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FLIGHT PATH CONTROL ANALYSIS FOR PARKER SOLAR PROBE

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An unprecedented NASA mission to study the Sun, known as Parker Solar Probe (PSP), is under development. The primary objective of the PSP mission is to gather new data within 10 solar radii of the Sun's center. The purpose of this paper is to review the statistical analysis of trajectory correction maneuvers (TCMs) for PSP's baseline trajectory. The baseline mission includes a total of 42 TCMs that will be accomplished with a monopropellant propulsion system that consists of twelve 4.4 N thrusters. Assuming current navigation models, statistical analyses for each reference trajectory during the 20-day launch period result in a total ΔV99 of less than 100 m/s.

INTRODUCTION

The countdown to launch the pathbreaking NASA Parker Solar Probe (PSP) to the Sun is currently underway. For almost 50 years, several heliophysics missions have studied our closest star and have provided a glimpse of the solar environment and its effects on the solar system. Formally known as Solar Probe Plus, PSP was renamed after astrophysicist Eugene Parker in May 2017.[1] Parker's pioneering work theorized dynamical models of solar wind that were confirmed by data gained from satellite observations.[2,3] PSP will launch on a Delta-IV Heavy launch vehicle as early as July 31, 2018 and within a 20-day launch period.

The PSP mission science objectives, coupled with innovative hardware, aim to better characterize the Sun. The probe will become the first spacecraft to fly by the Sun at 9.86 solar radii (R_S) or 6.8 million km after a 6.4-year ballistic journey. In comparison, the Helios II spacecraft flew by the Sun at about 43.5 million km in 1975. The spacecraft will also become the fastest satellite at closest approach of just under a speed of 200 km/sec (447,000 mph). PSP includes a suite of four instruments: Fields Experiment (FIELDS), Integrated Science Investigation of the Sun (IS$\odot$IS), Wide-field Imager for Solar PRobe (WISPR), and Solar Winds Electrons Alphas and Protons (SWEAP), as shown in Figure 1. This science payload will work together to collect data related to solar wind electrons, magnetic fields, and waves, and will examine the following science goals:[4]

- Trace the flow of energy that heats the corona,
- Determine the mechanisms that accelerate and transport energetic particles,

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- Explore dust plasma near Sun, and
- Determine structure and dynamics of magnetic fields at the sources of solar wind.

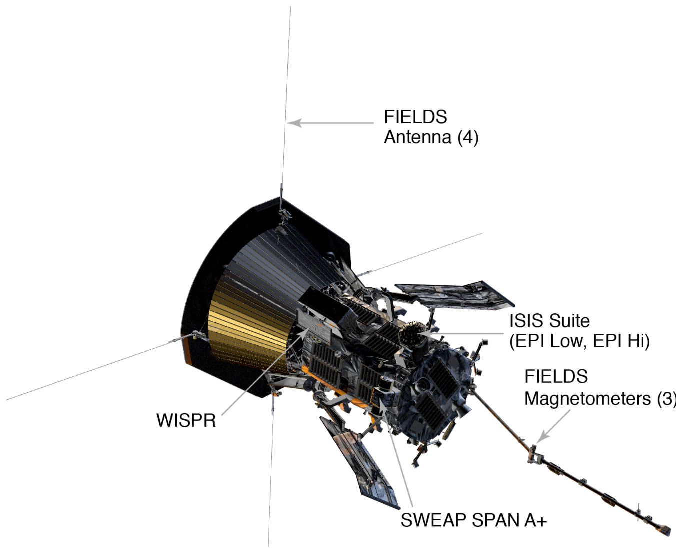


Figure 1. Parker Solar Probe and science payload (FIELDS, ISIS, WISPR, and SWEAP), Ram Facing View[5]

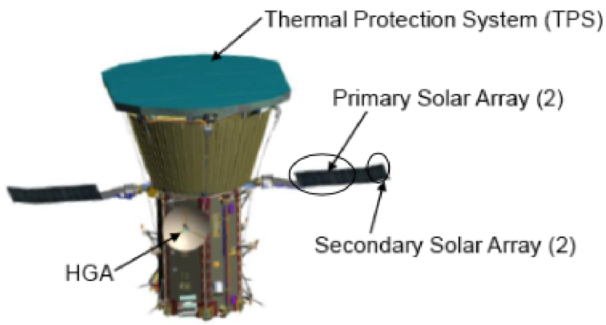
Currently in Phase D, the PSP project is led by the Johns Hopkins Applied Physics Laboratory (APL). While the mission design and spacecraft construction is managed by APL, navigation of the spacecraft is supported by the Jet Propulsion Laboratory (JPL). The navigation team will provide predictions of the spacecraft trajectory, work with mission design to plan and generate the trajectory correction maneuvers (TCMs), and release the final reconstructed spacecraft ephemeris.

Recently published papers give an overview of the mission design and navigation, as well as challenges associated with each.[6–8] The objective of this paper is to review the statistical analysis of TCMs for PSP's baseline trajectory with inputs provided by accompanying navigation and covariance anaylses made during the Preliminary Mission Analysis (PMA).[9,10] Several cycles of TCM analysis have been conducted; however, this is the first published paper that captures TCM statistical results. Studies have been made to determine the mission's total statistical ΔV, the cost of missing or cancelling a scheduled maneuver, and the sensitivity of TCM placement. Finally, this paper will point out the TCMs that are most important to execute based on the current navigation models and mission assumptions.

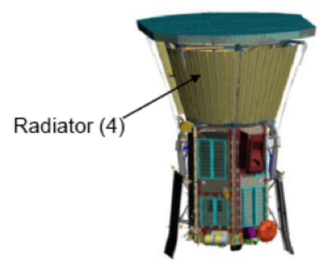
SPACECRAFT OVERVIEW

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. The TPS will always be pointed at the Sun (Figure 2) to protect the spacecraft bus from extreme temperatures. All of the science instruments will be covered by the TPS, with the exception of the 4 antennas that are part of the FIELDS experiment. Given a solar distance, the primary and secondary solar arrays will rotate to a particular flap angle.[11] Comprised of photovoltaic arrays, the primary array 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. Science downlink and communication will be made with the 0.6 meter Ka-band High Gain Antenna (HGA). Maneuvers will be accomplished with a monopropellant propulsion system that consists of a hydrazine tank and twelve 4.4 N thrusters.



(a) PSP near Earth



(b) PSP near Sun

Figure 2. Spacecraft configurations near Earth and Sun

BASELINE TRAJECTORY

The baseline trajectory, designed by APL, accommodates a 20-day launch period that starts on July 31, 2018, and continues through August 19, 2018. The 6.4-year trajectory to the Sun uses seven gravity assists of Venus (Figure 3). PSP will 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 from 36 R_S to 9.86 R_S. A backup trajectory is designed for a launch in 2019 and is based on shifting the baseline trajectory by one year. The backup design utilizes eight Venus flybys to approach the final perihelion target.

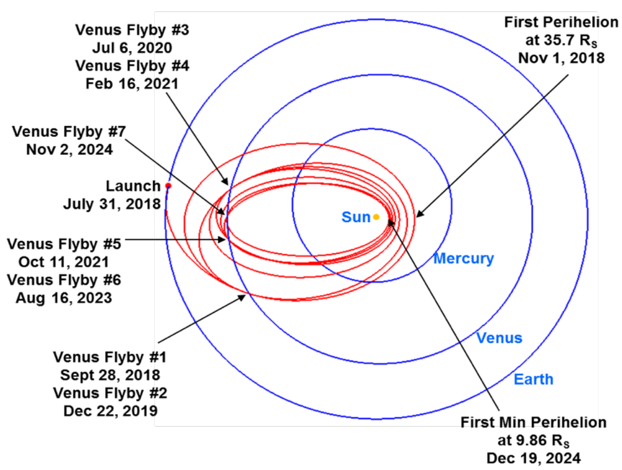


Figure 3. PSP's Baseline V^7-Gravity Assist Trajectory

While the baseline trajectory is ballistic and has no deep space or deterministic maneuvers, careful placement of the mission's statistical trajectory correction maneuvers (TCMs) is made to correct

Venus flyby errors and other unmodeled errors. 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 cleanup 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.

Table 1. TCM and Encounter Schedule for the 31 July 2018 Baseline Trajectory

Maneuver/ Encounter	Date	Time* (UTC)	Maneuver/ Encounter	Date	Time* (UTC)
TCM-01	07-Aug-2018	10:00:00	Venus-5	11-Oct-2021	18:35:12
TCM-02	19-Aug-2018	18:00:00	TCM-24	06-Dec-2021	18:00:00
TCM-03	07-Sep-2018	18:00:00	TCM-25	07-Mar-2022	18:00:00
TCM-04	23-Sep-2018	18:00:00	TCM-26	16-Jun-2022	18:00:00
Venus-1	28-Sep-2018	17:32:15	TCM-27	15-Sep-2022	18:00:00
TCM-05	11-Oct-2018	18:00:00	TCM-28	17-Nov-2022	18:00:00
TCM-06	05-Dec-2018	18:00:00	TCM-29	02-Apr-2023	18:00:00
TCM-07	12-May-2019	18:00:00	TCM-30	02-Jun-2023	18:00:00
TCM-08	06-Oct-2019	18:00:00	TCM-31	29-Jul-2023	18:00:00
TCM-09	03-Dec-2019	18:00:00	TCM-32	11-Aug-2023	18:00:00
TCM-10	16-Dec-2019	18:00:00	Venus-6	16-Aug-2023	21:04:02
Venus-2	22-Dec-2019	3:01:40	TCM-33	09-Oct-2023	18:00:00
TCM-11	05-Jan-2020	18:00:00	TCM-34	29-Nov-2023	18:00:00
TCM-12	05-Mar-2020	18:00:00	TCM-35	10-Apr-2024	18:00:00
TCM-13	18-Jun-2020	18:00:00	TCM-36	11-Jun-2024	18:00:00
TCM-14	01-Jul-2020	18:00:00	TCM-37	21-Aug-2024	18:00:00
Venus-3	06-Jul-2020	12:32:13	TCM-38	15-Oct-2024	18:00:00
TCM-15	16-Jul-2020	18:00:00	TCM-39	27-Oct-2024	18:00:00
TCM-16	23-Dec-2020	18:00:00	Venus-7	02-Nov-2024	4:27:22
TCM-17	26-Jan-2021	18:00:00	TCM-40	20-Nov-2024	18:00:00
TCM-18	11-Feb-2021	18:00:00	Periapsis-22	19-Dec-2024	20:02:27
Venus-4	16-Feb-2021	5:14:03	TCM-41	27-Jan-2025	18:00:00
TCM-19	02-Mar-2021	18:00:00	Periapsis-23	18-Mar-2025	6:43:41
TCM-20	10-May-2021	18:00:00	TCM-42	16-Apr-2025	18:00:00
TCM-21	20-Aug-2021	18:00:00	Periapsis-24	14-Jun-2025	17:24:15
TCM-22	23-Sep-2021	18:00:00			
TCM-23	06-Oct-2021	18:00:00			

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

REQUIREMENTS

Forty mission design and navigation requirements (MDNR)[12] were derived from the Level 2 Mission Requirements Document, and cite conditions that must be met during the mission. The following outlines seven flight path control-related requirements:

- **MDNR-3**: The spacecraft shall 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, and
- **MDNR-77**: Navigation Delivery Accuracy for Minimum Perihelion Delivery shall be within 500 km (3-σ) at 9.86 R_S perihelion.

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. 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"). Past mission design and navigation reviews confirmed that all items were met.[13] Other 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.

TARGETING STRATEGY

The targeting strategy shown in Figure 4 was employed for the trajectory simulation. This 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. The x-axis represents the maneuvers used in the optimization chain for a particular TCM, and the y-axis denotes the corresponding TCM. Each of the seven Venus encounters and final three perihelion are represented as vertical lines. Note that the last two maneuvers before an encounter are constrained to the same target. This increases the chance of cancelling the last TCM. Downstream TCMs within the chain are re-optimized after each TCM is executed. The last three maneuvers (TCMs 40, 41, and 42) only target perihelion distance, not position.

MATCH TRAJECTORIES

For all trajectory design cycles, the APL mission design team generates and delivers baseline reference trajectories to the PSP project. The results in this paper reflect the most recent trajectory design cycle, the Preliminary Mission Analysis. During PMA, mission designers delivered 20 reference trajectories that cover the July 31, 2018 to Aug 19, 2018 daily launch period, along with the corresponding TCM and targeted flyby locations. The navigation team reintegrates or "matches" these trajectories by targeting to three B-plane parameters[14] 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).

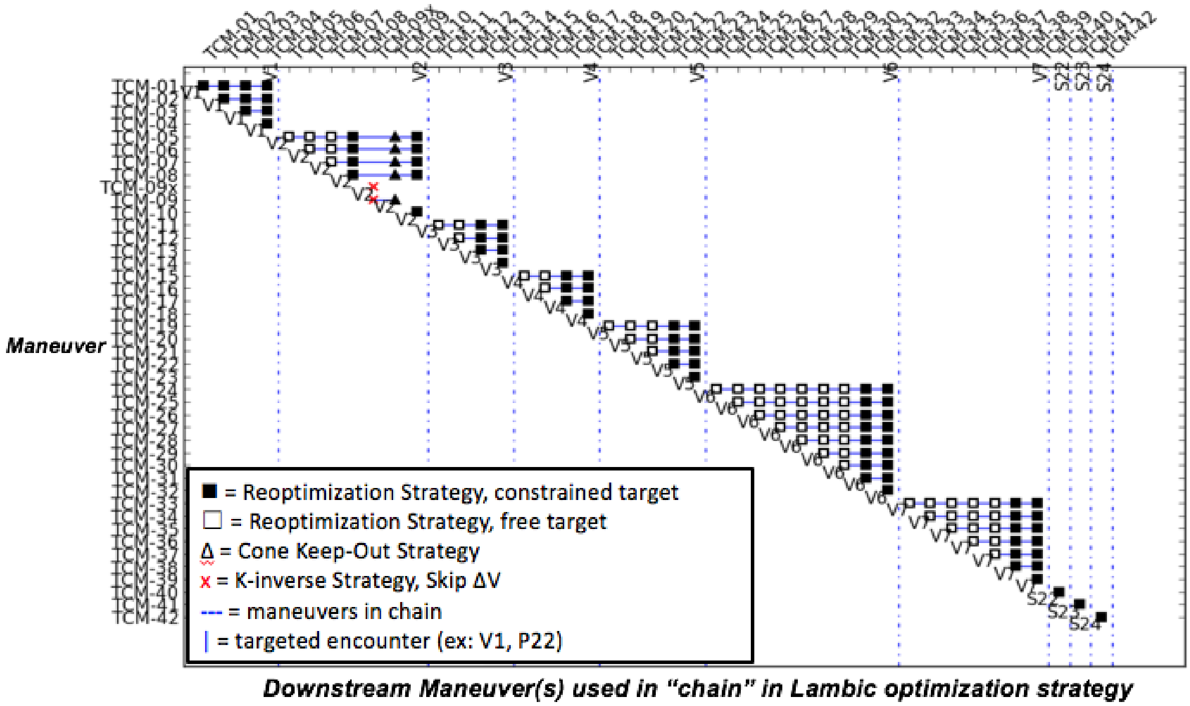


Figure 4. Targeting Strategy in MONTE-LAMBIC

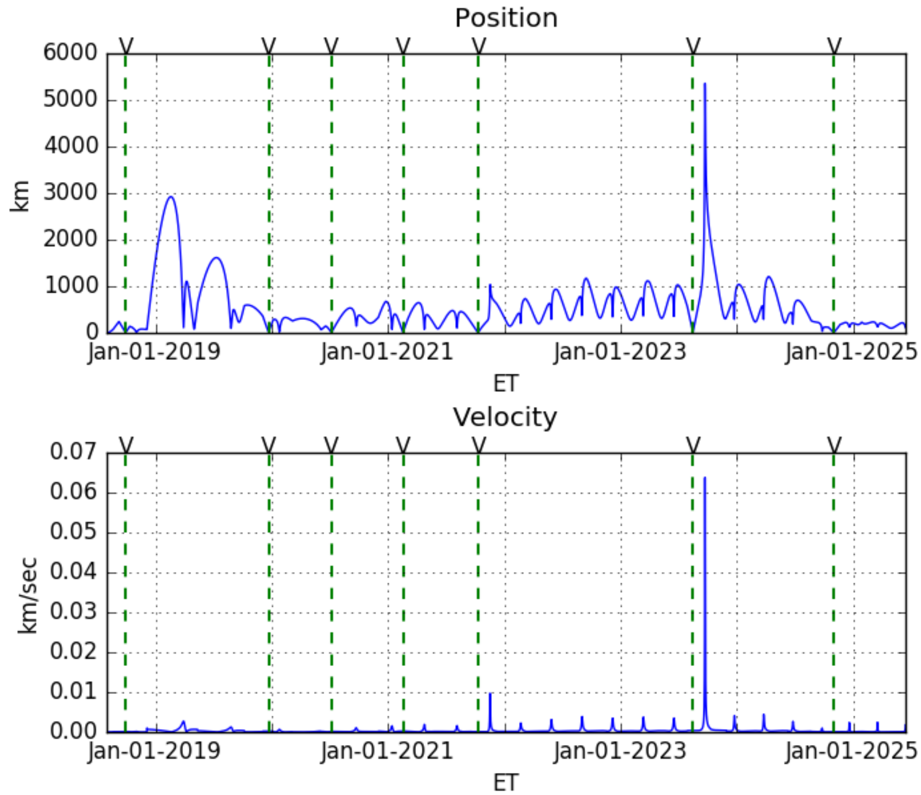
As expected, navigation results show small ΔV values (average TCM ΔV size less than 0.1 m/s) for each of the trajectories to match the APL reference trajectories, and that the total ΔV differences range from 4.0 to 5.5 m/s. These ΔV differences are a result of each's teams own software and integration schemes, and are an acceptable deterministic cost in the overall ΔV budget. The second column of Table 5 lists the match ΔV differences for each day during the launch period.

Figure 5 compares the position and velocity differences between the mission design reference trajectories and navigation match trajectories for the open (31 July 2018), middle (10 August 2018), and close (19 August 2018) of the launch period. The plots show that the approach TCM ΔV to each Venus target is zero. Also, there is no ΔV difference at post-Venus-7 periapsis, and this satisfies the PSP trajectory requirement for one TCM to achieve the 9.86 Rs periapsis distance after the final Venus flyby. There are minor position differences at most of the solar periapses, except after the Venus-6 flyby. The large post Venus-6 position difference is due to not targeting Periapsis-17 since there is no TCM placed between the Venus flyby and solar periapsis.

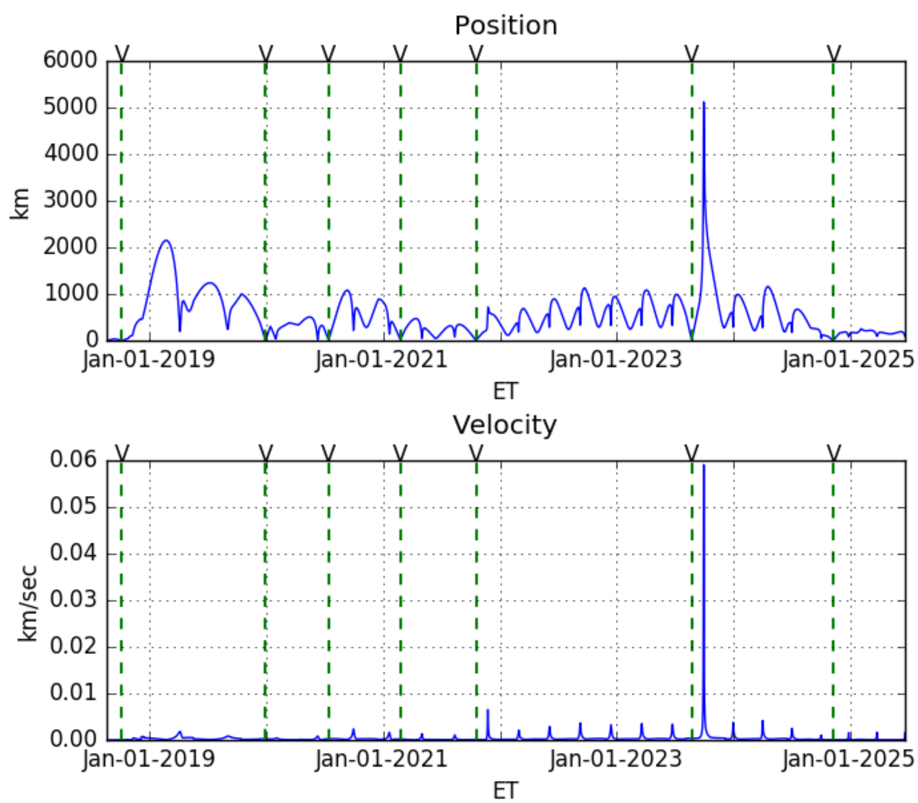
RESULTS

Assuming current navigation models, launch vehicle injection covariance matrices, an unscaled figure-of-merit*, and maneuver strategy, statistical analyses for each reference trajectory during the 20-day launch period were conducted. A single Gates execution-error model,[15] shown in Table 3, was implemented to represent maneuver execution errors. These errors account for four independent

*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) Differences for the open baseline trajectory.



(b) Differences for the close baseline trajectory.

Figure 5. Trajectory differences between mission design and navigation for PMA. *Each dotted vertical line represents one of the seven Venus flybys.*

Table 2. PMA Match ΔV and Statistics

PMA Reference Trajectory	Total Match ΔV(m/s)	ICM	TCM-01 ΔV 99%ile (m/s)	Total ΔV 99%ile (m/s)
	–	Open	37.2	81.5
31 July 2018	4.3	Middle	35.8	80.3
	–	Close	37.5	82.0
01 Aug 2018	4.4	Middle	37.9	80.5
02 Aug 2018	4.4	Middle	37.9	80.5
03 Aug 2018	5.0	Middle	37.5	81.9
04 Aug 2018	4.3	Middle	38.1	83.7
05 Aug 2018	4.3	Middle	37.1	82.3
06 Aug 2018	4.7	Middle	37.1	79.3
07 Aug 2018	4.8	Middle	37.3	81.4
08 Aug 2018	4.9	Middle	38.2	82.3
09 Aug 2018	4.9	Middle	38.0	83.7
	–	Open	38.6	86.9
10 Aug 2018	4.9	Middle	38.1	85.2
	–	Close	38.0	84.4
11 Aug 2018	5.0	Middle	40.0	84.0
12 Aug 2018	5.1	Middle	37.8	85.0
13 Aug 2018	5.2	Middle	39.4	82.6
14 Aug 2018	5.2	Middle	37.4	79.8
15 Aug 2018	5.5	Middle	37.8	83.7
16 Aug 2018	5.3	Middle	39.0	82.8
17 Aug 2018	4.5	Middle	38.4	89.4
18 Aug 2018	4.6	Middle	39.3	85.6
	–	Open	39.5	85.4
19 Aug 2018	4.4	Middle	39.5	85.1
	–	Close	38.1	84.6

error sources: fixed-and proportional magnitude errors, and fixed- and proportional-pointing errors. The Mission-analysis Operations and Navigation Toolkit Environment (MONTE)[16] Linear Analysis of Maneuvers with Bounds and Inequality Constraints (LAMBIC)[17] software was used to compute statistical ΔV via Monte Carlo analysis.

Table 2 lists the trajectory, corresponding total match ΔV, ICM, TCM-01 ΔV 99%ile, and total TCM ΔV 99%ile. The nomenclature used to describe the trajectories For the open (31 July 2018), middle (10 August 2018), and close (19 August 2018) trajectories within the launch period, three ICMs were provided for that day's launch window. Note that when using the open or close ICM, the trajectory is the same as the one listed for middle. For all the trajectories, statistical results in a TCM-01 ΔV 99%ile $\leq$ 40.0 m/s, and mission ΔV99 of less than 100 m/s (last two columns in Table 2).

These statistical results satisfy requirement MDNR-22, that is, the total post-launch statistical ΔV to 99% confidence, is not to exceed 135 m/s. To satisfy the pointing constraint (MDNR-69), TCM design required a cone angle constraint. As an example, TCM-9 (V2-18d, 3-Dec-2019) is performed in two burns to satisfy the pointing constraint.

Table 3. 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

Figure 6 presents the individual and cumulative 50%ile and 99%ile ΔV for the for the open and close trajectories. Each TCM statistical prediction is shown and offers a glimpse of which maneuver contributes most to the overall ΔV total. As expected, most of the post-Venus maneuvers have the largest components since these maneuver cleanup the previous Venus flyby errors. The figure also shows that TCM-01 has the largest statistical value since these maneuvers cleanup errors associated with launch.

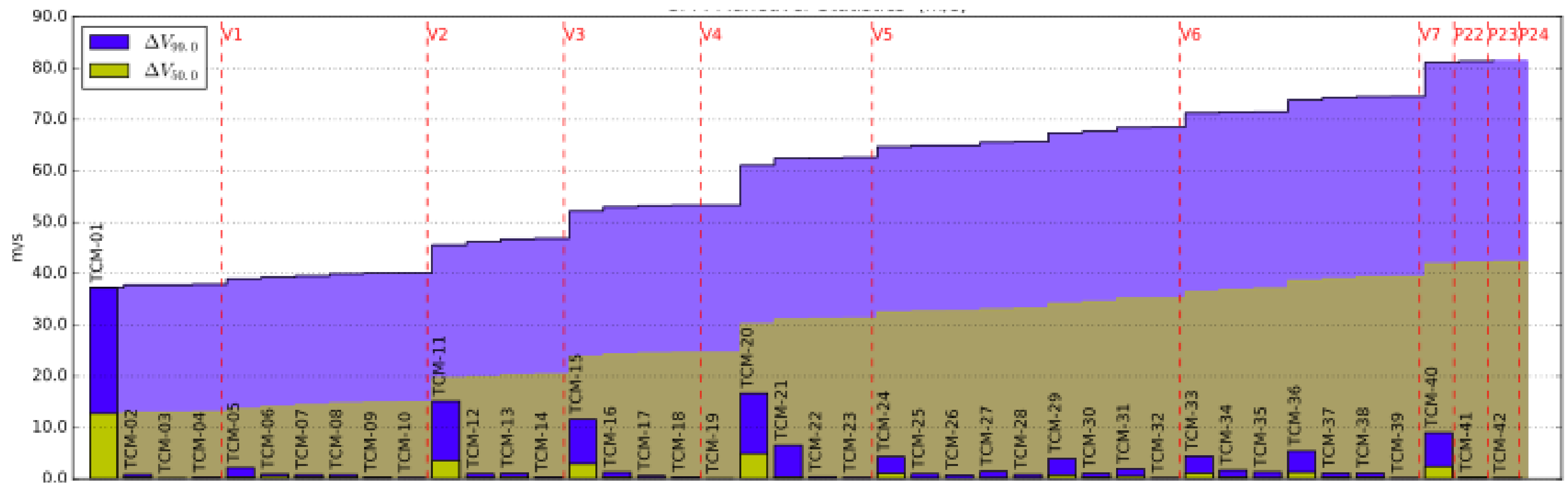
Table 4 shows comparisons of the PMA statistical predictions with the previous design cycle (Critical Design Review, or CDR) for the open, middle, and close trajectories. For each trajectory, it was observed that the total 99%ile ΔV was at least 20 m/s less than the CDR result. Sensitivity studies revealed that refined updates to the ICM and orbit determination assumptions led to the reduced ΔV results.

Table 4. PMA and CDR ΔV and Delivery Accuracy Comparison. *Middle trajectories for CDR 180809 were compared to PMA 180810 values due to available ICMs.*

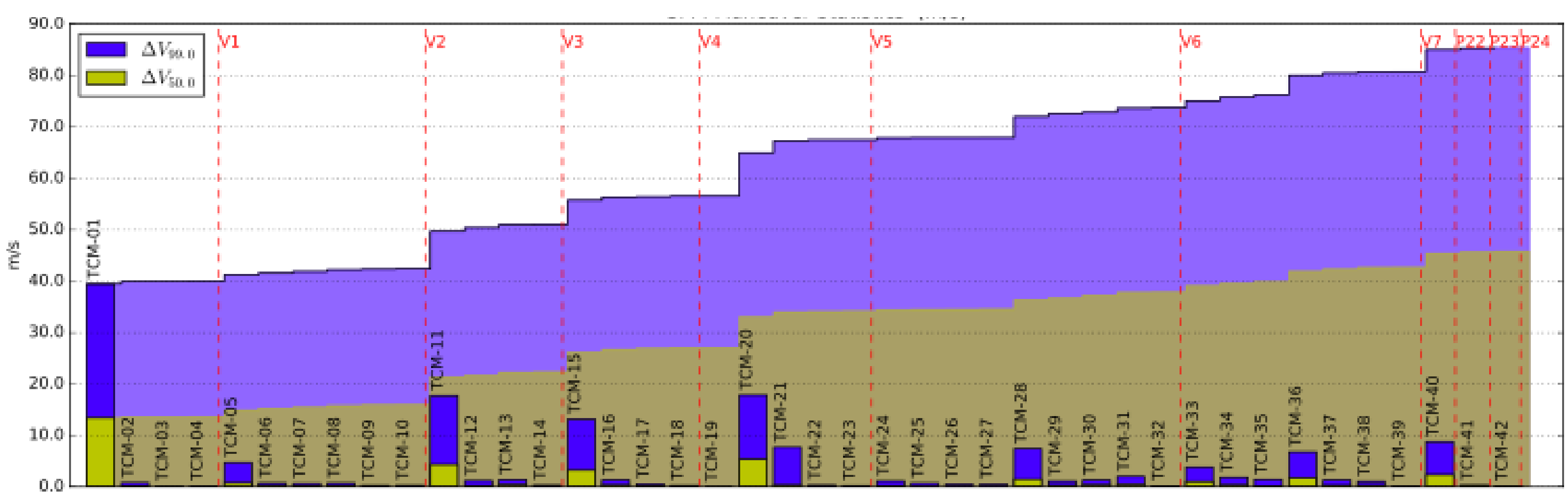
PMA Reference Trajectory	TCM-01 ΔV 99%ile (m/s)	Total ΔV 99%ile (m/s)	Delivery Accuracy for Min Perihelion (km) at Periapsis-22
CDR 31 July 2018	46.9	112.0	±106
PMA 31 July 2018	37.2	81.5	± 82
CDR 09 Aug 2018	–	119.3	–
PMA 10 Aug 2018	38.6	86.9	± 83
CDR 19 Aug 2018	–	111.1	–
PMA 19 Aug 2018	39.5	85.4	± 80

Additionally, TCM capability analysis was performed on all the PMA 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 constraints, or unfavorable dynamics. For example, a TCM could have linearly dependent ΔV gradients, or the angles between gradient vectors near 0 or 180 degrees. This trade confirmed similar results as previous studies and determined that TCM-19 is not required. TCM-19 ΔV $\approx$ 0 m/s until TCM-19 is placed at Venus-4 +28 days, and has similar trajectory geometry for all trajectories.

This study also revealed that TCM-17 for the last 5 trajectories in the launch window (i.e. 15 Aug 2018 through 19 Aug 2018) is located in a tracking gap. TCM-18 is also inside the tracking gap for the baseline close trajectory. Continued evaluation of these maneuvers will be included in the next design cycle.



(a) TCM Statistics for baseline open trajectory.



(b) TCM Statistics for baseline close trajectory.

Figure 6. TCM Statistics for PMA

CONCLUSIONS

This paper reviewed the statistical predictions for the TCMs with inputs provided by accompanying navigation and orbit determination anaylses made during PMA. Several cycles of TCM analysis have been conducted; however, this is the first paper that captures the TCM statistical results. Assuming current navigation models, each reference trajectory during the 20-day launch period results in a mission ΔV99 of less than 100 m/s. It was also determined that the navigation delivery accuracy for minimum perihelion was satisfied. Past experience shows every delivered trajectory is unique and TCM analysis and results can vary. An upcoming design cycle in October 2017 will provide the opportunity to regenerate statistical predications for PSP's baseline trajectory.

ACKNOWLEDGEMENTS

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REFERENCES

[1] "NASA Renames Solar Probe Mission to Honor Pioneering Physicist Eugene Parker," `https://www.nasa.gov/feature/goddard/2017/nasa-renames-solar-probe-mission\-to-honor-pioneering-physicist-eugene-parker`. Accessed: 2017-07-24.

[2] E. Parker, "Dynamical Theory of the Solar Wind," *Space Science Reviews*, Vol. 4, No. 5-6, 1965, pp. 666–708.

[3] *Physics and Chemistry in Space: Coronal Expansion and Solar Wind*. Springer-Verlag GmbH, 1 ed., 1972.

[4] "Parker Solar Probe Science Objectives," `http://parkersolarprobe.jhuapl.edu/The-Mission/index.php#Science-Objectives`. Accessed: 2017-07-24.

[5] "PSP Spacecraft Ram Facing View Instrument Description," `http://parkersolarprobe.jhuapl.edu/index.php#spacecraft`. Accessed: 2017-07-26.

[6] Y. Guo, "Solar Probe Plus: Mission Design Challenges and Trades," *Acta Astronautica*, Vol. 67, No. 9-10, 2010, pp. 1063–1072.

[7] Guo, Y., McAdams, Ozimek, M., and Shyong, W.J.,, "Solar Probe Plus Mission Design Overview and Mission Profile," *24th International Symposium on Space Flight Dynamics, Paper S6-2*, Laurel, Maryland, May 5-9, 2014.

[8] Jones, D.R., Goodson, T., Thompson, P., Valerino, P., and Williams, J., "Solar Probe Plus: Unique Navigation Modeling Challenges," *27th AAS/AIAA Space Flight Mechanics Meeting*, San Antonio, TX, February 5-9, 2016.

[9] Jones, D.R., Thompson, P., Valerino, P., Lau, E., Goodson, T., Chung, M.K., and Mottinger, N., "Orbit Determination Covariance Analyses for the Parker Solar Probe Mission," *to appear in proceedings of the 2017 AAS/AIAA Astrodynamics Specialists Conference, Paper AAS 17-576*, Stevenson, WA, August 20-24, 2017.

[10] Thompson, P., "Parker Solar Probe Navigation: One Year From Launch," *to appear in proceedings of the 2017 AAS/AIAA Astrodynamics Specialists Conference, Paper AAS-17-604*, Stevenson, WA, August 20-24, 2017.

[11] S. W.-J. Guo, Y. and C. Scott, "Solar Radiation Pressure Modeling in Mission Design Software for Solar Probe Plus," SEG-13-004, Johns Hopkins University Applied Physics Laboratory, Laurel, MD, 2013.

[12] Y. Guo, "Solar Probe Plus (SPP) Level 3 Mission Design and Navigation Requirements Document (MDNR)," Rev C, Internal document, Johns Hopkins University Applied Physics Laboratory, Laurel, MD, 2016.

[13] T. Goodson *et al.*, "Solar Probe Plus Navigation Plan," Internal document, Jet Propulsion Laboratory, Pasadena, CA, 2015.

[14] Kizner, W., "Method of Describing Miss Distances for Lunar and Interplanetary Trajectories," *JPL External Publications 674*, August 1959.

[15] Gates, C.R., "A Simplified Model of Midcourse Maneuver Execution Errors," *JPL Technical Report 32–504*, October 15, 1963.

[16] Smith, J., Taber, W., Drain, T., Evans, S., Evans, J., Guevara, M., Schulze, W., Sunseri, R., Wu, H.C., "MONTE Python for Deep Space Navigation," *Proceedings of the 15th Python in Science Conference* (S. Benthall and S. Rostrup, eds.), 2016, pp. 62 – 68.

[17] E. H. Maize, "Linear Statistical Analysis of Maneuver Optimization Strategies," *AAS/AIAA Astrodynamics Conference, AAS Paper 87-486*, Kalispell, Montana, August 1987.