STEREO Mission Design

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STEREO (Solar-TErrestrial RElations Observatory) is the third mission in the Solar Terrestrial Probes program (STP) of the National Aeronautics and Space Administration (NASA). STEREO is the first mission to utilize phasing loops and multiple lunar flybys to alter the trajectories of more than one satellite. This paper describes the launch computation methodology, the launch constraints, and the resulting nine launch windows that were prepared for STEREO. More details are provided for the window in late October 2006 that was actually used.

INTRODUCTION

NASA's Solar Terrestrial Relations Observatory (**STEREO**) launched in 2006 October 26 at 00:52:00.339 UT. The mission history is detailed by Sharer.[1] The spacecraft were simultaneously launched employing a single Delta II launch vehicle. STEREO is currently providing coordinated observations of the Sun and interplanetary medium using a two spacecraft formation in heliocentric orbit, as shown in Figure 1.

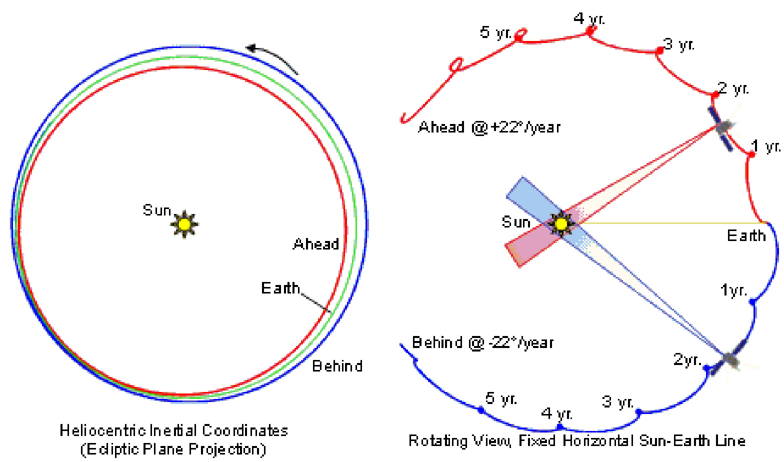

Figure 1 North-Ecliptic-Pole View of the STEREO spacecraft heliocentric orbits

The first detailed mission design was for a launch in November 2005, but the actual launch was almost a year later. Possible launch windows occur each month, but besides achieving the mission heliocentric orbits, there are other constraints on the mission, including avoidance of long eclipses by the Earth in the phasing orbits and avoiding coast times in the parking orbit that are too long (due to the limited capacity of the onboard batteries, on which the spacecraft depend until the solar panels are deployed a few minutes after injection). Moreover, a short coast might also be a problem. Boeing engineers have determined that the absolute minimum coast time is approximately 200 seconds. This minimum time assumes no maneuvers or rolls and a minimal settling time after the first cutoff of the second stage engine.

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During coast, the rocket might need to perform some maneuvers to line up the vehicle for solar constraints, as well as for telemetry coverage during the burn. For thermal reasons a barbeque (BBQ) roll might also be needed. The length of the maneuvers during the coast depends on the time of year and the length and timing of the burns. Another factor to consider is that NASA requires telemetry coverage of all burns. If the first restart burn is substantially earlier than typical, a mobile telemetry station (boat or aircraft) is required to cover the burn. This additional tracking asset would be an extra cost.

Other constraints, such as the perihelion and aphelion distances in the heliocentric orbits, and arrangement of mobile tracking assets required to observe the injection burns by the 2nd and 3rd stages, also had to be considered. The changing geometry of the Earth relative to the Moon's orbit and the Earth-Sun line, and the fixed ground track of the parking orbit (since the launch azimuth was fixed at 93deg. for the Cape launch, resulting in a 28.5 deg. inclination), resulted in a geometry similar to that of Figure 2 Figure for launches from late May to October, but in a reversed geometry (rotate Figure 2 180 deg, but keeping the direction to the Sun fixed to the left) during the other months of the year, which consequently had Behind having only one lunar swingby and Ahead having two of them.

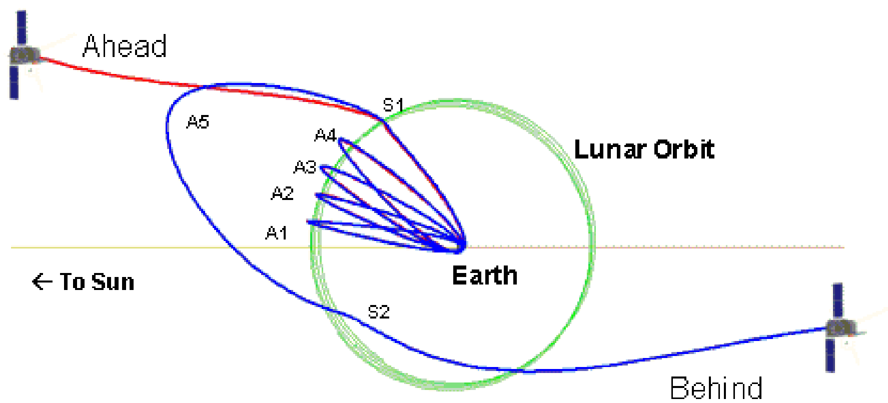

Figure 2 Phasing Orbit and Departure Trajectory (Fixed Earth-Sun line, Ecliptic projection)

During each month, there were launch opportunities on 14 to 16 consecutive days. The first lunar swingby (S_1) would always occur within a day of a nominal date selected for it that preliminary calculations found resulted in suitable heliocentric orbits, and the last two revolutions in the phasing orbits would also be nearly the same; the P_2 perigee (between the A_2 and A_3 orbits in Figure 2) would be selected with the Moon opposite it so that lunar perturbations would have minimal effect on the phasing orbits before the S_1 swingby. During the early part of the launch window, the launch injection was into a higher-energy orbit with period of about 14 days and apogee well beyond the Moon's orbit to reach P_2 on the right date. The period of the first two phasing orbits was gradually decreased during the following days of the launch window, with the launch energy decreasing and the apogee distances also decreasing, to reach P_2 on the same date. During most days of the launch window, lunisolar perturbations decreased the perigee height during the first orbit and, less commonly, the second orbit, making it necessary to perform a maneuver at the first apogee to raise the perigee to the desired 500 km altitude. The targeting of the lunar swingbys, needed only to achieve the desired heliocentric drift rates, was loose enough that it was possible to have two launch opportunities each day, separated by 68 minutes, for most months, and also to use the same launch conditions (coast time and injection C_3) with different launch times to form launch "blocks" two to three days long, decreasing the computations needed for the extensive work that Boeing needed to expend to set up each block. For the 68 minutes daily window separation, the goal was to have as wide a time between the start of the first opportunity and the end of the second opportunity as possible; this length maximization would provide the best chance to launch if something went wrong (weather, range intrusions, etc.) for the first opportunity. A given opportunity (coast time, C_3 combination) only works for 15 to 20 minutes or the spacecraft onboard ΔV's in the phasing orbits become too high.

This paper describes the methodology for the window construction. Nine detailed launch windows were prepared for STEREO, but this paper concentrates on the window in late October 2006 that was actually used. Initially, that window was not considered, but three months before launch, it was decided to attempt it, although the coast times were shorter than Boeing had ever flown before. Furthermore, to limit the number of tracking assets needed during the launch ascent, the coast time was fixed for the entire window and only one daily opportunity (15 minutes) was attempted. After almost a year of trajectory computations, STEREO was successfully launched on October 25th, 2006 (October 26th UTC).

LAUNCH VEHICLE AND SEQUENCE

The STEREO spacecraft mission utilized a Delta II 7925-10L launch vehicle. This vehicle consists of a booster with a Rocketdyne RS-27A main engine augmented by nine Alliant Graphite Epoxy solid propellant Motors (GEMs) with extended nozzles on the airlit GEMs, a second stage with an Aerojet AJ10-118K engine, and a Thiokol STAR 48B solid motor third stage. A stretched 10-foot payload fairing encloses the second stage, third stage, and payload during first stage flight and the early portion of second stage flight. The third stage utilizes a 3712A payload attach fitting and a yo-yo despin system.

The ascent trajectory design includes two performance enhancements employed most recently for the MESSENGER mission: 1) reducing the time between second stage cutoff and third stage spinup from 50 seconds to 40 seconds, and 2) including a small attitude maneuver between second stage cutoff and third stage spinup to achieve a more optimum burn attitude for the third stage. Additionally, pitch and yaw rates were included during the second stage restart burn to gain some performance. Finally, the maximum dynamic pressure constraint was increased to 1206.5 psf from 1185 psf after consultation with the Delta Controls group.

After coasting in a low Earth parking orbit, the injection into the high-energy phasing orbit is accomplished by restarting the 2nd stage motor to initiate the transfer that is completed by firing the 3rd stage solid rocket motor. The deployment sequence begins shortly after the burn-out of the Delta's 3rd stage solid rocket motor. The entire 3rd stage-spacecraft stack is de-spun from an initial spin rate near 60 revolutions per minute (rpm) to approximately 0.0 rpm using a yo-yo device. Table 1 details the timing of the ascent events.

Table 1 Best Estimate of the Launch Timeline (no wind)

ASCENT EVENTS ALL LAUNCH DATES	**TIME (SEC)**	**INJECTION EVENTS OCT. 26, 27 UT**	**TIME (SEC)**
Liftoff	0.0	First Restart – Stage II	937.0
Main Engine Cutoff (**MECO**)	265.9	Second Cutoff – Stage II (**SECO2**)	1034.4
Stage I-II Separation	274.5	Fire Spin Rockets	1074.5
Stage II Ignition	280.0	Jettison Stage II	1077.7
Fairing Separation	284.0	Stage III Ignition	1114.9
First Cutoff – Stage II (**SECO1**)	610.3	Stage III Burnout (**TECO**)	1203.8
		Initiate Yo-Yo De-spin	1495.6
		Jettison Stage III	1500.7

After TECO and de-spin, the two STEREO spacecraft were jettisoned from the 3rd stage while stacked. The spacecraft then initiated a second separation that released the two stacked spacecraft from each other. The push-off forces for both the Delta-Ahead/Behind and Ahead/Behind separation events were provided by springs. The spacecraft operate independently at all times and do not rely on any inter-spacecraft communications to coordinate their activities. Following the Ahead/Behind (A/B) separation, timers would start for turning on the Traveling Wave Tube Amplifier (TWTA) and attitude system components. Also, a spacecraft timer was in place to inhibit a momentum dump for a prescribed period following an initiation of safe mode after A/B separation to reduce the collision probability. Two minutes after A/B separation, the spacecraft released their solar arrays and continued to drift apart.

Once the TWTA were on and the spacecraft were in view of a ground station, the spacecraft activated their attitude control systems to dump any excess momentum and achieve a Sun-pointing attitude. The attitude is determined using digital Sun sensors and 3-axis rate information from an Inertial Measurement Unit (IMU). Attitude control is provided by four reaction wheels and twelve thrusters. If momentum dumping is required, thrusters are used to provide the torque necessary to achieve the desired momentum state. The nominal separation events and their relative ΔVs are shown in Figure 3.

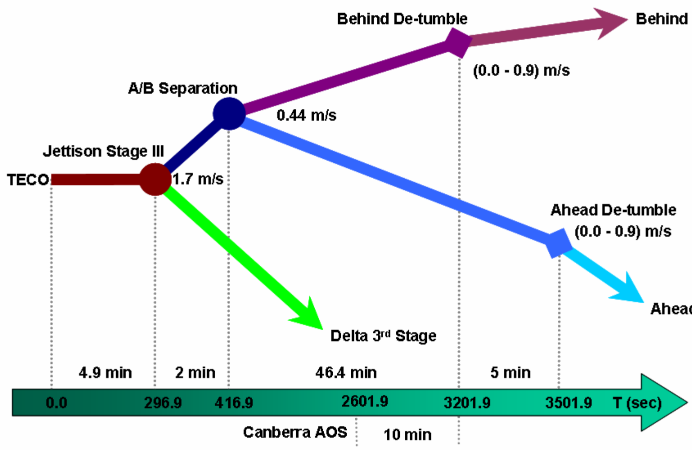

Figure 3 Nominal Separation Events, Actual Oct 26 Launch Timeline

LAUNCH WINDOW CONSTRUCTION

The basis for the STEREO launch windows employs the concepts of launch and coast times as clearly explained by Clarke[2] (according to Clarke, Krafft A. Ehricke[*] was the first to propose the launch coast along the parking orbit). In this paper coast time refers to the time between the second stage first cutoff and first re-start. See Table 1. The degrees of freedom provided by the launch and coast time variables coupled with launch from the Cape facilitate the computation of trajectories that target the Moon. Based on the Moon's position, software (using two-body problem dynamics) was set up to compute, classify, and organize launch opportunities in tables. These tables were used to quickly discard opportunities that violated ascent (including time to and duration of the first contact) and eclipse constraints. See Table 2 for the STEREO trajectory constraints. The data in the tables also were used as initial guesses into higher fidelity computations that were performed for each set of Detailed Test Objectives (DTO) targets input created.

Every month, based on the lunar motion, the desired escape trajectories, and the on-board propellant budget, 14 to 16 days are selected for launch. Furthermore, the monthly window geometry can have the perigees in the night side or in the day side. The selection of the perigees on the night or day side is based upon the trajectory and ground coverage constraints (time to move ground coverage assets from one location to another must also be considered). Once the selection has been made between night or day side perigees, daily windows are computed. Both descending and ascending solutions are available and are

[*] The first rocket stage to fly using liquid hydrogen and liquid oxygen as propellants was the Centaur stage on top of an Atlas intercontinental ballistic missile. Centaur was the brainchild of Krafft Ehricke.[3]

Table 2 STEREO Trajectory Constraints

Profile	Parameter	Minimum	Maximum
Ascent	Coast Time	300 sec*	55 min
	Eclipse Time	N/A	40 min
	First Station Contact	N/A	100 min
Maneuvers	+ X_{body} to Sun	N/A	45 deg
	+/- Z_{body} to Earth	N/A	90 deg
	ΔV Budget	N/A	182 m/s
Phasing + Flybys	Perigee altitudes	500 km	N/A
	Periselene altitudes	200 km	N/A
Heliocentric	Sun Distance: Ahead	0.909 AU	1.022 AU
	Sun Distance: Behind	0.983 AU	1.089 AU
	Earth Distance: Ahead	Height 500 km	0.750 AU
	Earth Distance: Behind	Height 500 km	0.881 AU

* Absolute minimum is 200 sec; N/A: Not Applicable

again selected subject to the trajectory and ground coverage constraints. In total, there are 14 to 16 days times 2 (night or day side perigees), times 2 (descending or ascending), times 2 (spacecraft), or 112 to 128 trajectories to consider every month. Again, software was set up to compute, classify, and organize these opportunities in tables. A typical plot showing the coast time behavior for orbits where Ahead gets to its mission orbit first (Lead>Lag Parking Orbit Coast Time) is shown in Figure 4. Recall from Table 2 that, for power and operational reasons, the maximum coast time allowed is 55 minutes, with a maximum eclipse time of 40 minutes, and with the first acquisition of signal taking place within 100 minutes of launch. Figure 5 displays the expected contact times and their durations as a function of coast time.

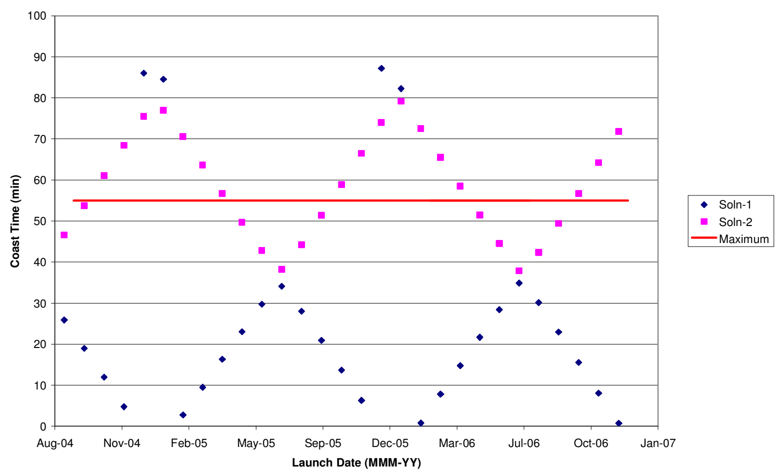

Figure 4 Parking Orbit Coast Time (Lead>Lag)

Within a given daily window, the ascent trajectory remains the same and only the time of launch varies. The phasing loop maneuvers are then used to absorb the offset in the first lunar flyby created by the different launch time. An allocation of 20 m/s per second is allocated for 15 minute daily window maintenance. (Longer or shorter windows might be prescribed depending on the particular window). Monte Carlo runs[4] were used to allocate propellant for launch error corrections and trajectory correction maneuvers (TCMs). Figure 6 illustrates a typical window for one of the spacecraft with the prescribed allocations and the deterministic ΔV (with finite burn penalties).

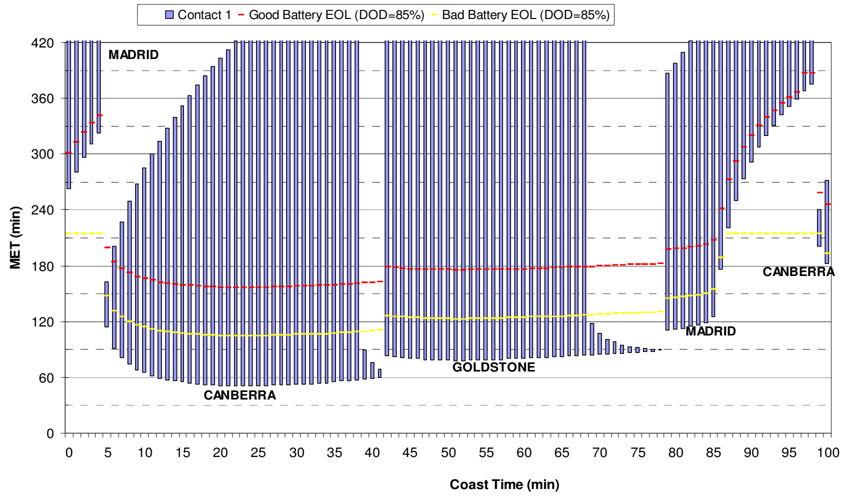

Figure 5 First Station Contact Times as a Function of Coast Time

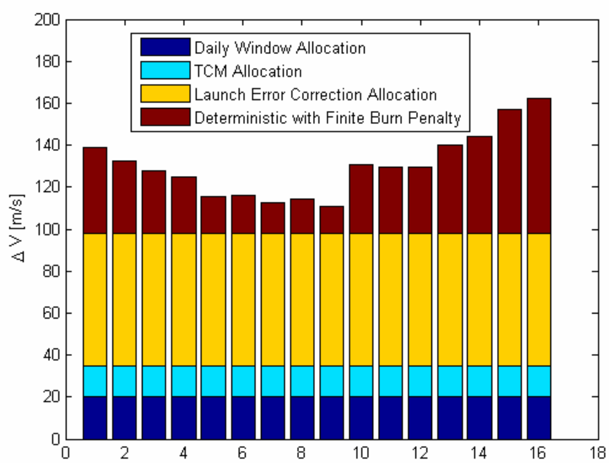

Figure 6 Typical ΔV Use Across a Window (Max. Allocations from Monte Carlo Runs)

It is also possible to have a second daily window by shifting the location of the first lunar swingby. An example of the dual daily geometry is shown in Figure 7 for the first day of a 14 day window and in Figure 8 for the last day. A geometrical exception to the dual daily was observed for STEREO: for the month of May 2006 the Moon inclination was the same as the injection parking orbit inclination of about 28.5 degrees (this geometry occurs every 18.6 years). This particular case got complicated by the fact that only the descending solution was viable for that opportunity.

For most of the DTO computations, dual daily opportunities were employed. Each daily opportunity uses a different ascent trajectory. Figure 9 shows a schematic with this information. It was desired to have the time between the daily opportunities to be as wide as possible; as this would provide the best chance to launch if something went wrong (weather, range intrusions, etc.) for the first opportunity. The first window is short so that the battery is not discharged very much. Boeing and NASA Kennedy Space Center (**KSC**) recommend a two minute first window vs. a one minute window. This is to address any Collision Avoidance (**COLA**) issue which usually clears in a minute. Then, for operational reasons (including fuel loading), Boeing specified that 66 min. was the maximum time available between opportunities. Moreover, the 66 min. between windows allows the spacecraft battery to be reconditioned

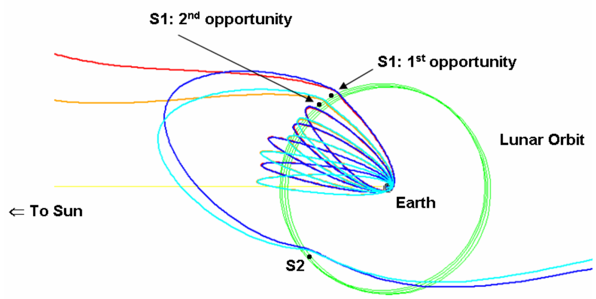

Figure 7 Typical Dual Daily Trajectories, Day 1 of 14

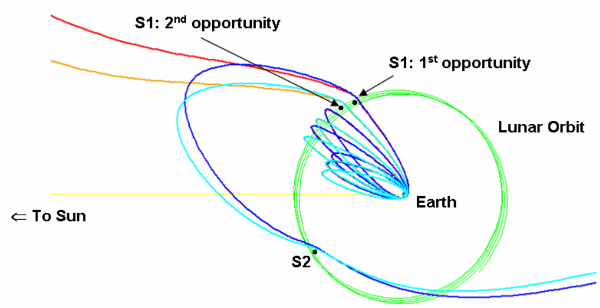

Figure 8 Typical Dual Daily Trajectories, Day 14 of 14

for the longer 2nd window. With a longer first window, the battery would be discharged more and could not be reconditioned to prime for the second window.

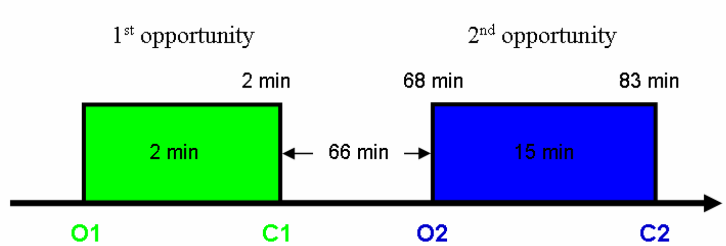

Figure 9 Dual Daily Launch Window Time Schematic

Table 3 displays the DTO inputs provided by the mission design team to the Boeing launch team. Note that the actual window in which STEREO launched had only one opportunity. The use of only one opportunity was the result of difficulties with the availability and movement of ground assets to cover the critical events during the ascent. Interestingly, the tracking and telemetry problem is mentioned by Clarke as the *most serious disadvantage* of the injection-to-parking orbit and coast launch model. For this reason, STEREO used blocks for the ascent trajectories. Within a given block, the ascent trajectory remains the same and only the launch time changes.

Table 3 DTO Windows Provided to Boeing Team

DTO No.	2006 Launch Windows	No. of Daily Opps.	No. of Days	Perigee Side	S/C with 2 flybys
1	04/11 to 04/24	2	14	Day	Ahead
2	05/26 to 06/08	1†	14	Night	Behind
3	06/23 to 07/07	2	15	Night	Behind
4	07/22 to 08/06	2	16	Night	Behind
5	08/20 to 09/04	2	16	Night	Behind
6	09/18 to 10/04	2	16*	Night	Behind
7	10/07 to 10/20	2	14	Day	Ahead
8	**10/19 to 11/02**	**1‡**	**16**	**Night**	**Behind**
9	11/04 to 11/17	2	14	Day	Ahead

†Dual daily not possible due to lunar orbit plane inclination and ascent coverage
*For 09/18, the second opportunity could not be calculated (no viable trajectories were found).
‡Only one opportunity for optimized ground coverage

LAUNCH BLOCKS

To facilitate launch ascent computations and operations at the Cape, the ascent trajectories were organized in blocks. Each block represented a unique ascent trajectory that could be used for a couple of days. For instance, block 1 would be the first opportunity on day 1 and, depending on the Sun-Earth-Moon geometry, could be used for two to three days. Then, block 2 would be the second opportunity on day 1 and again could be used for the same number of days as block 1. This arrangement would continue until at least a 14 day window was computed. Within a given block only the launch time would vary. During each block the date that was used to target the ascent trajectory and thus to obtain values for the coast time would be designated as **prime**. Figure 10 illustrates the block arrangement in terms of C_3 launch energy for all the DTO computations performed. Note that within blocks the C_3 energy remains essentially constant.

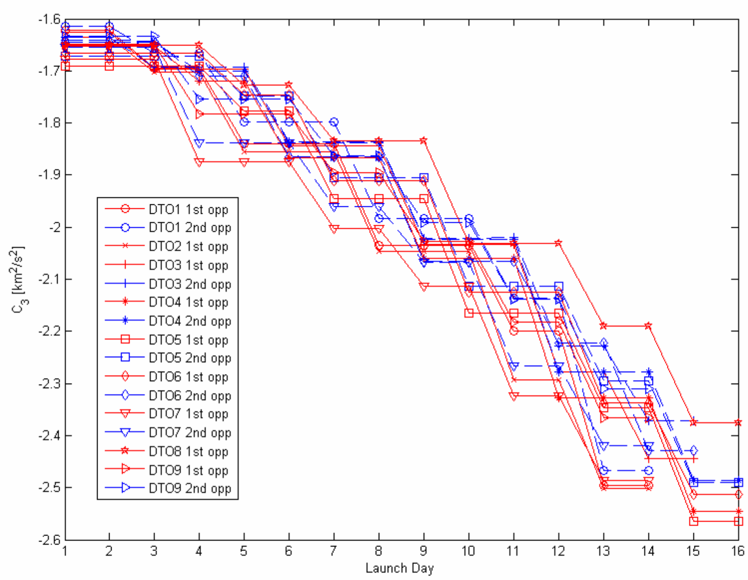

Figure 10 Launch Energy Behavior for all DTO Windows

Then, Figure 11 has the total deterministic ΔV for the same cases at the *start* of each block. Remember that during the early part of the launch window, the launch injection was into a higher-energy orbit with period of about 14 days and apogee well beyond the Moon's orbit to reach P_2 on the right date. The period of the first two phasing orbits was gradually decreased during the following days of the launch window, with the launch energy decreasing and the apogee distances also decreasing, to reach P_2 on the same date. Thus, up to half way into the 14 to 16 day window, the spacecraft maneuvers would effectively be decreasing the apogee heights. Midway into the 14 or 16 day window, the launch energy would be just about what is needed to reach the Moon's orbit without much spacecraft propulsion required. Then, in second half of the window, the first two apogee distances would be less than the Moon's orbit distance, and spacecraft propulsion would be needed to increase them after that. This window arrangement results in the concave up behavior of the deterministic ΔV in Figure 9. Some cases used maneuvers to avoid eclipses.

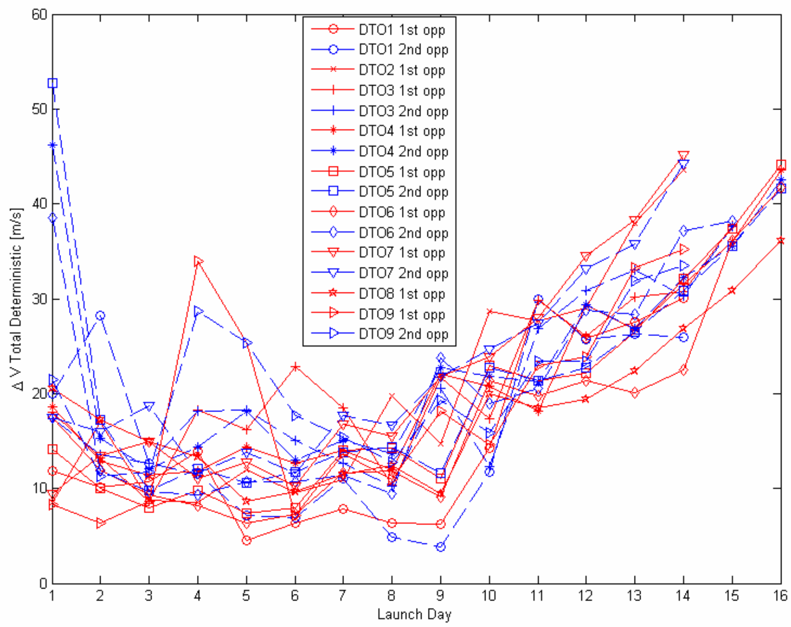

Figure 11 Deterministic ΔV for all DTO Windows (no penalties)

The actual budget also adds ΔV for the 15 minute launch window, finite burn penalties and up to 3σ errors in: launch, orbit determination, and maneuver execution errors. Additional ΔV might also be needed for targeting the spacecraft with only lunar swingby since, as explained next, the spacecraft with two flybys was used as the basis for the targeting.

MISSION DESIGN INPUTS TO BOEING

For each launch opportunity, a Target Interface Point (TIP) state was provided. The TIP state was computed approximately 5 minutes after TECO and was targeted to achieve the first lunar flyby B-Plane coordinates for the spacecraft that had two flybys. Calculations showed that targeting the two lunar swingbys for a spacecraft was more sensitive than the single lunar swingby for the other spacecraft, and once a trajectory was established for the spacecraft with two flybys, a different size for the second perigee (P_2) maneuver always worked to target the other spacecraft to its lunar swingby and mission orbit. Only a subset of the state parameters which includes the C_3, Inclination, Right Ascension of the Ascending Node (RAAN), argument of periapsis (AOP), and true anomaly (TA) are required to achieve the lunar flyby conditions needed for the mission. This target subset (C_3, Inclination, RAAN, AOP, and TA) was the basis of the launch vehicle targeting. The other state parameters were unconstrained and could be adjusted to optimize the launch vehicle performance (e.g. perigee altitude). The matching of the TA, although desirable, did not need to be matched as accurately as the other orbital elements. For days of the block that are not prime, the same trajectory as computed for the prime date is to be used, only varying the launch time to match the RAAN, and also loosely matching the TA. While the other elements were unconstrained, the launch trajectories were checked for consistency with the full state values and the deviations reported as part of the DTO.

BOEING ASCENT COMPUTATIONS

The data Boeing received from JHU/APL contained the following parameters: Launch Time, Time of Orbit Insertion, Semi-Major Axis (**SMA**), Eccentricity**,** Inclination, RAAN, AOP, TA, and C_3. The last 5 parameters were used to compute the TIP which is when and where orbit insertion is defined to occur. Portions of the orbit parameters changed for each day of the launch period. Using a 3 Degree of Freedom (**DOF**) computer simulation, Boeing optimized the liftoff time, the time of second stage engine restart, the duration of the restart burn, pitch and yaw maneuvers during and after the restart burn, and the time of the TIP to achieved the desired orbit parameters. The 3-DOF computer simulation was used as the basis for all subsequent analyses.

The 3-DOF computer simulation was used to create the DTO ascent trajectories. Before the DTO could be completed, telemetry sites had to be determined. Recall that NASA requires that all burns and separations must have telemetry coverage. Based on the preliminary DTO, data consisting of latitude, longitude, altitude, time of flight and a plot of the instantaneous impact points were sent to a Boeing engineer at Cape Canaveral to determine what telemetry stations were optimal. If a permanent telemetry site was not available or could not observe the burn or separation, a mobile site (either water, ground, or air based) had to be acquired. Once the coordinates of the telemetry sites were determined, these sites were entered into the 3-DOF program. Maneuvers required to point the antennae on the second stage towards the sites, while still maintaining the correct orbit parameters at TIP, then had to be determined.

The final computer simulation run for STEREO was a 5-DOF simulation based on the DTO but updated with inputs from Guidance, Controls and the actual masses of the launch vehicle and spacecraft. The results based on this simulation, the Best Estimated Trajectories (**BET**), were released approximately 1 week prior to launch. This simulation was the basis for the computer simulations run on the day of launch.

THE 2006 DTO INPUTS

The STEREO launch was originally scheduled for November 2005. Nonetheless, a variety of circumstances, including instrument delays, a strike of the International Association of Machinists and Aerospace Workers, other launches in the KSC manifest (including a shuttle mission), and concerns about the Delta II second stages delayed the STEREO launch many times. As a result, a total of nine DTO inputs were provided to Boeing. Each involved detailed calculations of the launch, phasing orbits, and resulting mission orbits. Moreover, both a main window and a backup window were provided each time. These computations kept the mission design team very busy during 2005 and 2006 and highlight some of the programmatic constraints that can take place in the launching of a mission. In this section, we briefly summarize some of the key events that caused launch delays during 2006.

After completion at APL, the observatories arrived at NASA Goddard Space Flight Center (GSFC) on November 9, 2005 for environmental testing. Then, on Tuesday, May 2nd, 2006 the truck carrying the observatories pulled away from NASA GSFC and started its trip to the Astrotech facility at NASA KSC. The observatories arrived on May 3rd and the team began preparations for the launch window (DTO number 4) opening on July 22 and extending through Aug. 6, 2006. On June 26, the launch was rescheduled to July 30 to finalize critical safety operations on the spacecraft, including fueling and spin balance testing. On July 7, due to a faulty crane at Pad 17-B, vehicle stacking of the solid rocket boosters was not able to proceed as planned. This problem pushed the launch to no earlier than August 1.

As launch preparations continued, on July 17 it was announced that the launch had been delayed to no earlier than August 20th and thus DTO number 4 was out. Earlier that week, during the fueling of Observatory A, one of the valves used to load the spacecraft with hydrazine propellant was observed to be leaking from a secondary seal. Fortunately, technicians suspended the fueling, made adjustments, and finished the fueling with no further leakage. However, as a precaution, the two observatories were not pressurized to allow an anomaly team to investigate. The anomaly team cleared STEREO for launch. Around the same time, concerns about the Delta II second stages surfaced. At the Boeing plant in Decatur, Alabama, a leak had been observed in the second stage oxidizer tank for the Delta II that had been scheduled to launch NASA's THEMIS spacecraft in November. As a result, NASA requested that all identical tanks scheduled for launch in the near future had to be checked. Then, on July 28th, NASA announced that it was slipping STEREO's launch 11 days to Aug. 31 in order to de-stack the rocket's second stage and take it to a nearby facility for leak testing. When no leak was detected, the second stage was returned to the launch pad and added back to the stack.

For most of August, preparations continued for an end of the month launch. Unfortunately, on August 21, the launch was postponed to no earlier than Sept. 18 and DTO number 5 was out. The additional time was necessary for further evaluation of the Delta II second stage to verify it was structurally sound for flight. To make things even more exciting Hurricane Ernesto passed KSC on August 28 and STEREO had to follow its "hurricane plan" while in its transport can at the Astrotech facility. Fortunately, the hurricane degraded to a tropical storm and no wind damage took place at KSC. However, an electrical checkout of the vehicle had to be performed due to lightning strikes within a one-third mile radius of Complex 17.

On September 1, NASA officially announced that a decision was made to once again remove the STEREO second stage from the launch vehicle and perform an inspection from inside the propellant tank to verify it was structurally sound for flight. There were still questions about the adequacy of the previous tests due to further engineering analysis revealing that a similar tank produced for another mission was marginally thin in an area of the oxidizer tank. The launch of STEREO was now targeted for no earlier than Oct. 18 and DTO numbers 6 and 7 were out. During all these delays the mission design team was kept well informed and windows were constantly being computed. However, additional challenges were faced with the computation of DTO number 8. These challenges are described next.

October-November Launch Window: A Very Short, Fixed Coast

Earlier, at the end of July, the mission design team and Boeing teams had performed preliminary computations for a window starting in October. Options in mid October were causing problems because the descending solution (short coast) had long (120 minutes) eclipses in the phasing loops and the ascending (long coast) solutions had first contact at Canberra about 79 minutes after launch. At this point, Dunham suggested the computation of a night-side perigee launch window that would have very short coasts with first contact at Canberra and only one opportunity per day. There was concern with the short coast times (in the order of 512.7 seconds in the mission design software), and thus a sample trajectory was provided to Boeing to verify that the short coast times were feasible. The Boeing team had no problems targeting the trajectory but had to shorten the coast time a bit further to about 475 seconds to have enough velocity reserves to meet the probability of command shutdown reserve requirements. At this point, all the Boeing subsystems had to be consulted as no previous mission had attempted such a short coast time[†].

[†] For the Delta II, the Boeing team had estimated the absolute barest minimum coast time between SECO 1 and first restart to be 200 seconds. This coast time assumes no maneuvers, including the BBQ roll (fortunately not needed for the night side perigee insertion) and a minimal post SECO 1 settling time.

Meanwhile, the short coast time of this window imposed additional challenges on the operations and navigation team. Specifically, the first contact was at Canberra about 68 minutes after launch. But the pass there was short, only about 3 hours and 20 minutes, followed by a 100-minute gap with no coverage until the second contact, at Madrid, 6.2 hours after launch; the Madrid pass was rather normal, lasting 7.1-7.2 hours, and coverage after that is normal as the spacecraft rise higher. The first Canberra pass was too short to do all of the planned 1st pass operations, or to determine the orbit well. Priority was given to just to ensure spacecraft survival through the 100-min. gap to the Madrid pass, which could then be used to complete the normal 1st-pass activities. Also, the team advised the navigation team that as much tracking should be obtained during the Canberra passes as possible. But for navigation, the first pass would contain only Doppler data, since the attenuators needed on the antennas preclude ranging[5].

In addition, there were concerns with the ground coverage assets. The Big Crow (an instrumented tracking airplane) would not be available for the second week of the window. Thus, only assets that would be fixed during the window could be used for the entire window. To further simplify the logistics of ground coverage, the first opportunity on each day was given up and the coast time was fixed for the entire window. The resulting coast times were even shorter at 364.1 seconds in the mission design software. The official letters with the (DTO number 8) target inputs were provided to Boeing on September 6 and on September 13 respectively. See Table 4 and Table 5 below for the mission design inputs.[‡]

Table 4 Launch Blocks for October-November Window

2006 Oct./Nov.	Block #	Coast time seconds	C_3 km^2/sec^2
18, 19, 20, **21**	1	364.1	-1.6504
22, **23**	2	364.1	-1.7278
25, 26, **27**	3	364.1	-1.8320
28, 29, **30**	4	364.1	-2.0313
31, **1**	5	364.1	-2.1901
2, **3**	6	364.1	-2.3762

Prime days in boldface; Oct. 23 is at 23h UT;
There is no launch on Oct. 24 UT; Oct. 25 is at 0h UT.

Table 5 October-November Window Behind Basic Information (data at window start)

Date	**Launch UT**	**Days to P_1**	**P_1 h km**	**A_1 ΔV**	**P_2 ΔV**	**A_3+ ΔV**	**Total ΔV m/s**
10/18	23:46:37	13.2	3917	0.0	-20.5	0.0	20.5
10/19	23:50:38	13.2	2193	0.0	-17.2	0.0	17.2
10/20	23:53:03	13.2	1257	0.0	-14.9	0.0	14.9
10/21	23:55:25	13.3	757	0.0	-13.3	0.0	13.3
10/22	23:49:12	12.7	485	0.0	-8.7	0.0	8.7
10/23	23:51:52	12.7	362	1.7	-8.0	0.0	9.7
10/25	00:42:28	11.2	-195	9.2	2.3	0.0	11.5
10/26	00:37:52	11.6	-188	9.1	3.3	0.0	12.4
10/27	00:26:11	11.2	-12	6.8	2.7	0.0	9.5
10/28	00:31:42	10.0	-84	8.4	11.6	0.0	20.0
10/29	00:26:26	10.0	73	6.1	12.4	0.0	18.5
10/30	00:16:50	10.0	-48*	8.0	11.4	0.0	19.4
10/31	00:19:01	8.9	307	2.9	19.5	0.0	22.4
11/1	00:10:15	8.9	-30*	8.3	18.5	0.0	26.8
11/2	00:12:20	7.9	319*	3.0	27.9	0.0	30.9
11/3	00:03:55	7.9	-43*	9.2	27.0	0.0	36.1

* means the h is for P_2, not P_1, whose h is greater; Prime days in boldface; there is no launch on 10/24 UT.

‡ In Table 5, the maneuver designated as A_3+ takes place shortly after the third apoapsis at 200 degrees of true anomaly, which was found to be the location that minimized the ΔV.

After careful consideration of all the ascent maneuvers and constraints, the Boeing team in conjuction with the NASA launch services team in KSC agreed that it would be feasible to utilize the October-November window. Tracking assets would be placed only at Sao Tome and Cape Verde. Eventually all the requirements were met but not without some additional excitement. To get the tracking equipment to Cape Verde, the equipment was flown first in a commercial flight from Johannesburg, South Africa (where it was used for the previous window) to Dakar, Senegal. Then, to transport the equipment from Dakar to Cape Verde, a produce flight had to be used. It also took some time to obtain permission from the government of Cape Verde to import the equipment. In fact, permission was granted the day the flight had to leave from Johannesburg. Fortunately, during the 3 days that the crew had to set up the equipment at Cape Verde, no problems requiring new parts were found, or the launch would have had to be delayed. Figure 12 illustrates the ground track plot for the October 26-27 DTO trajectory.

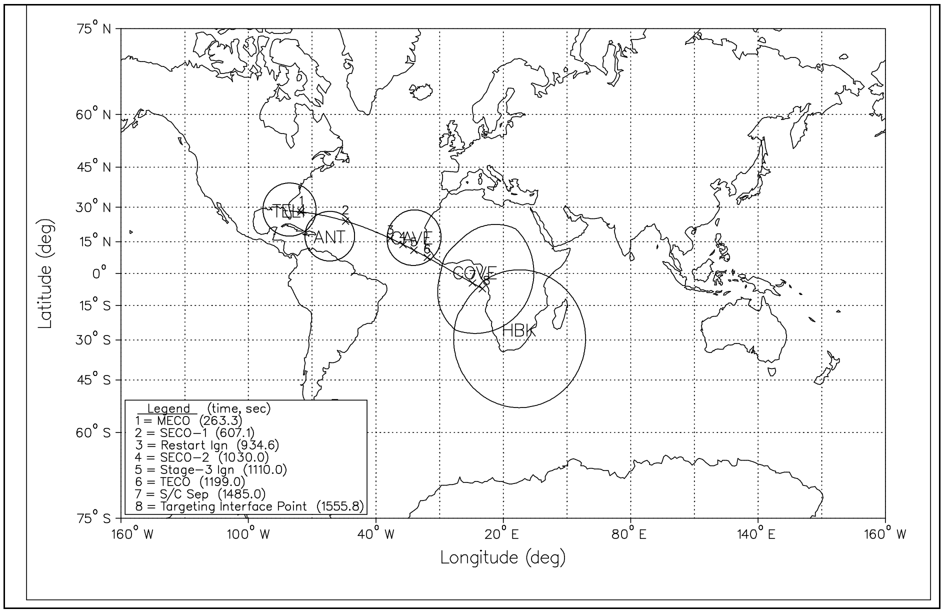

Figure 12 Ground-track for 26-27 October 2006 DTO Trajectory

In Figure 12 above, the following acronyms are used: radar site near Cape Canaveral (TEL1), Antigua (ANT), Cape Verde (CAVE), Sao Tome (COVE), and Hartebeeshoek (HBK).

Launch on the Minute

For practical purposes and launch coordination, it was decided to launch on the minute. That is, the start of the window was rounded to the nearest minute. The resulting launch window times for the October-November window are shown in Table 6 below. Each daily launch window was continuous. That is, while the Boeing launch director would likely call for launch on a whole minute within the window, it was not mandatory to do so. The actual launch time could take place at any time within the launch window to meet operational constraints.

Table 6 Launch on the minute, window start times (length is 15 minutes)

Launch UTC Date	Launch Block	Liftoff Time, U.T.C. (hh:mm:ss)	Liftoff Time, E.D.T.* (hh:mm:ss)
26-Oct-06	1	00:38:00.000	20:38:00.000
27-Oct-06	1	00:26:00.000	20:26:00.000
28-Oct-06	2	00:32:00.000	20:32:00.000
29-Oct-06	2	00:27:00.000	20:27:00.000
			Time Change E.S.T.*
30-Oct-06	2	00:17:00.000	19:17:00.000
31-Oct-06	3	00:19:00.000	19:19:00.000
01-Nov-06	3	00:10:00.000	19:10:00.000
02-Nov-06	4	00:12:00.000	19:12:00.000
03-Nov-06	4	00:04:00.000	19:04:00.000

* Liftoff occurs the previous day eastern time, Prime days in boldface

LAUNCH DAY

On the day of launch, weather balloons were released from the launch site in Florida starting 5 hours before launch. Wind speed and azimuth, temperature, and pressure data were transmitted to Boeing in California and inserted in the 5-DOF computer simulations run by the Trajectory Analysis, Controls, Guidance, and Structures groups to confirm that the vehicle could safely launch and obtain the desired orbit. On October 26 00:38:00.000 UT, the launch window opened. Initially, the countdown was holding at T-minus 4 minutes because Range Safety at the Cape was "no go". The wind data for the night was creating concerns that a launch explosion would make toxic gases drift over populated areas. Then, at 00:43 UT, the range announced that it was ready to go and the launch would resume at 00:48 UT. As expected the countdown resumed and launch took place on October 26 at 00:52:00.339 UT (14 minutes and 0.339 seconds into the 15 minute window).

The entire STEREO team was relieved that the launch proceeded without any problems. The first orbit and early operations are described elsewhere.[6] The mission design team was now ready to start flight computations of the maneuvers that the observatories would require to achieve their lunar flybys and respective mission orbits. Nonetheless, as expected, the launch at the end of the window meant that the observatories would now have to perform larger maneuvers. These maneuvers and more information are provided in Ref. 7.

SUMMARY

The STEREO mission design and Boeing launch teams computed nine detailed (14-16 day) windows. A variety of factors postponed the launch many times during 2006. This paper described the methodology employed to compute the nine detailed launch windows that were prepared. Details about the reasons for the delays were also provided. At the end, a window with a very short coast between the Delta II second stage burns was employed. Furthermore, to limit the number of tracking assets needed during the launch ascent, the coast time was fixed for the entire window and only one daily opportunity (15 minutes) was attempted. This strategy worked and after almost a year of trajectory computations, STEREO was successfully launched on October 26th at 00:52:00.339 UTC.

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