refers to the large 5 lbf thrusters (thrust axis toward +X)
R refers to the small 0.2 lbf thrusters, canted 45° off -X in the X, Z plane.
For precession maneuvers, use a single set, e.g., R1 and R2, once a spin cycle, or two sets, e.g., R1, R2 and R3, R4 in alternating half cycles for faster precessions, but with greater nutation at the end of precession.

Figure 3. Genesis Thruster Configuration

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)

TABLE 1. Thruster Combinations for Genesis

Maneuver Component	Error (Fixed)
Precession	≤0.03 m/s × sin (ψ/2) per axis (3σ) with respect to original spin pointing direction for one-way precession ψ < 180°; error applies for entire two-way precession; if total precession is 360°, corresponding errors are 0.01 m/s (3σ) along original spin axis direction and 0.035 m/s (3σ) per crosstrack axis
Spin Change	≤0.06 m/s × (spin change/16 rpm) (3σ) along original spin axis direction; ≤0.01 m/s × (spin change/16 rpm) (3σ) per crosstrack axis
Translational Δv Maneuver	*Use values indicated in panel below.*

Translational Δv Usage criteria	Thrusters	Magnitude proportionality %	Fixed magnitude m/s	Crosstrack proportionality % (per axis)	Fixed Crosstrack m/s (per axis)
Δv > 2.5 m/s; SRC closed	two 5 lbf	6.0	0	3.0	0
0.05<Δv<2.5 m/s; SRC open	four 0.2 lbf	6.0	0.01	4.0	0.005
0.05<Δv<2.5 m/s; SRC closed†	four 0.2 lbf	6.0	0.01	3.0	0.003

TABLE 2. Uncalibrated Maneuver Execution Errors

SPINNING SPACECRAFT DYNAMICS AND DECOMPOSITION ALGORITHM

Based on previous experience with the Galileo spacecraft[4], the Navigation Team has developed a decomposition algorithm to be used to support maneuver planning and mission analyses. The purpose of this algorithm is to decompose maneuvers into constituents to account for both the translational burn and spacecraft attitude changes required to carry out such a maneuver. Attitude changes may include precessions, as well as changes to the spacecraft spin rate, such as those required to increase stability for large maneuvers.

In general, the total propulsive maneuver can be decomposed into components associated with the turn or precession, spin changes (increase and decrease), as well as the burn or translational maneuver, which is usually but not always the largest component. This can be expressed in terms of the vector summation* :

$$\Delta\mathbf{v}_{total} = \Delta\mathbf{v}_{burn} + \Delta\mathbf{v}_{turn} + \Delta\mathbf{v}_{spinup} + \Delta\mathbf{v}_{spindown} \tag{3}$$

$\Delta\mathbf{v}_{total}$ is the desired propulsive maneuver, which is derived via the orbit determination process prior to start of maneuver planning. $\Delta\mathbf{v}_{total}$ is oriented relative to some initial attitude for the spacecraft.

In the case of precessions, Δv is obtained from a series of pulses which occur each revolution or half-revolution. The cumulative effect of these pulses is to produce a Δv vector which lies along the chord of a turn circle in spacecraft centered Δv space (or along the +X body axis), as illustrated in Figure 5. The circumference of a turn circle traces out induced Δv resulting from a series of thruster pulses. Thus, a 360° turn in the absence of execution errors results in a net induced Δv of zero.

The diameter v_0 of the two-way turn circle shown in Figure 5 can be derived from mass properties and characteristics of the spacecraft as follows:

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* Bold face denotes vector or matrix; "∧" denotes a unit vector

$$v_0 \cong \frac{4 I_{xx} \omega_x}{rm} \tag{1}$$

where I_{xx} is the spacecraft moment of inertia about the spin axis (x), ω_x is the component of angular velocity along the spin axis, r is the lever arm associated with either a 5 lbf thruster or 0.2-lbf thruster pair and m is the spacecraft mass[4]. Whenever the desired Δv falls inside the two-way turn circle (typically $v_0 <$ 0.5 m/s), Δv resulting from spacecraft precession cannot be used effectively as a component of the desired Δv, and must therefore be removed by precessing at least one complete revolution around the turn circle. Most TCMs and SKMs are estimated to be small enough that 360° precessions might be required most of the time. However, biasing strategies are currently under investigation to attempt to reduce the number of such precessions that might otherwise be required.

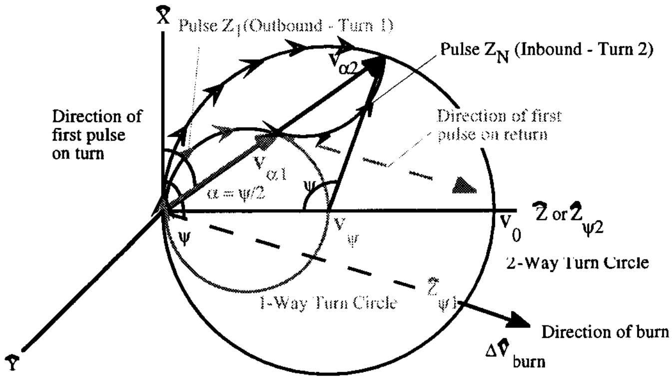

Figure 4. Turn Circle Geometry for Spinning Spacecraft

Spin change can be characterized extremely well, because a spin change of magnitude $\Delta\omega_x$ produces a Δv_{spin}, along the +x axis and inertially fixed, according to the following relationship:

$$\Delta v_{spin} \cong \frac{I_{xx} \Delta\omega_x}{rm} \tag{2}$$

The thruster lever arm r is well defined beginning before launch. Mass properties are also fairly well defined at launch, but will change over the course of the mission. Because there are no accelerometers on Genesis, Δv_{spin} cannot be determined by the on-board ACS software. However, through observation of a spin change event from the ground coupled with spin rate estimates available from telemetry throughout the event, the spacecraft mass property I_{xx}/m can be established very accurately. In particular, studies[5] have demonstrated that reduction of all fixed errors to 3 mm/s and proportional errors to 1% would permit all of the aforementioned entry requirements to be met with reasonable performance margin.

DETERMINATION OF TURNS AND BURN

The initial attitude can be defined in terms of the transformation from inertial to precession plane coordinates, provided by the direction cosines:

$$\mathbf{A}_{\text{initial}} = \begin{bmatrix} \hat{\mathbf{x}} \\ \hat{\mathbf{y}} \\ \hat{\mathbf{z}} \end{bmatrix}, \ \hat{\mathbf{x}} = \hat{\boldsymbol{\omega}}_{\text{initial}}^{EME2000}, \ \hat{\mathbf{y}} = \frac{\Delta \mathbf{v}_{\text{total}}^{EME2000} \times \boldsymbol{\omega}_{\text{initial}}^{EME2000}}{\left\| \Delta \mathbf{v}_{\text{total}}^{EME2000} \times \boldsymbol{\omega}_{\text{initial}}^{EME2000} \right\|}, \ \hat{\mathbf{z}} = \hat{\mathbf{x}} \times \hat{\mathbf{y}} \tag{4}$$

where $\omega_{\text{initial}}^{\text{EME2000}}$ is the initial angular velocity of the spacecraft, defining the initial direction of the spin axis and thruster alignment, and $\Delta\mathbf{v}_{total}^{EME2000}$ is the desired propulsive maneuver, both specified in terms of the inertial coordinate frame associated with the Earth Mean Equator of January 1, 2000 (EME2000). The angle θ of the desired maneuver within the precession plane can be determined by:

$$\theta = \cos^{-1}\left(\hat{\Delta\mathbf{v}}_{total}^{EME2000} \cdot \hat{\boldsymbol{\omega}}_{initial}^{EME2000}\right) \tag{5}$$

Thus, the total maneuver in the precession plane can be expressed as the 2-vector (x and z spacecraft directions, respectively):

$$\Delta\mathbf{v}_{total} = \left[\Delta v_{total}\cos\theta, \Delta v_{total}\sin\theta\right] = \left[\left(\Delta v_{total}\right)_x, \left(\Delta v_{total}\right)_z\right] \tag{6}$$

However, owing to the contribution of other components, the translational component $\Delta\mathbf{v}_{burn}$ must be executed at a somewhat different angle ψ, which is the angle through which the spacecraft must precess between the initial attitude and the burn attitude. Assuming spin changes are not part of the maneuver sequence for the time being, the turn and burn components $\Delta\mathbf{v}_{turn}$ and $\Delta\mathbf{v}_{burn}$ are oriented in the precession plane as shown in Figure 5.

Therefore, the burn and turn components in the precession plane can be expressed as the following two component vectors:

$$\Delta\mathbf{v}_{burn} = \left[\Delta v_{burn}\cos\psi, \Delta v_{burn}\sin\psi\right] = \left[\left(\Delta v_{burn}\right)_x, \left(\Delta v_{burn}\right)_z\right] \tag{7a}$$

$$\Delta\mathbf{v}_{turn} = \left[\Delta v_{turn}\cos\left(\psi/2\right), \Delta v_{turn}\sin\left(\psi/2\right)\right] = \left[\left(\Delta v_{turn}\right)_x, \left(\Delta v_{turn}\right)_z\right] \tag{7b}$$

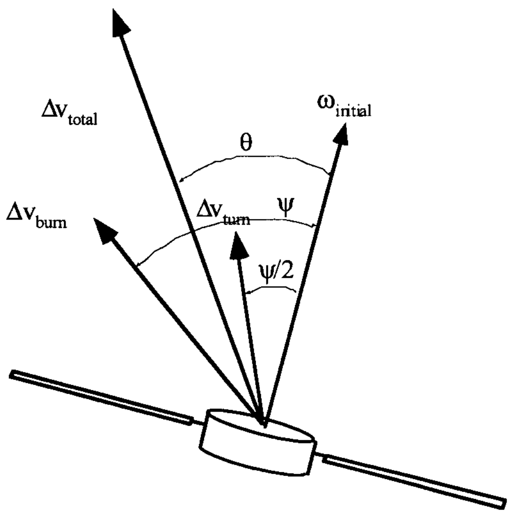

Figure 5. Maneuver Decomposition Disregarding Spin Changes

$\Delta\mathbf{v}_{burn}$ is the sum of outbound and inbound turn components ($\mathbf{v}_{\alpha 1}$ and $\mathbf{v}_{\alpha 2}$) respectively, oriented along the chord of the turn circle at half of the precession angle, as shown in Figure 5. A more precise expression for the diameter $\mathbf{v}_0$ of the two-way turn circle (as opposed to Equation 1) is related to known mass properties and characteristics of the spacecraft as follows:

$$v_0 = \frac{4I_{xx}\omega_x}{rm\left(\sin\gamma/\gamma\right)},\ \gamma = \omega_x\frac{\Delta T}{2} \tag{8}$$

where I_{xx} is the spacecraft moment of inertia about the spin axis, ω_x is the component of angular velocity along the spin axis, r is the lever arm associated with the net thrust along the spin axis direction, m is spacecraft mass and $\sin\gamma/\gamma$ is an efficiency factor related to the duty cycle of thrusting where ΔT is the total pulse duration per spin revolution. Therefore, for a two-way precession, where the outbound and inbound turns are identical:

$$\left\| \mathbf{\Delta v}_{turn} \right\| = v_{\alpha 1} + v_{\alpha 2} = v_0 \sin\left(\psi/2\right) \tag{9}$$

or for a one-way precession,

$$\left\| \mathbf{\Delta v}_{turn}^{1-way} \right\| = v_\psi \sin\left(\psi/2\right),\ v_\psi = \frac{v_0}{2} \tag{10}$$

where v_ψ is the diameter of the one-way turn circle (also, the radius of the two-way turn circle). In general, the final attitude of the spacecraft after the maneuver will be close enough to the initial attitude prior to the maneuver, that the two-way turn circle geometry is applicable. Corrections for differences between initial and final attitude will be described later.

The primary goal of the decomposition algorithm is to determine the precession angle ψ and the magnitude of the Δv_{burn} for the translational component. Use equations 3, 6, 7, but ignore the effects of spin changes. This yields:

$$\begin{aligned}\left(\Delta v_{total}\right)_x &= \left\| \mathbf{\Delta v}_{burn} \right\| \cos\psi + \left\| \mathbf{\Delta v}_{turn} \right\| \cos \psi/2 \\ \left(\Delta v_{total}\right)_z &= \left\| \mathbf{\Delta v}_{burn} \right\| \sin\psi + \left\| \mathbf{\Delta v}_{turn} \right\| \sin \psi/2\end{aligned} \tag{11}$$

Spin change components $\mathbf{\Delta v}_{spinup}$ and $\mathbf{\Delta v}_{spindown}$ are required either when large thrusters are needed (e.g., when $\mathbf{\Delta v}_{total} > 2.5$ m/s) or in lieu of $\mathbf{\Delta v}_{burn}$ when precise maneuvers are required, such as those prior to entry. Application of spin change components will be discussed later.

By applying equations 9 and 10 and trigonometric identities, the following two equations are obtained:

$$\begin{aligned}\left(\Delta v_{total}\right)_x &= \left\| \mathbf{\Delta v}_{burn} \right\| \cos\psi + v_\psi \sin\psi \\ \left(\Delta v_{total}\right)_z &= \left\| \mathbf{\Delta v}_{burn} \right\| \sin\psi + v_\psi \left(1 - \cos\psi\right)\end{aligned} \tag{12}$$

From these, a quadratic equation may be obtained in cos ψ:

$$\left[R^2 + \left(\Delta v_{total}\right)_x^2\right] \cos^2\psi + 2v_\psi R \cos\psi + \left[{v_\psi}^2 - \left(\Delta v_{total}\right)_x^2\right] = 0 \tag{13}$$

whose solutions are:

$$\cos\psi = \frac{-v_\psi R \pm \left|\left(\Delta v_{total}\right)_x\right| \sqrt{\left(\Delta v_{total}\right)_x^2 + R^2 - {v_\psi}^2}}{\left(\Delta v_{total}\right)_x^2 + R^2} \tag{14}$$

where

$$R = \left(\Delta v_{total}\right)_z - v_\psi .$$

If the radical

$$\left(\Delta v_{total}\right)_x^2 + R^2 - v_\psi^{\ 2} < 0$$

then $\Delta \mathbf{v}_{total}$ lies inside the two-way turn circle of radius v_ψ. In this situation, $\Delta \mathbf{v}_{turn}$ cannot be used as a component of $\Delta \mathbf{v}_{total}$ and must be nullified by implementing a total precession of 360° around the turn circle; in the absence of any spin changes, this results in $\Delta \mathbf{v}_{burn} = \Delta \mathbf{v}_{total}$ with an initial precession of θ and a final precession of 360°- θ.

When not inside the turn circle, there are two solutions for cos ψ which give rise to four possible solutions for ψ. This ambiguity can be resolved through trial and error. Equation 9 can be applied to estimate the magnitude of the turn for each of the four cases, and equation 12 can be applied as follows to estimate the magnitude of the burn for each case:

$$\left\| \Delta \mathbf{v}_{burn} \right\| = \begin{Bmatrix} \dfrac{\left(\Delta v_{total}\right)_x - v_\psi \sin\psi}{\cos\psi} \quad \textit{when} \left|\cos\psi\right| > \sqrt{2}/2 \\ \dfrac{\left(\Delta v_{total}\right)_z + v_\psi \left(\cos\psi - 1\right)}{\sin\psi} \quad \textit{when} \left|\cos\psi\right| \le \sqrt{2}/2 \end{Bmatrix} \tag{15}$$

One and only one of the four possibilities for turn and burn magnitudes as obtained from equations 15 and 9 respectively, should satisfy equations 11 (or provide a result which is reasonably close to satisfying the equality). Moreover, the correct solution should also result in a positive burn magnitude.

If the resulting ψ > 180°, then it is generally recommended that $\Delta \mathbf{v}_{turn}$ not be applied to the maneuver design, since this would entail a two-way precession of greater than 360° and unnecessarily increase the off-sun time during the maneuver sequence. In this situation, just like the condition of being inside the turn circle, $\Delta \mathbf{v}_{burn} = \Delta \mathbf{v}_{total}$ is imposed with an initial precession of θ and a final precession of 360°- θ. Figure 6 illustrates the aforementioned conditions in which a 360° precession would be applied.

For maneuvers involving only a single precession, such as the final SRC release and deboost maneuvers, equation 10 is applied in place of equation 9 with the consequence that v_ψ in all subsequent equations would now represent the radius of the one-way turn circle and would be halved in value.

All components obtained from the aforementioned algorithm can be transformed back to EME2000 using the transpose of $\mathbf{A}_{initial}$ from equation 4, assuming $\hat{\omega}_{initial}^{EME2000} \approx \hat{\omega}_{final}^{EME2000}$.

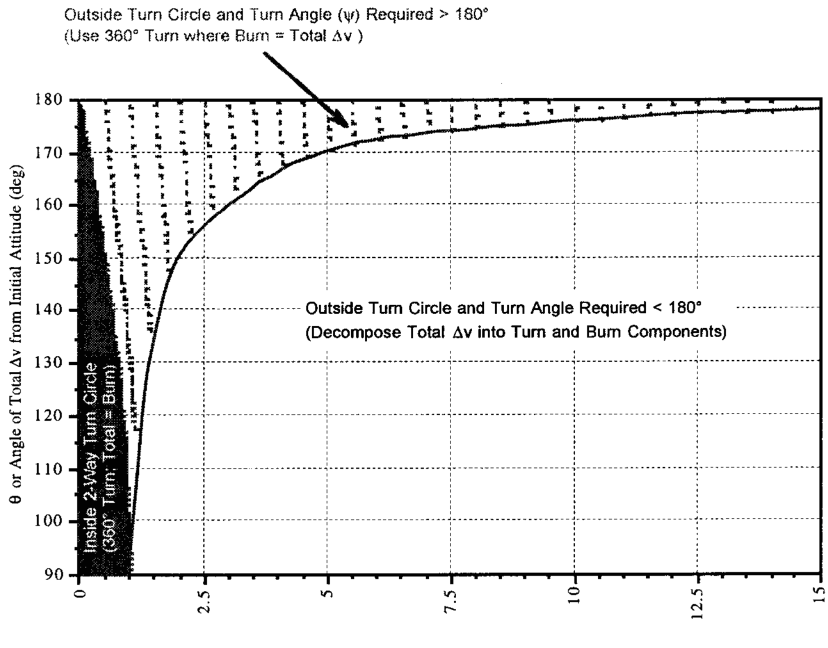

Figure 6. Conditions for Application of 360° Precession

MODIFICATIONS FOR SPIN CHANGES

For cases where spin changes are used, each spin change component is estimated as follows:

$$\left\| \Delta \mathbf{v}_{\text{spin}} \right\|_i \cong \frac{I_{xx} \left\| \Delta \omega \right\|_i}{rm} \tag{16}$$

based on the magnitude of the change in the spin rate of the spacecraft. The spin change component is aligned more or less with the spacecraft spin axis and will generally occur at points before and after the burn which accommodate a minimal time when more than 30° off sun for power reasons. This would occur either along the burn attitude (when before the burn or when after the burn and within 30° of the sun direction) or at an attitude which is at a prescribed off-sun angle α within the plane defining the inbound precession (when after a burn greater than 30° off sun).

Currently, the strategy for spin up entails precessing to the burn attitude using smaller thrusters and spinning up just prior to the translational maneuver. For this situation:

$$\Delta \mathbf{v}_{\text{spinup}} = \left\| \Delta \mathbf{v}_{\text{spin}} \right\| \hat{\Delta \mathbf{v}}_{\text{burn}} \tag{17a}$$

$$\Delta \mathbf{v}_{\text{burn}}^{\textit{corrected}} = \Delta \mathbf{v}_{\text{burn}} - \Delta \mathbf{v}_{\text{spinup}} \tag{17b}$$

which is applied after $\Delta \mathbf{v}_{\text{burn}}$ is determined via the aforementioned algorithm, but prior to transforming back into the EME2000 coordinate frame.

In the case of spin down after large maneuvers (> 2.5 m/s) where $\Delta \mathbf{v}_{\text{total}}$ is greater than 30° off sun, the final attitude is assumed to be the sun direction and the spin change would occur at an angle α from the final spacecraft attitude during the post-burn precession in order to minimize off-sun time. For large maneuvers, it can be assumed that $\hat{\omega}_{\text{initial}}^{\text{EME2000}} \approx \hat{\omega}_{\text{final}}^{\text{EME2000}} \approx -\hat{\mathbf{r}}_{\text{SC}}^{\text{EME2000}}$, where $\mathbf{r}_{\text{SC}}^{\text{EME2000}}$ is spacecraft position relative to the sun in EME2000; this entails correcting $\Delta \mathbf{v}_{\text{total}}$ in the precession plane coordinate frame prior to applying the decomposition algorithm, as follows:

$$\Delta\mathbf{v}_{spindown} = \left\| \Delta\mathbf{v}_{spin} \right\| \begin{bmatrix} \cos\alpha \\ 0 \\ \sin\alpha \end{bmatrix} \tag{18a}$$

$$\Delta\mathbf{v}_{total}^{corrected} = \Delta\mathbf{v}_{total} - \Delta\mathbf{v}_{spindown} \tag{18b}$$

These equations may also be applied to address any spin up which may be required for the case of large maneuvers, in lieu of equations 17, since initial pointing for this case will be at some angle α off sun.

If $\Delta\mathbf{v}_{total}$ is within 30° of the sun, then spin down can occur immediately after the burn, so that $\Delta\mathbf{v}_{spindown}$ would be computed and $\Delta\mathbf{v}_{burn}$ corrected in the same manner as in equations 17.

For the case where spin changes are employed in lieu of the burn itself, $\Delta\mathbf{v}_{burn}$ is set to zero and replaced with some combination of spin change components, such that:

$$\Delta\mathbf{v}_{spinup} + \Delta\mathbf{v}_{spindown} = \sum_{i=1}^{N} \left\| \Delta\mathbf{v}_{spin} \right\|_i \hat{\Delta\mathbf{v}}_{burn} \tag{19a}$$

$$\left\| \Delta\omega \right\|_i = \frac{rm \left\| \Delta\mathbf{v}_{spin} \right\|_i}{I_{xx}} \tag{19b}$$

Corrected components can be transformed back to EME2000 using the transpose of $\mathbf{A}_{initial}$ from equation 4, assuming $\hat{\omega}_{initial}^{EME2000} \approx \hat{\omega}_{final}^{EME2000}$.

CORRECTIONS FOR PRECESSION ASYMMETRY

For cases where initial and final attitudes differ significantly, such as when a propulsive maneuver is combined with a sun or solar wind pointing correction, or portions of the precession are performed with a different thruster combination and spin rate, adjustments to $\Delta\mathbf{v}_{turn}$ and $\Delta\mathbf{v}_{burn}$ must be applied to correct the previous precession estimate and to compensate for error in the previous burn estimate in the along-track direction. This is done after transforming back to EME2000 using $A_{initial}^{-1}$ derived from equation 4. For the case where only smaller thrusters are used for precession and $\hat{\omega}_{initial}^{EME2000} \neq \hat{\omega}_{final}^{EME2000}$,

$$\mathbf{v}_{\alpha 1}^{EME2000} = \frac{\Delta\mathbf{v}_{turn}^{EME2000}}{2} \tag{20a}$$

$$\left(\mathbf{v}_{\alpha 2}^{EME2000}\right)^{corrected} = v_{\psi} \sin\left(\psi'/2\right) \left[\frac{\hat{\Delta\mathbf{v}}_{burn}^{EME2000} + \hat{\boldsymbol{\omega}}_{final}^{EME2000}}{\left\| \hat{\Delta\mathbf{v}}_{burn}^{EME2000} + \hat{\boldsymbol{\omega}}_{final}^{EME2000} \right\|} \right]$$

$$\text{where } \psi' = \cos^{-1}\left(\hat{\Delta\mathbf{v}}_{burn}^{EME2000} \cdot \hat{\boldsymbol{\omega}}_{final}^{EME2000} \right) \tag{20b}$$

$$\left(\Delta\mathbf{v}_{turn}^{EME2000}\right)^{corrected} = \mathbf{v}_{\alpha 1}^{EME2000} + \left(\mathbf{v}_{\alpha 2}^{EME2000}\right)^{corrected} \tag{20c}$$

$$\left(\Delta\mathbf{v}_{\text{burn}}^{EME2000}\right)^{corrected} = \Delta\mathbf{v}_{\text{burn}}^{EME2000} + \hat{\Delta\mathbf{v}}_{\text{burn}}^{EME2000}\left\{\hat{\Delta\mathbf{v}}_{\text{burn}}^{EME2000}\cdot\left[\left(\mathbf{v}_{\alpha2}^{EME2000}\right)^{corrected} - \mathbf{v}_{\alpha1}^{EME2000}\right]\right\} \tag{20d}$$

Errors in the burn estimate in the cross-track direction are not compensated for; however, it can be shown that these errors are no larger than $v'_{\psi}\sin^2(\Delta\psi/2)$ in the worst case where $\Delta\psi = \psi' - \psi$. The worst-case estimate of uncompensated cross-track error introduced by the algorithm as a result of a difference in initial and final attitude for $\Delta\psi < 10°$ is typically ~1% of the uncalibrated cross-track execution error. For the case where large thrusters are required for a burn more than 30° off sun, rapid precession on large thrusters is performed for the first part of the inbound precession (i.e., until within sun angle α), so that $v'_{\psi} \neq v_{\psi}$ due to a different spin rate ω'_x and thruster lever arm r' affecting the turn circle size (equation 8). For this situation, let us assume $\hat{\omega}_{\text{initial}}^{\text{EME2000}} \approx \hat{\omega}_{\text{final}}^{\text{EME2000}}$ and replace equation 20b with the following:

$$\left(\mathbf{v}_{\alpha2}^{EME2000}\right)^{corrected} = v'_{\psi}\sin\left(\frac{\psi-\alpha}{2}\right)\left[\frac{\hat{\Delta\mathbf{v}}_{\text{burn}}^{EME2000} + \hat{\Delta\mathbf{v}}_{\text{spindown}}^{EME2000}}{\left\|\hat{\Delta\mathbf{v}}_{\text{burn}}^{EME2000} + \hat{\Delta\mathbf{v}}_{\text{spindown}}^{EME2000}\right\|}\right]$$

$$v_{\psi}\sin\left(\frac{\alpha}{2}\right)\left[\frac{\hat{\Delta\mathbf{v}}_{\text{spindown}}^{EME2000} + \hat{\omega}_{\text{final}}^{EME2000}}{\left\|\hat{\Delta\mathbf{v}}_{\text{spindown}}^{EME2000} + \hat{\omega}_{\text{final}}^{EME2000}\right\|}\right] \tag{21}$$

CURRENT LIMITATIONS

Note that this algorithm ignores both the effects of nutation introduced over the course of the maneuver and wobble due to misalignment of the spin axis with a principal axis of the spacecraft. Further improvements to the algorithm may be required to compensate for these effects and to allow for adjustments to various components during operations on the basis of spacecraft performance as derived from previous maneuvers and special maneuver calibrations, including an estimate of confidence or uncertainty level.

Strictly speaking, this algorithm does not accommodate large maneuvers coinciding with sun or solar wind pointing corrections. The assumption for such maneuvers would be that $\hat{\omega}_{\text{initial}}^{\text{EME2000}} \approx \hat{\omega}_{\text{final}}^{\text{EME2000}}$ and that any asymmetry required in the final precession could be treated as a separate attitude control event, completely decoupled from the propulsive maneuver.

Also, durations of various components and delay times between components need to be added to the algorithm or specified directly by the Spacecraft Team based on scenarios developed and tested for assembly, test and launch operations (ATLO). This is of particular importance for the final pre-entry maneuvers, where specific execution errors and durations become much more significant.

CONCLUSION

A decomposition algorithm has been developed for the Genesis mission which addresses spacecraft design limitations and constraints to date. Implementation and testing of the algorithm for Genesis are now underway. This algorithm is also applicable to other missions using spin-stabilized spacecraft with axisymmetric thrusters.

ACKNOWLEDGMENT

The research described in this paper was carried out by the Jet Propulsion Laboratory (JPL), California Institute of Technology, under a contract with the National Aeronautics and Space Administration. This paper was produced under the auspices of the Genesis Project and with the cooperation of Lockheed-Martin Astronautics (LMA). The author would like to acknowledge W. E. Bollman and J. K. Miller at JPL and P. E. Hong and R. P. Zietz at LMA, in particular, for various ideas and discussions which contributed to this paper.

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