Parker Solar Probe Highly Constrained Maneuver Design via Vector Decomposition

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***Abstract* – The successful delivery of Parker Solar Probe (PSP) to touch the Sun via an intricate V^7GA trajectory requires a decisive application of trajectory correction maneuvers (TCMs) throughout the mission under stringent spacecraft orientation constraints. These constraints restrict the spacecraft from orienting freely to align thrusters with a TCM and challenge PSP's TCM implementation, especially when a TCM ΔV falls in the spacecraft thrust-excluding zone. A new method for implementing a TCM ΔV in the spacecraft thrust-excluding zone by decomposing it into two new ΔV vectors along the zone boundary thrust directions and implementing them in two separate burns is described. PSP's TCM design on different types of maneuver implementation under various spacecraft attitude modes are presented.**

I. INTRODUCTION

Parker Solar Probe (PSP) is the first mission ever able to reach close to the Sun, for collecting in situ measurements and images inside the Sun's corona to study the origin and evolution of solar wind. The exceedingly high energy required to get close to the Sun and being able to operate in the Sun's harsh environment make it the most technically challenged mission to realize, from mission design [1], flight system development, to mission operations. The mission is designed [2] for launching at a high C3 up to 154 km^2/s^2, by Delta IV Heavy launch vehicle with a Star 48BV upper stage, and utilizing Venus Gravity Assist (VGA) to obtain the enormous orbit changes, totalled at 22.314 km/s of ΔV, required for getting close to the Sun, via a unique V^7GA trajectory as shown in Fig. 1. In the 7-year mission, PSP is to fly by Venus 7 times while orbiting around the Sun 24 times at gradually decreased perihelion distances to the minimum of 9.86 solar radii (R_S).

As the first spacecraft ever entering the region within 0.29 AU of the Sun, PSP is anticipated to face unprecedented challenges in flight operation and trajectory control, such as to experience numerous significant perturbation forces when orbiting around the Sun. Although the Mission Design and Navigation trajectory modelling has 12 different force models [3], many of the non-gravitational perturbation forces are unpredictable and cannot be modelled precisely. The successful delivery of PSP to the Sun following the planned V^7GA trajectory requires a decisive application of trajectory correction maneuvers (TCMs) throughout the intricate mission trajectory involving seven Venus gravity-assist flybys and 24 solar encounters under stringent spacecraft and mission operation constraints.

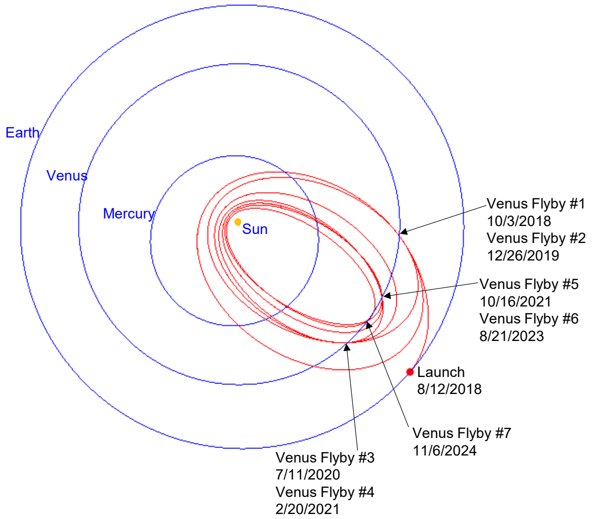

Fig. 1. Parker Solar Probe mission trajectory.

Unlike other deep space missions, the PSP spacecraft's attitude during the mission is strictly constrained to a fixed orientation relative to the Sun according to the range from the Sun in order to withstand the harsh Sun environment and satisfy the thermal and power conditions. These orientation constraints prevent the spacecraft from turning its thrusters to the ΔV direction of a required TCM for implementing the TCM. In some cases, the TCM can be implemented by resolving the ΔV vector into components along the directions of different thruster groups. But in other cases, the ΔV direction is in the spacecraft thrust-excluding zone where no thrust can be produced by the different groups of thrusters in any combination. In this situation, the TCM cannot be implemented in any previously known method.

This highly constrained TCM implementation problem is solved using an analytical vector decomposition method by decomposing the original TCM ΔV vector into two or more new vectors to be achievable by the spacecraft in multiple burns. An optimal decomposition solution found by the author is described, which provides a simple and fast approach in the design of this type of unusually constrained TCM.

In this paper PSP's TCM design under the unusual maneuver implementation constraints is presented. Section II introduces TCMs' critical role in PSP's in-flight trajectory control and the unique aspects of this mission's TCMs, followed with Section III on maneuver design constraints, including spacecraft thruster configuration and orientation constraints. Section IV discusses maneuver implementation analysis on the various defined spacecraft attitude modes. The new maneuver implementation method for TCM ΔV in spacecraft thrust-excluding zone is described in Section V. PSP's specific TCM design, including realistic maneuver modelling and example TCM designs representing the various maneuver implementation methods used in actual flight operation, such as turn-and-burn, vector-burn, and two-burn vector decomposition, is discussed in Section VI.

II. TRAJECTORY CORRECTION MANEUVER

PSP's in-flight trajectory control uses a systematic two-level control method and divides the complex trajectory into 8 simple segments separated by the Venus flybys [4]. The in-flight trajectory re-optimization, as the first level of control, selects an optimal flight path for the entire remaining trajectory after a major orbit change event, such as launch and a VGA, and defines the Venus flyby target at the terminal control point of each trajectory segment. TCMs, as the second level control element, are used for applying small ΔV changes to adjust an individual trajectory segment to meet the target at the end control point after the target is set by the in-flight trajectory re-optimization.

There are 42 TCMs planned, two for launch correction, two prior to each Venus flyby for targeting the desired VGA, one after the flyby for correcting VGA errors, and one on each orbit for taking out accumulated orbit errors following each solar encounter, as listed in Table 1. The critical TCMs, identified in the pre-launch analysis that could cause a significant consequence if missed, are added with a backup opportunity one day later, such as TCM-1c being the backup of TCM-1.

Due to the nature of the mission trajectory, trajectory correction ΔV is highly sensitive to TCM location in orbit and varies non-linearly and dramatically. TCM placements are optimized in terms of ΔV cost by comprehensive analysis, being deconflicted with science observations and spacecraft activities and satisfying conditions required for TCM operation. All TCMs are placed at solar distances greater than 0.45 AU due to spacecraft thermal constraints. For each TCM there must be sufficient Telecommunications and available Deep Space Network (DSN) tracking for Orbit Determination (OD), TCM commands uplink, and TCM monitoring during the burn. No TCMs are placed during solar conjunctions (Sun-Earth-Probe angle < 3° for X-band, < 1.7° for Ka-band) and during the thermal protection system blockage period (Sun-Probe-Earth angle < 15°).

Table 1. TCM schedule.

TCM	Function	Relative Placement	Date	Sun Distance (AU)	Orbit
1	Launch correction	L+7.1d	8/19/18	1.007	1
1c	TCM-1 backup	L+8.1d	8/20/18	1.006	1
2	TCM-1 cleanup	V1-32.7d	8/31/18	0.974	1
2c	TCM-2 backup	V1-31.7d	9/1/18	0.970	1
3	Venus 1 targeting	V1-21.7d	9/11/18	0.918	1
3c	TCM-3 backup	V1-20.7d	9/12/18	0.912	1
4	Venus 1 targeting	V1-4.8d	9/28/18	0.779	1
4c	TCM-4 backup	V1-3.8d	9/29/18	0.769	1
5	Venus 1 cleanup	V1+13.4d	10/16/18	0.545	1
5c	TCM-5 backup	V1+14.4d	10/17/18	0.529	1
6	Venus 1 cleanup	V1+67.5d	12/9/18	0.726	1
6c	TCM-6 backup	V1+68.5d	12/10/18	0.737	1
7	Venus 2 targeting	V2-227.0d	5/13/19	0.778	2
8	Venus 2 targeting	V2-76.9d	10/10/19	0.781	3
9	Venus 2 targeting	V2-17.8d	12/8/19	0.873	4
10	Venus 2 targeting	V2-4.9d	12/21/19	0.776	4
10c	TCM-10 backup	V2-3.9d	12/22/19	0.767	4
11	Venus 2 cleanup	V2+15.1d	1/10/20	0.527	4
11c	TCM-11 backup	V2+17.1d	1/12/20	0.491	4
12	Venus 3 targeting	V3-124.4d	3/8/20	0.777	4
13	Venus 3 targeting	V3-18.4d	6/22/20	0.470	5
14	Venus 3 targeting	V3-5.4d	7/5/20	0.669	5
14c	TCM-14 backup	V3-4.4d	7/6/20	0.681	5
15	Venus 3 cleanup	V3+8.4d	7/19/20	0.783	5
15c	TCM-15 backup	V3+9.4d	7/20/20	0.788	5
16	Venus 4 targeting	V4-54.0d	12/28/20	0.561	7
17	Venus 4 targeting	V4-20.0d	1/31/21	0.458	7
18	Venus 4 targeting	V4-5.1d	2/15/21	0.681	7
18c	TCM-18 backup	V4-4.1d	2/16/21	0.691	7
19	Venus 4 cleanup	V4+14.9d	3/7/21	0.782	7
20	Venus 5 targeting	V5-153.6d	5/15/21	0.512	8
20c	TCM-20 backup	V5-151.6d	5/17/21	0.546	8
21	Venus 5 targeting	V5-51.6d	8/25/21	0.505	9
22	Venus 5 targeting	V5-16.5d	9/29/21	0.783	9
23	Venus 5 targeting	V5-4.5d	10/11/21	0.754	10
23c	TCM-23 backup	V5-2.5d	10/13/21	0.743	10
24	Venus 5 cleanup	V5+55.5d	12/10/21	0.567	10
25	Venus 6 targeting	V6-526.8d	3/12/22	0.494	11
26	Venus 6 targeting	V6-426.8d	6/20/22	0.556	12
27	Venus 6 targeting	V6-334.7d	9/20/22	0.485	13
28	Venus 6 targeting	V6-272.6d	11/21/22	0.569	14
29	Venus 6 targeting	V6-136.8d	4/6/23	0.573	15
30	Venus 6 targeting	V6-74.8d	6/7/23	0.481	16
31	Venus 6 targeting	V6-17.8d	8/3/23	0.754	16
32	Venus 6 targeting	V6-4.8d	8/16/23	0.748	17
32c	TCM-32 backup	V6-3.8d	8/17/23	0.745	17
33	Venus 6 cleanup	V6+53.4d	10/13/23	0.512	17
34	Venus 7 targeting	V7-337.9d	12/4/23	0.628	18
35	Venus 7 targeting	V7-205.0d	4/15/24	0.525	19
36	Venus 7 targeting	V7-145.0d	6/14/24	0.504	20
37	Venus 7 targeting	V7-72.0d	8/26/24	0.714	21
38	Venus 7 targeting	V7-17.9d	10/19/24	0.571	21
39	Venus 7 targeting	V7-4.9d	11/1/24	0.703	21
39c	TCM-39 backup	V7-3.9d	11/2/24	0.709	21
40	Venus 7 cleanup	V7+18.1d	11/24/24	0.678	22
40c	TCM-40 backup	V7+20.1d	11/26/24	0.662	22
41	Peri adjustment	P23-49.1d	2/1/25	0.725	22
42	Peri adjustment	P24-58.6d	4/21/25	0.679	23

In flight operation TCMs are applied according to the pre-launch defined TCM plan (Tab. 1), with only minor adjustments post launch, shifting by one or two days due to DSN track conflicts. TCMs are needed for correcting launch errors, OD and TCM execution errors, errors due to trajectory perturbations from un-modelled solar radiation pressure and spacecraft thermal re-radiation, and small forces of momentum dumps. Timely trajectory correction by TCM is critical to maintain sufficient fuel margin and to keep the spacecraft on track to the target.

III. MANEUVER DESIGN CONSTRAINTS

A. *Thruster Configuration*

The PSP spacecraft is equipped with a blowdown monopropellant hydrazine propulsion system consisting of a small propellant tank loaded with 82.77 kg of hydrazine at launch and 12 4.4-N thrusters for both attitude control and trajectory ΔV maneuvers [5]. The limited amount of onboard propellant constrains the TCMs applied for trajectory control must be optimally designed to consume as less fuel as possible during the execution of the 7-year intricate 7-Venus flyby trajectory. On the other hand, the mission faces unavoidable extra ΔV cost in implementing a ΔV into a spacecraft maneuver, called maneuver implementation penalty, at an unprecedentedly high level due to the stringent spacecraft operation requirements. In order for the spacecraft to be fully controllable in attitude, all 12 thrusters are amounted at some canted angles, which although increases thruster controllability and redundancy but costs more fuel for TCMs with added maneuver implementation penalty.

The 12 thrusters are divided into three groups A, B, and C to produce thrust in the spacecraft +Z-axis, +X-axis, and -Z-axis direction respectively, as shown in Fig. 2. Each group contains 4 thrusters canted at different angles: A-thrusters at 20°, B-thrusters at 10°, and C-thrusters at 30°. In a TCM mode, all 4 thrusters in a group are fired simultaneously to produce a thrust in the desired direction.

B. *Spacecraft Orientation Constraint*

Spacecraft maneuvers like other spacecraft activities are required to comply with the spacecraft pointing and orientation constraints to meet the spacecraft environmental design requirements. The PSP spacecraft's orientation relative to the Sun during the entire mission is completely defined to a strictly specified fixed attitude mode according to the spacecraft's distance from the Sun (Fig. 3), for protecting the spacecraft from the harsh solar environment, meeting thermal constraints of the cooling system, spacecraft and instruments, and remaining power positive within the capacity of the electrical power system and the solar array cooling system.

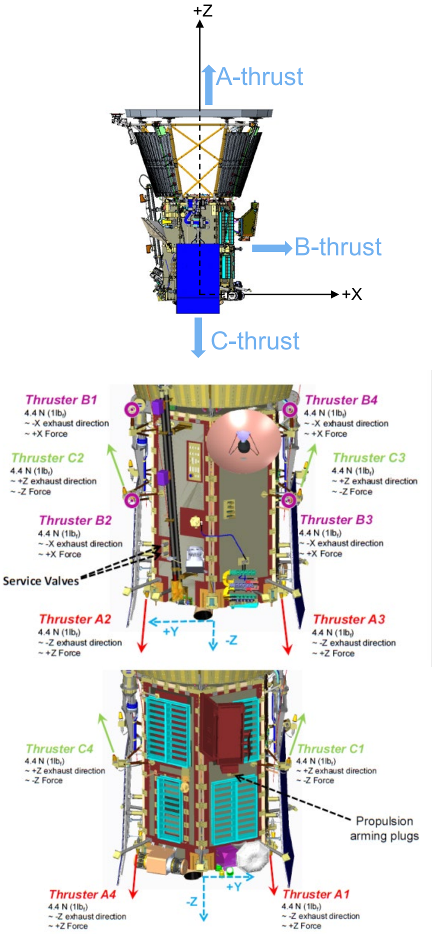

Fig. 2. Thruster configuration.

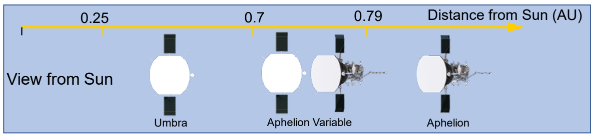

Fig. 3. Spacecraft orientation constraint.

There are three main attitude modes: Umbra, Aphelion Variable, and Aphelion, as shown in Fig. 3. At solar distances less than 0.7 AU the spacecraft must be in the Umbra attitude mode with the +Z-axis pointed at the Sun, in which the thermal protection system (TPS) is facing the Sun to completely shield the sunlight from the spacecraft bus. The spacecraft is allowed to rotate around the Spacecraft-Sun line as long as the +Z-axis is maintained pointing at the Sun. At solar distances greater than 0.79 AU, the spacecraft must be in the Aphelion attitude mode and orient in such a way that the spacecraft-to-Sun line is 45° from the spacecraft +Z-axis in the -X+Z quadrant of the X-Z plane to maintain an adequate heat load into the cooling system. Rotation of the spacecraft around the spacecraft-Sun line is also allowed in this attitude mode as long as the required Sun position relative to the spacecraft is maintained. A more detailed graphic illustration of the spacecraft orientation with respect to the Sun in the Umbra and Aphelion attitude mode is shown in Fig. 4. Between 0.7 AU and 0.79 AU, the spacecraft is in the Variable Aphelion attitude mode, which is a transition from Umbra to Aphelion with the spacecraft-to-Sun line allowed to vary from 0° to 45° from the spacecraft +Z-axis. During this transition period, either the Umbra or the Aphelion mode is also allowed if desired.

All TCMs, except for TCM-1 and other two early TCMs (TCM-2 and TCM-3), must be conducted in the defined spacecraft attitude mode according to the solar distance. TCM-1 is allowed for a special Launch Correction attitude, and the two early TCMs located at solar distances greater than 0.79 AU are allowed to use the Umbra mode before the cooling system is deployed.

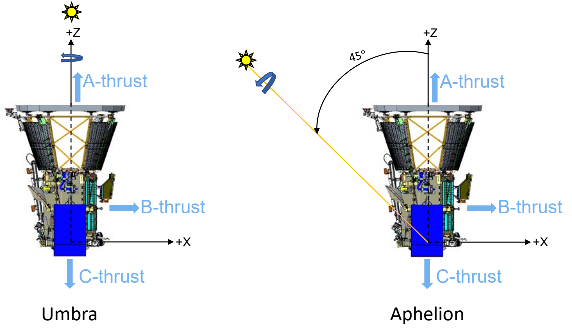

Fig. 4. Illustration of Umbra and Aphelion attitude.

IV. MANEUVER IMPLEMENTATION ANALYSIS

The planned 42 TCMs are located at solar distances between 0.45 AU and 1.01 AU. How a TCM can be implemented depends on the TCM ΔV vector direction with respect to the Sun and the spacecraft attitude mode it is in. Possible TCM implementations with the defined spacecraft attitude modes are analyzed.

A. *Maneuver Implementation with Launch Correction Attitude*

The special Launch Correction attitude is defined specifically for TCM-1, the first and largest TCM anticipated. This special attitude allows the spacecraft to align one group of thrusters along the TCM-1 ΔV direction to reduce maneuver implementation penalty. The only constraint is that the Sun must be on the spacecraft -X hemisphere. Depending on the Sun-Spacecraft-ΔV angle, TCM-1 can be achieved by firing either the A-thrusters or the B-thrusters, as illustrated in Fig. 5. These two group thrusters have smaller cant angles and use less fuel than the C-thrusters.

B. *Maneuver Implementation with Umbra Attitude*

A TCM with spacecraft in the Umbra attitude mode cannot be achieved by one group of thrusters because the TCM ΔV direction in general is different from the three thrust directions. Maneuver implementation in this situation must use two of the three groups of thrusters in a vector form, resolving the ΔV vector into two components along the thrust directions of two groups of thrusters. The TCM is achieved by firing the two groups of thrusters simultaneously.

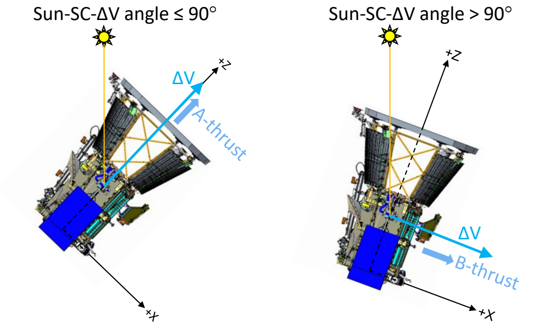

Fig. 5. TCM-1 implementation.

As shown in Fig. 6, spacecraft in the Umbra attitude mode is allowed to rotate about the spacecraft-Sun line. By rotating the spacecraft about the +Z-axis, all possible TCM ΔV vectors can be placed in the spacecraft X-Z plane on the +X-axis side where the three groups of thrusters are located. Selection of which two groups of thrusters for the maneuver is determined by the Sun-SC-ΔV angle. The A- and B-thrusters are used if the Sun-SC-ΔV angle is less than 90°, and the B- and C-thrusters are selected if the Sun-SC-ΔV angle is greater than 90°, as shown in Fig. 6.

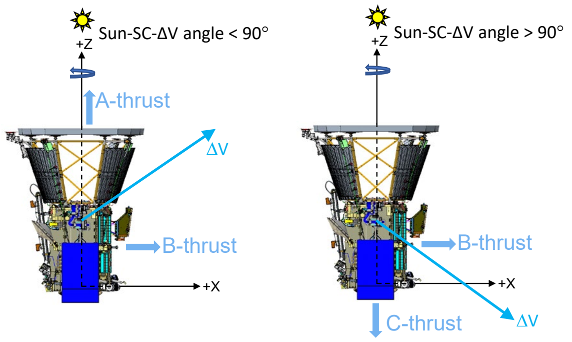

Fig. 6. Maneuver implementation with Umbra attitude.

C. *Maneuver Implementation with Aphelion Attitude*

Maneuver implementation becomes more constrained when the spacecraft is in the Aphelion attitude mode. First, we place the TCM ΔV vector in the same plane with the spacecraft thrust forces by rotating the spacecraft about the spacecraft-Sun line while keeping the Sun direction at 45° from the +Z-axis on the -X side to satisfy the attitude mode requirements. The angle of the ΔV vector from the Sun can vary from 0° to 180°. Depending on the value of the Sun-SC-ΔV angle, there are three possible maneuver implementation cases, as shown in Fig. 7. For the Sun-SC-ΔV angle between 45° and 135°, the maneuver can be achieved by using the A- and B-thrusters in a vector form, and for the Sun-SC-ΔV angle between 135° and 180°, the maneuver can be achieved by the B- and C-thrusters also in a vector form. But if the Sun-SC-ΔV angle is less than 45°, the ΔV is on the -X side, out of the range of the thrusters. In other words, the TCM is in the spacecraft thrust-excluding zone.

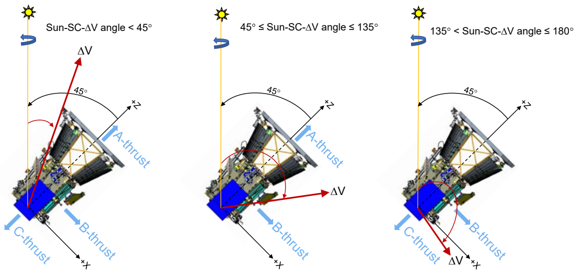

Fig. 7. Maneuver implementation with Aphelion attitude.

V. NEW METHOD FOR THE HIGHLY CONSTRAINED MANEUVER IMPLEMENTATION

The traditional method of maneuver implementation fails when a TCM ΔV falls in the spacecraft thrust-excluding zone in the Aphelion attitude mode as shown in Fig. 7. This highly constrained maneuver implementation problem is solved through an analytical approach based on vector decomposition. The idea is to change the form of representation of the ΔV vector under consideration by transforming it into a new representation that is achievable by the spacecraft's thrusters in the Aphelion attitude mode. The original ΔV vector is decomposed into multiple new vectors, each of which is either along the A-, B-, or C-thrust direction or along a resultant direction of two groups of the thrusters. The sum of all the new vectors must equal to the original ΔV vector. There can be many different decomposing solutions but will result in different total ΔV cost or fuel usage. What we seek is an optimal solution with minimal fuel usage.

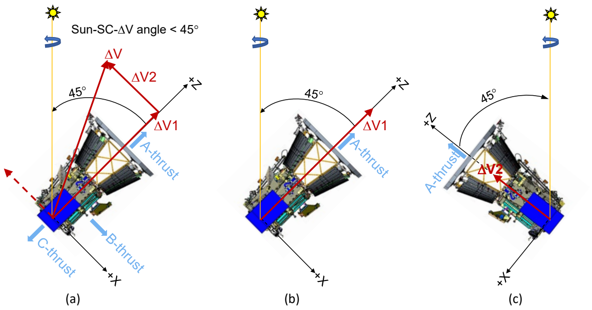

Fig. 8. Illustration of decomposing ΔV in the thrust-excluding zone into two separate burns.

An optimal solution is found. It is to decompose the original ΔV vector in the thrust-excluding zone into two new vectors, $\Delta V1$ and $\Delta V2$, both being along the A-thrust direction but implemented at two separate burns. This optimal decomposition method is illustrated in Fig. 8. The original ΔV is decomposed into $\Delta V1$ and $\Delta V2$ in such a way that $\Delta V1$ is the projection of the ΔV vector onto the spacecraft +Z-axis direction, and $\Delta V2$ is the projection of the ΔV vector onto the -X-axis direction as shown in Fig. 8 (a). The $\Delta V1$ can be achieved by the A-thrusters with the spacecraft orientation shown in Fig. 8. (b) in the Aphelion attitude mode. After the first burn of $\Delta V1$, the spacecraft rotates 180° about the spacecraft-Sun line to the orientation shown in Fig. 8. (c) for the second burn of $\Delta V2$ also by the A-thrusters.

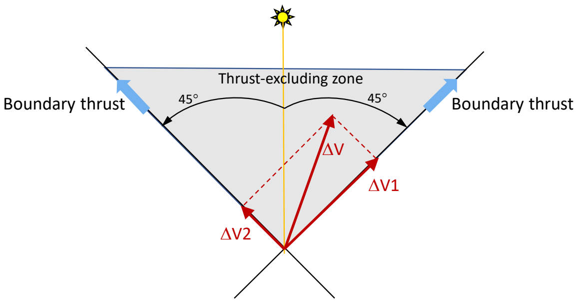

Fig. 9. Method for implementing TCM with ΔV vector in thrust-excluding zone.

The new method can be generalized as: to decompose the ΔV vector in the thrust-excluding zone into two new vectors along the zone boundary thrust directions as illustrated in Fig. 9; the new vectors are the projections of the original vector onto the two boundary thrust directions that can be achieved by the spacecraft in two separate burns while keeping in the Aphelion attitude mode. This new method provides an optimal way for implementing this type of highly constrained maneuvers.

VI. IN-FLIGHT TCM DESIGN

TCMs are designed for use in PSP's flight operation for trajectory control. A TCM design includes determining a required trajectory correction ΔV and implementing it into an achievable maneuver by the PSP spacecraft in real operation. Design values of the TCM serve as onboard control parameters during the spacecraft maneuver execution.

A. Modelling

In the PSP's TCM design, a TCM ΔV is modelled as one or two spacecraft burns by firing the chosen thrusters according to the maneuver implementation method selected for that TCM as discussed in Sections IV & V. The thrust produced by the thrusters, along with propellant usage, is modelled with real-time performance of the PSP Propulsion system, which is a function of the propellant tank pressure and depends on the canted angles of the thrusters.

Mission specific models, including each thruster's pointing direction and Propulsion thrust and Isp model, are built into the Mission Design team's TCM design software package based on STK/Astrogator. The mission specific models also include high fidelity force models, models for solar radiation pressure, and other components needed for trajectory modelling and analysis. Spacecraft orientation including body and solar panels is specified in a spacecraft attitude kernel file.

A TCM's ΔV determination, involving the in-flight trajectory analysis concerning flight dynamics and orbit conditions, and the ΔV-to-maneuver implementation, involving the spacecraft flight systems (Propulsion and G&C), are determined together in an integrated TCM design process, and computed in the same trajectory targeting run using the most up-to-date operational force models and spacecraft Propulsion parameters, striving to be as accurate as possible. Both ΔV values and burn parameters are produced in the TCM design.

B. *Examples of Designed in-flight TCMs*

So far 35 of the 42 planned TCMs have completed in PSP's flight operation, in which 16 were executed and 19 were not needed and cancelled. The 16 executed TCMs were conducted under various spacecraft orientation constraints involving all the defined attitude modes. A representative TCM design for each attitude mode is presented here.

1) Engineering Burn and TCM-1 in Launch Correction Attitude

During the first a few days after PSP's launch on August 12, 2018, the spacecraft made much more frequent momentum dumps than the pre-launch analysis predicted, and on August 15 the ΔV magnitude of momentum dumps by the B thrusters was orders larger than expected, which raised concerns about the thruster performance. On August 16, a decision was made by the project to conduct a small engineering burn (Eng-burn) to verify the use of thrusters before implementing TCM-1. The Eng-burn would use the scheduled TCM-1 time on August 19 and the TCM burn would use the TCM-1c time on August 20, so the originally planned DSN tracks could support both burns.

To accomplish the engineering check and verification, the Eng-burn was chosen at 1 m/s in magnitude and a particular spacecraft orientation: Sun in the spacecraft -X+Z quadrant for thermal and power constraint and Earth in the spacecraft X-Z plane for use of the Fan beam antenna for communication with the Earth-line at -75° of Declination. The TCM-1c design would take into account the Eng-burn and complete the required trajectory correction.

The first in-flight trajectory re-optimization (RO1) process had already completed on August 14, which re-designed the entire post-launch trajectory including all seven VGA flybys to an optimal path. The B-plane target of VGA#1 of the RO1 trajectory was used as the aim point for TCMs 1-4 to target the first Venus flyby on October 3, 2018. The required ΔV for the trajectory correction by TCM-1c was determined to be about 80° from the Sun direction, which indicated the A-thrusters would be used according to the TCM-1 maneuver implementation in Fig. 5. The Eng-burn was designed by selecting its burn direction as close as possible to the TCM-1c ΔV direction while satisfying the Eng-burn spacecraft orientation constraints. Figure 10 shows the final design of Eng-burn and TCM-1c, with the maneuver design parameters listed in Table 2.

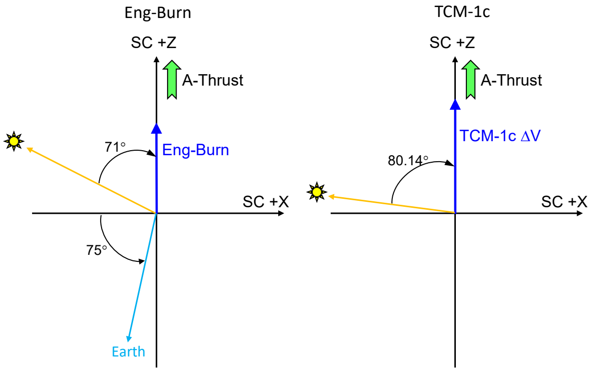

Fig. 10. Eng-Burn and TCM-1c design.

Table 2. Eng-burn and TCM-1c design parameter.

	Eng-Burn	TCM-1c
ΔV Magnitude (m/s)	1	9.230
Right Ascension (deg)	209.187	221.218
Declination (deg)	-19.828	-17.051
Burn Duration (s)	37.55	364.22
Fuel Usage (kg)	0.305	2.806

The Eng-burn went nominally so we proceeded with executing the designed TCM-1c on the next day successfully. Even though the launch errors were corrected by TCM-1c, unusually large and previously un-modelled orbit perturbations beyond the usual outgasing were encountered during the early operations phase. On August 31, a second trajectory correction was made with TCM-2 to remove the orbit errors accumulated since TCM-1c, at a ΔV of 0.743 m/s. After TCM-2, orbit error build-up slowed down, and TCM-3 was not needed and cancelled.

As the investigation on the B-thruster issue was still on-going, use of the B-thrusters was excluded for both momentum dumps and for TCMs. The Launch Correction attitude originally assumed only for TCM-1 in the pre-launch rules was extended to TCM-2 after assessing the actual spacecraft flight conditions. TCM-2 was also implemented in the Launch Correction attitude and used the A-thrusters.

2) TCM-4 in Aphelion Variable Attitude

As the solar distance decreased, the spacecraft orientation became more constrained due to the thermal conditions. The Launch Correction attitude could not be extended to TCM-4. At the solar distance of 0.779 AU, TCM-4 was allowed to use Umbra or Aphelion Variable attitude. The Umbra attitude is eliminated because it would require the use of the B thrusters. Therefore TCM-4 and TCM-4c at solar distance of 0.769 AU were implemented using the Aphelion Variable attitude. The final TCM-4 and TCM-4c implementation design is illustrated in Fig. 11, using the C-thrusters. The design parameters of TCM-4 and TCM-4c are listed in Table 3.

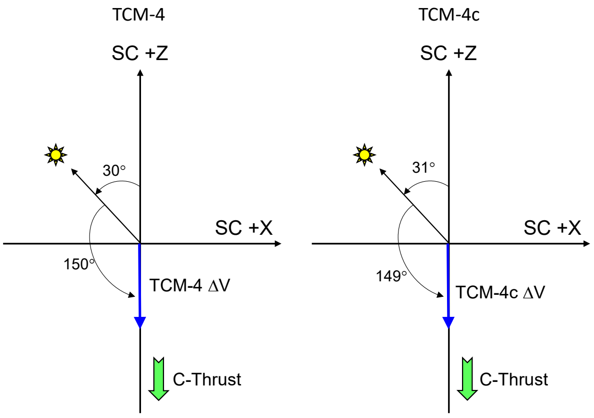

Fig. 11. TCM-4 and TCM-4c implementation design in Aphelion Variable attitude.

Table 3. TCM-4 and TCM-4c design parameter.

	TCM-4	TCM-4c
ΔV Magnitude (m/s)	0.054	0.069
Right Ascension (deg)	325.039	325.045
Declination (deg)	4.556	4.473
Burn Duration (s)	2.293	2.907
Fuel Usage (kg)	0.018	0.023

At one hour before the scheduled TCM-4 burn start time, the burn was suddenly aborted. The team acted quickly and initiated the contingency operation procedures immediately. After identified the possible cause of the abortion, a minor modification was made to the maneuver command to avoid being aborted. The TCM-4c command load was re-tested and uploaded to the spacecraft overnight. TCM-4c was successfully executed 24 hours after the TCM-4 abort incident. After the final trajectory correction by TCM-4c, the Venus flyby #1 was right on target with the flyby time off by only 0.1 s and flyby distance was 355 m closer than the desired altitude of 2429.123 km, which resulted in an achieved VGA ΔV of 3114.003 m/s, just 0.124 m/s over the design value. TCM-5 was then cancelled.

3) TCM-6 in Umbra Attitude

Six TCMs, TCMs 5-10, were planned between VGA#1 and VGA#2 for the in-flight trajectory control of this segment. With TCM-5 being cancelled, TCM-6 was to take out the VGA#1 maneuver error and orbit errors accumulated since VGA#1, including orbit perturbations from the first solar encounter, and to aim at the new VGA#2 target. After VGA#1, a second in-flight trajectory re-optimization was performed and updated the B-plane target of VGA#2.

The required trajectory correction to the new VGA#2 target for TCM-6 was determined. By that time the B-thruster issue was resolved and the use of B thrusters had been verified through momentum dumps. Therefore TCM-6, at solar distance of 0.726 AU, could be implemented in the Umbra attitude, which would be the first in-flight TCM conducted in the Umbra attitude using two groups of thrusters. The angle of the TCM-6 ΔV vector from the Sun direction was about 103°, thus the B- and C-thrusters were used to produce the required ΔV. The final design of TCM-6 and TCM-6c was shown Fig. 12, with the design parameters listed in Table 4. TCM-6 was successfully executed with excellent performance, TCM-6c was cancelled so was TCM-7 and TCM-8.

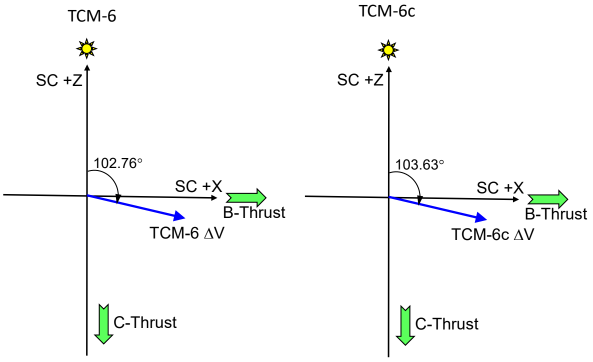

Fig. 12. TCM-6 and TCM-6c implementation design in Umbra attitude.

Table 4. TCM-6 and TCM-6c design parameter.

	TCM-6	TCM-6c
ΔV Magnitude (m/s)	1.101	1.100
Right Ascension (deg)	311.740	311.720
Declination (deg)	54.475	53.856
Burn Duration (s)	42.861	42.644
Fuel Usage (kg)	0.39	0.394
B-thrusters Duty Cycle (%)	100	100
C-thrusters Duty Cycle (%)	25.5	27.5

4) TCM-9 in Aphelion Attitude

TCM-9 was scheduled on Dec 8, 2019 as the second to last TCM for targeting the VGA#2 on Dec 26, 2019. It was positioned at 18 days prior to VGA#2 near orbit aphelion at the solar distance of 0.873 AU, so the maneuver had to be conducted in the Aphelion attitude mode. The trajectory correction ΔV required for TCM-9 was about 20° from the Sun vector, which fell in the thrust-excluding zone (Fig. 7). The new two-burn decomposition method described in Section V was therefore used to design TCM-9.

The TCM-9 ΔV was decomposed into two vectors, ΔV1 and ΔV2 with **ΔV**=**ΔV**1+**ΔV**2 and implemented in two separate burns: TCM-9A for ΔV1 and TCM-9B for ΔV2, both in the Aphelion attitude mode as shown in Fig. 13. At TCM-9A, the spacecraft was oriented in such a way that the TCM-9 ΔV vector is in the X-Z plane and the Sun line is at 45° from the +Z-axis in the -X+Z quadrant. The ΔV1 was produced by using the A-thrusters. After completing TCM-9A, the spacecraft rotated about the spacecraft-Sun line for 180° to the TCM-9B orientation while keeping in the Aphelion attitude. The ΔV2 was achieved by also using the A-thrusters. TCM-9B was set 2 hours later than TCM-9A, which allowed for sufficient time for spacecraft transition, including the slew from TCM-9A orientation to the TCM-9B orientation, while retaining both burns within the same DSN track for real-time monitoring.

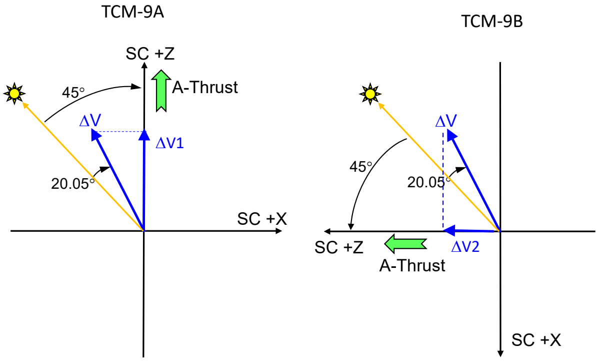

Fig. 13. TCM-9 implementation design in Aphelion attitude.

Table 5. TCM-9A and TCM-9B design parameter.

	TCM-9A	TCM-9B
ΔV Magnitude (m/s)	0.3006	0.1406
Right Ascension (deg)	204.891	119.057
Declination (deg)	-9.067	24.150
Burn Duration (s)	12.265	5.747
Fuel Usage (kg)	0.091	0.043

The TCM-9A and TCM-9B design parameters are listed in Table 5. Both burns were executed flawlessly. TCM-10 scheduled at VGA#2-5days would be a sub-second burn, much smaller than the G&C execution limit, and was cancelled. TCM-9 ended as the last trajectory correction made before VGA#2 which produced an orbit change ΔV of 2,928 m/s and reduced the orbit perihelion from 36 R_S to 28 R_S. All TCMs after TCM-9 are located at solar distances less than 0.79 AU and have been implemented using the Umbra attitude mode so far. Their implementation designs are like that of TCM-6.

VII. CONCLUSION

The successful delivery of Parker Solar Probe to touch the Sun following a planned intricate V^7GA trajectory requires timely application of TCMs throughout the mission under stringent spacecraft orientation constraints. These constraints significantly challenge PSP's maneuver implementation; some TCMs falling in the spacecraft thrust-excluding zone cannot be achieved in the traditional way.

This unprecedented highly constrained TCM implementation problem is solved in an analytical approach by a vector decomposition method that decomposes a TCM ΔV vector in the spacecraft thrust-excluding zone into two new ΔV vectors as the projections of the original ΔV vector onto the zone boundary thrust directions and implements them in two separate burns. The new method provides an optimal and simple way to implement this type of highly constrained TCMs and can be applied to other flight missions with similar situations.

Examples of designed in-flight TCMs are presented in details to illustrate PSP's TCM design and maneuver implementation in various spacecraft attitude modes using different maneuver implementation methods to achieve the desired trajectory corrections in targeting the VGAs, including the traditional turn-and-burn, vector-burn by two groups of thrusters, and the new two-burn of vector decomposition in two separate burns. All of them executed successfully, resulting in the accomplishment of planned VGAs and orbit reduction on target. PSP is on track to make the final VGA on November 6, 2024 and the closest encounter with the Sun on December 24, 2024.

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