SOLAR PROBE PLUS MISSION DESIGN OVERVIEW AND MISSION PROFILE

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Abstract: *The Solar Probe Plus mission, scheduled to launch in 2018, will go to the Sun within 10 solar radii (R_S) from the center of the Sun for the first time. The spacecraft will approach the Sun on a series of elliptical heliocentric orbits across the inner solar system. The perihelion distances of the orbits will gradually decrease through a Venus gravity assist until reaching 9.86 R_S. Key elements of the baseline mission design include launch, the seven Venus gravity-assist V^7GA mission trajectory, and the unprecedented 24 solar encounters over the 7-year mission duration. Science observations and measurements will start three months after launch at the first perihelion of 36 R_S, which will be a new record of closest spacecraft distance to the Sun, and will continue throughout the entire mission with frequent visits of the Sun at 3 to 4 times per year. Solar conjunction will occur more often due to the nature of the mission trajectory in the inner solar system, and communication with the spacecraft may be affected. The complete communication coverage profile is shown orbit by orbit, along with the baseline trajectory correction maneuver schedule.*

Keywords: *Solar Probe Plus, Solar Mission, Mission Design, Trajectory Design, Venus Gravity Assist*

1. Introduction

An idea for a solar probe mission to send a space probe to the Sun was proposed in 1958 [1] soon after the first manmade satellite successfully launched into an Earth orbit. Studies [2-16] on implementing a solar probe mission continued for the next five decades and resulted in no mission since sending a spacecraft to the Sun is much more challenging technically than going to Mars or to any other planetary bodies. The challenge comes mainly in two aspects -- the extraordinary orbital velocity reduction required to come close to the Sun and the ability to survive in the harsh environment near the Sun. In 2007 another study [17] was directed by NASA to investigate the feasibility of the solar probe mission under a new set of mission constraints. The prohibitions of RTGs to power the spacecraft eliminated the only known type of trajectory (Jupiter gravity assist) able to send a spacecraft close to the Sun. In the 2007 study, a new trajectory named V^7GA [18-19], which utilized seven Venus gravity assists to get close to the Sun, was proposed and quickly accepted by the NASA Science and Technology Definition Team (STDT) [20] and the science community. The V^7GA trajectory revolutionized the original solar probe mission concept and offered significant advantages in both technical implementation and science return compared with the original solar probe mission, and therefore the new mission based on the V^7GA trajectory was christened by STDT as the "Solar Probe Plus" mission [20].

Since 2008 the Solar Probe Plus (SPP) mission has been funded by NASA for development by the Johns Hopkins University Applied Physics Laboratory [21]. From July 2008 to November 2009, the SPP project completed a Pre-Phase A study aimed at the new technology development such as the spacecraft's thermal protection system, the solar arrays, and the cooling system. After completion of Phase A development in January 2012, a two-year Phase B development concluded in March 2014, two months after a successful Preliminary Design Review (PDR) by NASA. NASA confirmed the 2018 launch date and secured the necessary funding to support this launch schedule. The mission development is well underway and is currently in Phase C.

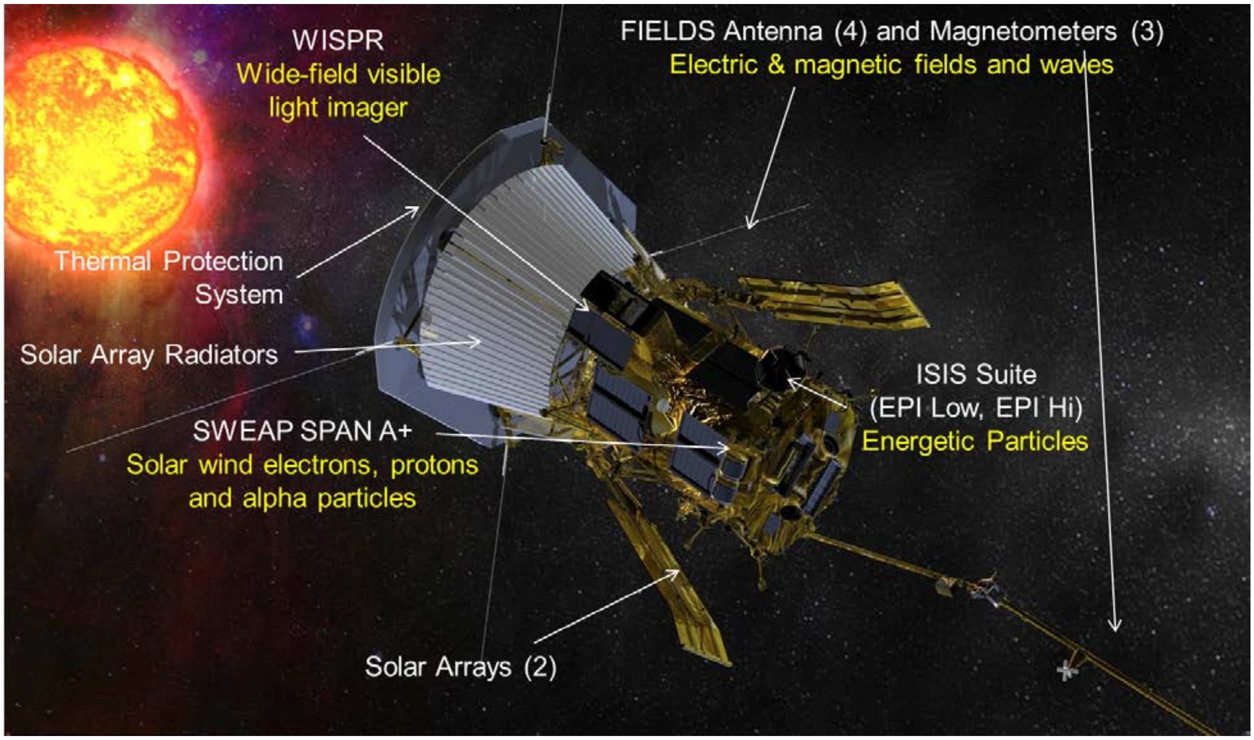

Figure 1. Reference Design of the Solar Probe Plus Spacecraft

A reference design of the SPP spacecraft is shown in Fig. 1. The Sun-facing deck has the thermal protection system (TPS) made of carbon-composite material [21]. The TPS acts as a heat shield and can protect the spacecraft bus from temperatures exceeding 2550 degrees Fahrenheit. The maximum diameter of the TPS is 2.3 m. Under the TPS the 4.4 m^2 solar array radiators actively cool the solar arrays. Next to the radiators is the 1-m diameter spacecraft bus. Two movable solar arrays, each consisting of a primary and a secondary solar panels, have a total area of 1.54 m^2. The solar arrays can supply 384 W electric power at the solar encounter. The 0.6-m high gain antenna (HGA) will use Ka-band and can provide science data downlink rate of 163 kb/s at an Earth distance of 1 AU. The monopropellant propulsion system includes 12 4.4-N thrusters and a hydrazine tank located at the center of the spacecraft bus. The overall height of the spacecraft is about 3 m.

Science investigations of the Solar Probe Plus mission were selected by NASA in September 2010 through an Announcement of Opportunity. It includes four instruments as shown in Fig. 1, SWEAP (solar wind electrons, protons and alpha particles) by Smithsonian Astrophysical

Observatory, FIELDS (electric and magnetic fields and waves) by UC Berkeley, WISPR (wide-field visible light imager) by Naval Research Laboratory, ISIS (energetic particles) by Southwest Research Institute, and the heliospheric origins investigation by Jet Propulsion Laboratory (JPL). The science objectives are to determine the mechanisms that produce fast and slow solar winds, solar coronal heating, and the transport of energetic particles. To accomplish the science objectives, the mission must complete at least three orbits with a perihelion distance below 10 solar radii (R_S) from the center of the Sun and to spend no less than 950 hours closer than 20 R_S from the center of the Sun and dwell no less than 14 hours closer than 10 R_S from the center of the Sun according to the Level 1 mission requirements.

This paper describes the Solar Probe Plus mission design features and mission profiles as of the mission PDR. A mission design overview in Section 2 explains the key mission elements of launch, heliocentric trajectory, the final solar orbit, and the overall mission timeline. Section 3 describes the Solar Probe Plus mission trajectory, followed by the trajectory geometry for each of the seven Venus flybys in Section 4. Details of the solar encounters during all 24 solar orbits, as well as the perihelion geometry, are described in Section 5. Unique mission features characterizing the Solar Probe Plus mission and the times within various near-Sun regions appear in Section 6. Solar conjunction will occur more often than during other interplanetary missions due to the nature of the mission trajectory in the inner solar system. During the solar conjunction periods, communication with the spacecraft will be significantly degraded or totally unavailable. Besides the solar conjunction, obstruction of the spacecraft's TPS on the Telecomm antennas will also prevent communication with the spacecraft. Communication gaps due to both solar conjunction and TPS obstruction are identified for every orbit of the mission in Section 7. Trajectory corrections are indispensable due to launch errors and navigation uncertainties. The baseline trajectory correction maneuver plan is revealed in Section 8.

2. Mission Design Overview

The Solar Probe Plus mission will send a spacecraft close to the Sun for the first time, going deep into solar corona and reaching closer than 10 R_S from the center of the Sun. The spacecraft must be closer to the center of the Sun than 10 R_S for more than 14 hours to meet science investigation requirements. The MESSENGER mission recently visited Mercury, the closest planet to the Sun, and went as close as 0.302 AU (65.0 R_S) from the Sun. The closest distance a spacecraft has ever reached from the Sun is 0.29 AU, or 62.4 R_S, by the Helios 2 spacecraft in 1976. The region of space within 0.29 AU of the Sun will remain unexplored by any spacecraft until late in 2018 when SPP spacecraft becomes the first spacecraft to arrive there.

2.1. Launch

The SPP baseline mission is scheduled to launch in July or August 2018. The baseline launch opportunity has a 20-day launch period from July 31 through August 19, 2018. SPP's launch phase will be similar to the other interplanetary missions, first being placed into an Earth parking orbit and then being injected into the required heliocentric mission trajectory after a short coast in the Earth parking orbit. The launch energy is much higher than most interplanetary missions and requires a powerful three-stage launch system. The maximum launch C3 over the 20-day launch period is 154 km^2/s^2. The baseline launch system is an EELV (Evolved Expendable

Launch Vehicle) Delta IV Heavy class launch vehicle with a standard Star 48 BV upper stage. During the Phase B development, an EELV Atlas V 551 launch vehicle was assumed. The recent switch to the more powerful Delta IV Heavy class launch vehicle will allow for more launch mass and increase spacecraft mass margin for the Phase C development.

2.2. Trajectory to the Sun

The trajectory able to send the spacecraft within 10 R_S of the Sun center is a Venus-Venus-Venus-Venus-Venus-Venus-Venus-Gravity-Assist (V^7GA) trajectory [18], a unique trajectory developed to enable the Solar Probe Plus mission without a Jupiter gravity assist. Even with the most powerful launch vehicle and upper stage, a spacecraft cannot get close to the Sun from Earth directly [19]. Extra energy must be shed off the spacecraft's orbit to further reduce its heliocentric orbital velocity in order to encounter the Sun under 10 R_S. The V^7GA trajectory allows for the spacecraft to reduce the necessary orbital speed via multiple Venus gravity assists. The amount of required orbital speed reduction required at aphelion is too large to come from one or two Venus flybys. Attaining the aphelion orbital speed reduction will require seven Venus flybys. Following each Venus flyby, the orbital speed at aphelion will decrease, resulting in a smaller orbit with a shorter perihelion distance. After seven Venus flybys, orbit perihelion distance will gradually decrease to 9.86 R_S, the minimum solar distance required for the baseline mission. Throughout the mission there are no additional deep space maneuvers; all the orbit changes as well as the phasing (Venus-to-Venus transfer location and timing) between each Venus flyby are achieved through the control of the Venus flybys by appropriate selection of the Venus flyby target parameters. To minimize the mission duration, both resonant and non-resonant Venus flybys [18] are utilized in this trajectory design.

2.3. Final Solar Orbit

After the 7^{th} Venus flyby, the SPP spacecraft will enter a solar orbit whose perihelion is 9.86 R_S and aphelion is 0.73 AU. This final solar orbit of the mission satisfies the science requirements. The final solar orbit is oriented close to the ecliptic plane, inclined 3.4° from the ecliptic plane. The orbit period is 88 days which happens to be the same as the planet Mercury's orbit period. Without any close encounter with Mercury, there will be no significant gravity perturbation from Mercury to alter the final solar orbit. The SPP spacecraft will remain in this final solar orbit and encounter the Sun every 88 days.

2.4. Mission Timeline

The baseline mission will last for 7 years from launch to completion of the science investigations at the Sun and the subsequent science data playback. It takes only two months from launch to the first Venus flyby and three months from launch to the first perihelion of 36 R_S, which will be the first time for a spacecraft to be that close to the Sun. The onboard science instruments will begin in situ measurements to collect the solar data for the first time at the near-Sun region. Science measurements will be conducted starting from the solar distance of 0.25 AU (53.7 R_S) before perihelion (P-0.25 AU) to the solar distance of 0.25 AU after the perihelion (P+0.25 AU). The time from P-0.25 AU to P+0.25 AU on each solar orbit is allocated for the science investigations and designated as the science phase. While science measurements continue on each solar pass, the closest approach distance from the Sun will decrease after each Venus flyby. It takes 6.4 years from launch to complete the seven Venus flybys to reach the minimum perihelion distance of 9.86 R_S. Three solar passes at the minimum perihelion are required for the baseline mission. The total mission duration of seven years includes 6.4 years from launch to the first 9.86-R_S perihelion, the three solar passes at the 9.86-R_S perihelion, and the time needed for the science data playback following the last solar pass.

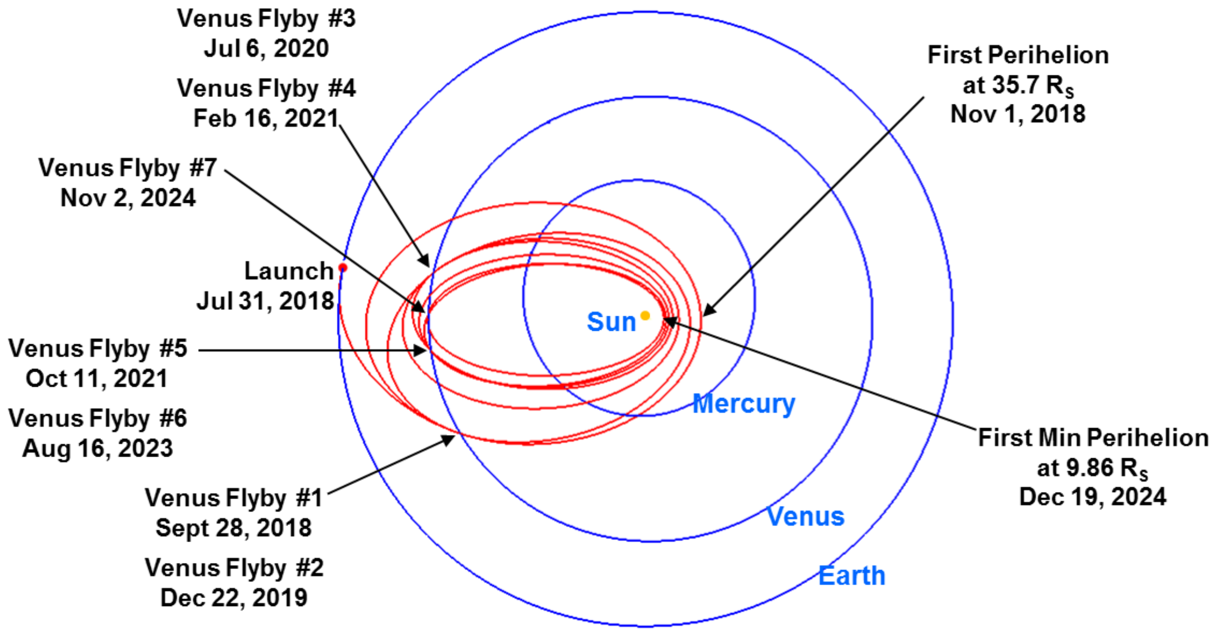

Figure 2. The V^7GA Mission Trajectory

3. Baseline Mission Trajectory

A reference trajectory of the Solar Probe Plus baseline mission for the opening of the launch period is shown in Fig. 2. Starting at the Earth departure on July 31, 2018, the SPP spacecraft will travel from Earth orbit to a final solar orbit through a series of highly elliptical heliocentric orbits across the inner solar system by means of seven Venus gravity assist flybys. The first Venus flyby will occur on September 28, 2019, 59 days after launch. This first Venus flyby will take place on the first Earth-Sun inbound leg. The second Venus flyby will occur three orbits later on December 22, 2019 at the same Venus orbit location, which corresponds to a 3:2 resonant orbit transfer. The third Venus flyby will occur on July 6, 2020 on the outbound leg at the other orbit intersection with the Venus orbit; this is a non-resonant orbit transfer. The fourth Venus flyby will also be on the outbound leg on February 16, 2021. The fifth Venus flyby is a non-resonant orbit transfer that will return to the inbound leg Venus orbit intersection on October 11, 2021. The sixth Venus flyby will happen at the same inbound leg Venus orbit intersection 674 days later on August 16, 2023. The seventh Venus flyby will occur on November 2, 2024 at the outbound leg Venus orbit intersection. Shortly after the seventh Venus flyby, the spacecraft will reach the closest distance of 9.86 R_S from the Sun center, the first minimum perihelion, on December 19, 2024.

4. Geometry of Venus Flybys

Figure 3 shows the spacecraft trajectory orientation and Venus solar illumination for each of the seven Venus flybys. The spacecraft trajectory at closest approach of Venus flybys #1, #2, #5, and #6 will be between the Sun and Venus, where the spacecraft will be exposed to full sunlight. These four flybys will take place at the inbound leg Venus orbit intersection. The spacecraft trajectory at Venus flybys #3, #4, and #7 will be further from the Sun than the center of Venus. Some portion of the spacecraft trajectory will be in the shadow cast by Venus (solar eclipse). The spacecraft will experience a brief solar eclipse during these three Venus flybys. The longest solar eclipse will be 661 seconds at the third Venus flyby, and the shortest solar eclipse of 501 seconds will occur at the seventh Venus flyby. These brief solar eclipse periods do not violate any spacecraft power supply or thermal constraint during the Venus flybys. Among the seven Venus flybys, the closest flyby will occur at 317 km altitude at Venus flyby 7. The second closest will occur at 834 km altitude at Venus flyby 3. The rest of the Venus flybys will occur at larger altitudes, ranging from 2392 to 3939 km. These flyby distances do not raise any concerns for spacecraft safety and do not require optical navigation in order to improve orbit prediction accuracy.

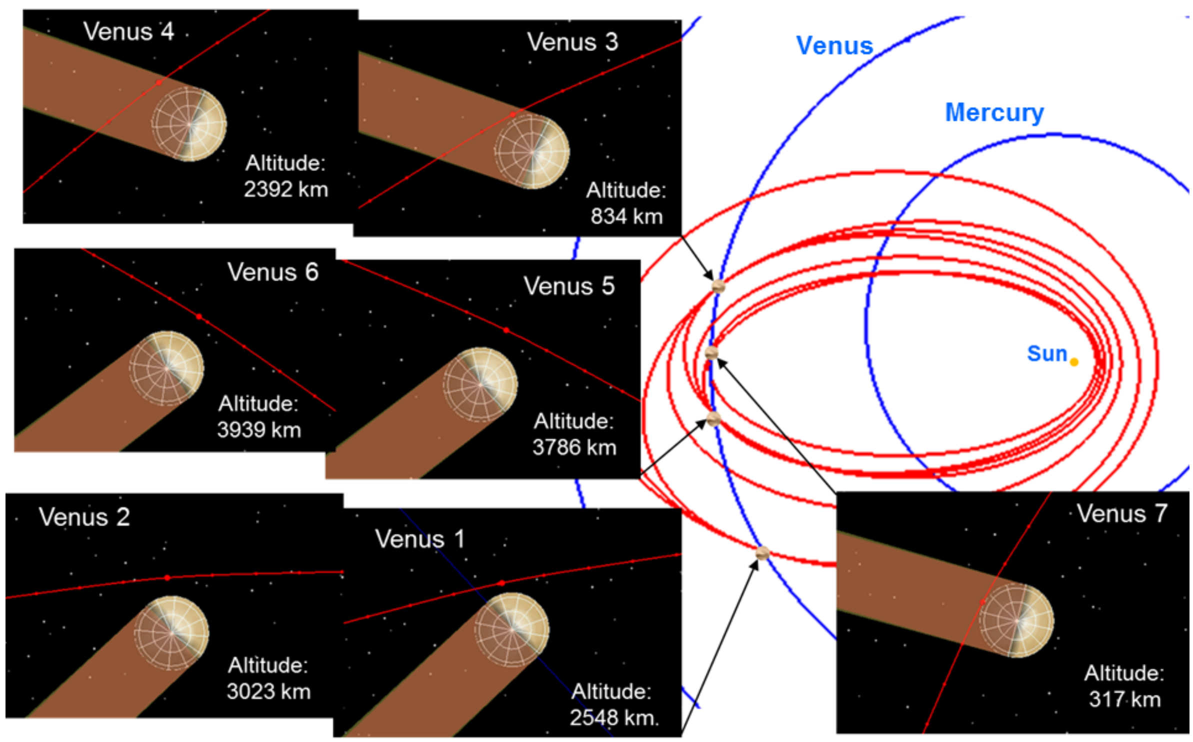

Figure 3. Geometry of the Seven Venus Flybys

5. Solar Encounters

The mission trajectory in Fig. 2 contains 24 individual solar orbits and provides unprecedented 24 close solar encounters. The solar encounter will start three months after launch and continues throughout the 7-year mission duration from 2018 to 2025 on an average of three to four solar encounters per year. Some of the solar encounters are at the same solar distance on repeated solar orbits and some encounters are at different solar distances. The 24 solar orbits have seven distinctive perihelia, P1, P4, P6, P8, P10, P17, and P22, as shown in Fig. 4. The seven different perihelia correspond to the seven orbit changes resulting from each Venus gravity-assisted flyby. From P1 to P22, each Venus flyby brings the SPP spacecraft closer to the Sun, from 35.7 R_S to 9.86 R_S from the Sun center.

5.1. Solar Passes

There are multiple repeated solar encounter passes at each of the seven distinctive perihelion distances. The three perihelia P4, P6, and P8 each have two repeated solar passes. The two perihelia P1 and P24 have three repeated solar passes. The perihelion P17 has five repeated solar passes, and the perihelion P10 has seven repeated solar passes. These repeated solar passes offer multiple redundant (at the same range of solar distances) opportunities for science observation and measurements and increase the time spent at the near Sun region which is critical to the science investigations. Detailed solar distance and velocity profiles of the solar encounter on each solar pass over the science phase are plotted in Fig. 4.

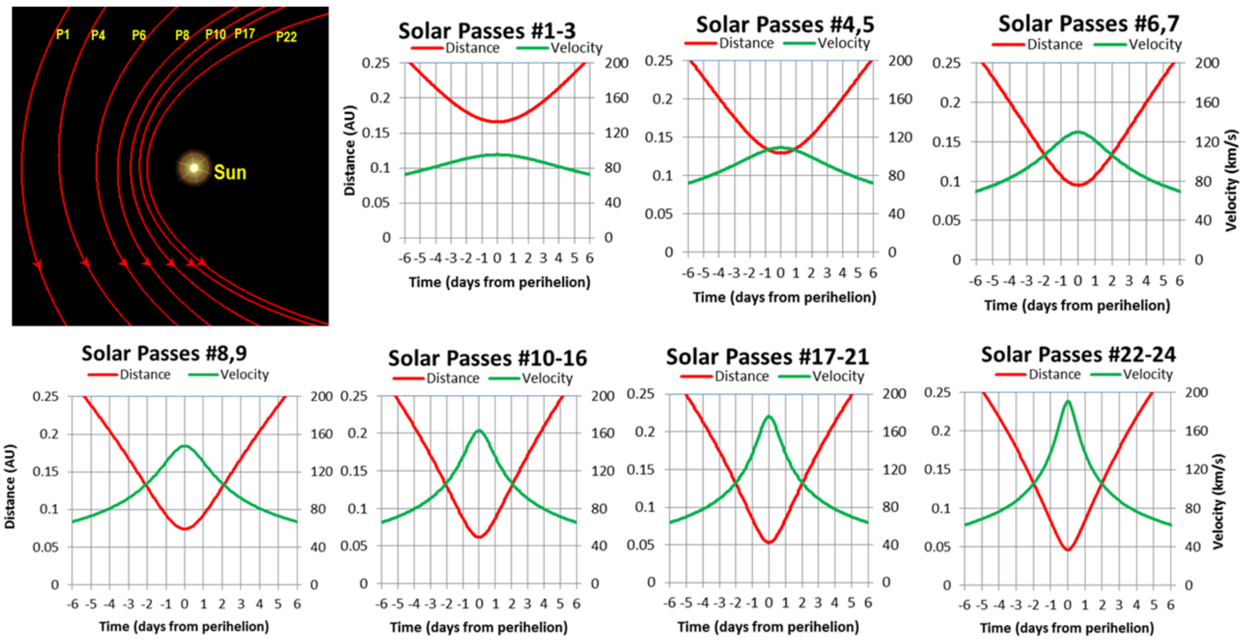

Figure 4. Solar Encounters

The heliocentric speed at perihelion will increase with each reduction in perihelion distance after each Venus flyby. The heliocentric speed will range from 95.3 km/s at perihelia P1-P3 to 190.8 km/s at perihelia P22-24. The maximum velocity of 190.8 km/s, which will occur at the minimum solar distance of 9.86 $R_{S,}$ will set the record for the highest spacecraft speed with respect to the Sun. At such a high velocity, the relativity effects may be detectable, and relevant experiments are likely to be conducted during the mission if operation constraints and resource permit. Speed and encounter distance determine the time required to fly a solar pass during the science phase. Science instruments will be active to start the in situ measurements when the solar distance drops to 0.25 AU and to stop when the solar distance comes back to 0.25 AU. The spacecraft operating mode, flight operations rules, and operational constraints will be different during the science phase than during the remainder of the mission. The duration of the solar passes at solar distances less than 0.25 AU varies from 11.6 to 9.8 days.

5.2. Minimum Perihelion Geometry

One of the SPP mission design requirements places a restriction on perihelion geometry. At least one solar encounter should be visible from Earth. This is to conduct simultaneous observations of the Sun by the in situ SPP spacecraft and Earth-based instruments. More of this kind of observation covering different regions of the Sun is better since this will cover more surface area of the Sun. The 24 solar encounters will provide numerous opportunities for the coordinated ground and onboard observations of the Sun. Figure 5 displays the perihelion geometry of the three solar encounters of orbits 22-24 at the mission's minimum perihelion distance. The Earth's location is shown at the time when the SPP spacecraft is at perihelion. The perihelion geometry of the final three solar encounters is different since the locations of Earth changes with each perihelion. During orbit 22 the geometry will enable observation of the Sun's west limb, while orbit 23 will offer observation of the east limb of the Sun.

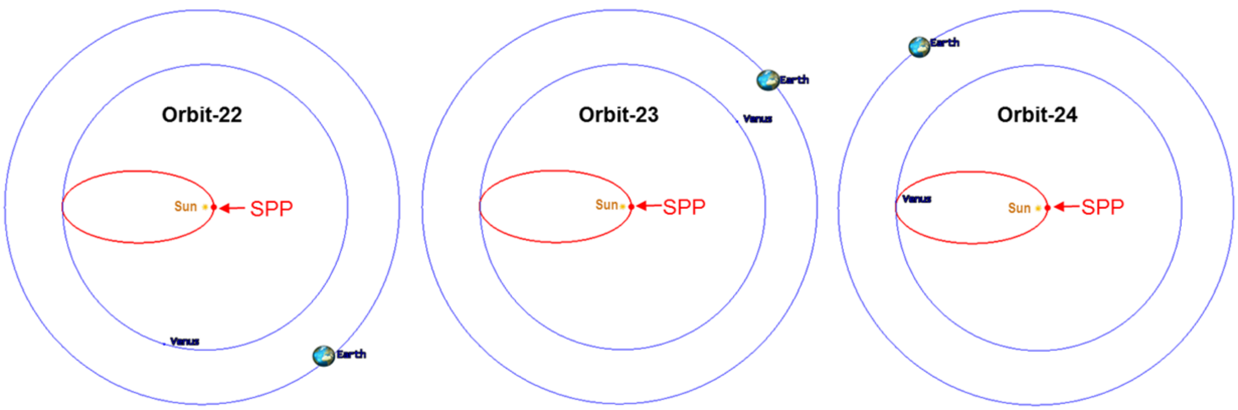

Figure 5. Solar Orbits of Minimum Perihelion

6. Solar Distance Profile

Solar distance of the SPP spacecraft versus time during the 7-year mission duration is shown in Fig. 6. The number of solar orbits of the mission is clearly revealed in this solar distance profile. There are 25 aphelia (A1 through A25) and 24 perihelia (P1 through P24), a total of 24 complete solar orbits. Each orbit begins at aphelion, goes through perihelion, and ends at the next aphelion. For example, orbit number n, starts at An, goes through Pn, and ends at A(n+1). The perihelion distances gradually decrease as well as the aphelion distances. At the same time, the time between two aphelia (or two perihelia) decreases (the space between two aphelia in Fig. 6 becomes smaller), indicating a reduction in orbital period. Orbit period of the corresponding solar orbit in days appears at the top of Fig. 6. It will take 168 days to complete the first orbit and only 88 days to complete the last orbit, the period being reduced by nearly 50% during the mission. The orbit changes are attributed to the Venus gravity assists. Occurrences of the seven Venus flybys are marked on the distance plot.

The range of the spacecraft-Sun distance is a major driver for the flight system design of the SPP spacecraft. Solar distance affects the spacecraft power supply and thermal management concerning the solar arrays, the thermal protection system, and the cooling system. Figure 6 shows the 1.018 AU maximum solar distance in orbit #1 and the 0.04587 AU (9.86 R_S) minimum solar distance occurring in orbits #22-24. The trajectory will never go farther from the Sun than Earth's orbital distance, which enables a solar powered SPP spacecraft and minimizes the size of the solar panels.

Orbit #	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
Period (d)	168	150	150	140	121	112	107	102	102	100	96	96	96	96	96	96	96	92	92	92	87	88	88	88

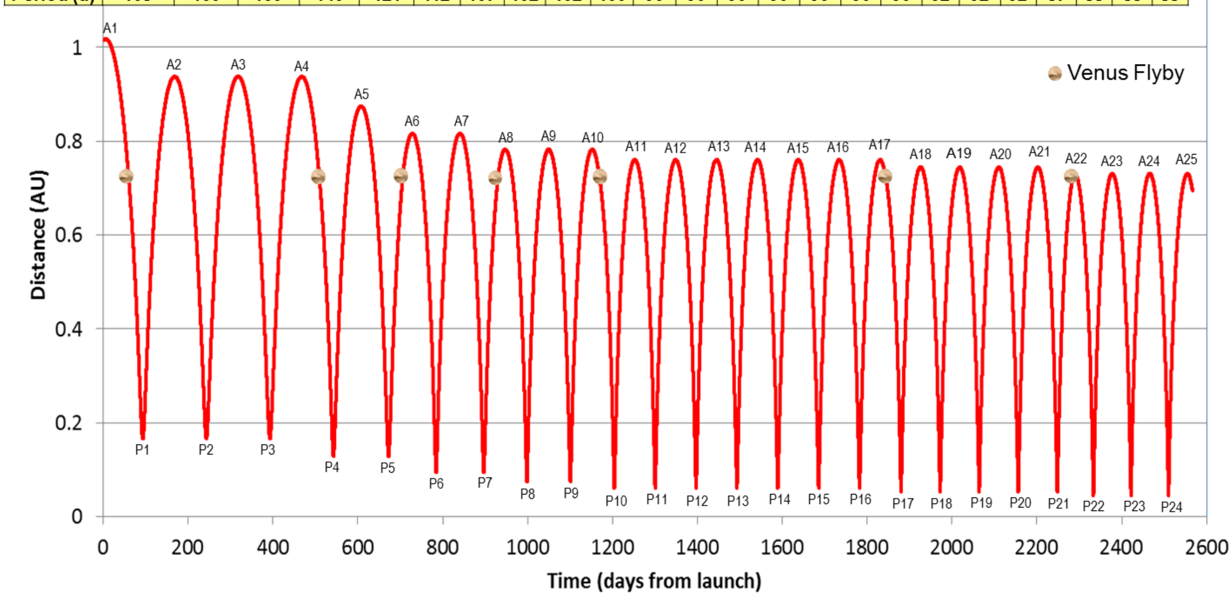

Figure 6. Solar Distance Profile

The solar distance profile in Fig. 6 also shows the mission's approach for getting closer to the Sun. The spacecraft will enact a gradual "walk-in" process in which perihelion is reduced seven times, once per Venus flyby. The perihelion reduction strategy will start on an orbit with 0.166 AU (35.66 R_S) perihelion distance after the first Venus flyby, and then will continue with three solar encounters (P1-P3) at the same perihelion distance. The second Venus flyby will then lower perihelion distance to 0.130 AU (27.85 R_S) for the next two orbits (P4 and P5). This process continues until P24. On each step, the spacecraft lowers the orbit perihelion and stays at that new perihelion distance for a few orbits. The perihelion distance reduction after each Venus flyby is greater early in the mission when the perihelion distance is greater and becomes less when the perihelion distance is lower later in the mission. This perihelion reduction strategy will provide opportunity to increase knowledge on spacecraft performance and experience for flight operations incrementally before entering the extreme and unknown environment near the Sun. This strategy will impose lower risk than the direct rapid drop to a lower perihelion on a trajectory from Jupiter as was proposed with the original solar probe approach.

Besides the technical advantage, this approach will greatly enhance the science return of the mission. Unlike other interplanetary missions, there will be no cruise phase and no need to wait for years before science operations can start. The science investigation will start less than 3 months from launch and will continue throughout the 7-year mission duration. The in situ measurements will be taken at the Sun every few months during each solar pass, and new measurements and observations will be revealed frequently when the perihelion distance is reduced each time. The numerous repeated solar orbits provide abundant opportunities to visit the Sun as well as a significant amount of time spent in the near Sun region. Table 1 lists the perihelion distance and the time per orbit spent within the distances of 30, 20, 15, and 10 R_S of the Sun. The total time spent in the 30-R_S region will be more than 2130 hours over the last 21 solar passes; the time in the 20-R_S region is more than 937 hours over the last 17 solar passes; the time in the 15-R_S region is more than 440 hours over the last 15 solar passes; and the time in the 10-R_S region is more than 14 hours over the last three solar passes. The frequent visits close to the Sun three to four times per year will not only increase the time spent at the near Sun region collecting in situ data, but also will increase the probability of capturing unpredictable significant solar activities in the near Sun region.

Table 1. Accumulated Time in the Near-Sun Region

Solar Pass #	Perihelion (AU)	Perihelion (R_S)	Time within			
			30 R_S (hr)	20 R_S (hr)	15 R_S (hr)	10 R_S (hr)
1	0.166	35.66				
2	0.166	35.66				
3	0.166	35.66				
4	0.130	27.85	61.04			
5	0.130	27.85	61.05			
6	0.095	20.35	104.22			
7	0.095	20.35	104.22			
8	0.074	15.98	108.55	48.06		
9	0.074	15.98	108.55	48.06		
10	0.062	13.28	107.27	55.13	24.75	
11	0.062	13.28	107.27	55.13	24.75	
12	0.062	13.28	107.27	55.12	24.75	
13	0.062	13.28	107.27	55.13	24.75	
14	0.062	13.28	107.27	55.12	24.74	
15	0.062	13.28	107.27	55.12	24.74	
16	0.062	13.28	107.27	55.12	24.73	
17	0.053	11.42	105.03	56.91	32.23	
18	0.053	11.42	105.03	56.91	32.23	
19	0.053	11.42	105.03	56.91	32.23	
20	0.053	11.42	105.03	56.91	32.23	
21	0.053	11.42	105.03	56.91	32.23	
22	0.046	9.86	102.40	57.02	35.22	4.94
23	0.046	9.86	102.40	57.02	35.22	4.95
24	0.046	9.86	102.40	57.02	35.22	4.95
Total			2130.85	937.58	440.03	14.85

7. Communication Coverage Profile

Adequate communication links between ground and spacecraft are essential for mission operations. Transmissions of spacecraft operation commands, spacecraft telemetry, science observation sequences, and instrument measurement data between the SPP spacecraft and ground are through the spacecraft Telecomm system and NASA's Deep Space Network (DSN) of tracking stations located at Goldstone in the United States, Canberra in Australia, and Madrid in Spain. Besides the data transmission, navigation of the SPP spacecraft will rely on regular and periodic tracking of the spacecraft through the DSN. The communication coverage of the spacecraft over the mission duration directly affects the spacecraft's operation, science data download, navigation, and the control of the flight trajectory. Due to launch and navigation errors, the flight trajectory needs to be periodically adjusted by applying a trajectory correct maneuver (TCM). Availability of adequate navigation tracking and communication links to the spacecraft dictates the placement of the trajectory correction maneuvers, which has direct impacts on the onboard ΔV budget.

A comprehensive study of detailed communication coverage over the entire mission was conducted in Phase B across multiple SPP subsystem teams. Because of the unique operation environment of the SPP mission, many factors must be understood in order to maintain adequate communications with the spacecraft. First, the highly elliptical solar orbits across the inner solar system cause frequent solar conjunctions, sometimes with extended periods. And secondly, the spacecraft's TPS obstructs the view of the antenna and causes extra outage of communication times.

Solar conjunction zones are revealed via examination of the relative geometry of the spacecraft, Earth, and Sun. Figure 7 shows the Sun-Probe-Earth (SPE) and Sun-Earth-Probe (SEP) angles over the mission duration. When the SEP angles are small and the Sun is between Earth and the spacecraft (SPE angles are small), the Sun's plasma and other electromagnetic noises will cause various levels of communication disruption between Earth-based DSN antennas and the spacecraft. Solar conjunction based communications degradation during past missions were useful in determining a cutoff value of the SEP angle for potential communication outage. When the SEP angle is less than 3°, X-band communication is assumed to be unavailable. When the SEP angle is less than 1°, Ka-band communication is assumed to be unavailable. The SPP spacecraft's RF (Radio Frequency) Telecomm system can operate using either X-band or Ka-band. The X-band is baselined for spacecraft tracking for navigation and works for both uplink and downlink modes. The Ka-band is mainly for science data downlink and works only for the downlink mode. Figure 7 shows many times when SEP angle is less than 3°, which indicates frequent solar conjunctions and the outage or degradation of X-band communication with the spacecraft.

Figure 7. Sun-Earth-Probe and Sun-Probe-Earth Angles

Besides the communication outage due to the solar conjunctions attributed to the viewing geometry of Sun, Earth, and the spacecraft, the TPS of the spacecraft sometimes causes additional outage. Because of the extremely high heat radiated from the Sun, the spacecraft bus must be constantly protected from direct solar radiation to prevent overheating. When spacecraft solar distance is less than 0.7 AU, the spacecraft must be oriented with the TPS pointed at the Sun, so that the spacecraft bus and components including the antennas are behind the TPS and are protected inside the TPS umbra. Since the antennas are behind the TPS, some of the radio transmission is obstructed by the TPS. About 14° of the field of view from the center of the TPS is blocked. When the direction of Earth is near the direction of the Sun and within the 14° cone angle about the TPS center, the view from the SPP antenna to Earth is obstructed by the TPS, thereby preventing communication between Earth and the spacecraft.

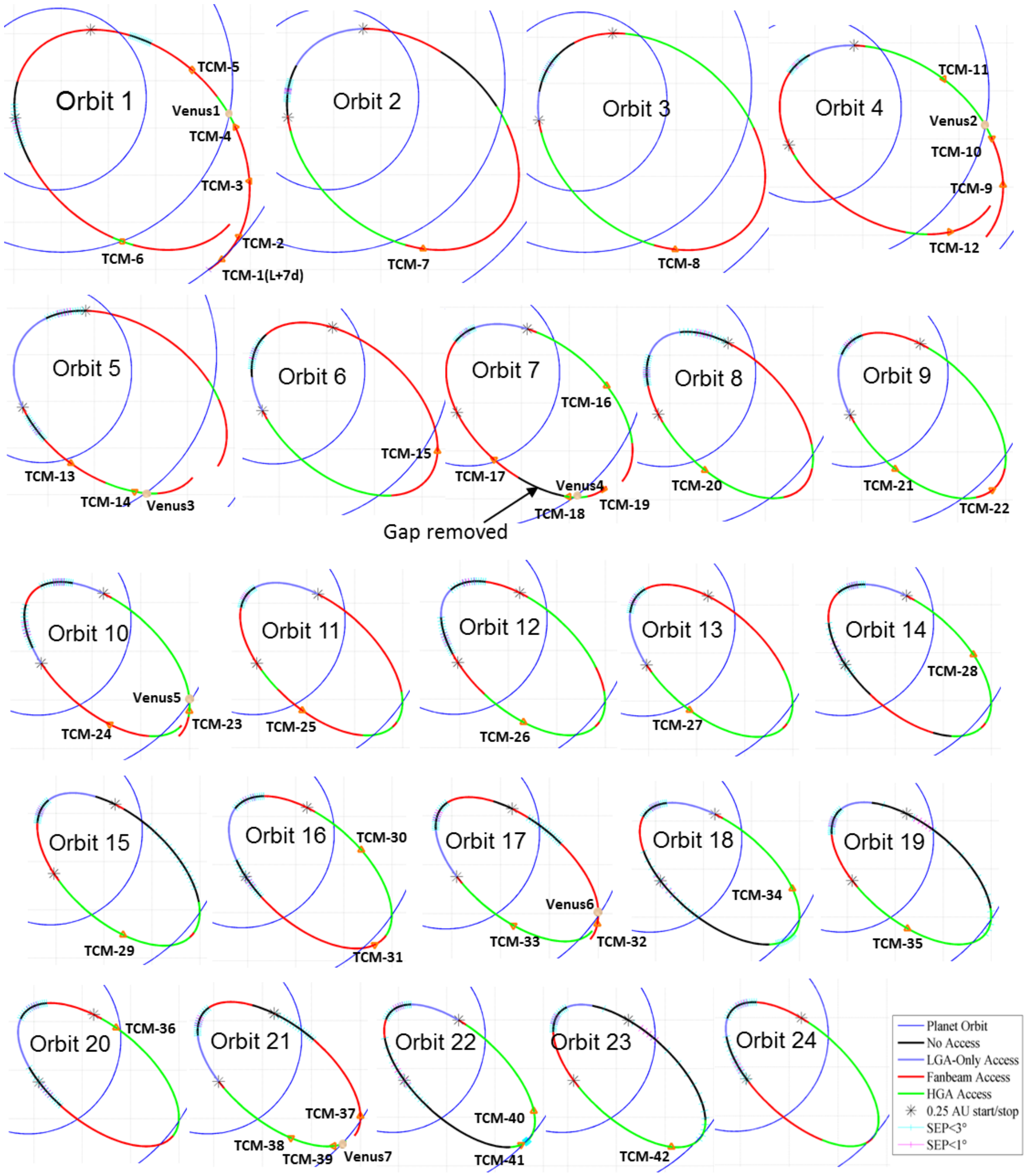

Figure 8. Communication Coverage and TCM Placement

Complete communication coverage over the entire mission was analyzed based on the current Telecomm system design assumptions and the spacecraft orientation constraints for flight operations. The communication coverage profile is presented in Figure 8 for orbits 1 to 24. The line color of the SPP spacecraft orbit depicts the communication status and the length of the line displays the extent of that status. The black portion of the orbit represents no access to the spacecraft for that segment of the orbit. A solid black line indicates that the outage is due to TPS obstruction; a black line with aqua colored bars indicates that the outage is due to SEP angle less than 3°; and a black line with magenta colored bars indicates that the outage is due to SEP angles being less than 1°. The red color of the orbit indicates that spacecraft communications access is available through one of the two fan-beam antennas mounted on the spacecraft -X-axis side. The blue color of the orbit indicates that spacecraft communications access is available through the low-gain antenna (LGA) on the +X-axis side. Both the fan-beam antennas and the LGA operate using X-band. The green color of the orbit indicates that spacecraft communications access is available through the high-gain antenna (HGA) operating with Ka-band.

Communication gaps will occur on every orbit, with some gaps being short and other gaps being long. The short gaps are not a concern and impose little impacts on flight operations. The long gaps on orbits 14, 15, 18, 19, 22, and 23, lasting from 8.5 days to 31.9 days, were evaluated by the navigation team on their potential impacts on navigation, especially on the predicted orbit determination accuracy during the solar passes immediately following the long tracking gaps. It was found from these analyses that the navigation requirements could still be met with these long tracking gaps. The 12-day gap on orbit 7 before the fourth Venus flyby would have some impact, forcing the last TCM prior to Venus 4 (TCM-18) to occur too close to the Venus flyby. The gap was eventually removed by a slight adjustment of the spacecraft pointing rule at that time.

8. Baseline Trajectory Correction Maneuver Schedule

Although the nominal mission trajectory does not include any deep space maneuvers, TCMs may be required to correct launch errors or navigation orbit determination (OD) errors. Estimate of the propellant allocation for TCMs is based on pre-launch analyses of the worst-case anticipated trajectory conditions. The SPP trajectory differs from most interplanetary spacecraft trajectories in that the required TCM ΔV is highly sensitive to the TCM orbit location. In other words, TCM placement has a significant impact on the mission's ΔV budget.

Prior to any TCM, a good trajectory OD solution must be obtained from adequate navigation tracking, which means communication links from the spacecraft to the DSN tracking stations must be available before a TCM. For some critical TCMs, for example, those TCMs between launch and the first Venus flyby, real-time telemetry and TCM burn monitoring are required. This further constrains implementation of the TCM to only times when satisfactory communication conditions exist. The TCM placement is closely dependent on the communication coverage profile. A baseline TCM schedule developed in Phase B by the mission design and navigation teams is listed in Table 2. Locations of the individual TCMs in Table 2 are shown with the communication coverage profile in Fig. 8.

Table 2. Baseline Trajectory Correction Maneuver Schedule

TCM	Function	Time	Date	Earth Distance (AU)	Solar Distance (AU)	SEP Angle (deg)	Orbit
1	Launch correction	L+7d	08/07/2018	0.05	1.02	92.62	1
2	TCM-1 cleanup	L+19d	08/19/2018	0.14	1.00	81.34	1
3	Venus 1 targeting	V1-19d	09/09/2018	0.27	0.90	59.69	1
4	Venus 1 targeting	V1-3.0d	09/25/2018	0.36	0.76	39.31	1
5	Venus 1 cleanup	V1+13d	10/11/2018	0.48	0.55	15.50	1
6	Venus 1 cleanup	V2-381d	12/05/2018	1.63	0.73	15.97	1
7	Venus 2 targeting	V2-223d	05/12/2019	1.01	0.81	47.10	2
8	Venus 2 targeting	V2-72d	10/10/2019	1.15	0.82	44.15	3
9	Venus 2 targeting	V2-18d	12/03/2019	1.40	0.88	38.38	4
10	Venus 2 targeting	V2-3.4d	12/18/2019	1.35	0.76	33.55	4
11	Venus 2 cleanup	V2+14.6d	01/05/2020	1.19	0.54	26.38	4
12	Venus 3 targeting	V3-119d	03/09/2020	1.72	0.82	15.96	4
13	Venus 3 targeting	V3-18d	06/18/2020	0.56	0.48	12.65	5
14	Venus 3 targeting	V3-2.8d	07/03/2020	0.44	0.70	34.41	5
15	Venus 4 targeting	V3+36d	08/11/2020	0.28	0.78	29.01	6
16	Venus 4 targeting	V4-54d	12/23/2020	1.26	0.57	26.03	7
17	Venus 4 targeting	V4-20d	01/26/2021	1.40	0.45	7.83	7
18	Venus 4 targeting	V4-1.5d	02/14/2021	1.67	0.72	9.24	7
19	Venus 4 cleanup	V4+15d	03/02/2021	1.72	0.78	12.28	7
20	Venus 5 targeting	V5-154d	05/10/2021	0.85	0.50	29.95	8
21	Venus 5 targeting	V5-52d	08/20/2021	0.71	0.50	27.03	9
22	Venus 5 targeting	v5-17d	09/23/2021	0.73	0.78	50.68	9
23	Venus 5 targeting	V5-3d	10/08/2021	0.80	0.75	47.50	10
24	Venus 5 cleanup	V5+56d	12/06/2021	1.45	0.57	16.03	10
25	Venus 6 targeting	V6-527d	03/07/2022	1.34	0.49	17.21	11
26	Venus 6 targeting	V6-426d	06/16/2022	0.62	0.57	29.59	12
27	Venus 6 targeting	V6-335d	09/15/2022	0.88	0.47	28.17	13
28	Venus 6 targeting	V6-272d	11/17/2022	1.02	0.56	32.57	14
29	Venus 6 targeting	V6-136d	04/02/2023	1.29	0.58	25.45	15
30	Venus 6 targeting	V6-75d	06/02/2023	1.14	0.49	25.29	16
31	Venus 6 targeting	V6-17d	07/29/2023	0.30	0.75	24.02	16
32	Venus 6 targeting	V6-3d	08/13/2023	0.28	0.74	12.01	17
33	Venus 7 targeting	V7-389d	10/09/2023	1.01	0.52	29.98	17
34	Venus 7 targeting	V7-338d	11/29/2023	1.20	0.63	31.89	18
35	Venus 7 targeting	V7-205d	04/10/2024	1.19	0.52	25.40	19
36	Venus 7 targeting	V7-138d	06/17/2024	1.07	0.33	18.27	20
37	Venus 7 targeting	V7-72d	08/21/2024	0.30	0.72	8.63	21
38	Venus 7 targeting	V7-17d	10/15/2024	1.05	0.58	32.64	21
39	Venus 7 targeting	V7-3d	10/29/2024	1.15	0.71	38.05	21
40	Venus 7 cleanup	V7+19d	11/20/2024	1.22	0.67	33.61	22
41	Perihelion adjust	V7+87d	1/27/2025	1.71	0.72	3.27	22
42	Perihelion adjust	V7+166d	4/16/2025	1.33	0.68	29.81	23

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