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On Track to Touch the Sun: Parker Solar Probe Flight Path Control Experience through Venus-5

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Abstract

Successfully launched in August 2018, Parker Solar Probe is spending seven years looping ever closer to the Sun hoping to understand some of its mysteries. After fourteen solar encounters, the spacecraft has made critical contributions to characterize our solar environment and advance our understanding of our star. To achieve its science objectives, the baseline reference trajectory utilizes 42 trajectory correction maneuvers to correct Venus flyby and other unmodeled errors. This paper documents the flight path control experience between the first and fifth planetary flybys, including 28 planned trajectory correction maneuvers and fourteen solar encounters.

Keywords: Parker Solar Probe, Venus flyby, navigation, trajectory correction maneuver

Acronyms/Abbreviations

APL	Applied Physics Laboratory
AU	Astronomical Unit
DSN	Deep Space Network
FIELDS	Electromagnetic Fields Investigation
HGA	High-Gain Antenna
ICM	Injection Covariance Matrix
IEM	Integrated Electronics Module
ISOIS	Integrated Science Investigation of the Sun
JPL	Jet Propulsion Laboratory
LAMBIC	Linear Analysis of Maneuvers with Bounds and Inequality Constraints
MDNR	Mission Design and Navigation Requirement
MONTE	Mission-analysis Operations and Navigation Toolkit Environment
OD	Orbit Determination
PDU	Power Distribution Unit
PSP	Parker Solar Probe
$\mathbf{R}_S$	Solar Distance
SEP	Sun-Earth-Probe
SRP	Solar Radiation Pressure
SWEAP	Solar Wind Electrons Alphas and Protons
TCM	Trajectory Correction Maneuver, typically a cruise phase maneuver
TPS	Thermal Protection System
WISPR	Wide-field Imager for Solar Probe

1. Introduction

On August 12, 2018, the Parker Solar Probe (PSP) spacecraft began its 7-year mission to study the Sun's corona, launching from Cape Canaveral, Florida, onboard of a Delta IV heavy rocket with a Star-48BV third stage. Parker Solar Probe's science goals are to better characterize the solar environment first hinted at by solar astrophysicist, Dr. Eugene Parker, who theorized that our Sun gives off a flow of gas, or solar wind, that affects the satellites around it. In four years, the spacecraft has already broken several records, including withstanding the hottest temperatures (2500°C), making the closest approach to the Sun for a human-made object (25 million km from Sun's surface), and becoming the fastest spacecraft (95 km/s).[1] A total of 24 planned perihelion flybys will allow data to be collected by a suite of four instruments, which will trace the flow of energy that heats the corona, determine the mechanisms that transport energetic particles, and establish the dynamics of magnetic fields at the source of solar wind.[2] To achieve these science objectives, the baseline trajectory exploits seven gravity assist flybys of Venus to provide most of the velocity change needed to fly through the Sun's corona. Each Venus gravity assist reduces the perihelion distance, starting from 35.7 R_S after the first Venus flyby to 9.86 R_S after the final Venus flyby. The reference trajectory relies on a total of 42 planned Trajectory Correction Maneuvers (TCMs) throughout the prime mission to maintain its path and correct any flyby and other unmodeled errors.[3]

Parker Solar Probe was developed as part of NASA's Living With a Star program to explore aspects of the Sun-Earth system that directly affect life and society. The Living With a Star program is managed by the agency's Goddard Space Flight Center in Greenbelt, Maryland, for NASA's Science Mission Directorate in Washington. The Johns Hopkins Applied Physics Laboratory in Laurel, Maryland, designed, built, manages, and operates the spacecraft for NASA. Teams led by the Naval Research Laboratory, Princeton University, the University of California, Berkeley, and the University of Michigan built and now operate the science instrumentation. The navigation for NASA's Parker Solar Probe is led by the agency's Jet Propulsion Laboratory in Pasadena, California, which also has a role in two of the spacecraft's four onboard instrument suites. As illustrated in Figure 1, Parker Solar Probe carries four main instruments onboard: FIELDS (Electromagnetic Fields Investigation), ISOIS (Integrated Science Investigation of the Sun), WISPR (Wide-field Imager for Solar Probe), and SWEAP (Solar Wind Electrons Alphas and Protons).

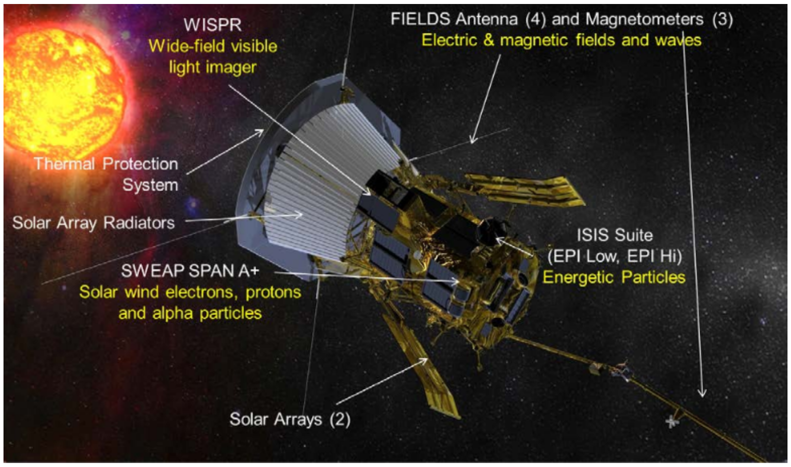

Figure 1: Illustration of the Parker Solar Probe spacecraft with science instruments

Previous papers from the Parker Solar Probe Navigation Team report on the maneuver experience during pre-launch, launch, and the early mission TCM experience.[4,5] The objectives of this paper are to provide a review of the analysis made to support the current mission up to the fifth Venus flyby. Maneuver activities during this time period are summarized, including cancelation and alternate maneuver strategy considerations and first-time events, such as the Sun-angle pointing cone angle constraint enforced on the design and execution of TCM-09. The operations schedule for the prime mission period covered in this paper includes five flybys of Venus ranging in altitude from 3786 km to 834 km and eight resonant and non-resonant transfers:

- Venus-1 occurred 59 days after launch, on October 3, 2018, on the first Earth-Sun inbound leg.
- Venus-2 took place on December 26, 2019 at the same Venus orbit location, after a 3:2 resonant orbit transfer.
- Venus-3 occurred on July 11, 2020 after a non-resonant transfer, on the outbound leg at the other orbit intersection with Venus' orbit.
- Venus-4 happened on February 20, 2021 and the spacecraft was able to capture truly stunning views of Venus at a closest approach altitude of 2392 km. The main objective of the fourth Venus flyby was to reduce the perihelion distance of Parker's orbit from 20 to 16 solar radii for the 8th solar encounter on April 29, 2021.
- Venus-5 took place on October 16, 2021 at a different location on Venus' orbit, but at the same location as the upcoming sixth Venus flyby, planned on August 21, 2023. Parker Solar Probe is currently following an inbound to inbound 7:3 resonant transfer to Venus-6, where PSP will complete 7 revolutions in the same amount of time it will take Venus to complete 3 revolutions.

For reference, in a Venus-to-Venus m:n resonant transfer, the time-of-flight is an integer multiple of Venus' period, where m represents the number of spacecraft revs around the Sun and n is the number of Venus revs.[6] Consequently, the flybys at the beginning and end of a resonant transfer occur at approximately the same place in Venus' orbit. Resonant orbits are a key element in the design of planetary and satellite flybys and powerful transfer mechanisms between orbits, potentially reducing the maneuver cost associated with transferring from one orbit to another to virtually zero. As noted above, Parker Solar Probe's baseline trajectory features multiple resonant transitions.

A detailed evaluation of the spacecraft navigation performance along with a number of challenges – and how the Parker Solar Probe Mission Design and Navigation Team overcame them throughout the last four years of successful operations – is addressed in the following sections.

2. Spacecraft Overview

Parker Solar Probe 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. As illustrated in Figure 2, PSP is packaged behind the carbon-carbon TPS to protect it from this extreme solar environment and allow it to operate at standard space thermal environments while the TPS experiences temperatures of 1400°C on its sun-facing surface. The TPS is always pointed at the Sun to protect the spacecraft bus from extreme temperatures. All of the science instruments are covered by the TPS, with the exception of the four antennas that are part of the FIELDS experiment. Parker Solar Probe utilizes actively cooled solar arrays for power generation maintaining the solar cells within required temperature limits.[2]

The design uses a blowdown monopropellant hydrazine system for propulsion, with twelve 4.4 N thrusters for attitude control and trajectory correction. Star Trackers and an internally redundant IRU (Inertial Reference Unit) are included for guidance and control.[9] The avionics suite is based on the APL IEM (Integrated Electronics Module) and PDU (Power Distribution Unit) used in most APL missions

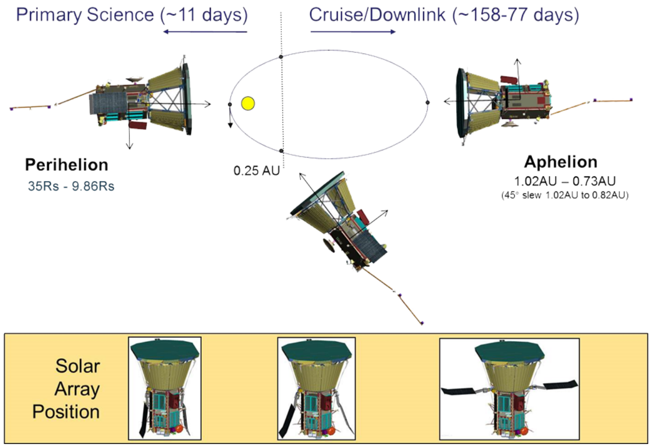

Figure 3: Diagram of concept of operation of the Parker Solar Probe spacecraft[8]

over the last decade or more. The IEM houses the command and data handling processor, solid-state recorder, interface to the guidance and control instruments, and payload interface. The PDU is an internally redundant box that includes all power switching. Science downlink and communication are made with the 0.6 meter Ka-band High Gain Antenna (HGA). Parker Solar Probe's primary science data collection takes place for approximately 11 days surrounding each perihelion, as depicted in Figure 3.

Given a solar distance, the primary and secondary solar arrays will rotate to a particular flap angle. Comprised of photovoltaic arrays, both the primary and secondary arrays will be used outside of 0.24 AU, and the secondary array will be 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.

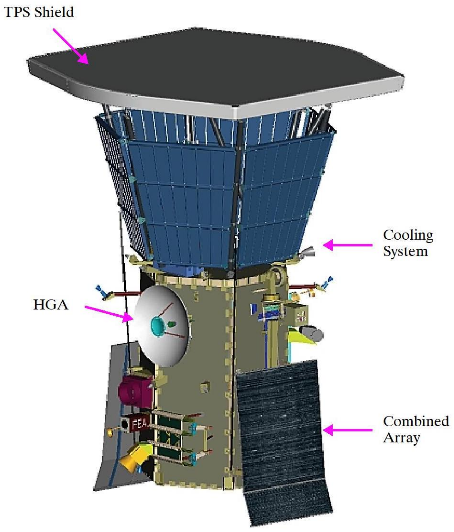

Figure 2: Illustration of the Parker Solar Probe spacecraft configuration

3. Mission Design and Navigation Overview

The baseline reference trajectory, designed by APL, accommodated a 20-day launch period that started on July 31, 2018, and continued through August 19, 2018.[10] The nominal 6.4-year trajectory to within 9.86 R_S of the Sun uses seven gravity assist flybys of Venus, as illustrated in Figure 4. Parker Solar Probe will continue to achieve three to four solar encounters per year for a total of 24 solar encounters during the course of the mission. After the final Venus flyby, the spacecraft's perihelion distance will be reduced to 9.86 R_S.

While the baseline trajectory is ballistic and has no deep space or deterministic maneuvers, careful placement of the mission's statistical trajectory correction maneuvers was made to correct Venus flyby errors, maneuver execution errors, and unmodeled accelerations.[5,7] To control the spacecraft, TCMs are scheduled in the following manner: two TCMs post-launch, two TCMs pre-Venus encounter, one TCM post-Venus encounter, and at least one TCM per solar revolution, if possible. The post-flyby TCM is scheduled 13 days or more after each flyby. A trajectory requirement mandates that one TCM targets solar periapsis after the final Venus flyby. The baseline mission includes a total of 42 TCMs as listed in Table 1 along with the dates of all encounters. A total of 19 maneuver opportunities – TCM-5 through TCM-23 – were designed to target Venus-2 through Venus-5 flybys, of which 12 were executed

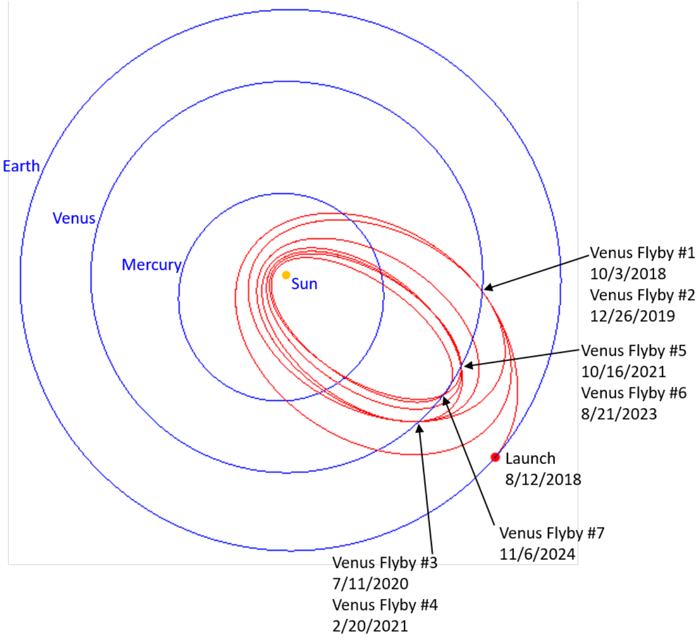

Figure 4: Parker Solar Probe reference trajectory with Venus flyby events[7]

and 7 were canceled. A planned maneuver can be canceled if it is determined that its execution will not improve encounter conditions, yield downstream propellant savings, or if a subsequent maneuver can attain the encounter conditions at a similar ΔV cost.

A number of navigation-related requirements are imposed on the design and implementation of trajectory correction maneuvers and the orbit determination process:

Table 1: Requirements imposed on the mission design*

MDNR-03	The spacecraft shall not spend less than 920 hours below 20 R_S and 14 hours below 10 R_S
MDNR-69	Adhere to TCM pointing constraints
MDNR-70	Adhere to constraints for TCMs at solar distance greater than equal 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

* Mission design is performed by the APL Mission Design Team

Table 2: Requirements imposed on the navigation design*

MDNR-22	The baseline total TCM ΔV99 can not exceed 135 m/s
MDNR-25	Predicted heliocentric position errors no greater than 1200 km, for solar ranges $\leq$ 1/4 AU, delivered no later that 48 hr before last possible uplink
MDNR-26	Predicted heliocentric position errors no greater than 8500 km, in any direction for solar range $>$ 1/4 AU and greater than 5 days from Venus encounter
MDNR-74	Predicted Earth-line position $\leq$ 4 arcmin, within 5 days of a Venus encounter
MDNR-77	Navigation delivery accuracy for minimum perihelion delivery shall be within 500 km (3-σ) at 9.86 R_S perihelion

* Navigation design is performed by the JPL Navigation Team

There are a number of additional navigation constraints imposed on the trajectory optimization strategy, such as all Venus flybys can be no lower than 300 km. Also, maneuvers cannot be scheduled inside 0.45 AU from the Sun, and maneuvers outside 0.82 AU are implemented with 45 degree Sun-ΔV angle constraint (i.e."cone keep-out"). Tables 1 and Table 2 summarize the most relevant requirements imposed on the mission design and navigation system.

4. Navigation Strategy

Navigating PSP requires the use of two-way coherent Doppler, two-way ranging, and delta-differential one-way ranging (Delta-DOR, or ΔDOR) measurements from the NASA Deep Space Network (DSN), which are data types commonly used by all deep space missions. The primary sources of navigation uncertainty are associated with momentum desaturation maneuvers (on unbalanced thrusters) and solar and thermal radiation pressure.[16] The orbit determination must also tolerate some long duration tracking gaps, where communication is not permitted due to low Sun-Earth-Probe (SEP) angle or when the thermal protection system (TPS) blocks the antenna. In fact, this is particularly challenging for PSP because there are periods in the mission in which keeping the spacecraft Sun-pointed prevents a radio link with Earth that can be several weeks longs for some orbits. Even in the absence of data gaps, much of the usable tracking data is affected by the radio signal passing through solar plasma, so measurements must be properly weighted as a function of SEP and declination (for ΔDOR). The most challenging requirements for orbit determination are MDNR-25, MDNR-26, and MDNR-74 described in Table 1 and Table 2.

Trajectory correction maneuvers are designed to correct launch errors, orbit determination, and maneuver execution errors, errors due to trajectory perturbations from unmodeled solar radiation pressure and spacecraft thermal re-radiation, and momentum desaturation maneuvers. Maneuvers are accomplished with the monopropellant propulsion system: three groups (A, B, C) of four thrusters each are used to yield a TCM or velocity change while enforcing the TPS to be pointed to the Sun. For a given TCM design, a thruster selection is made based on the spacecraft's location and geometry relative to the Sun and in compliance with with spacecraft operation and TCM design constraints. Each TCM design is initiated by the Mission Design Team, followed with ΔV design verification by the Navigation Team, and concluded by the Guidance and Control Team on maneuver implementation prior to command for execution. The spacecraft can be configured for a burn's cutoff based on time or estimated ΔV99.[9]

The general TCM schedule was developed before launch to de-conflict with other competing resources and activity schedules, including more opportunities than minimum needed for placeholders. However, the TCM locations are re-evaluated during flight as needed, with small changes in the order of ±2 hours. All TCMs are placed at solar distances greater than 0.45 AU due to spacecraft thermal constraints. For each TCM there must be sufficient power, RF, and G&C pointing budget, and available DSN tracking for OD, TCM commands uplink, TCM monitoring during the burn. Solar conjunctions, where the Sun-Earth-Probe angle is less than 3 degrees for X-band and less than 1.7 degrees for Ka-band, are also avoided for maneuver placement, and so is TPS blockage, where the Sun-Probe-Earth angle is less than 15 degrees.[7]

In the reference trajectory design process, an optimization strategy is implemented for the flight path control to minimize propellant usage and satisfy constraints.[7] Trajectory re-optimization is performed periodically by the Mission Design Team in flight operations to update the reference trajectory to an optimal flight path that requires a minimal trajectory correction to achieve the desired Venus gravity assists. The downstream maneuvers are used to target the upcoming Venus flyby of the updated reference trajectory. The Venus B-plane target is provided by the Mission Design Team. Since launch in 2018, there have been six reference trajectory re-designs, R01 through R06. In flight, for a given transfer between flybys, a maneuver optimization strategy is used within a linear Monte Carlo simulation to help determine which TCM's to implement and which ones to cancel. However, for operations, TCMs are designed and tested one at a time.

4.1 Maneuver Execution Errors

For the statistical analysis of all trajectory correction maneuvers, an execution error model, or Gates model,[12] is used to model the distribution of the 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 defined by four independent error sources: fixed-and proportional-magnitude errors, and fixed-and proportional-pointing errors. The Gates execution error model assumed for the current navigation set-up is shown in Table 3. These values can be updated throughout the mission to include in-flight TCM experience.

Table 3: Gates maneuver execution error model (3-σ)

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

5. Maneuver Analysis: TCM Designs per Venus Flybys

A total of seven Venus flybys are needed for PSP to touch the Sun. If all seven flybys were targeted perfectly, the spacecraft would reach the minimum perihelion without the need to execute any maneuvers. However, due to system mismodeling, the spacecraft has to perform small correction maneuvers using the available onboard propellant (135 m/s at the time of launch) to achieve the Venus flyby targets as accurately as possible. Because the seven flybys are connected via a series of resonant and non-resonant arcs, every Venus flyby must be precisely targeted via the design and implementation of TCMs. That is, missing the flyby targets of one encounter would have a large negative impact on all subsequent encounters. A summary of all seven Venus encounters is given in Table 4 and a summary of all TCM opportunities up to the Venus-6 flyby is given in Table 5.

Table 4: Venus gravity assist encounters (Targets in km, EME2000)

Encounter	Date	Target $\mathbf{B}\cdot\mathbf{R}$	Achieved $\mathbf{B}\cdot\mathbf{R}$	Target $\mathbf{B}\cdot\mathbf{T}$	Achieved $\mathbf{B}\cdot\mathbf{T}$
V1	03-OCT-2018	1845.451	1844.022	8888.101	8888.040
V2	26-DEC-2019	-2795.760	-2793.691	9245.582	9241.238
V3	11-JUL-2020	406.957	407.125	-7462.573	-7464.705
V4	20-FEB-2021	1114.232	1111.079	-8963.377	-8962.971
V5	16-OCT-2021	-3972.882	-3972.238	9680.768	9675.166
V6	21-AUG-2023	-3860.395	–	9928.997	–
V7	06-NOV-2024	1398.992	–	-6883.955	–

As a side note, while Parker Solar Probe's primary goal is solar science, the Venusian flybys are providing exciting opportunities for bonus data that was not expected at the mission's launch: WISPR has imaged Venus' orbital dust ring, FIELDS made direct measurements of radio waves in the Venusian atmosphere, helping scientists understand how the upper atmosphere changes during the Sun's 11-year cycle of activity, and new findings about the rediscovery of the comet-like tail of plasma streaming out behind Venus, called a ”tail ray”.

Figure 5 and Figure 10 indicate trajectory correction maneuver placement from TCM-6 (post-Venus-1) through TCM-28 (post-Venus-5) as a function of time. For reference, the y-axis shows the spacecraft solar distance in AU as a function of time. Additional mission events, like solar encounter and Venus flyby epochs (vertical red lines) are also represented in these plots.

Table 5: Trajectory correction maneuver timeline

Burn	Target	Date	DV, m/s	RA, deg	DEC, deg	Performance
TCM-01	V1	19-AUG-2018	1.000 / 9.231	209.5 / 221.23	-19.93 / -17.05	executed
TCM-02	V1	31-AUG-2018	0.733	64.95	28.35	executed
TCM-03	V1	11-SEP-2018	-	-	-	canceled
TCM-04c	V1	29-SEP-2018	0.069	325.04	4.47	executed
TCM-05	V2	17-OCT-2018	-	-	-	canceled
TCM-06	V2	09-DEC-2018	1.101	311.74	54.48	executed
TCM-07	V2	13-MAY-2019	-	-	-	canceled
TCM-08	V2	10-OCT-2019	-	-	-	canceled
TCM-09a	V2	08-DEC-2019	0.301	204.89	-9.07	executed
TCM-09b	V2	08-DEC-2019	0.141	119.01	24.15	executed
TCM-10	V2	21-DEC-2019	-	-	-	canceled
TCM-11	V3	10-JAN-2020	0.912	136.85	-6.79	executed
TCM-12	V3	08-MAR-2020	-	-	-	canceled
TCM-13	V3	22-JUN-2020	0.158	31.49	4.27	executed
TCM-14	V3	05-JUL-2020	-	-	-	canceled
TCM-15	V4	19-JUL-2020	1.505	190.10	-22.99	executed
TCM-16	V4	28-DEC-2020	0.070	79.37	23.30	executed
TCM-17	V4	31-JAN-2021	-	-	-	canceled
TCM-18	V4	15-FEB-2021	0.411	72.21	23.95	executed
TCM-19	V5	07-MAR-2022	-	-	-	canceled
TCM-20	V5	15-MAY-2021	0.911	298.84	49.54	executed
TCM-21	V5	25-AUG-2021	-	-	-	canceled
TCM-22	V5	29-SEP-2021	0.097	305.06	-20.12	executed
TCM-23	V5	11-OCT-2021	-	-	-	canceled
TCM-24	V6	11-DEC-2021	-	-	-	canceled
TCM-25	V6	12-MAR-2022	0.774	319.71	-18.98	executed
TCM-26	V6	20-JUN-2022	–	-	-	canceled
TCM-27	V6	20-SEP-2022	–	-	-	canceled
TCM-28	V6	21-NOV-2022	–	-	-	canceled

5.1 Venus-1 to Venus-2: TCM-5 through TCM-10

During the mission's first Venus gravity assist on October 3, 2018, Parker Solar Probe took measurements of the Venusian bowshock, allowing for exciting research outside of the primary mission. A total of six TCMs (plus backup locations) were scheduled following the first Venus flyby up to the second, that is, TCM-5 through TCM-10. The maneuver design process and execution of each maneuver are described in the following paragraphs.

TCM-05 After a nominal first Venus flyby, and although the Project canceled TCM-05 prior to the final maneuver design on considerations not directly related to ΔV, the Navigation Team performed a preliminary trade study of TCM design options for the second Venus encounter including TCM-05 through TCM-10. The results of this study included only the ΔV required to correct B-Plane errors of the orbit determination solution accounting for uncertainties. See Appendix for more details on the B-Plane definition. The results are summarized in Table 6. TCMs 9 and 10 are excluded from the results. TCM-10 is the final approach maneuver and has the same target as TCM-09 and, thus, results in zero ΔV for each case analyzed. In minimizing the sum of these TCMs, TCM-09 also results in zero ΔV for each case as it has the least capability of all burns in this sequence. Each case results from minimizing total ΔV for the indicated TCMs to correct the orbit determination solution to the Venus-2 target. When combining TCMs 6, 7, and 8 to make the necessary trajectory correction, TCM-07 was reduced to zero or near zero ΔV. Designing TCM-06 with TCM-08 was only about 0.1 m/s more

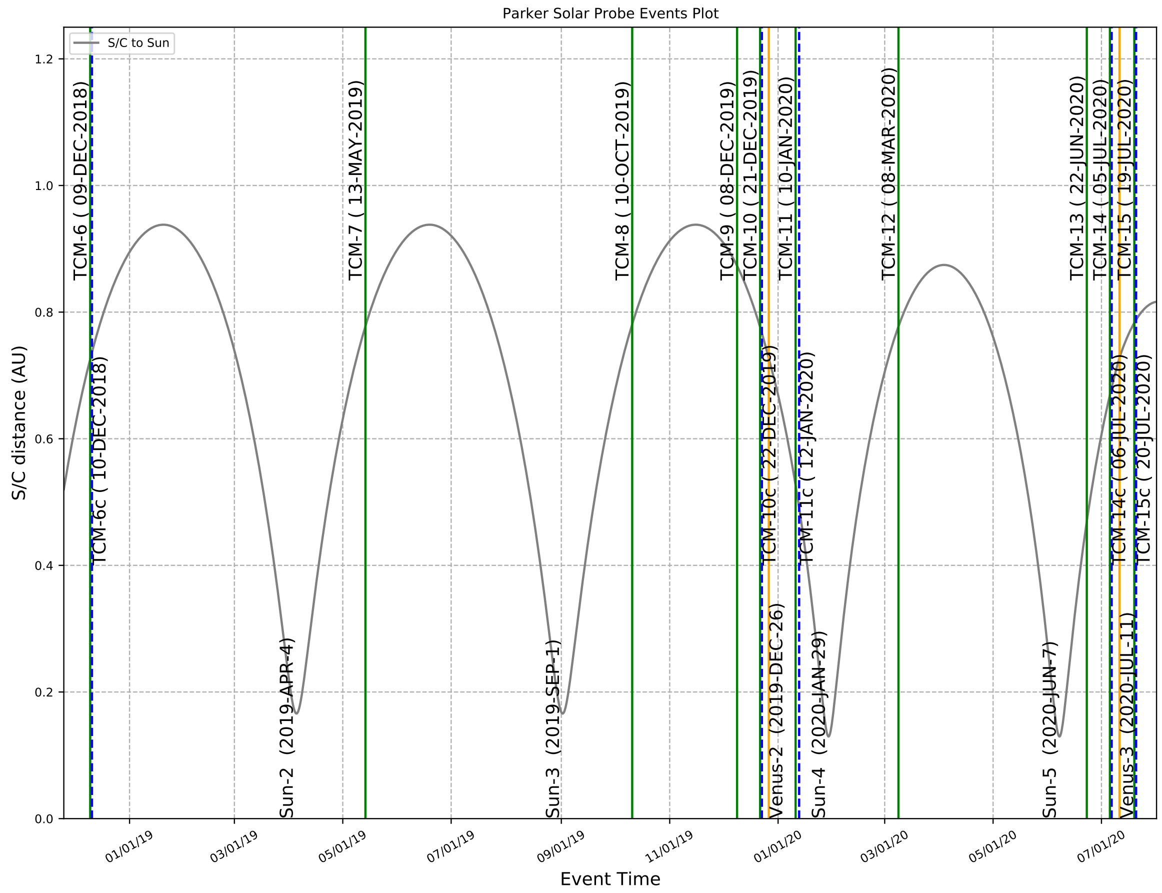

Figure 5: Trajectory correction maneuver placement: TCM-6 through TCM-15

expensive than TCM-05 with TCM-06. The Project decided to cancel TCM-05 on October 8, 2018 to also allow the team to fully focus an on-going review of spacecraft health.

Table 6: Downstream design cost estimates for TCM-05 design

TCM-05	TCM-06	TCM-07	TCM-08	Total (m/s)
0.17	1.03	–	–	1.20
0.15	0.68	0.02	0.35	1.19
–	1.12	0.26	–	1.38
–	0.81	–	0.47	1.28
–	0.81	0.003	0.47	1.28

TCM-06 The subsequent burn, TCM-06, was successfully performed on December 9, 2018 in the default spacecraft attitude, that is, Umbra with the +Z-axis pointed at the Sun. The angle between the TCM ΔV and the Sun direction was 102.8 degrees. The B thrusters were primary with the A and C thrusters enabled. The estimated burn duration was 44.5 second and the burn used approximately 409 grams of propellant for a total ΔV magnitude of 1.101 m/s. TCM-06 used the Venus-2 B-Plane targets from the re-optimized reference trajectory, which shifted the original targets to reduce the TCM-06 ΔV by about 0.6 m/s, that is, from 1.7 m/s to 1.1 m/s.

TCM-07 The seventh TCM was canceled on April 2, 2019. The final orbit determination solution (OD042) used for the final TCM-07 design resulted in a very small burn (0.139 m/s) and, thus, the Mission Design and Navigation Teams recommended to cancel the burn and do the required trajectory correction with a subsequent burn.

TCM-08 TCM-08 was also canceled, on October 3, 2019. The Mission Design and Navigation Teams recommended this TCM for two primary reasons: 1) the size of the trajectory correction from TCM-08 was very small relative to the level of orbit determination errors and 2) the burn magnitude is small and the cancelation cost in delaying the correction to TCM-09 and/or TCM-10 is not prohibitively large in terms of overall delta-V cost. The Project concurred with MDNav's assessment and TCM-08 was canceled.

TCM-09 TCM-09 was a first time event for PSP. It was split into two burns (A and B) due to a pointing cone constraint violation. The first part of the burn, TCM9a, was performed on December 8, 2019 at 17:00 EST using the A thruster group only. The burn used approximately 96 grams of propellant. The second part of the burn, TCM-9b, was successfully performed 2 hours after TCM-9a, also using mostly the A thruster group with some small counts on group C. TCM-9b consumed approximately 46 grams of propellant. For reference, the trajectory diagram in 6 illustrates the location TCM-09 on the reference trajectory.

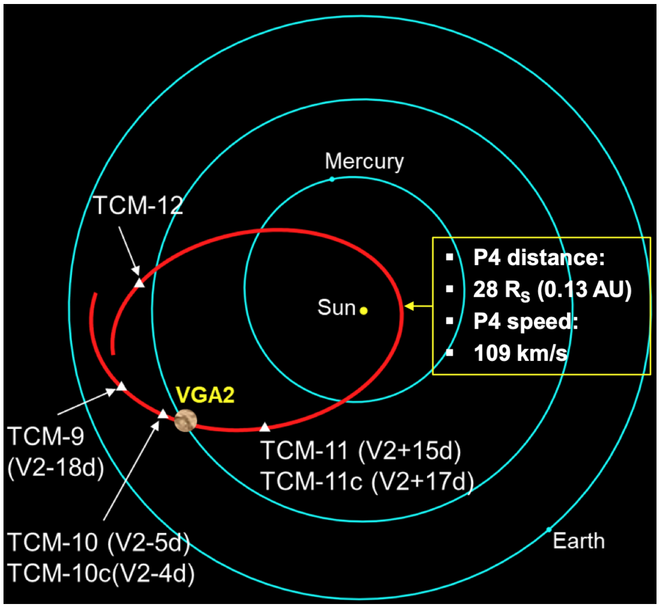

Figure 6: Trajectory diagram illustrating TCM-9 and TCM-10 targeting the Venus-2 flyby followed by post-flyby TCM-11 and TCM-12.[13]

The final Venus-2 B-Plane plot is illustrated in Figure 7, with the x,y-axes representing the $\mathbf{B} \cdot \mathbf{T}$, $\mathbf{B} \cdot \mathbf{R}$ components, respectively. The ellipses represent the delivery uncertainties for different solutions: the blue ellipse corresponds to the TCM design solution and the green ellipse represents the orbit determination solution without the TCM trajectory correction in it. The red cross marks the Venus flyby aimpoint. As expected, the center of the TCM delivery ellipse (blue circle) overlaps with the target point. The distance between the center of the OD delivery ellipse (green square) represents the expected B-Plane miss if the burn is canceled. The differences in the time to periapsis, the third target parameter in the Venus flyby aimpoint, are represented in the bottom rectangular plot. In general, the smaller the difference, the smaller the TCM magnitude.

TCM-10 The last correction maneuver prior to Venus-2 was scheduled on December 21, 2019, five days prior to the planetary encounter. The Project made the decision to cancel TCM-10 on December 18, 2019 given the burn magnitude. The 12.8 mm/s burn was too small to accurately implement and the correction in the B-Plane was small to have an accurate flyby.

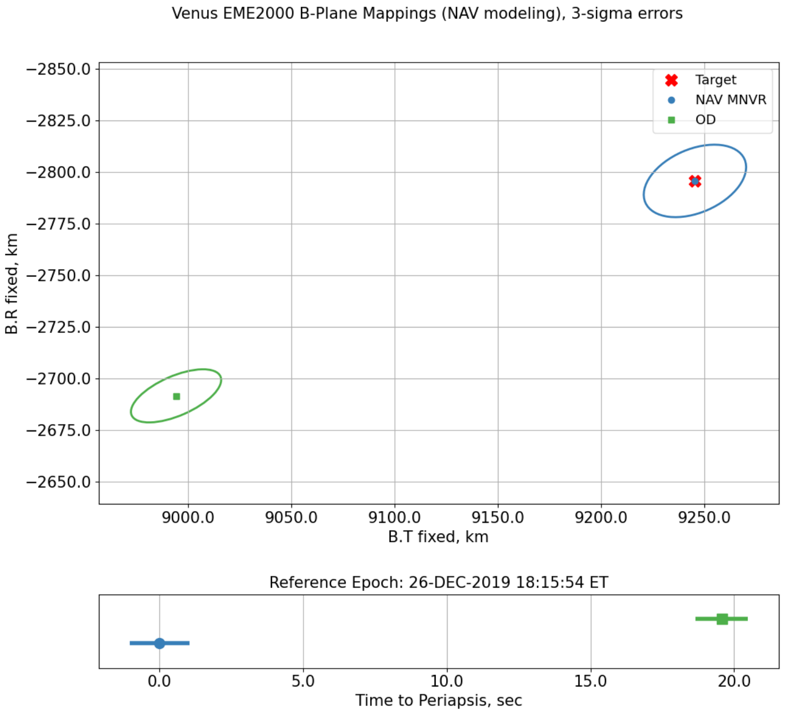

Figure 7: B-Plane Plot for the Venus-2 Flyby with and without the TCM-9 trajectory correction. The blue ellipse represents the delivery uncertainty associated with the TCM design solution and the green ellipse represents the delivery uncertainty of orbit determination solution without the TCM trajectory correction in it. The OD solution is a propagation of the spacecraft state at the time of the burn to the B-Plane encounter time. The distance between the two ellipse centers represents the predicted Venus flyby miss if the TCM is not executed as planned. The red cross marks the B-Plane target.

5.2 Venus-2 to Venus-3: TCM-11 through TCM-14

The second Venus gravity assist occurred on December 26, 2019 at an altitude of 3009 km, providing additional measurements of the bowshock of Venus and allowing Parker Solar Probe to lower its perihelion to 27.8 R_S for its fourth solar encounter. A total of four TCMs (plus backup locations) were scheduled following the second Venus flyby up to the third, that is, TCM-11 through TCM-14. The maneuver design process and execution of each maneuver are described in the following sections.

TCM-11 The first Venus-3 targeting maneuver, TCM-11, was successfully executed as planned on January 10, 2020 at 20:30 UTC in the Umbra burn attitude (solar distance $R < 0.79$ AU). At the time of the burn, the one-way light time was 580.29 seconds. After an accurate Venus-2 flyby and as a result of trajectory re-optimization post-flyby, the designed TCM magnitude was smaller than the pre-flyby design: 0.912 m/s with a burn duration of 31.88 seconds.

TCM-12 The subsequent burn, TCM-12, scheduled on March 8, 2020, was officially canceled by the Project on February 12, 2020 after careful consideration. The main reason for the cancelation was that TCM-13 was more effective than TCM-12 and required less ΔV to make the required trajectory correction. In addition, the offset of the orbit determination prediction from the Venus-3 target was much smaller than the orbit determination uncertainty.

TCM-13 The third Venus-3 targeting maneuver, TCM-13, was successfully executed on June 22, 2020 at 18:00 UTC, 18 days prior to the planetary encounter. Since the solar distance was below 0.79 AU, the selected burn attitude was Umbra. The location of TCM-13 with respect to the Venus flyby is illustrated in Figure 8.

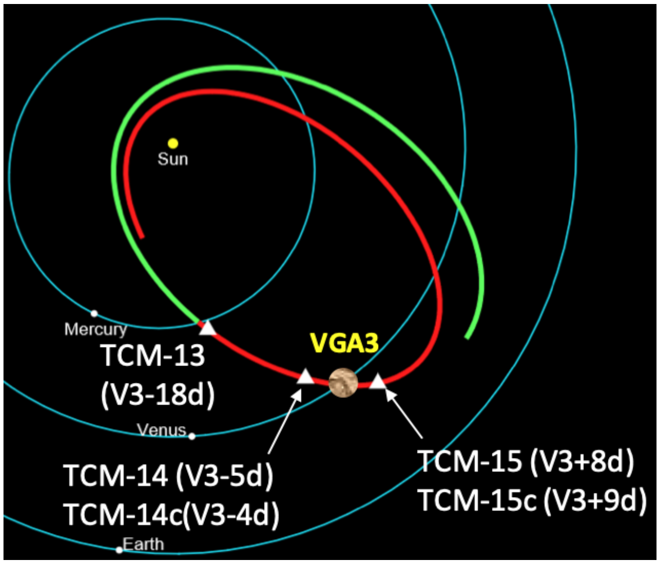

Figure 8: Trajectory diagram illustrating TCM-13 and TCM-14 targeting the Venus-3 flyby followed by post-flyby burns TCM-15.[14]

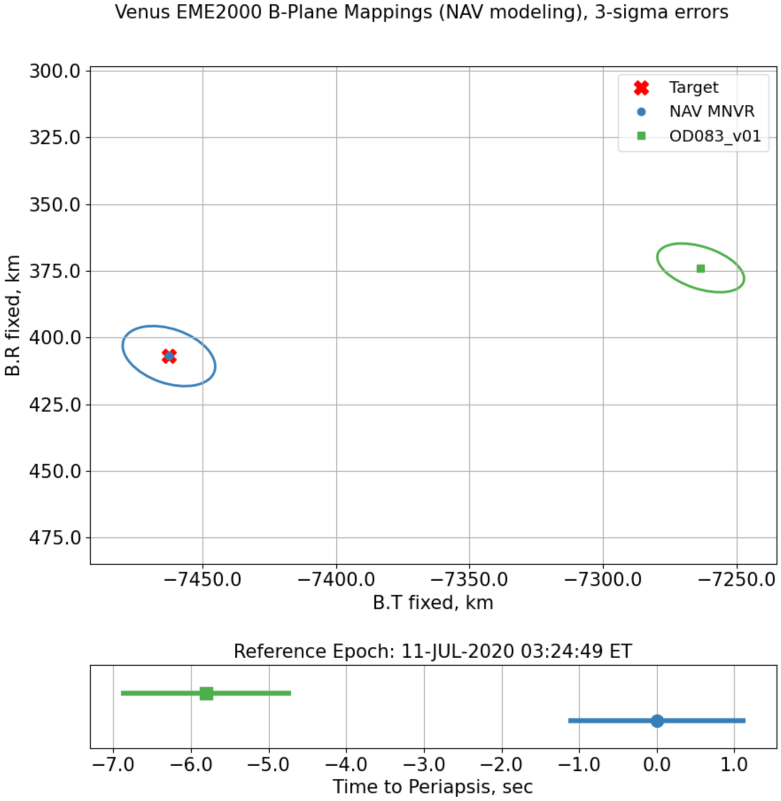

Figure 9: B-Plane Plot for the Venus-3 Flyby with and without the TCM-13 trajectory correction. The blue ellipse represents the delivery uncertainty associated with the TCM design solution and the green ellipse represents the delivery uncertainty of orbit determination solution without the TCM trajectory correction in it. The distance between the two ellipse centers represents the predicted Venus flyby miss if the TCM is not executed as planned. The red cross shows the location of the target on the B-Plane.

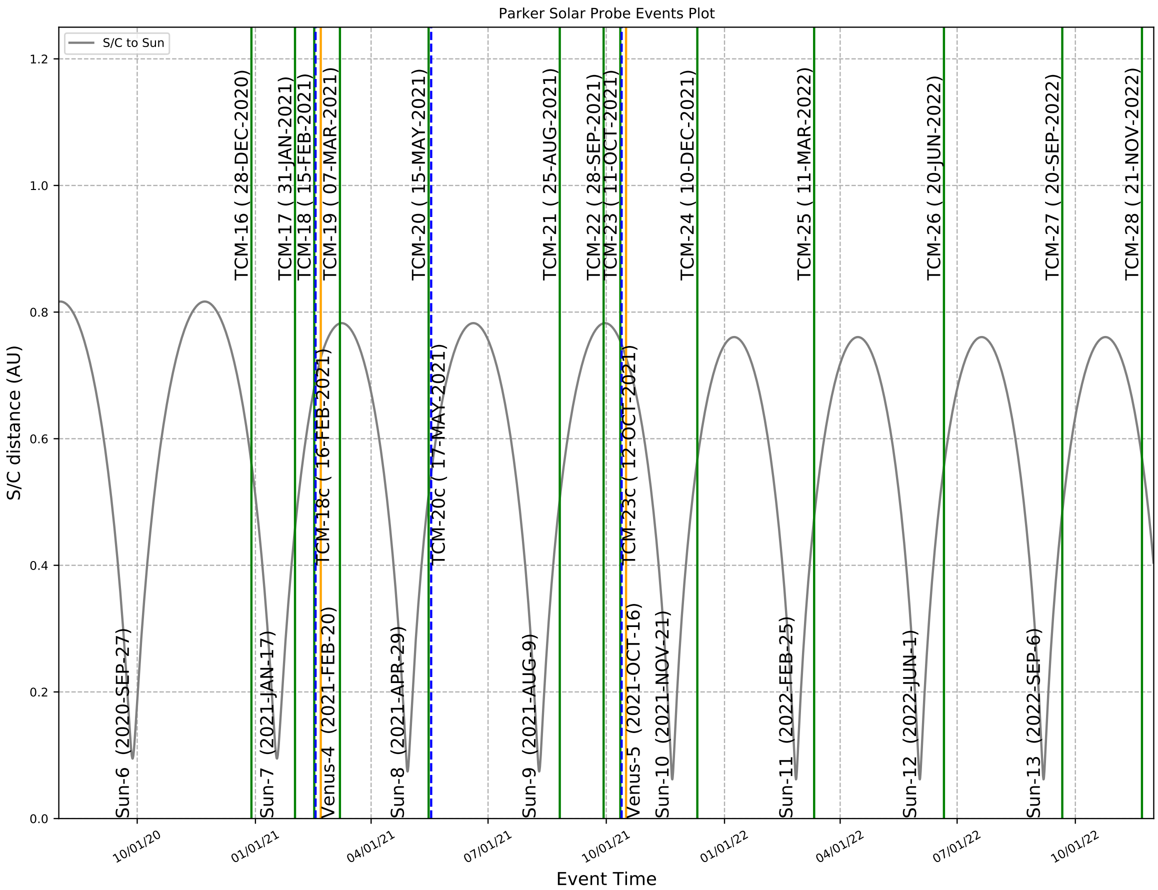

Figure 10: TCM placement: TCM-16 through TCM-28

TCM-14 The final approach maneuver opportunity prior to the third Venus encounter was officially canceled by the Project on July 2, 2020. TCM-14, scheduled on July 5, 2020 at 18:00 UTC, was a small burn in magnitude (17.5 mm/s) with little to no downstream ΔV penalty. The Project accepted a small built-in miss and allowed the teams to enjoy the US Independence Day holiday.

5.3 Venus-3 to Venus-4: TCM-15 through TCM-18

During the mission's third Venus gravity assist on July 11, 2020, WISPR captured a striking image of the planet's nightside from an altitude of 831 km. This gravity assist, designed to lower perihelion from 28R_S to 20R_S, was followed by four trajectory correction maneuvers (TCM-15, TCM-16, TCM-17, and TCM-18) to carefully target the B-Plane conditions at the next flyby encounter, Venus-4, on February 20, 2021. The maneuver design process and execution of each maneuver are described in the following sections. Figure 10 illustrates the trajectory correction maneuver placement from TCM-06 (post-Venus-1) through TCM-28 (post-Venus-5) as a function of time, in addition to other mission events, like solar encounter and Venus flyby epochs (vertical red lines). The y-axis shows the spacecraft solar distance in AU as a function of time.

TCM-15 The first Venus-3 post-flyby burn opportunity, TCM-15, was successfully executed on July 19, 2020 at 12:00 UTC, approximately eight days after the the third Venus flyby. The burn attitude for TCM-15 was Umbra (+Z-axis pointed at the Sun) as the solar distance was below 0.79 AU. The designed burn magnitude was 1.5048 m/s with a burn duration of 56.611 seconds. The fuel used during this burn was estimated to be 596 grams. After review, the burn was deemed nominal with less than 1-σ errors.

TCM-16 TCM-16 was a small burn executed as planned on 28-DEC-2020 at 13:10:13 UTC. At the time, the one-way light time was 613.3996 sec and the designed burn magnitude was 69.8 mm/s. After NAV's evaluation of the solution, the burn showed a 0.1 sigma error in the line-of-sight component, consistent with a nominal burn.

TCM-17 After careful review of the orbit determination data and maneuver design, TCM-17 was officially canceled by the Project on January 27, 2021. The OD solution, which incorporated all navigation measurements taken up to that day, showed that the trajectory offset from the B-Plane target of fourth Venus flyby was small and within the OD uncertainty ellipse. Additional trajectory corrections to further refine the spacecraft trajectory to hit the Venus-4 B-Plane target was better deferred to the next burn opportunity, TCM-18, when the orbit determination solution uncertainty was expected to be about 10 times smaller.

TCM-18 The last trajectory correction maneuver opportunity prior to the 4th Venus gravity assist flyby on February 20, 2021, was scheduled on February 15, 2021 with a contingent TCM-18c scheduled on February 16. Figure 11 illustrates the B-Plane correction accomplished by TCM-18. The designed burn magnitude was 411.85 mm/s with an expected burn duration of 14.26 seconds. TCM-18 was deemed a must-do burn given the high cancelation ΔV penalty post-flyby, as evidenced by the Navigation's team analysis showing a TCM-19 burn magnitude of 14.5 m/s if TCM-18 was canceled as opposed to 0.866 m/s if TCM-18 was executed as planned.

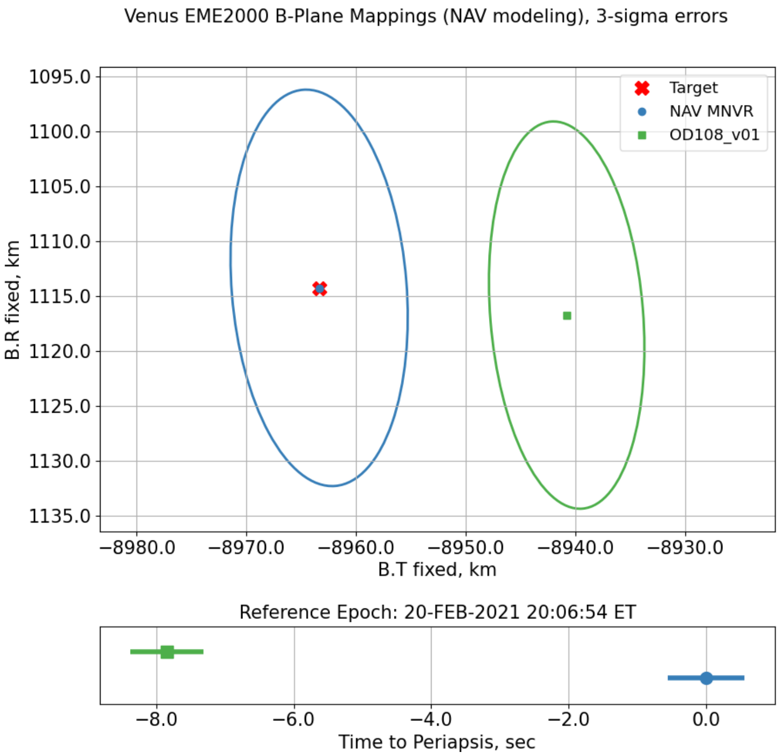

Figure 11: B-Plane Plot for the Venus-4 Flyby with and without the TCM-18 trajectory correction. The blue ellipse represents the delivery uncertainty associated with the TCM design solution and the green ellipse represents the delivery uncertainty of orbit determination solution without the TCM trajectory correction in it. The distance between the two ellipse centers represents the predicted Venus flyby miss if the TCM is not executed as planned. The red cross represents the Venus flyby target.

5.4 Venus-4 to Venus-5: TCM-19 through TCM-23

Parker Solar Probe nailed its fourth swing past Venus on February 20, 2021, bending its orbit to set up for close approaches to the Sun on April 29 and August 9, 2021. During these solar encounters, Parker set a new record when it flew approximately 10.4 million kilometers from the Sun's surface, which is about 1.9 million miles closer than on the mission's previous perihelion on January 17. The goal of Venus-4 was to reduce the perihelion distance of the spacecraft's orbit from 20 to 16 solar radii for the next 8th solar encounter on April 29, 2021.To clean up for small flyby errors, a total of five TCMs were scheduled between Venus-4 and Venus-5, that is, TCM-19 through TCM-23. The maneuver design process and execution of each maneuver are described in the following sections.

TCM-19 After a very successful 4th Venus gravity-assist flyby, TCM-19 scheduled on March 7, 2021 was officially canceled by the Project. The small trajectory errors from Venus-4 would be corrected by TCM-20 on May 15, 2021. TCM-20 was clearly a better opportunity than TCM-19, making the desired trajectory correction using much less ΔV.

TCM-20 The subsequent burn, TCM-20, was a 910 mm/sec burn executed on May 15, 2021 to post-flyby Venus-4 flyby errors. The location of TCM-20 is represented in Figure 12. The one-way light time at the time of the burn was 439.55 seconds and the Earth-SC-ΔV angle was 100.04 degrees. The estimated burn duration was 37.5 seconds.

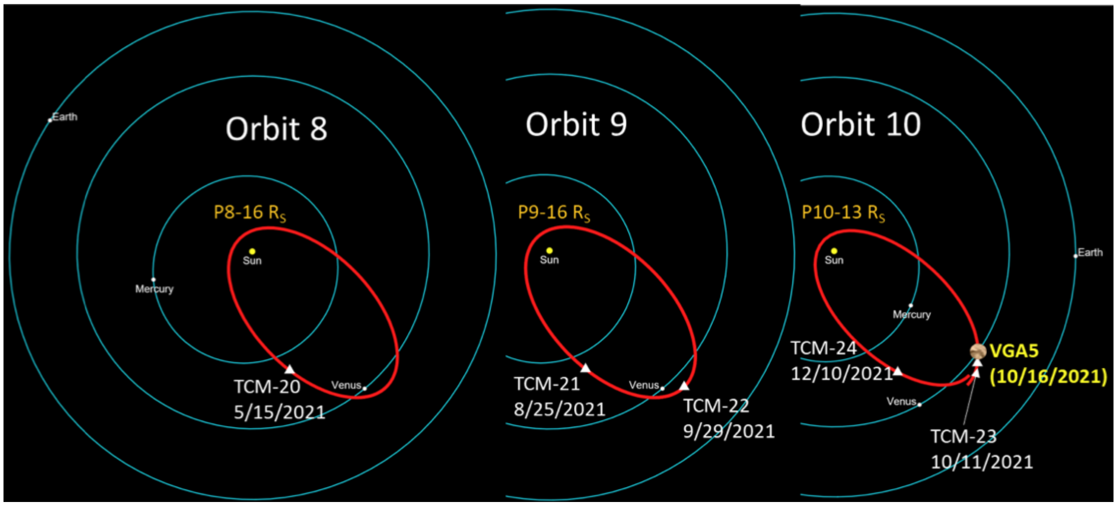

Figure 12: Trajectory diagram illustrating TCM-19, TCM-20, TCM-21, and TCM-22 targeting the Venus-5 flyby followed by post-flyby burn TCM-24.[15]

TCM-21 After a nominal TCM-20 burn, the Project made the decision to cancel TCM-21 scheduled on August 25, 2021. At the time of the cancelation meeting, the post solar encounter 9 orbit determination solution showed that the spacecraft trajectory was close to the Venus-5 target, with a small error of approximately 150 km from the B-Plane target and 0.7 seconds off the desired closest approach time. The nominal TCM-21 designed resulted in a very small ΔV of 18 mm/s, which is considerably less than the TCM minimum implementable size of 50 mm/s. In addition, statistical analysis performed by the Navigation Team on all three TCMs (TCMs 21, 22, and 23) planned before Venus-5 indicated that it was more efficient to defer the trajectory correction until TCM-22.

TCM-22 The subsequent burn in the chain, TCM-22, was successfully executed on September 29, 2021. The burn magnitude was 97 mm/s with a burn duration of 4.5 seconds. The Project decided to execute TCM-22 as planned to avoid a cancelation downstream ΔV penalty of approximately 374 mm/s. The B-Plane plot at the time of the TCM-22 design is shown in Figure 13. TCM-22 made a correction of approximately 52 km in $\mathbf{B} \cdot \mathbf{R}$, 139 km in $\mathbf{B} \cdot \mathbf{T}$, and 0.1 sec in time to Venus periapsis.

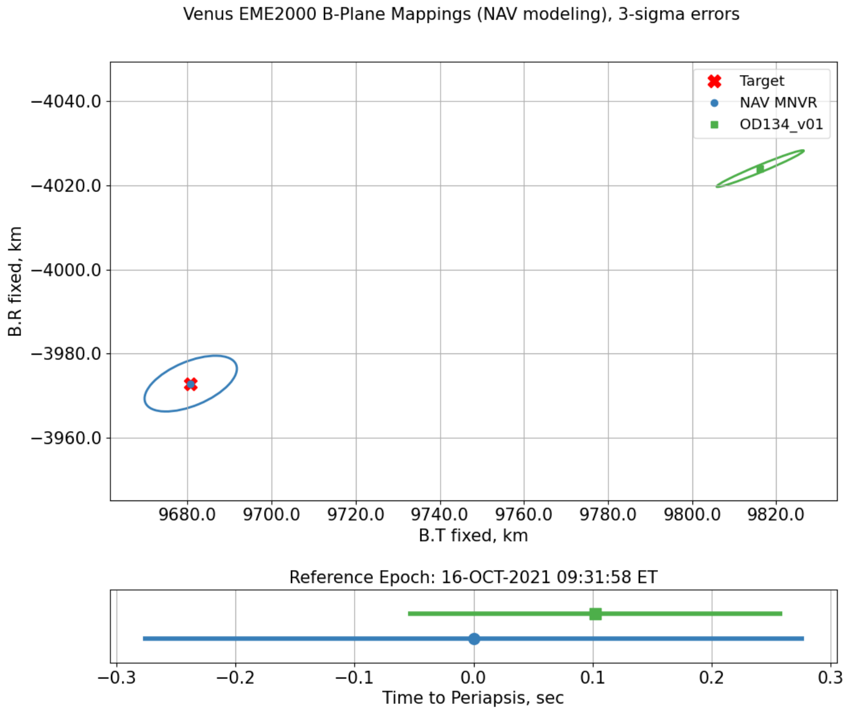

Figure 13: B-Plane plot for the Venus-5 Flyby with and without the TCM-22 trajectory correction. The blue ellipse represents the delivery uncertainty associated with the TCM design solution and the green ellipse represents the delivery uncertainty of orbit determination solution without the TCM trajectory correction in it. The distance between the two ellipse centers represents the predicted Venus flyby miss if the TCM is not executed as planned. The red cross shows the flyby target on the B-Plane.

TCM-23 The Project decided to cancel TCM-23, the last approach burn opportunity to aim for the Venus-5 flyby on October 16, 2021. Based on the orbit determination solution at the time of cancelation, TCM-23, an 11 mm/s burn, was deemed too small to execute. TCM-23 would have been a very short burn (0.4 sec in duration), and considering the TCM execution errors, the maneuver would have likely not improved the trajectory conditions. Additionally, the downstream cost of the flyby miss was expected to be between 1.0 and 3.0 m/sec, an acceptable amount of propellant. Therefore, TCM-23 and its backup burn, TCM-23c, were officially canceled by the Project on October 7, 2021.

5.5 Upcoming Venus-5 to Venus-6: TCM-24 through TCM-32

On October 16, 2021, Parker Solar Probe successfully used the planet's gravity a fifth time to shape its path for its next closest approach to the Sun. The 3810 km altitude flyby reduced the spacecraft's orbital speed by approximately 9,720 km/hr and set it up for its 10th perihelion on November 21, 2021. The sixth Venus gravity assist is planned to occur on August 21, 2023 at an altitude of 3900 km. This second to last Venus flyby will lower the spacecraft's solar distance from 13.3 R_S to 11.4 R_S at the time of the 17th solar encounter on September 27, 2023. While the geometry of the next flybys likely will not allow Parker to image the nightside, scientists will continue to use Parker's other instruments to study Venus' space environment. In November 2024, the spacecraft will have a final chance to image the surface on its seventh and final flyby. Table 7 shows the number of TCMs planned for the rest of the mission. The 15th of 24 perihelia will occur on March 12, 2023 and there are six TCMs planned in

2023: TCM-29 through TCM-34. The mission design and navigation teams will continue to review the past experience and conduct analysis for upcoming maneuvers.

Table 7: Schedule of TCM events

Event	TCMs Before Next Event	Days Between Events
Venus-5	9	674
Venus-6	7	443
Venus-7	3	225

TCM-26 was officially canceled by the Project on April 12, 2022. With the successful execution of TCM-25 on March 12, 2022, trajectory errors from the fifth Venus flyby and orbit errors accumulated during solar encounter 10 and 11 were corrected. Analysis performed at the time showed that TCM-26 would have been a very small correction, and TCM-27 would make the correction at a lower ΔV. Consequently, TCM-26 was not needed. TCM-27 was officially canceled by the Project on September 16, 2022. Based on the orbit determination solution at the time, the predicted B-Plane offset from the Venus-6 flyby target was significantly smaller than the orbit determination uncertainty, so there was no need to perform TCM-27 to correct an uncertain offset. Given that there are five TCM opportunities (TCM-28 through TCM-32) to make trajectory corrections if needed before the Venus-6 flyby on August 21, 2023, TCM-27 was deemed not required. TCM-28 was also officially canceled by the PSP Project on November 16, 2022. The trajectory was stable and very close to the next Venus-6 flyby target. The offset from the target was small and much less than the orbit determination uncertainty. Additionally, the analysis also showed that future TCMs were more effective at correcting trajectory dispersions, reducing the overall ΔV Therefore, TCM-28 was also deemed not necessary.

6. Linearized Monte Carlo Analysis

There are no deterministic maneuvers in the nominal trajectory design and, therefore, all trajectory control and adjustments are statistical. The JPL Mission-analysis Operations and Navigation Toolkit Environment (MONTE)[17] Linear Analysis of Maneuvers with Bounds and Inequality Constraints (LAMBIC)[18] software is used to compute statistical ΔV via Monte Carlo analysis. These statistical predictions are valuable in assessing overall navigation performance against the 135 m/s ΔV budget. LAMBIC, an in-house developed software, produces the statistics of ΔV magnitude and delivery accuracy by simulating the execution of a sequence of maneuvers through the use of the Monte Carlo method. In essence, the simulation is initiated with an injection covariance mapped to the first encounter. Then, for each maneuver, samples of commanded ΔV, actual ΔV, as well as pre-maneuver, post-maneuver, and estimated aimpoint offsets from the nominal values of the aimpoint parameters are analyzed to compute the ΔV statistics and delivery accuracy.

Assuming current navigation models, sources of uncertainty, and maneuver strategy, a statistical analysis for PSP's reference trajectory was conducted. Table 8 shows the summary of TCMs performed or canceled after the first Venus flyby to the last TCM evaluated to date, TCM-28, prior to Venus-6. Each TCM statistical prediction shows which maneuver contributes most to the overall ΔV total. As expected, most of the post-flyby maneuvers have the largest components since these burns correct, or clean-up, errors after a Venus flyby. However, an accurate flyby reduces the magnitude of the statistical burns significantly. With very small flyby misses, it is not surprising that the actual ΔVs are significantly smaller than the statistical predictions. Note that the statistical ΔV for TCM-19 is essentially zero, indicating that this burn is not needed given its capability relative to its location. A burn capability is measured in terms of target/ΔV gradient magnitudes and angles between gradient vectors. Pre-launch studies showed that TCM-19 was only needed for certain, but not all, trajectories in the launch period. Nonetheless, for mission planning purposes, a placeholder was bookkept for TCM-19 even though it was not needed for the August 12, 2018 reference trajectory.

Table 8: LAMBIC predicted maneuver statistics vs. commanded and reconstructed burn ΔVs

Burn	Epoch	Mean (m/s)	1-σ (m/s)	ΔV99 (m/s)	Commanded ΔV (m/s)	Reconstructed ΔV (m/s)
TCM-05	17-OCT-2018	0.82	0.95	4.03	canceled	canceled
TCM-06	09-DEC-2018	0.41	0.27	0.92	1.101	1.100
TCM-07	13-MAY-2019	0.32	0.23	0.91	canceled	canceled
TCM-08	10-OCT-2019	0.38	0.21	0.89	canceled	canceled
TCM-09a	08-DEC-2019	0.14	0.05	0.28	0.300	0.300
TCM-09b	08-DEC-2019	–	–	–	0.140	0.141
TCM-10	21-DEC-2019	0.02	0.05	0.24	canceled	canceled
TCM-11	10-JAN-2020	3.14	1.96	9.23	0.911	0.912
TCM-12	08-MAR-2020	0.26	0.23	1.01	canceled	canceled
TCM-13	22-JUN-2020	0.29	0.16	0.75	0.158	0.159
TCM-14	05-JUL-2020	0.09	0.07	0.28	canceled	canceled
TCM-15	19-JUL-2020	2.97	2.62	12.66	1.504	1.506
TCM-16	28-DEC-2020	0.42	0.28	1.32	0.070	0.071
TCM-17	31-JAN-2021	0.21	0.14	0.62	canceled	canceled
TCM-18	15-FEB-2021	0.1	0.06	0.29	0.411	0.413
TCM-19	07-MAR-2022	0.00	0.00	0.00	canceled	canceled
TCM-20	15-MAY-2021	4.80	2.86	12.45	0.911	0.908
TCM-21	25-AUG-2021	0.54	0.85	4.42	canceled	canceled
TCM-22	29-SEP-2021	0.09	0.08	0.34	0.097	0.099
TCM-23	11-OCT-2021	0.04	0.06	0.22	canceled	canceled
TCM-24	11-DEC-2021	1.47	1.18	4.89	canceled	canceled
TCM-25	12-MAR-2022	0.18	0.24	0.96	0.774	0.771
TCM-26	20-JUN-2022	0.03	0.12	0.66	canceled	canceled
TCM-27	20-SEP-2022	0.29	0.36	1.44	canceled	canceled
TCM-28	21-NOV-2022	0.18	0.20	0.82	canceled	canceled
TOTAL	(m/s)	17.20		33.26	6.29	6.38

The statistical results in Table 8 satisfy requirement MDNR-22, which states that the total post-launch statistical ΔV to 99% confidence, is not to exceed 135 m/s. To satisfy the pointing constraint specified in MDNR-69, TCM-09 design required a cone angle constraint and was decomposed into two burns, TCM-09a and TCM-09b, as a result. However, the cone constraint was not applied to the LAMBIC TCM-09 design and, thus, there are no statistics available for TCM-09b.

Close inspection of the predicted ΔV statistics reveal that the sum of the total TCM design ΔV, i.e., 6.3 m/s, is less than the mean ΔV, a result of the highly accurate Venus flybys and, most notably, trajectory re-optimization efforts immediately after a flyby. The large reduction in TCM ΔV comes from redesigning subsequent Venus flybys, exploiting the Venus gravity assists to make the required trajectory corrections downstream.

In terms of maneuver performance, the last column in Table 8 represents the post-burn reconstructed values, calculated by the Orbit Determination Team after each executed TCM. The small differences between the commanded and reconstructed ΔV values demonstrate the accuracy of the flight system and the navigation prediction.

7. Concluding Remarks

The ground-breaking Parker Solar Probe mission has accomplished much within the first four years, breaking many records, and will continue to break them before the end of the prime mission. Certain intensive operations periods have allowed the Project to exercise various maneuver design strategies: a contingency burn, multiple back-to-back maneuver cancellations (especially during the last flyby transfer), and a decomposed, two-part burn to avoid violating safe pointing constraints. This navigation experience provides a great opportunity for the PSP Navigation Team to re-assess and continue improve current design strategies and in-flight processes.

Parker Solar Probe's space flight performance continues to exceed all expectations and outperform pre-launch predictions. Trajectory reoptimization efforts help redirect the spacecraft towards an optimal trajectory path to Venus-7, the last planned Venus gravity assist flyby, while reducing downstream ΔV costs. More importantly, solar encounters continue to go nearly exactly as designed and predicted, with dispersions well within the navigation requirements. This paper reviews the deterministic and statistical designs for the TCMs with inputs provided by accompanying navigation and orbit determination analyses made from the first to the fifth Venus flybys, showing that navigation delivery accuracy for minimum perihelion is always satisfied. However, past experience shows that every delivered trajectory is unique and TCM analysis and results can vary, so the PSP Navigation Team plans to continue documenting the probe's flight experience.

Acknowledgment

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Appendix A: B-Plane Description

Planet or satellite approach trajectories are typically described in aiming plane coordinates referred to as "B-Plane" coordinates[11] (see Figure 14). 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 **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). **T** is arbitrary, but it is typically specified to lie in the ecliptic plane (e.g., EMO2000), or in a body equatorial plane (e.g., EME2000). Finally, **R** completes an orthogonal triad with **S** and **T** (i.e., $\mathbf{R} = \mathbf{S} \times \mathbf{T}$).

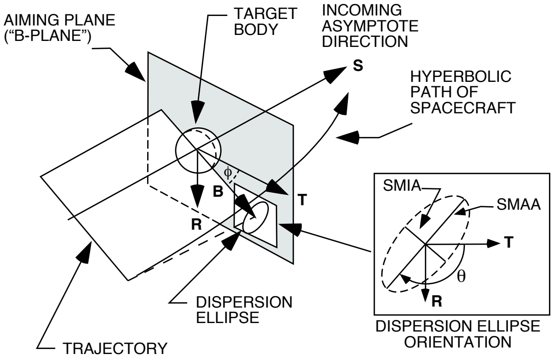

Figure 14: B-Plane coordinate system

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 $\mathbf{S}$ 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 14. 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 $\mathbf{S}$ direction, numerically equal to the time-of-flight error multiplied by the magnitude of the $\mathbf{V}_\infty$ vector.

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