Solar Probe Plus: Primary and Backup Launch Windows

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Launching a probe to the Sun is extremely challenging because the immense launch energy required to reach the Sun far exceeds that needed to reach any of the planets in the solar system. Solar Probe Plus, the first mission to the Sun, is made possible by utilizing planetary gravity assists to make up the launch energy shortage and reach the Sun at 9.86 solar radii from the center, through seven repeated flybys of Venus on a unique V^7GA trajectory for 24 solar encounters within 7 years after launch. The current launch planning includes two launch windows, a primary and a backup. The primary launch window opens on July 31, 2018 for 24 days, and the backup launch window 10 months later is created by designing a new V^8GA trajectory that is slightly different from the baseline mission trajectory but retains all the orbit features of the baseline mission.

Key Words: Solar Probe Plus, launch window, launch target, V^7GA trajectory, V^8GA trajectory

1. Introduction

The Sun, the most technically challenging destination to reach, will soon be explored with the launch of the Solar Probe Plus (SPP) mission, which is currently in the final development stage of integration and testing of the spacecraft and instruments. Less than 15 months from launch, the launch integration by all parties has completed the preliminary mission analysis (PMA) cycle. The launch target specification for the final mission analysis (FMA) has just been delivered to the launch provider.

The SPP mission aims to address fundamental questions about the Sun that have been the top-priority science objectives for decades, including how the Sun's corona is heated and how the solar wind is accelerated. Answering those questions requires direct and in-situ measurements by sending a spacecraft into the near-Sun region.[1]

2. SPP Launch Challenges

Of the solar system bodies, including all planets, asteroids and comets, the Sun is the most difficult destination to reach for a space probe launching from Earth. The Sun is much closer to Earth in terms of distance than the outer planets, but the launch energy required for sending a probe to the Sun is tremendously higher than that required to reach any of the planets. Table 1 lists example launches in 2018 from Earth to the planets and Sun on a simple direct flight, the required launch energy (C3) and Earth departure excess speed (V_{ex}). The launch to the Sun assumes a close Sun distance of 10 solar radii (R_S); the C3 will be higher if it is closer. As shown in Table 1, the C3 for a launch to the Sun is 423.4 km^2/s^2, far greater than that for a launch to any of the planets. Such a high C3 is far beyond the capability of any launch vehicle currently available.

Table 1. Example launch to Sun and planets.

Destination	Launch date	Arrival date	C3 (km^2/s^2)	V_{ex} (km/s)
Mercury	9/4/2018	12/27/2018	58.85	7.67
Venus	7/30/2018	12/1/2018	7.369	2.71
Mars	5/17/2018	1/8/2019	7.674	2.77
Jupiter	1/16/2018	5/25/2020	76.059	8.72
Saturn	2/26/2018	6/11/2022	116.217	10.78
Uranus	6/19/2018	3/31/2031	131.404	11.46
Neptune	4/30/2018	9/27/2034	154.647	12.44
Pluto	3/9/2018	1/26/2030	216.432	14.71
Sun	7/31/2018	10/9/2018	423.396	20.58

The only possible way to launch a probe to the Sun is to use planetary gravity assists to obtain extra energy to supplement the energy from a launch vehicle. For a solar probe mission studied before 2007, Jupiter, the most massive planet in the solar system, had to be used for gaining the enormous gravity assist needed to get to the Sun. The Jupiter Gravity Assist (JGA) trajectory was considered the only feasible trajectory for a solar probe mission from 1958,[2] when the initial solar probe concept was proposed, through 2007.[3-14] Since the probe would be going out to Jupiter at more than 5 AU from the Sun, too far to use solar power, the JGA trajectory required the use of a Radioisotope Thermoelectric Generator (RTG) to power the probe.

A turning point for the solar mission occurred in 2007, when the assumed RTG was no longer available and NASA tasked the Johns Hopkins University Applied Physics Laboratory with a study for a solar mission without an RTG. A completely new trajectory design was created for a solar mission requiring no JGA and no RTG and using solar power, a uniquely sequenced seven Venus gravity assist trajectory called V^7GA.[15-16] The seven Venus flyby architecture arranged in a tightly knitted sequence not only offers the enormous gravity assists demanded for a solar mission but also satisfies NASA's budget constraints on the mission duration. Because of the new trajectory design, the new mission concept was completely different from the old one, including 24 solar encounters in 7 years while the old mission concept included 2 solar encounters in 9 years.[14] The new mission was named Solar Probe Plus by the NASA Science Technology Definition Team[1] for its numerous advantages both scientifically and technically over the old Solar Probe mission.[15-16]

3. SPP Mission Concept

The SPP mission is based on the V^7GA trajectory architecture as shown in Figure 1, which contains 24 solar orbits (Fig. 2) whose perihelion distances are gradually reduced following each of the 7 Venus flybys at the inbound and outbound intersections with the Venus orbit. The perihelion distances start at 35.7 R_S until reaching 9.86 R_S of the required minimum solar distance for the mission. Science measurements are conducted during the solar passes over the time period when the solar distances are less than 0.25 AU. For science investigations the time spent in the near Sun region is critically important. The last three orbits are at 9.86 R_S of perihelion and offer more than 14 hours of accumulated time within 10 R_S of the Sun.[17] Over the course of the mission, the accumulated time within the 20-R_S near-Sun region is more than 937 hours.

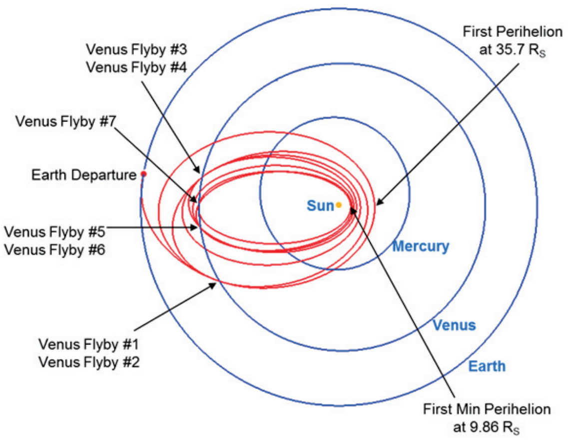

Fig. 1. Solar Probe Plus V^7GA mission trajectory.

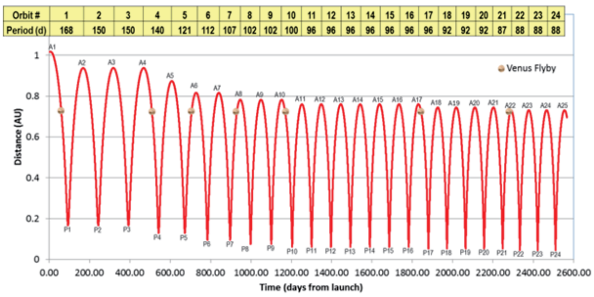

Fig. 2. Solar distance profile of the V^7GA trajectory.

4. SPP Launch Window

A launch window defines a finite timespan within which a spacecraft can be launched from Earth to reach its destination in space. The launch window for interplanetary missions is sometimes further refined to launch period, covering the entire timespan of the launch window, and daily launch window, the permitted launch time of each day within the launch period.

The SPP launch windows are selected from potential launch opportunities that meet the program schedule and the launch vehicle's performance. The launch opportunity of a spacecraft is directly tied to the planned spacecraft's trajectory that transfers the spacecraft from Earth to its final destination. For SPP, the final destination is to get to within 9.86 R_S of the Sun using the V^7GA trajectory. To enter the route of the V^7GA trajectory, SPP must first get to Venus, so the launch opportunity depends on the transfer from Earth to Venus. There are many Earth-to-Venus transfer options, but only those where the Venus arrival can start the V^7GA architecture can become SPP launch opportunities.

SPP will be launched from Florida's Cape Canaveral Air Force Station using a launch system customized specially for SPP. It is a powerful 3-stage launch system, consisting of a 2-stage Delta IV Heavy launch vehicle and a vector-activated Star-48BV solid motor third stage.

Since interplanetary launch opportunities do not occur frequently, it is important for mission planning to have more than one launch window ready, a primary and a backup. The backup launch window serves as a contingency for unanticipated events or circumstances that may cause launch delay and miss of the primary launch window.

4.1. Primary Launch Window

The primary launch window of SPP opens on July 31, 2018. There is a 20-day baseline launch period from July 31 through August 19, 2018 and a 4-day extended period from August 20 through 23, for a total of 24 days. Launch during the 20-day baseline period with a maximum C3 of 154 is a requirement to the SPP launch system, and launch during the extended 4 days is optional if launch system performance permits. The extended launch days will become possible if the spacecraft wet mass becomes lighter than the not to exceed (NTE) mass, which currently appears likely.

The primary launch window coincides with the 2018 launch opportunity of the V^7GA trajectory. Launch opportunities of the V^7GA trajectory occur every 584 days, or 19.2 months, which is the synodic period of Venus from Earth.

The Earth departure conditions to be achieved for SPP launch are defined as launch target in three parameters: launch energy C3, right ascension of launch asymptote (RLA), and declination of launch asymptote (DLA). They serve as the aim point for the launch system to deliver the SPP spacecraft. One launch target is defined for each of the 24 launch days of the primary launch window. The launch targets are determined at the Target Interface Point (10 minutes from the third stage ignition) from the SPP trajectory design, which is integrated from liftoff through the end of the SPP mission. Figure 3 shows the C3, RLA, and DLA of the primary launch window.

On each launch day, a continuous daily launch window is planned, ranging from 30 minutes to 2 hours, depending on the final launch vehicle performance.

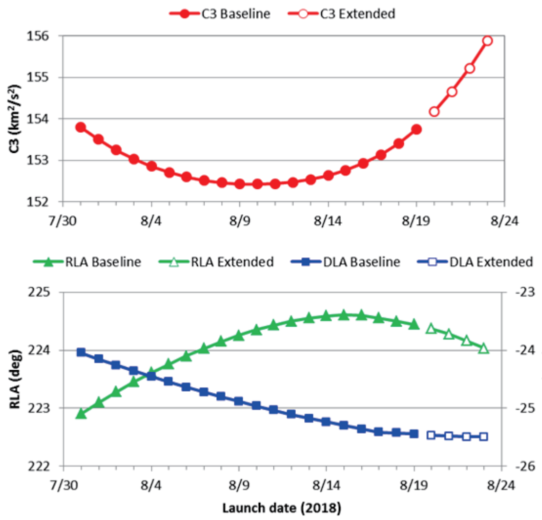

Fig. 3. Primary launch window C3, RLA, and DLA.

4.2. Backup Launch Window

4.1.1. Problem encountered

The next launch opportunity of the V^7GA trajectory is in March 2020 when a similar Earth-Venus orbit configuration reappears. Even though the orbit configuration matches, the required launch C3 is much higher in 2020, 165 km^2/s^2 for a 15-day launch period. That is more than 10 units above the baseline launch C3 requirement. The launch energy variation is due to the orbit variation of Earth and Venus, because both orbits are not perfectly circular and not coplanar. The C3 is very sensitive to the orbit variation and the slight orbit variation has caused the launch energy to exceed the SPP launch system's capacity. The March 2020 launch opportunity is therefore not viable.

The following opportunity after March 2020 is October 2021 which does not look promising. First, it would require a wait time of 38 months, leaving the mission to be grounded for too long. Second, the required C3 is still too high.

4.1.2. Method for solving the problem

The strategy used to solve the backup launch window problem is to search for new launch solutions. As discussed above, launch opportunities are tied to a particular mission trajectory. A new launch opportunity means a new mission trajectory, but the SPP mission is based on the V^7GA trajectory. The SPP spacecraft is designed to operate with the mission profile of the V^7GA trajectory, and the science instruments are selected for the science investigations based on the orbit features and 24 solar passes of the V^7GA trajectory. The new launch opportunity associated with a new mission trajectory must not change the foundation of the SPP mission and must use the same spacecraft and instruments to accomplish the same science investigations. One of the key requirements when looking for new solutions is that the launch must retain the V^7GA trajectory architecture.

A new launch opportunity, different from the V^7GA class, is created by constructing a new mission trajectory that is slightly different from the V^7GA trajectory but retains the V^7GA architecture. The difference of the new mission trajectory from the original mission trajectory is reduced to the minimum necessary for adding a desired new launch opportunity between the 2018 and 2020 launch opportunity of the V^7GA. The new launch opportunity to be created needs to have two things to be viable: 1) it occurs after the primary launch dates and preferably no later than the V^7GA 2020 launch opportunity; 2) its required launch C3 is less than that of the V^7GA 2020 opportunity.

4.1.3. New launch opportunity

A viable new launch opportunity in May 2019 is created with the creation of a new mission trajectory named V^8GA. The new launch opportunity's timing is ideal, 10 months after the primary launch window, which leaves sufficient time for fixing potential issues that may cause the miss of the primary launch window but does not ground the mission for too long. The new V^8GA mission trajectory, as shown in Fig. 4, fully retains the V^7GA architecture.

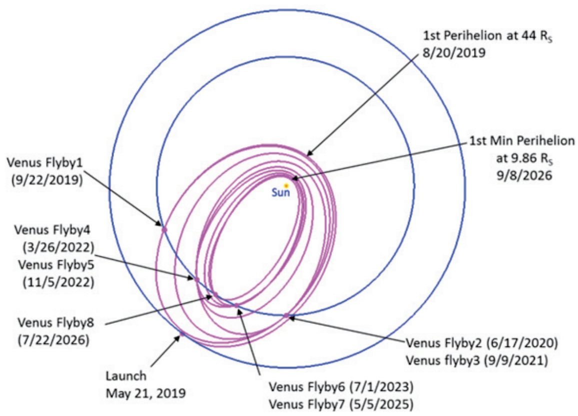

Fig. 4. New V^8GA mission trajectory for backup launch.

The mission profile of the V^8GA trajectory is very similar to the original mission profile, as shown in Fig. 1. The difference is the addition of an extra Venus flyby prior to the V^7GA architecture. The distance of the spacecraft from Earth and Sun over the added trajectory segment remains within the maximum range of the original mission and therefore requires no change of the spacecraft design for its flight operations. The new mission trajectory only increases the number of solar orbits from 24 to 26 and mission duration from 7 to 8 years. Fig. 5 shows the difference of the V^8GA versus the V^7GA trajectory in terms of the solar orbits and solar distance profile. The launch C3 of the new launch opportunity is compatible to that of the primary launch and is within the capacity of the launch system. In other words, a new viable launch opportunity is created by a minor modification of the V^{7}GA trajectory. The modification is essential for the creation of the new launch window but does not affect the mission and the spacecraft.

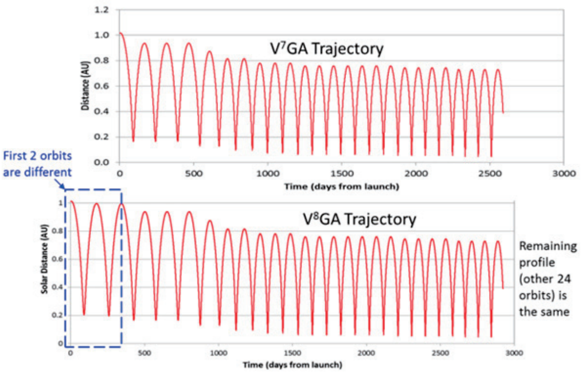

Fig. 5. Comparison of V^{8}GA versus V^{7}GA trajectory.

4.1.4. 2019 backup launch window

The backup launch window has a baseline period of 14 days from May 21 to June 3, 2019 with a maximum C3 of 154.6 km^2/s^2 and 6-day extended period (4 days prior to and 2 days after the baseline period) for a total of 20 days from May 17 through June 5, 2019. The extended days are optional pending on available launch vehicle performance. The launch plan for the 2019 backup launch window is similar to that of the 2018 primary launch, with one launch target for each launch day and 30 minutes to 2 hours of continuous daily launch window. Launch targets over the 2019 backup launch window are shown in Fig. 6.

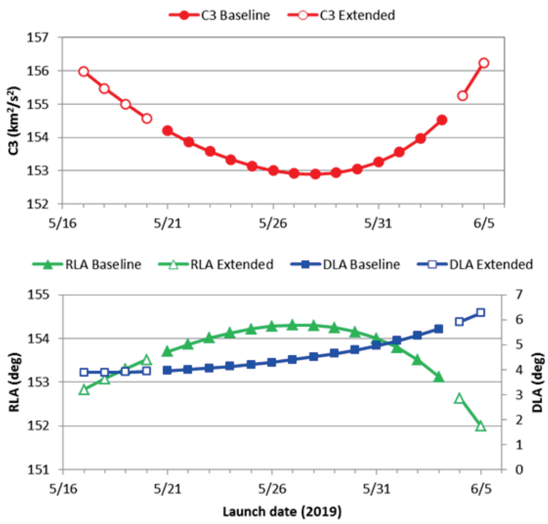

Fig. 6. Backup launch window C3, RLA, and DLA.

5. Conclusion

Solar Probe Plus is the first mission to the Sun, and launching the spacecraft to the Sun has been extremely challenging. The immense launch energy required to get to the Sun far exceeds the ones needed to reach any of the planets in the solar system and is unachievable by current launch vehicles.

The SPP mission is made possible by using planetary gravity assists to make up the launch energy shortage and is implemented through seven repeated flybys of Venus in a unique V^{7}GA trajectory architecture, containing 24 solar orbits whose distance to the Sun get as close as 9.86 R_S.

Two launch windows, a primary and a backup, are in current SPP launch planning. The primary launch window opens on July 31, 2018 and has 24 days. For each day, the Earth departure conditions required for SPP to enter the V^{7}GA trajectory are defined and specified as a launch target to the SPP launch system for launch delivery.

Because the 2020 V^{7}GA launch opportunity cannot be used due to higher C3 demand, a viable new launch opportunity is created as the backup launch window. It is enabled by designing a new V^{8}GA trajectory, which not only fully retains the orbit features in the baseline mission but also accommodates the need of the backup launch window. The backup launch window has 20 days and occurs at 10 months from the primary launch window in 2019.

Acknowledgments

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