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CHARTING A COURSE TO THE SUN: FLIGHT PATH CONTROL FOR PARKER SOLAR PROBE

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The successful launch of the Parker Solar Probe (PSP) on August 12, 2018 with a Delta IV rocket and Star-48BV third stage has placed the spacecraft on a 7-year trajectory to study the Sun. The goals of PSP are to better characterize our solar environment and advance our understanding of the Sun at 9.86 Rs. A total of 42 trajectory correction maneuvers are planned. This paper documents trajectory correction maneuver analysis performed just prior to launch until just past the first solar encounter. The pre-launch analysis culminated in two final design cycles which analyzed 24 reference trajectories.

INTRODUCTION

On August 12, 2018 at 3:31 a.m. EDT from Cape Canaveral, Florida, Parker Solar Probe (PSP) began a 7-year campaign to the Sun's corona. To achieve the high Earth departure energy necessary to reach the Sun (C_3 = 154 km^2/s^2), PSP was launched on a Delta IV heavy rocket with a Star-48BV third stage. In comparison, most interplanetary missions on a ballistic trajectory require C3 between 7-16 km^2/s^2 and the New Horizons mission to Pluto needed 170 km^2/s^2. PSP's science goals are to better characterize the solar environment first hinted at by solar astrophysicist, Dr. Eugene Parker.

In 1958, Dr. Parker theorized that our Sun gives off a flow of gas, or solar wind, that affects the satellites around it.[1] The solar wind model that Dr. Parker proposed was revolutionary because most scientists believed that interplanetary space was a vacuum void of any influences by the Sun's charged particles. This theory was proven in 1959, and later in 1962, when the Luna-1 and Mariner-2 probes first detected a strong concentration of ionized plasma in outer space radiating from the Sun's direction. Since the 1990s, several NASA missions were proposed to assess the Sun's environment at close proximity. PSP is the most recent project that carries out these objectives. PSP is a project managed by the Johns Hopkins Laboratory Applied Physics Laboratory (APL) and is under NASA's Living With a Star program with navigation assistance provided by the Jet Propulsion Laboratory. Already within the first four months of the mission, PSP's use of innovative materials has enabled the spacecraft to break several records: to withstand the hottest temperatures (2,500 °F), to make the closest approach to the Sun (25 million km from Sun's surface); and to become the fastest spacecraft (95 km/s). The closest approach and speed records were previously held by Helios 2 in 1976 at 43 million km and 70 km/s, respectively.

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PSP will make a total of 24 perihelion flybys during which data will be collected by a suite of four instruments: Fields Experiment (FIELDS), Integrated Science Investigation of the Sun (IS⊙IS), Wide-field Imager for Solar PRobe (WISPR), and Solar Winds Electrons Alphas and Protons (SWEAP). These instruments will work together in concert to trace the flow of energy that heats the corona, determine the mechanisms that transport energetic particles, as well as establish the dynamics of magnetic fields at the source of solar wind.[2]

To achieve the science objectives, the baseline reference trajectory utilizes Trajectory Correction Maneuvers (TCMs) to correct flyby errors and other unmodeled errors. This paper presents the pre-launch, launch, and early mission TCM experience. In particular, the following sections provide an overview of the baseline trajectory, the spacecraft, and maneuver execution. Also, a review of the analysis made to support the current mission will be shown, as well as the TCM activities until the first solar encounter. Finally, upcoming work will be discussed.

OVERVIEW OF BASELINE TRAJECTORY

The baseline trajectory, designed by APL, accommodated a 20-day launch period from July 31, 2018 through August 19, 2018. Before launch of the spacecraft, this launch period was extended until August 23, 2018 to include four additional launch day opportunities. Over the course of 6.4 years, PSP's baseline trajectory will use seven gravity assists of Venus (Figure 1) to place the spacecraft within the Sun's corona. PSP will achieve three to four solar encounters per year for a total of 24 solar encounters during the mission. After the final Venus flyby, the spacecraft's perihelion distance will be reduced from 36 R_S to 9.86 R_S. A backup trajectory was designed for a launch in 2019 and was based on shifting the baseline trajectory by one year. The backup design utilizes eight Venus flybys to approach the final perihelion target.

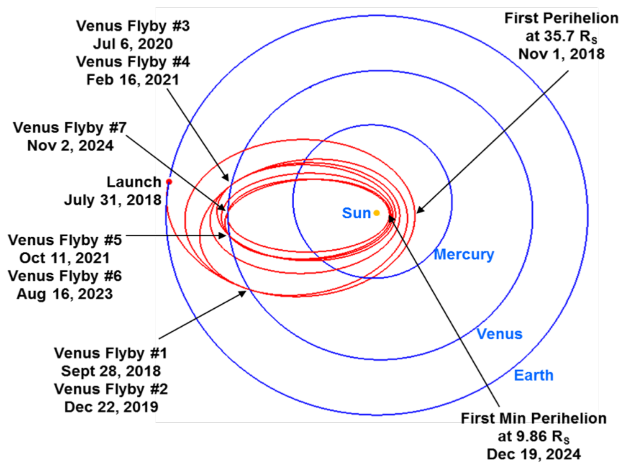


Figure 1. PSP's Baseline V^7-Gravity Assist Trajectory

While PSP employs seven gravity assists of Venus to provide most of the velocity change needed to fly through the Sun's corona, the trajectory design includes 42 statistical TCMs to maintain its path. The general TCM strategy is to schedule two TCMs post-launch, two TCMs pre-Venus encounter, one TCM post-Venus encounter, and one TCM per solar rev, if possible. The cleanup TCM is scheduled +13 days or more after each flyby, and all TCMs are optimized together to target the upcoming Venus B-plane aim point. TCMs planned in the baseline trajectory are closely monitored to ensure the ΔV cost are within the propellant budget, the ultimate goal being that the spacecraft will be as close as 9.86 Rs (4 million miles) away from the Sun.

SPACECRAFT OVERVIEW

About the size of a compact car, PSP is a solar-powered, three-axis stabilized spacecraft consisting of a Thermal Protection System (TPS) made of carbon composite that is 2.3 meters in diameter and 11.43 centimeters thick. The TPS will be pointed at the Sun (Figure 2) to protect the spacecraft bus from extreme temperatures. All of the science instruments are covered by the TPS, with the exception of the 4 antennas that are part of the FIELDS experiment. PSP's primary science data collection takes place for approximately 11 days surrounding each perihelion.

Given a solar distance, the primary and secondary solar arrays rotate to a particular flap angle.[3] Comprised of photovoltaic arrays, the primary array is used outside of 0.24 AU, and the secondary array is used inside 0.24 AU, through closest approach. Since temperatures are expected to reach more than 2,500° F (1,370° C), the secondary array utilizes pumped-fluid coolant. Science downlink and communication are made with the 0.6 meter Ka-band High Gain Antenna (HGA).

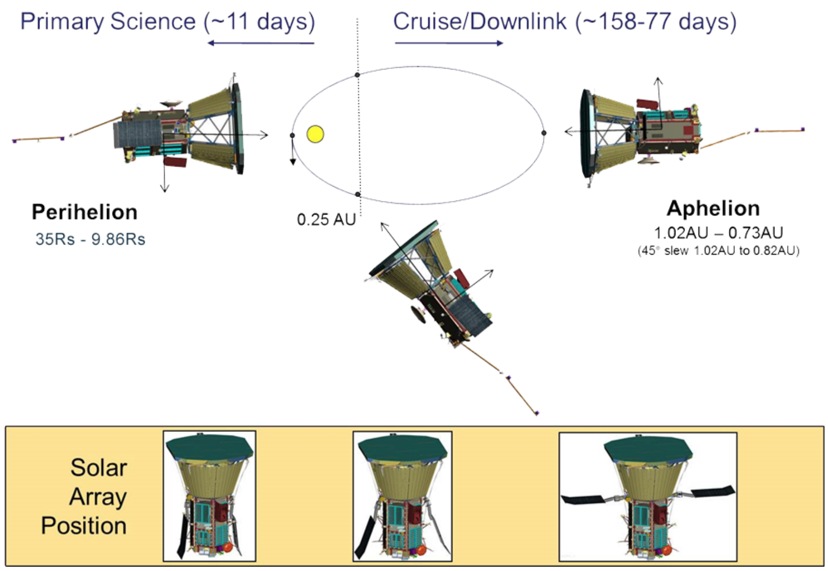


Figure 2. Spacecraft operations concept

Maneuver Execution

Maneuvers are accomplished with a monopropellant propulsion system that consists of a hydrazine tank and twelve 4.4 N thrusters. Three groups (A, B, and C) of four thrusters each are used to yield a TCM or velocity change while enforcing the TPS to be pointed to the Sun. Depending on the spacecraft's location and geometry relative to the Sun, a thruster selection is made. Given a particular TCM design, the spacecraft can be configured for a TCM's cutoff based on time or estimated ΔV.[4] An on-board guidance and control system selects appropriate thrusters to be fired. Maneuvers located beyond 0.82 AU with a ΔV angle $> 45°$ must be implemented with a cone-angle constraint. This requirement is necessary to satisfy a spacecraft-pointing constraint (see Figure 3). Other navigation-related requirements are listed in Table 1. These requirements were imposed on the TCM analysis as constraints for part of the simulation set-up. Additional navigation constraints correspond to the trajectory optimization strategy, such as all Venus flybys can be no lower than 300 km.

Some of the challenges PSP will encounter include interruptions of communications and tracking of the spacecraft due to the significant occurrences of solar conjunctions as a result of the trajectory's highly elliptical orbits. Additional navigation challenges are outlined in previous conference papers.[5,6]

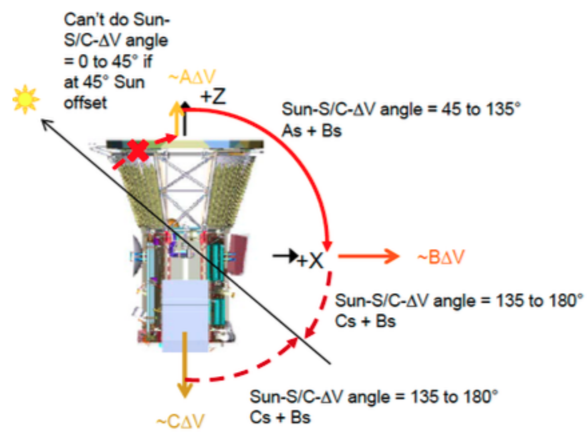


Figure 3. Parker Solar Probe TCM geometry (+Z axis to Sun)

Table 1. Navigation Requirements Summary

Requirement	Description
MDNR-03	The spacecraft can not spend less than 920 hours below 20 RS and 14 hours below 10 RS
MDNR-22	The baseline total TCM ΔV99 can not exceed 135 m/s
MDNR-69	Adhere to TCM pointing constraints
MDNR-70	Adhere to constraints for TCMs at solar distance$\geq$0.45 AU
MDNR-71	There can be no consecutive burns more than 20 hours apart
MDNR-72	Each TCM burn can be no longer than 5200 seconds
MDNR-77	Navigation delivery accuracy for minimum perihelion delivery is 500 km (3-σ) at 9.86 Rs perihelion

For trajectory simulation, a maneuver optimization strategy was chosen so that downstream maneuvers were used in a "chain" to target the upcoming Venus encounter to minimize propellant and satisfy constraints. This optimization strategy was chosen to minimize propellant and satisfy constraints. Downstream TCMs within the chain are re-optimized after each TCM is executed.

During each of the trajectory design cycles, the APL mission design team generated and delivered baseline reference trajectories to the PSP project. The navigation team reintegrated or "matched" these trajectories by targeting to three B-plane parameters[7] of each encounter; the spatial components B·R, B·T, and the time of closest approach for Venus periapsis (Venus-1 to Venus-7); time for solar periapsis (Periapsis-1 to Periapsis-21, except Periapsis-10 and Periapsis-17); and periapsis position for the last three solar periapses (Periapsis-22 to Periapsis-24).

For the statistical analysis of all TCMs, an execution error model was used to account for the difference between a planned ΔV and an achieved ΔV. The execution error model is provided by the APL guidance and control team and represents the knowledge of the thrust vector delivered by the engines with respect to the thrusters. The execution error model has magnitude and pointing components that is defined by four independent error sources: fixed-and proportional-magnitude errors, and fixed-and proportional-pointing errors. The Gates execution error model[8] is assumed for the current navigation set-up and is shown in Table 2. These values may be updated throughout the mission to include in-flight TCM experience.

Table 2. Guidance & Control Gates Maneuver Execution-Error Model (3-σ)

Magnitude	Fixed (mm/s)	1.2
	Proportional (%)	2
Pointing (per axis)	Fixed (mm/s)	3.2
	Proportional (mrad)	20

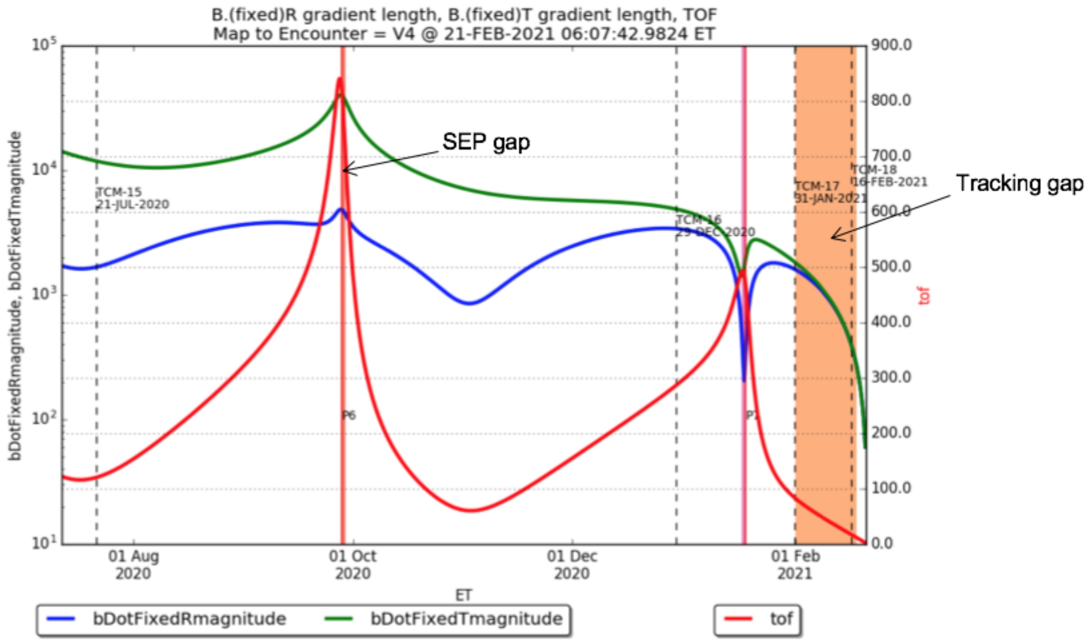
PRE-LAUNCH MANEUVER ANALYSIS

Within the year of the planned PSP launch date, assessments of the baseline reference trajectories were made during the Final Mission Analysis (FMA) and Best Estimate Trajectories (BET) design cycles. The purpose of FMA was to provide verification of the Preliminary Mission Analysis (PMA) results while satisfying navigation requirements; this included high-fidelity models, updates to the tracking schedules, and refinements in the navigation assumptions (see References 9 and 10 for further details). An additional objective of FMA was to review four extra launch dates which was initiated by the launch provider since this mission would be the first to use a Star-48BV 3rd stage.

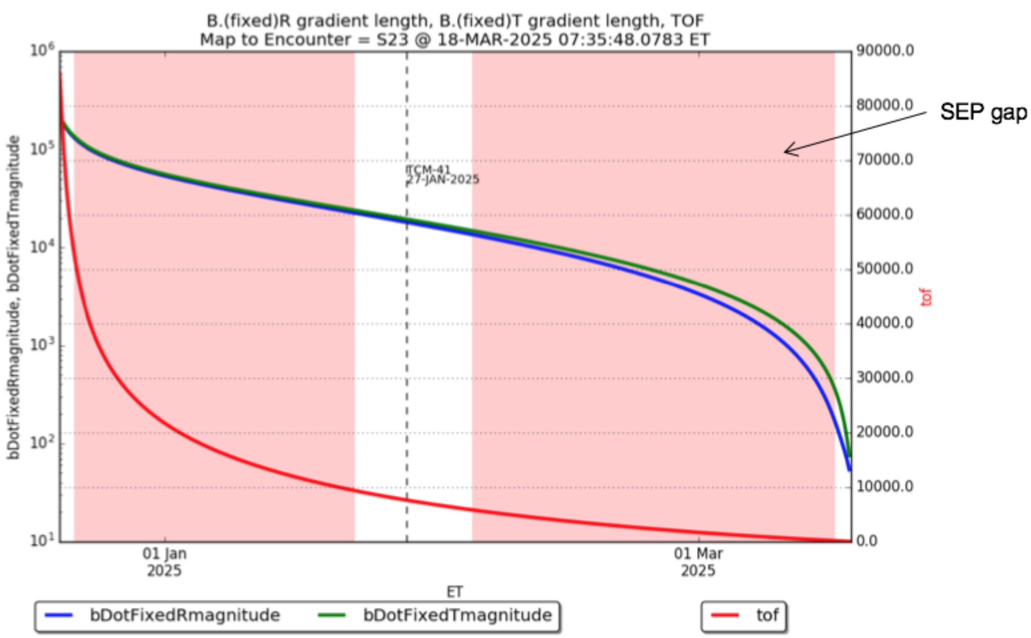
General assumptions included the use of the FMA launch vehicle injection covariance matrices (delivered by the launch vehicle provider), an unscaled figure-of-merit*, and maneuver strategy. Statistical analyses for each reference trajectory during the 24-day launch period were conducted. The JPL Mission-analysis Operations and Navigation Toolkit Environment (MONTE)[11] Linear Analysis of Maneuvers with Bounds and Inequality Constraints (LAMBIC)[12] software was used to compute statistical ΔV via Monte Carlo analysis.

TCM capability analysis was performed on all the FMA trajectories. TCM locations relative to their tracking schedules were evaluated to decide whether a TCM should be moved. This was done by assessing TCM target ΔV gradient magnitudes and angles between gradient vectors. TCMs can be in poor locations due to tracking gaps, Sun-Earth-Probe (SEP) constraints, or unfavorable dynamics. A TCM could have linearly-dependent ΔV gradients, or the angles between gradient vectors near 0 or 180 degrees. For example, this study confirmed that TCM-17 and TCM-18 are either inside or near communication tracking gaps for the baseline trajectory (see Figure 4a). For this reason, it was recommended to move TCM-17 days earlier, and to remove TCM-18 from the TCM strategy for the final 10 trajectories (August 14-23). Also, FMA analysis revealed that TCM-41 was in an SEP gap for all the trajectory dates (Figure 4b). TCM-41 location will remain in the baseline schedule as a placeholder for contingency purpose, and will be reviewed later for further analysis.

*A figure-of-merit (FOM) is a parameter used to approximate the size of the first TCM given the capability of the launch vehicle.



(a) TCM-17 and TCM-18 located in Communication Tracking Gaps. *The orange shaded area denotes the tracking gap.*



(b) TCM-41 located in Communications Tracking Gaps due to the Sun-Earth-Probe (SEP) constraints. *The pink shaded area denotes an SEP gap that surrounds both sides of TCM-41.*

Figure 4. TCM Capability for TCMs 17, 18, and 41. *The vertical dotted lines represent TCM locations for the (a) Venus-4 flyby and (b) Perihelion-23 encounter.*

Each reference trajectory resulted in a mission total ΔV99 of less than 100 m/s (see Table 3) and satisfy MDNR-22 (baseline total TCM ΔV can not exceed 135 m/s). The mission ΔV99 values were lower for the first 10 trajectories from the PMA design cycle, primarily due to the refinement the orbit determination assumptions. However, note that the total ΔV99 is 10-30 m/s larger starting on the 14 August 2018 launch date compared to the first 14 dates; this is a result of the removal of TCM-18 from the last 10 trajectory dates as discussed previously. The analysis also determined that the navigation delivery accuracy requirement for minimum perihelion was satisfied (MDNR-77 in Table 1) for every design cycle.

Table 3. FMA Match ΔV and Statistics

Reference Trajectory	Total Match ΔV (m/s)	ICM	TCM-01 ΔV99%ile (m/s)	Total ΔV99%ile (m/s)
31-July-2018	4.9	Middle	32	69
01-Aug-2018	5.1	Middle	33	68
02-Aug-2018	5.3	Middle	34	69
03-Aug-2018	5.2	Middle	34	69
04-Aug-2018	5.3	Middle	34	69
05-Aug-2018	5.2	Middle	34	70
06-Aug-2018	5.5	Middle	33	71
07-Aug-2018	5.7	Middle	34	72
08-Aug-2018	5.0	Middle	33	73
09-Aug-2018	3.7	Middle	34	72
10-Aug-2018	4.6	Middle	34	72
11-Aug-2018	4.4	Middle	33	71
12-Aug-2018	4.8	Middle	35	75
13-Aug-2018	4.5	Middle	35	75
14-Aug-2018	4.7	Middle	35	99
15-Aug-2018	4.5	Middle	34	78
16-Aug-2018	5.6	Middle	35	91
17-Aug-2018	3.3	Middle	34	81
18-Aug-2018	3.2	Middle	34	88
19-Aug-2018	3.4	Middle	34	99
20-Aug-2018	5.2	Middle	35	87
21-Aug-2018	3.5	Middle	36	82
22-Aug-2018	3.4	Middle	34	85
23-Aug-2018	3.4	Middle	35	82

Table 4 presents statistical predictions and Perihelion-22 delivery accuracy values for FMA, PMA, and CDR* design cycles for 3 launch dates. The table clearly shows a decrease in TCM-01 ΔV values for design cycles leading up to the launch period. Similar observations can be seen in the total mission ΔV with the exception of PMA to FMA for the August 19, 2018 launch date. The increase of ΔV from 85 m/s to 99 m/s is attributed to the removal of TCM-18 for the final 10 trajectories in the FMA design cycle. However, this value satisfies the total mission ΔV requirement (MDNR-22). Finally, the delivery accuracy for minimum perihelion at Perihelion-22 ($\pm 3\sigma$) is also listed; these values are acceptable.

Table 4. CDR, PMA, and FMA ΔV and Delivery Accuracy Comparison. *Middle trajectories for CDR 09-Aug-2018 were compared to PMA and FMA 10-Aug-2018 values due to available ICMs.*

Reference Date Trajectory	TCM-01 ΔV 99%ile (m/s)	Total ΔV 99%ile (m/s)	Delivery Accuracy for Min Perihelion (km) at Periapsis-22
CDR 31-July-2018	47	112	±106
PMA 31-July-2018	37	82	± 82
FMA 31-July-2018	32	69	± 81
CDR 09-Aug-2018	–	119	–
PMA 10-Aug-2018	39	87	± 83
FMA 10-Aug-2018	34	72	± 89
CDR 19-Aug-2018	–	111	–
PMA 19-Aug-2018	40	85	± 80
FMA 19-Aug-2018	34	99	± 189

The BET design cycle was completed with the inclusion of improved launch vehicle inputs for the 24 reference trajectories that covered the launch period from July 31 to August 23. Since there would be little time to conduct a full baseline trajectory assessment using the BET inputs, only a few trajectories would be analyzed and compared. BET and FMA trajectories with the largest mission ΔV99 and the largest TCM-01 ΔV99 were compared. Results showed that TCM-01 and total ΔV99%ile using BET ICMs† were 1-2 m/s less than with the FMA (Table 5). Since the level of statistical uncertainty in ΔV99%ile is between 3 and 5 m/s for LAMBIC runs, the BET ΔV99 values are not statistically different from FMA. Therefore, this result gave confidence that the BET trajectories were similar to FMA.

Table 5. FMA and BET comparison

ICM	TCM-01 ΔV 99%ile (m/s)	Total ΔV 99%ile (m/s)
BET 14-Aug-2018	33	95
FMA 14-Aug-2018	34	96
BET 21-Aug-2018	33	81
FMA 21-Aug-2018	35	83

*The Critical Design Review (CDR) was the part of the 2014 Phase C design cycle.

†An Injection Covariance Matrix (ICM) is a state covariance matrix for a given launch vehicle at the target interface point and is the primary error source after launch.

LAUNCH THROUGH FIRST SOLAR ENCOUNTER EXPERIENCE

The 24-day period (July 31-August 23) was planned in case the project had to delay the launch. For different circumstances, PSP's launch date was postponed three times: From July 31 to August 3 to allow for further spacecraft software testing; then until August 6 and August 11 for additional payload fairing inspection.[13,14] After a last-minute launch scrub on August 11 due to a gaseous helium red pressure alarm, PSP successfully lifted-off on the open of the launch window on August 12, 2018. Table 6 lists all the TCM locations along with the dates of the encounters based on the August 12 launch opportunity from the re-optimized trajectory after launch.

Table 6. TCM and Encounter Schedule for the 12 August 2018 Baseline Trajectory

Maneuver/ Encounter	Date	Time* (UTC)	Maneuver/ Encounter	Date	Time* (UTC)
TCM-01	19-Aug-2018	10:00:00	Venus-5	16-Oct-2021	09:27:54
TCM-02	31-Aug-2018	16:40:00	TCM-24	11-Dec-2021	18:00:00
TCM-03	11-Sep-2018	15:30:00	TCM-25	12-Mar-2022	18:00:00
TCM-04	28-Sep-2018	14:30:00	TCM-26	20-Jun-2022	18:00:00
Venus-1	03-Oct-2018	08:44:28	TCM-27	20-Sep-2022	18:00:00
TCM-05	17-Oct-2018	19:00:00	TCM-28	21-Nov-2022	18:00:00
TCM-06	09-Dec-2018	20:30:00	TCM-29	06-Apr-2023	18:00:00
TCM-07	13-May-2019	18:00:00	TCM-30	07-Jun-2023	18:00:00
TCM-08	10-Oct-2019	18:00:00	TCM-31	03-Aug-2023	18:00:00
TCM-09	08-Dec-2019	18:00:00	TCM-32	16-Aug-2023	18:00:00
TCM-10	21-Dec-2019	18:00:00	Venus-6	21-Aug-2023	11:57:28
Venus-2	26-Dec-2019	18:12:09	TCM-33	14-Oct-2023	18:00:00
TCM-11	10-Jan-2020	18:00:00	TCM-34	04-Dec-2023	18:00:00
TCM-12	08-Mar-2020	18:00:00	TCM-35	15-Apr-2024	18:00:00
TCM-13	22-Jun-2020	18:00:00	TCM-36	15-Jun-2024	18:00:00
TCM-14	05-Jul-2020	18:00:00	TCM-37	26-Aug-2024	18:00:00
Venus-3	11-Jul-2020	03:20:44	TCM-38	19-Oct-2024	18:00:00
TCM-15	21-Jul-2020	18:00:00	TCM-39	01-Nov-2024	18:00:00
TCM-16	28-Dec-2020	18:00:00	Venus-7	06-Nov-2024	18:42:18
TCM-17	31-Jan-2021	18:00:00	TCM-40	24-Nov-2024	18:00:00
TCM-18	15-Feb-2021	18:00:00	Periapsis-22	24-Dec-2024	11:49:53
Venus-4	20-Feb-2021	20:02:34	TCM-41	01-Feb-2025	18:00:00
TCM-19	07-Mar-2021	18:00:00	Periapsis-23	22-Mar-2025	22:29:32
TCM-20	15-May-2021	18:00:00	TCM-42	21-Apr-2025	18:00:00
TCM-21	25-Aug-2021	18:00:00	Periapsis-24	19-Jun-2025	09:08:50
TCM-22	28-Sep-2021	18:00:00			
TCM-23	11-Oct-2021	18:00:00			

*TCM times are not yet finalized and subject to change.

The purpose of the flight path control activities during operations is to compare TCM ΔV designs with the APL mission design team, and to verify the implementation ΔV design prepared by the guidance and control subsystem. Note that for every TCM opportunity, the mission design team may potentially re-optimize the baseline trajectory. JPL flight path control analysts also make maneuver cancellation recommendations if a potential ΔV savings is determined.

TCM-01: A tale of two burns

Although the PSP trajectory is ballistic, TCMs are planned throughout the mission to make small orbit corrections as needed. TCMs 1-5 were designated by the PSP project as critical maneuvers that were necessary to achieve the Venus-1 flyby on October 3, 2018. TCM-01 was deemed most important given the need to correct launch dispersions, and was scheduled to take place Launch+10 days for the baseline trajectory. Since statistical predictions projected that TCM-01 could be the largest ΔV (35 m/s for the August 12 launch opportunity) in the mission, the pre-launch plan was for TCM-01 to be modeled as a turn and burn maneuver.

After launch, an assessment of the spacecraft's location relative to the baseline trajectory was performed. The re-optimized trajectory reduced the ΔV cost that launch deviations introduced. In addition, several planned spacecraft commissioning activities were performed, such as science instrument deployment and checkout. Soon after these events, spacecraft controllers observed more than expected momentum removal or dumps by the spacecraft.[*] Evaluation of the spacecraft dynamics after the commissioning activities led to the project's decision to perform maneuvers only using the A and C thrusters, and to exclude B-thruster use until further analysis. As a result, TCM-01 was designed as an engineering burn with two parts that ensured the use of A and C thrusters: TCM-01 was successfully performed on August 19 with ΔV=0.1 m/s, and TCM-01c was executed on August 20 with ΔV= 10.0 m/s.

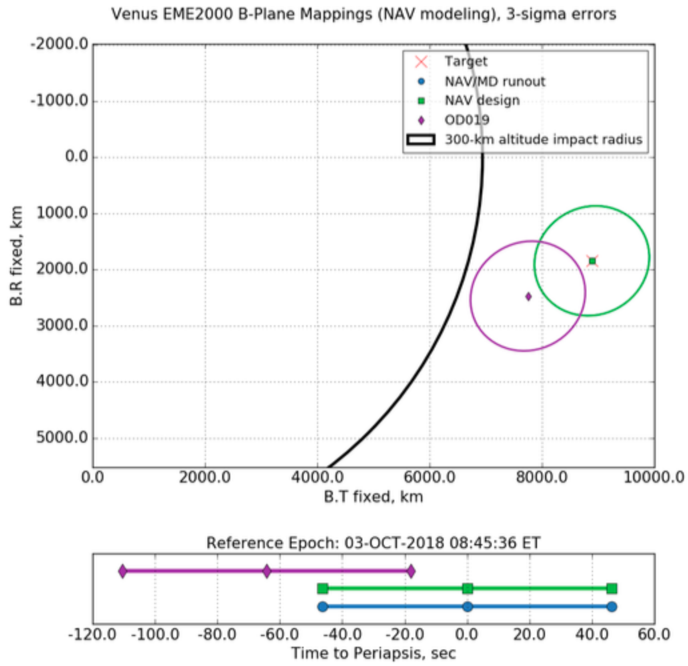
TCM-02 and TCM-03: Nominal and cancelled maneuvers

TCM-01 and TCM-01c burns were successful in removing most of the launch injection errors; therefore, the TCM-02 ΔV was expected to be small. Part of flight path control analysis includes plotting the orbit determination and maneuver dispersions for a given TCM. Figure 5a represents the Venus-1 B-plane[†] with the TCM-02 orbit determination dispersions using the OD019 solution (purple ellispse), the JPL navigation maneuver design dispersions based on the OD019 solution (green ellipse), and the runout of the APL mission design team's maneuver design (blue ellipse). This plot shows that both the navigation team and mission design team's TCM-02 design (ΔV= 0.73 m/s) moves the probe to the baseline trajectory's Venus-1 B-plane target location. Maneuver analysis of the downstream ΔV costs for TCM-03 was calculated to be 1.06 m/s if the TCM-02 opportunity was missed. TCM-02 was successfully performed using the full set of A-thrusters on August 31, 2018, approximately 33 days before the Venus-1 encounter.

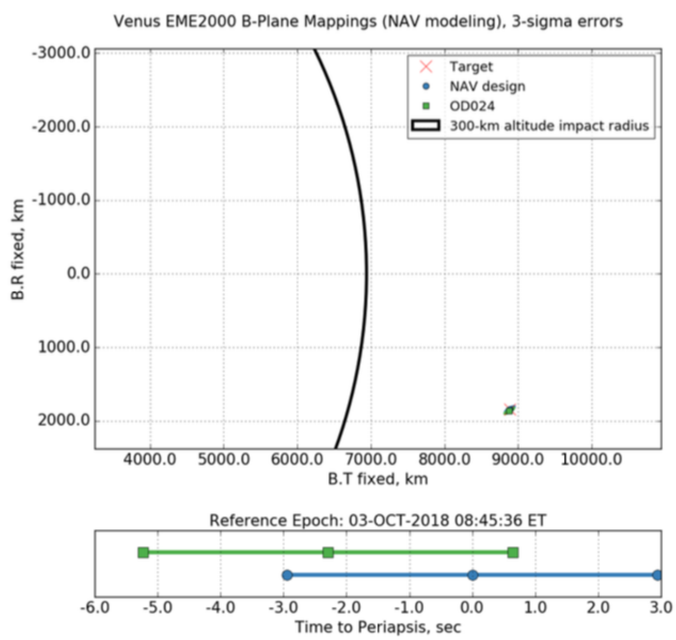
TCM-03 was planned to take place on September 11, 2018 (22 days before the Venus-1 flyby). The B-plane plot shown in Figure 5b represents the orbit determination and maneuver dispersions with respect to the Venus-1 Flyby target for the TCM-03. As the figure indicates, the TCM-03 delivered uncertainties were small since TCM-02 execution did not introduce large execution errors. In addition, downstream TCM analysis showed that TCM-04 ΔV was estimated to be 0.14 m/s without TCM-03 which was acceptable by the project. The resulting TCM-03 ΔV design was ΔV = 0.031 m/s. Note that the minimum ΔV recommended by the spacecraft team for the spacecraft to perform is 0.05 m/s; therefore, TCM-03 was cancelled.

[*] To maintain spacecraft attitude control, the PSP guidance and control system relies on reaction wheels and thrusters to manage the momentum experienced by the spacecraft. A momentum dump occurs when the wheel speeds reach a given threshold. More information on PSP's Guidance and Control System can be found in Reference 4.

[†] For an explanation of the B-plane, see Appendix B and Reference 7.



(a) TCM-02 Venus-1 B-plane Dispersions. *The purple ellipse represents the TCM-02 orbit determination dispersions (OD019 solution), along with the JPL navigation maneuver design dispersions (green ellipse), and the runout of the APL mission design team's maneuver design (blue ellipse).*



(b) TCM-03 Venus-1 B-plane Dispersions. *The purple ellipse represents the TCM-03 orbit determination dispersions (OD024 solution), along with the JPL navigation maneuver design dispersions (green ellipse). The preliminary TCM-03 design generated a maneuver too small to be executed by the spacecraft; therefore, TCM-03 was cancelled.*

Figure 5. Venus-1 B-plane Plots for TCMs 2 and 3. *The Venus-1 baseline target is denoted by the red "x" on each plot. The Venus-1 minimum altitude is also shown (300 km) for reference.*

TCM-04c: Contingency maneuver

Since TCMs 1-5 were considered critical events, the project scheduled a contingency or backup maneuver at approximately 1-day after each prime maneuver location. In general, contingency maneuvers were scheduled in case there was an uplink command issue. The plan to perform TCM-04 was altered when a spacecraft sequence was aborted right before the maneuver execution. After a nominal checkout of the spacecraft, TCM-04c was performed with a $\Delta V = 0.07$ m/s on September 29, 2018, four days before the Venus-1 flyby. While the ΔV size was small, cancelling TCM-04c would have increased the post-flyby maneuver, TCM-05, from 3.7 m/s to 4.5 m/s. Performing TCM-04c help place the spacecraft in a better location for the upcoming Venus-1 flyby.

Venus-1 Flyby and the cancellation of TCM-05

The first of seven Venus gravity assists occurred on October 3, 2018 08:44:27 UTC, and it was considered nominal. The Venus flyby generated a ΔV equivalent to 3,114 m/s (at 0.17 AU). Navigation results show that spacecraft was within 0.1 sec of the targeted closest approach time and the flyby distance was within 400 meters of the targeted altitude.

As a result of a successful first Venus flyby, navigation analysis showed that the cancellation of TCM-05 did not generate a large ΔV downstream cost. Moreover, an extensive parametric study that considered minimizing the total ΔV for TCMs 5-10 (maneuvers between the Venus-1 and Venus-2 encounters) revealed that total ΔV for would be no more than 1.4 m/s. In addition, TCMs 6-10 are planned before the Venus-2 flyby on December 26, 2019; therefore, there are several opportunities to make the necessary trajectory corrections. Lastly, the cancellation of TCM-05 provided time for an on-going review of spacecraft health.

First Solar Perihelion and the nominal execution of TCM-06

The first solar encounter began on October 31, 2018 after the spacecraft entered a solar range of 0.25 AU. Due to expected solar interference during encounter, spacecraft commanding was not possible. Perihelion occurred on November 6 when the probe was 15 million miles from the Sun's surface. After solar encounter exit on November 11, the operations team reported that all systems were operating nominally. Interestingly enough, it was found that the spacecraft only performed one momentum dump during the encounter. Momentum dumps are expected during the solar encounters, as wheels spin up to counter increasing torque from gravitational effects of the solar environment.

TCM-06, the first maneuver after the solar encounter, was scheduled to cleanup any errors attributed to the Venus-1 flyby and solar encounter momentum dumps. A re-optimized trajectory was generated for the TCM-06 design to help decrease downstream maneuver ΔV. This trajectory update reduced ΔV to 1.1 m/s from 1.7 m/s. TCM-06 was purposely designed to exercise the A & B thrusters, and performed successfully on December 9, 2018.

Table 7 shows the summary of TCMs performed or cancelled during Launch to TCM-06. Close inspection of the predicted ΔV statistics reveal that the sum of the total TCM design ΔV is very close to the mean ΔV. Although the statistical predictions represent the FMA trajectory, the sum of design ΔV expenditure is close to FMA results.

Table 7. Predicted Statistics and Design ΔV for TCM-01 through TCM-06. *All numbers are in m/s.*

Maneuver	Predicted ΔV Statistics			Design ΔV
	Mean	1-sigma	ΔV99	
TCM-01 and TCM-01c	12.75	6.95	34.59	10.23
TCM-02	0.19	0.14	0.66	0.734
TCM-03	0.004	0.018	0.086	Cancelled
TCM-04c	0.051	0.049	0.18	0.069
TCM-05	0.824	0.95	4.03	Cancelled
TCM-06	0.405	0.272	0.92	1.10

CURRENT AND UPCOMING ACTIVITIES

Downlink of science data started on December 7 and will continue for several weeks. At the time of this writing, PSP scientists have released initial findings of the first perihelion pass during the 2018 American Geophysical Union in Washington, D.C.

Table 8 shows the number of TCMs planned for the rest of the mission. Note that the most events scheduled during a short period of time was during the 52 days from Launch to the Venus-1 flyby. The 2nd of 24 perihelia will occur on April 4, 2019, and TCM-07 is planned to take place on May 13, 2019. The flight path control team will continue to review the past experience and conduct analysis for upcoming maneuvers, which include a possible accommodation of the 45-degree Sun-ΔV angle constraint for TCM-09.

Table 8. Scheduled TCM Events

Event	TCMs Before Next Event	Days Between Events
Launch	4	52
Venus-1	6	449
Venus-2	4	198
Venus-3	4	224
Venus-4	5	238
Venus-5	9	674
Venus-6	7	443
Venus-7	3	165
Perihelion-24	–	–

CONCLUSION

The ground-breaking PSP mission has poised the probe for exciting new discoveries. The mission has accomplished much within the first five months: a successful launch, the execution of four TCMs, the flyby of Venus-1, and the first solar encounter. Speed and solar proximity records have been broken by the spacecraft, and it will break them, again before the end of the mission. The expected challenges that the spacecraft will encounter include interruptions of communications and tracking of the spacecraft due to the significant occurrences of solar conjunctions as a result of the trajectory's highly elliptical orbits.

The intensive launch and early operations period has generated several events that allowed the flight path control team to exercise various maneuver design strategies: an engineering burn in two parts, the cancellation of a maneuver, and a contingency maneuver. This experience provides a great opportunity to access current design strategies and in-flight processes.

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APPENDIX

B-Plane Description. Planet or satellite approach trajectories are typically described in aiming plane coordinates referred to as "B-plane" coordinates[7] (see Figure 6). The B-plane is a plane passing through the target body center and perpendicular to the asymptote of the incoming trajectory (assuming two-body conic motion). The "B-vector," **B**, is a vector in that plane, from the target body center to the piercing-point of the trajectory asymptote. The B-vector specifies where the point of closest approach would be if the target body had no mass and did not deflect the flight path. Coordinates are defined by three orthogonal unit vectors, **S**, **T** and **R**, with the system origin at the center of the target body. The $\mathbf{S}$ vector is parallel to the spacecraft $\mathbf{V}_\infty$ vector (approximately the velocity vector at the time of entry into the gravitational sphere of influence). $\mathbf{T}$ is arbitrary, but it is typically specified to lie in the ecliptic plane (Earth Mean Orbital Plane and Equinox of J2000.0 (EMO2000)), or in a body equatorial plane (Earth Mean Equatorial Plane and Equinox of J2000.0 (EME2000)). Finally, **R** completes an orthogonal triad with **S** and **T** (i.e., $\mathbf{R} = \mathbf{S} \times \mathbf{T}$).

A target point can be described in terms of the B-vector dotted into the **R** and **T** vectors ($\mathbf{B} \cdot \mathbf{R}$ and $\mathbf{B} \cdot \mathbf{T}$). The spacecraft state in the B-plane can be represented by the following six quantities: $\mathbf{B} \cdot \mathbf{R}$, $\mathbf{B} \cdot \mathbf{T}$, TF (time-of-flight), $\mathbf{S} \cdot \mathbf{R}$, $\mathbf{S} \cdot \mathbf{T}$, and C_3. $\mathbf{S} \cdot \mathbf{R}$ and $\mathbf{S} \cdot \mathbf{T}$ are the declination and right ascension of the incoming asymptote **S** and C_3 is the vis-viva integral (V_∞^2). The B-plane error (miss) is determined by $\Delta\mathbf{B} \cdot \mathbf{R}$, $\Delta\mathbf{B} \cdot \mathbf{T}$, and ΔTF; the asymptote error is determined by $\Delta\mathbf{S} \cdot \mathbf{R}$, $\Delta\mathbf{S} \cdot \mathbf{T}$, and ΔC_3.

Trajectory errors in the B-plane are often characterized by a 1-σ dispersion ellipse, shown in Figure 6. SMAA and SMIA denote the semi-major and semi-minor axes of the ellipse; θ is the orientation angle of the ellipse measured clockwise from the $\mathbf{T}$ axis. The dispersion normal to the B-plane is typically given as a 1-σ time-of-flight error, where time-of-flight specifies what the time to encounter would be from some given epoch if the magnitude of the B-vector were zero. Alternatively, this dispersion is sometimes given as a 1-σ distance error along the **S** direction, numerically equal to the time-of-flight error multiplied by the magnitude of the $\mathbf{V}_\infty$ vector.

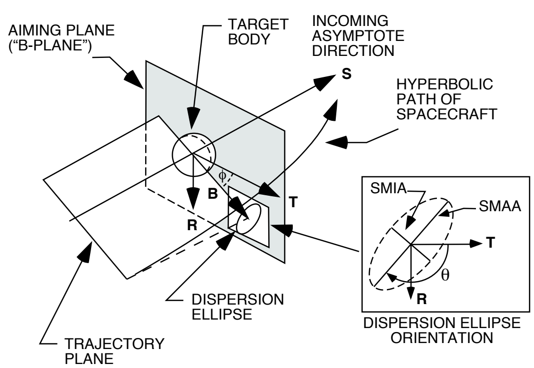

Figure 6. B-Plane Coordinate System

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