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PARKER SOLAR PROBE NAVIGATION: ONE YEAR FROM LAUNCH*

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Parker Solar Probe (PSP) will be the first spacecraft designed to fly deep within the Sun's lower corona and also becoming the fastest spacecraft flown. Launch is scheduled for next year, with a 20-day launch period beginning on 31 July 2018. PSP will be on a ballistic trajectory, requiring seven Venus flybys to progressively lower the perihelion over the seven-year mission. This near-solar environment can be particularly challenging from a spacecraft design as well as a navigation perspective. We discuss an overview of the mission along with some of the particular challenges in navigating PSP.

INTRODUCTION

To be launched in mid-2018, Parker Solar Probe (PSP)*** will be the first spacecraft to fly deep within the solar corona. The primary science goals of PSP are to determine the structure and dynamics of the Sun's coronal magnetic field, understand how the solar corona and wind are heated and accelerated, and determine what processes accelerate energetic particles[1]. In order to achieve these objectives, the baseline nominal mission is a ballistic trajectory consisting of 24 orbits about the Sun over approximately seven years. In this time, seven Venus flybys are required to gradually reduce the spacecraft's perihelion from 35 R_s to 9.86 R_s, where R_s is one solar radius. This will be the closest any spacecraft has come to the Sun and the fastest spacecraft flown. Once the perihelion is reduced to 9.86 R_s, it will achieve a peak heliocentric velocity of approximately 190 km/s.

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*** Until recently, the mission was referred to as Solar Probe Plus (SPP). In May 2017, the name was changed to Parker Solar Probe. Previously published work and much of the current project documentation refers to it as SPP.

There are a number of things which make navigating this spacecraft particularly challenging. One complication with having a ballistic trajectory associated with every launch opportunity is that there is not just one reference trajectory for this mission. While there are no deterministic maneuvers built into the reference trajectories for each launch day (ignoring launch itself), there are 42 opportunities identified for trajectory correction maneuvers (TCMs) in order to meet navigation requirements. However, every launch opportunity requires a unique reference trajectory with different Venus flyby targets, a different maneuver schedule, and a different tracking schedule. This means that we must accommodate 20 unique trajectories when designing a navigation plan and verifying requirements. In the interest of keeping this paper manageable, not every trajectory will be discussed here in detail. Every trajectory has the same requirements and similar challenges, but the details vary from launch day to launch day.

No other spacecraft has experienced solar radiation pressure of this magnitude. Uncertainties in our ability to predict this force on the spacecraft will affect the total ΔV needed to make course corrections as well as our ability to accurately orient the thermal protection shield towards the Sun. Torque due to the effects of solar radiation pressure is also the primary need for thruster activity during the solar encounters. While the spacecraft will be three-axis stabilized via reaction wheels, thrusters will be used repeatedly to dump wheel momentum near perihelion. These momentum dumps will be done autonomously and without tracking data during the events. Sometimes these momentum dumps will take place as often as every few hours near perihelion. Uncertainties in solar radiation pressure and the associated difficulty in predicting the number and timing of momentum dumps are the two primary dynamical errors sources.

Also related to the solar environment are the effects of solar plasma on the radiometric tracking data, both in terms of quantity and quality. Frequently, there are times in the mission in which the attitude strategy (e.g., keeping the spacecraft Sun-pointed) will prevent a radio link with Earth. These gaps in tracking can be as large as several weeks in duration for some orbits. Even in the absence of data gaps, much of the usable tracking data will be affected by the radio signal passing through solar plasma. Two-way Doppler data which travels through solar plasma is affected by a type of colored noise. It is not uncommon for spacecraft navigation teams to significantly down weight this data below a certain Sun-Earth-probe (SEP) angle; attempting to account for the reduced accuracy. Furthermore, many missions will even delete all tracking data for SEP less than ~3-5 deg (e.g., see the Juno solar conjunction strategy in Reference 2). We will not be able to ignore such large quantities of tracking data or ignore the fact that the noise contained in the data is not white noise.

MISSION

Overview

The baseline launch period is 31 July 2018 to 19 August 2018. Recently, four additional days from 20 August to 23 August 2017 were added in order to extend the launch period. Further analysis and discussion by the PSP project will determine if those days will become part of the baseline launch period. The daily launch widow duration is currently two hours – it may be reduced but will not exceed this duration. Launch opportunities will be at 5-min centers during the daily window (Figure 1).

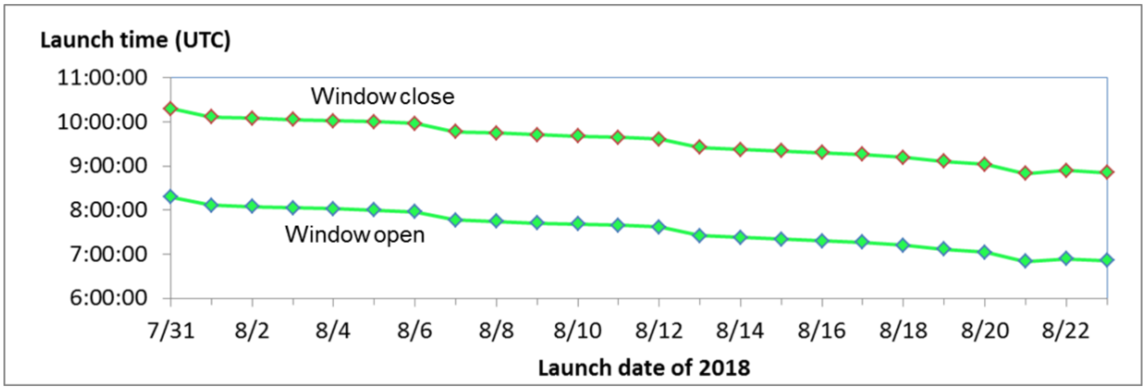

Figure 1. Daily launch windows for baseline and extended launch periods

The basic navigation objective is to manage the trajectory of the spacecraft in order to fulfill the mission objectives within the resources provided, e.g., propellant, DSN tracking time, and budget. Once launched, the spacecraft will be on a ballistic trajectory consisting of 24 solar orbits over seven years. The first 21 orbits contain seven gravity-assist Venus flybys in order to gradually lower the perihelion to a distance of 9.86 R_s. It is the last three orbits of the primary mission that will achieve the minimum perihelion distance that is necessary to achieve at least one of the primary science requirements. This trajectory is presented in Figure 2 for the first day of the launch period, 31 July 2018.

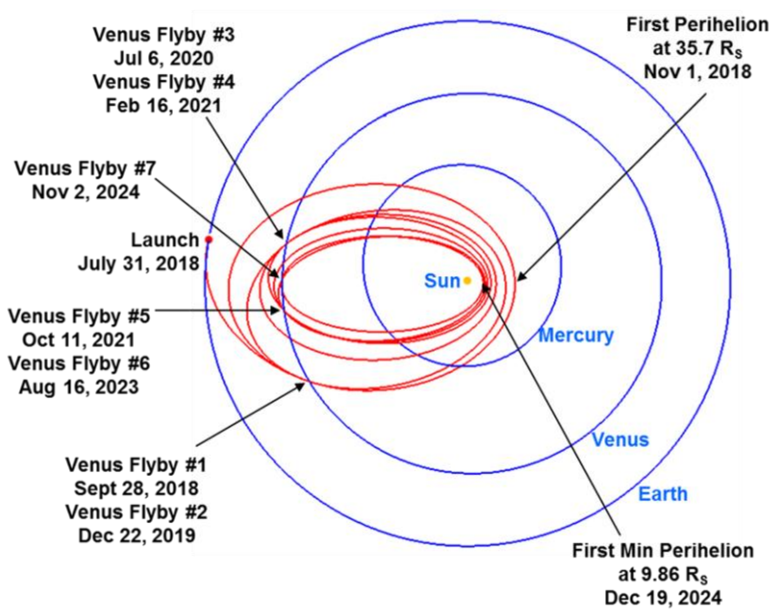

Figure 2. PSP Reference Trajectory for 31 July 2018 Launch

There are no deterministic deep space maneuvers, but statistical navigation maneuvers will be required to correct launch injection errors and to target the Venus flybys and the minimum perihelion passes. There are 42 maneuver opportunities identified during the mission in order to do trajectory correction maneuvers (TCMs). The necessary TCMs will be accomplished with a monopropellant propulsion system consisting of twelve 4.4 N thrusters. These thrusters are also used for momentum dumping of the reaction wheels, where the wheels are used as the primary means of controlling attitude in nominal operations[3]. Figure 3 illustrates the SPS spacecraft in the flight configuration, with solar arrays and instrument booms deployed. There are no thrusters which point directly in the +Z-direction, or directly towards the thermal protection system (TPS), which means it is difficult to efficiently produce a delta-V in all possible directions. This configuration implies that for some TCMs, the spacecraft will likely be turned in order to execute the desired TCM. It also means that when dumping momentum, the thrusting will be significantly unbalanced – momentum dumps and any use of the thrusters to turn the spacecraft will produce a non-negligible amount of delta-V.

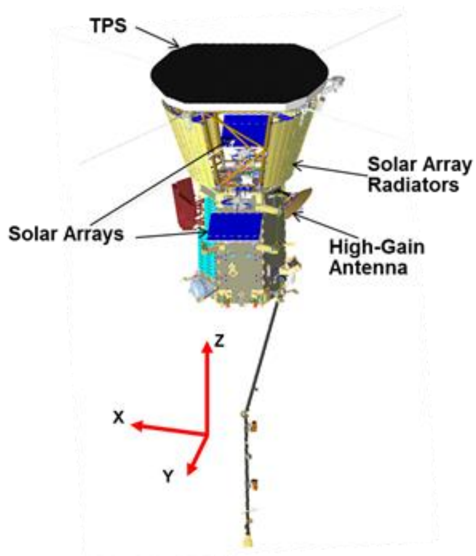

Figure 3. PSP spacecraft in the flight, with solar arrays, electric field, and mag booms deployed. Note that the solar arrays are deployed at nearly a 90-deg angle in this example, which will only occur near aphelion.

What is discussed herein is primarily the work of the Navigation Team. The Mission Design Team is responsible for producing the reference trajectory, making updates to the reference, and calculating the maneuvers needed to tune the trajectory. Before launch, the primary role of the Navigation Team is to verify that we meet the navigation requirements. These requirements are summarized in Table 1. The requirements for navigation mostly fall under four basic categories: (1) ensuring spacecraft safety by predicting the spacecraft-Sun relative ephemeris, (2) ensuring communication by predicting the spacecraft-Earth relative ephemeris, (3) verifying that sufficient propellant is allocated for TCMs, and (4) supporting science results by providing a reconstructed ephemeris. All of these navigation requirements have been analyzed and verified for the primary launch window opportunities (31 July 2018 – 19 August 2018). Recent work done to verify these requirements are detailed in this conference in References 4 & 5. During operations, the primary role of the Navigation Team will be to provide updates to the predicted and reconstructed spacecraft ephemerides, with a secondary role in helping validate TCM ideal delta-V as calculated by the Mission Design Team.

Table 1. Summary of Key Navigation Requirements

Req. #	Requirement	Purpose
22	Statistical delta-V, to 99% confidence, to not exceed 135 m/s, assuming no maneuver less than 0.05 m/s	Total mission propellant
24	Reconstructed heliocentric position errors no greater than 1200 km, 3-sigma for solar ranges <= 0.25 AU.	Support science
25	Predicted heliocentric position errors no greater than 1200 km, 3-sigma for solar ranges <= 0.25 AU, delivered no later than 48 hr before last possible uplink	Spacecraft-Sun relative pointing
26	Predicted heliocentric position errors no greater than 8500 km, 3-sigma in any direction for solar range > 0.25 AU and greater than 5 days from Venus encounter.	Spacecraft-Sun relative pointing
27	Predicted heliocentric velocity of 0.1 km/s, 3-sigma in any direction.	Spacecraft telecom
73	During tracking passes (DSN), following 3-sigma accuracies: 1 m/s for range rate, 0.1 sec for range, an angular accuracy of 0.009 degrees, and a 0.0027 m/s/s for rate of range rate.	Spacecraft telecom
74	Predicted Earth-line position <= 4 arcmin, 3-sigma , within 5 days of a Venus encounter (for telecom system)	Spacecraft telecom
75	Predicted Earth-line range errors no greater than 10,000 km, 3-sigma for distances > 0.25 AU.	Spacecraft telecom
77	Delivery accuracy to the minimum perihelion of 9.86 R_s with uncertainty no greater than 500 km (3-sigma).	Support science objectives

Launch

One of the challenges presented by this mission is the highly energetic launch. Launch vehicle injection targets for missions are frequently specified in terms of hyperbolic injection energy per unit mass (C3), declination of the launch asymptote (DLA), and right ascension of the launch asymptote (RLA). This is true for this mission as well. For the current best estimate of a spacecraft mass of 685 kg, the targeted C3 corresponds to roughly 152-154 km^2/s^2 (Figure 4). This is a relatively large energy; for comparison, New Horizons had a C3 of 164 km^2/s^2 while InSight is expected to have a C3 of 41.1 km^2/s^2. In other words, a solar mission launch is energetically similar to a mission to explore the Kuiper Belt. This highly energetic launch is one of the reasons that the selected launch vehicle is a Delta IV Heavy with a Star-48BV third stage.

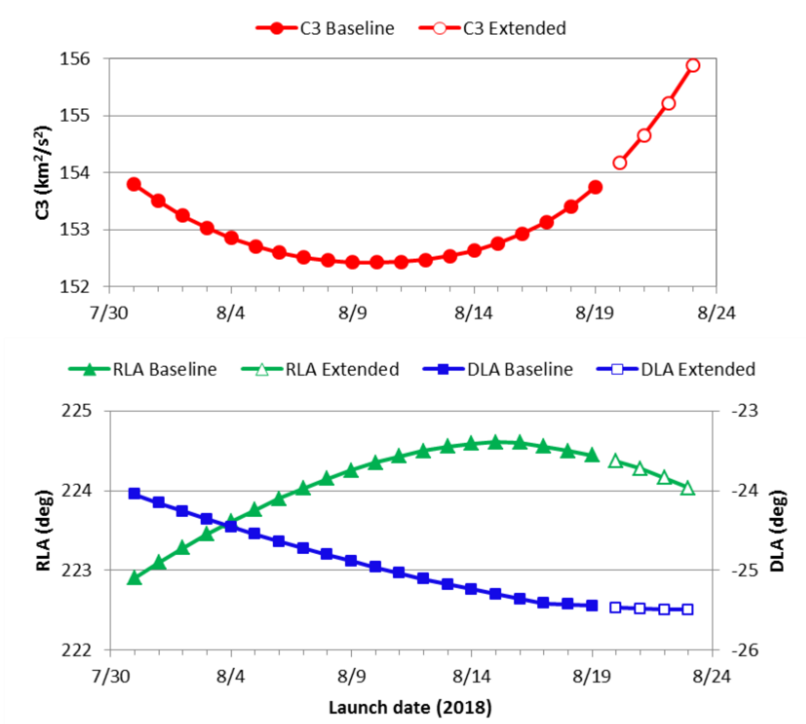

Figure 4. PSP Launch Targets: C3 (top), and RLA and DLA (bottom).

While this launch vehicle configuration will help us achieve the necessary injection conditions, it is the first time that this particular configuration will have been used (that is, the combination of primary launch vehicle and third stage). There are larger *a priori* injection errors that we have to account for at the time of DSN initial acquisition than have usually been assumed for previous interplanetary missions. Also, the geometry itself is unfavorable for tracking the spacecraft with DSN assets during the period of time immediately following separation. A hint of this issue can be seen by observing the ground track immediately after launch in Figure 5. Notice the rapidly evolving ground track within the first 30-60 min after spacecraft separation from the third stage (SEP). Spacecraft SEP from the third stage on the first day of the launch window, 31 July 2018, occurs between 36 min (window close) to 43 min (window open) after launch. Canberra rise occurs from 1-10 minutes after SEP. The elevation changes are very rapid for Canberra (DSS 34 rise and DSS 34 set in Figure 5).

When taking the injection errors into account, the problem of acquiring the spacecraft signal immediately after Canberra rise is readily evident (Figure 6). Taking the injection covariance matrix (ICM) for the 31 July 2018 launch and sampling the 3-sigma dispersions, we can see how that will manifest in azimuth and elevation space – the space relevant for characterizing DSN tracking. It is clear that even for a relatively nominal launch, the possible dispersions are much larger than the half-power beam width of the Canberra antenna. This makes initial acquisition difficult, but not impossible. Search patterns are being developed to look for the spacecraft. Also, this problem is significantly reduced with time as the dispersions are more tightly focused in azimuth and elevation as the spacecraft Earth-range increases. We will eventually be able to track the spacecraft, though initial acquisition may be delayed along with a subsequent reduction in available tracking data.

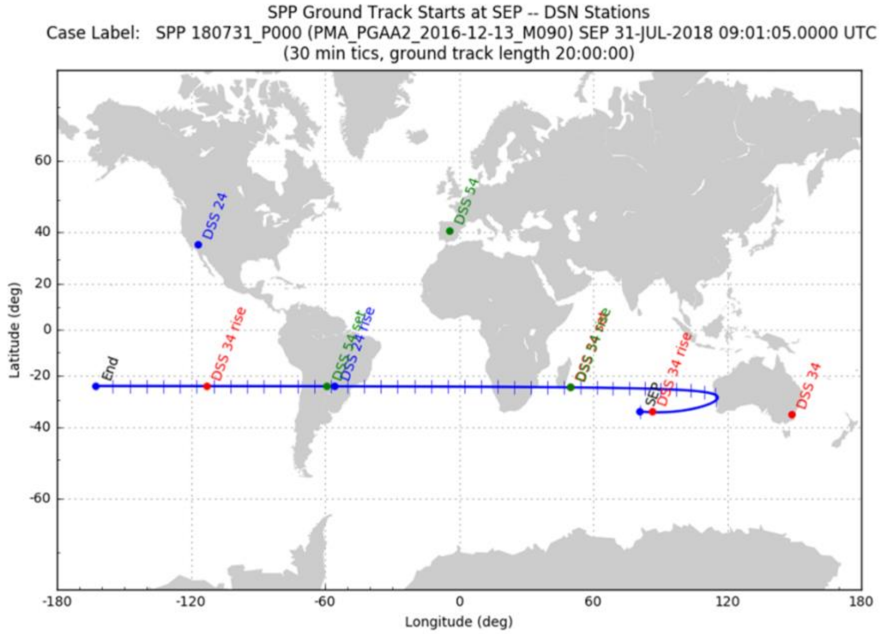

Figure 5. Ground track for launch on 31 July 2018, showing the rise/set times for DSN stations at Canberra (DSS 34), Madrid (DSS 54), and Goldstone (DSS 24). Tick marks are 30 min.

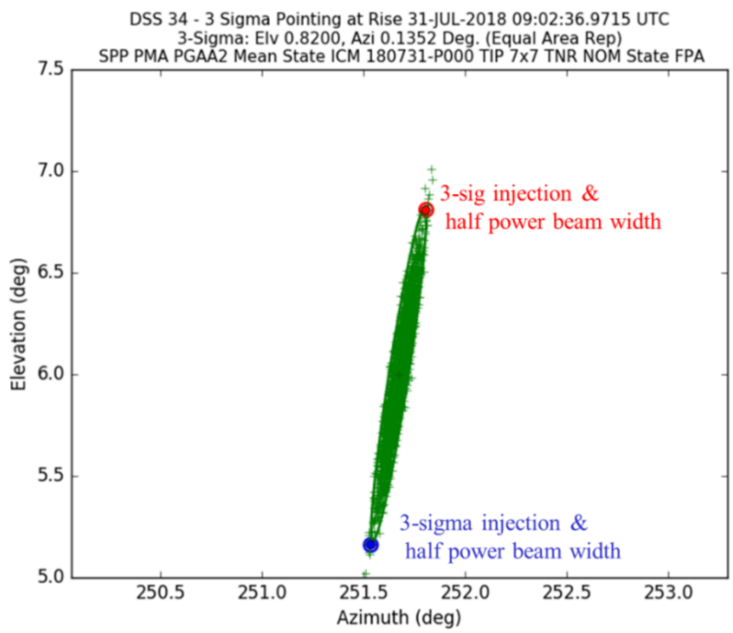

Figure 6. Three sigma pointing dispersions at Canberra rise for initial acquisition for the DSN on a launch for 31 July 2018. Also shown are two examples of the half-power beam width for injection samples at either end of elevation (red and blue circles)

The challenge in acquiring the spacecraft and being able to provide spacecraft ephemeris updates to the DSN is also compounded by how the DSN view periods vary later in the launch window on a particular day (Figure 7). This variation across the launch window is more significant than the small variation seen in the view period from day-to-day in the launch period. As expected, over the two-hour launch window the SEP and Canberra rise times also occur roughly two-hours later. However, other DSN view period related events such as Canberra set (DSS 34 set) or Madrid rise (DSS 54 rise) are relatively invariant – they vary by a few minutes at most. The effect of this is that pass duration of the first DSN station tracking PSP is effectively shortened by the same amount of time that a launch is slipped relative to the opening time of the daily window.

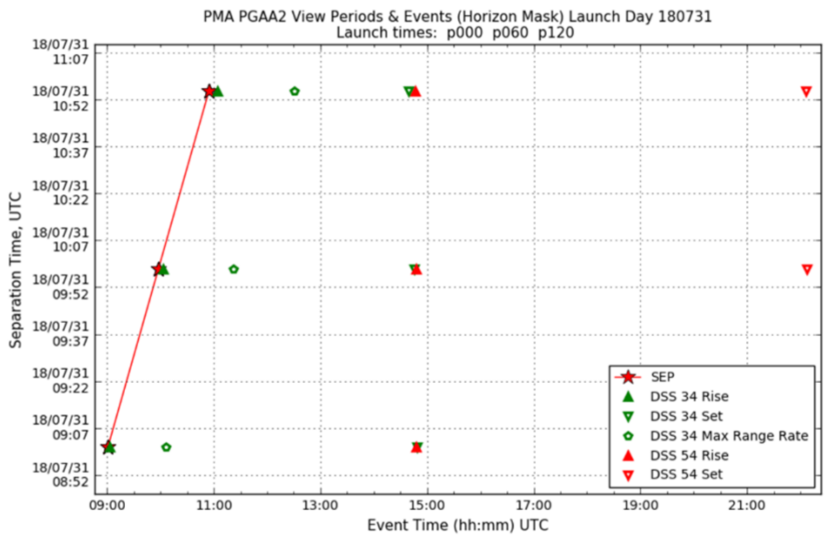

Figure 7. Trends in DSN station rise/set times shown for Canberra (DSN 54) and Madrid (DSS 34), across the two-hour window for the first launch day on 31 July 2018.

One thing that is difficult to see in Figure 7 is that there is a very real gap between SEP and the first DSN station that has PSP in view (Canberra). There is also a gap between the first and second DSN stations (Canberra and Madrid). Since there is a desire to monitor the spacecraft during separation and the sequence of activities which follows (e.g., solar panel deployment, cooling system activation, battery charging), additional non-DSN assets are required. The PSP project has obtained the services of the Swedish Space Corporation (SSC) in order to use the stations at Dongara, Australia and Hartebeesthoek, South Africa. The purpose of these stations is to monitor the activities in real-time and to record telemetry during the initial phases of the separation sequence. These passes will not be used for navigation data, e.g., two-way Doppler, as uplink is not planned for either stations.

Navigation Tracking Strategy

The primary data types for this mission are: (1) 2-way, coherent X-Band Doppler with opportunities for X-band up / Ka-band down Doppler tracking, (2) two-way ranging, and (3) delta-delta-DOR. There are several antennas that will be utilized for tracking services and they are illustrated in Figure 8. Most tracking will take place via the X-band fanbeams (red). The fanbeams are used for nominal coverage in cruise and they span the –X/Z half-plane in the spacecraft frame. The two low-gain antennas (LGAs) (blue) are pointed in the +X and –X-directions, providing near-omni directional coverage. These LGAs will be used for initial operations after launch, TCMs, and other contingencies where the fanbeams do not provide the required coverage. The high-gain antenna (HGA) will be used for Ka-band only downlink. It can slew 45-deg in order to point to Earth and avoid slewing the spacecraft. The HGA's primary purpose is to provide greater bandwidth for downlink of science observations, particularly large amounts of recorded data during the solar encounter phases. However, when combined with the X-band uplink on the fanbeam, the HGA will allow for some X-band up / Ka-band down, two-way tracking.

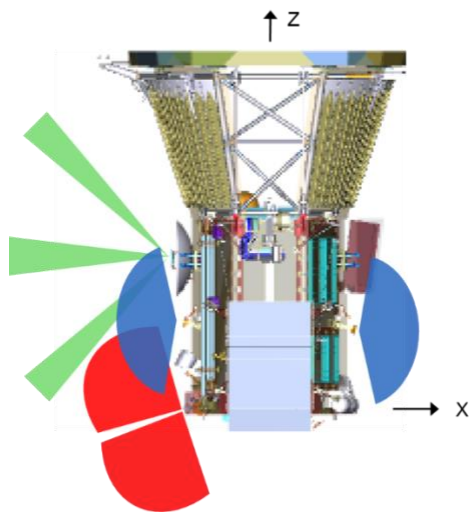

Figure 8. Antenna placement and beam diagram. Shows the X-band fanbeams (red), LGAs (blue), and examples of the range of HGA travel (green)

The nominal tracking assumptions used for navigation analysis are shown in Table 2. At this time, these are only notional guidelines until specific tracking requests are later negotiated with the DSN. Also, keep in mind that tracking requests near launch will have to cover the idiosycrancies of all possible launch dates during the 20-day launch period.

Table 2. Baseline Navigation Tracking Assumptions.

Phase	Period	Type of contact
Doppler and Range		
Launch and Early Ops	Launch to Launch +1 week	Continuous
	Launch + 1 week to Launch + 2 weeks	16-hr per day
	Launch + 2 weeks to Launch + 4 weeks	Five 10-hr passes per week
Venus Flybys	Venus – 5 weeks to Venus – 1 week	Five 10-hr passes per week
	Venus – 1 week to V + 1 week	One 10-hr pass per day
Cruise	All other times	Three 8-hr passes per week
DDOR		
Venus Flybys	Venus – 3 weeks to Venus + 2 weeks	2 sessions per week
Cruise	All other times	1 session per week

What isn't readily evident from Table 2 are the large number and different types of gaps in the available tracking. Examples of gaps include not being able to use the transmitter due to power and thermal contstraints, rules excluding tracking within 35 R_s of the Sun, low link margin due to low SEP, TPS blocking all antennas. The result is that there are signifcant periods of time as long as a few days to over 30 days during some orbits where there will be gaps in the availabe tracking (Figure 9).

Reduction in data due to gaps and reduced quality of data due to solar plasma both make the ephemeris accuracy requirements particualry challenging. It also can be a challenge in scheduling TCM support, where data is needed in time for OD, uplink of the TCM, TCM execution, and then tracking data for reconstruction after the burn. There are a few places where the placement of these gaps makes it necessarly to make special plans that vary from launch date to launch data in order to support TCM-22, for example.

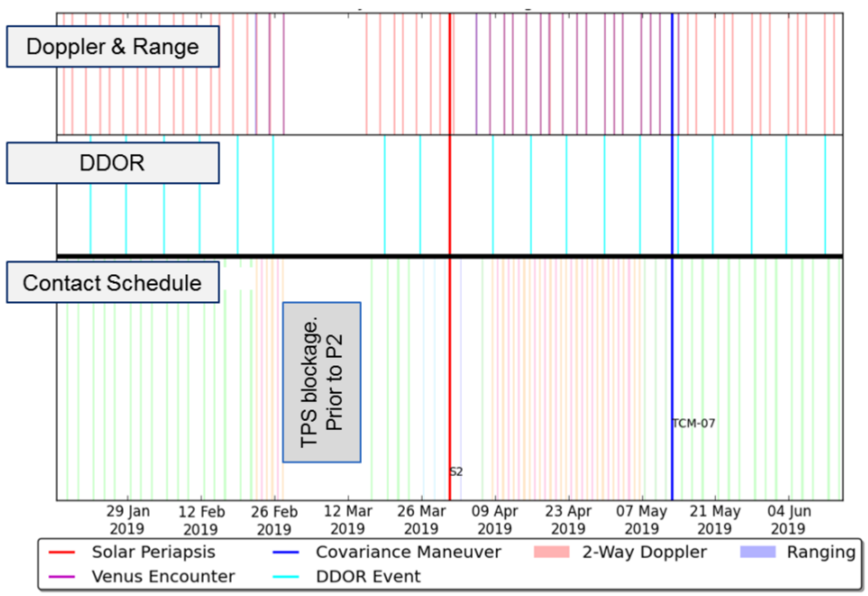

Figure 9. Example of tracking and contact schedule for near perihelion #2. Doppler & Range and DDOR tracking contacts are subsets of the complete telecom contact schedule.

In addition to the gaps in tracking opportunities, the near-solar environment also affects the accuracy and quality of the tracking data. At high Earth-Sun-Probe (ESP) angles, the solar plasma along the signal path will introduce significant non-white noise and/or systematic errors. One way to adjust for this to de-weight the data and to treat it was white noise. For the purposes of orbit determination (OD) covariance studies, this was the strategy which was used[4]. For a given distance, the deweighting factor used is a power-law function of Sun-Earth-Probe (SEP) angle[6]. Figure 10 shows SEP and the deweighting factor assumed for PSP analysis, which assumed that the spacecraft was 1 AU from Earth, on average. However, SEP alone is not the sole factor in determining the amount of solar plasma traversed by the radio signal. To be more accurate, we should also take into account the distance from Earth in order to properly characterize the full path taken through the solar plasma environment. This means that weights we used for our analysis at this time are more conservative than necessary; future analysis will attempt to take into account both SEP and Earth-range.

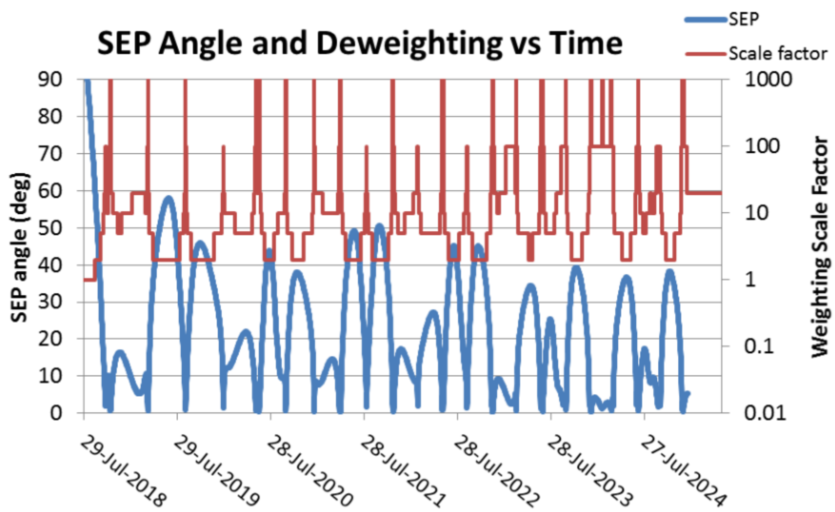

Figure 10. SEP and associated data deweighting factor for 31 July 2018 launch trajectory

In operations, we plan to do more than simply deweight the data to account for non-white noise. Due to solar plasma effects, the Doppler data is correlated to nearby data points within a tracking pass. A whitening algorithm will be used to first "whiten" the data. This algorithm has been implemented into software used to perform the OD function: Mission analysis and Operation Navigation Toolkit Environment (MONTE) program[7]. Testing is already in progress with data near solar conjunction time periods for Maven, Juno, and other spacecraft. This should allow us to treat the data as being affected by white noise and reduce the level of deweighting assumed in the covariance analysis. Furthermore, corrections will be made to account for biases in range data due to the solar plasma effects.

Orbit Determination

The primary goals for OD during operations will be to: (1) provide a predicted spacecraft ephemeris to the spacecraft team and the spacecraft, (2) provide a reconstructed spacecraft ephemeris to support science analysis, and (3) support TCM design. Arguably, the most challenging task for OD is providing a predicted spacecraft ephemeris that meets the 1200-km position error, 3-sigma, within 0.25 AU solar range (see Req #25 in Table 1). This period of time is considered the "solar encounter phase" where primary science observations will be collected and recorded. It is also the most extreme environment that the spacecraft will encounter during every orbit. During this time, the radio link with the spacecraft is very limited at best. For all solar encounters, the operational plan is to not allow for any uplink to the spacecraft in within a 0.25 AU range of the Sun. What this means for OD is that prior to entering a solar encounter (and losing contact), the predicted spacecraft ephemeris must be determined and uplinked. It also implies that no ephemeris updates can be made until some time after exiting the solar encounter (solar range > 0.25AU), enough time has passed to collect tracking once contact has been reestablished, the OD process has been completed to produce a spacecraft ephemeris, and then upload the ephemeris to the spacecraft.

For a detailed analysis of how all these requirements are currently being met see Reference 4. While not trivial, during the rest of the orbit the OD related requirements in Table 1 (Req. #24,26,27, 73,74, and 75) are more readily met. Even with significant gaps in tracking lasting up to a few weeks, those remaining OD-related requirements are easier to meet. Some exceptions to this are OD deliveries for some of the TCMs during specific reference trajectories. As mentioned before, for some launch days, some of the gaps align in such a way to make it more challenging to support the nominal TCM design process.

Attitude Plan

The primary attitude for most of the mission will be with the TPS directed face-on to the Sun, that is with +Z-axis Sun-pointed (see Figure 3), and the primary means for maintaining and changing the attitude will be through the use of the reaction wheels. Two star trackers and an inertial measurement unit (IMU) containing four gyros will provide knowledge of inertial attitude and angular rotation rates. The thrusters, which are also used for TCM execution, will be used to maintain the desired nominal attitude while dumping momentum from the reaction wheels. Because of the dynamics of strong solar torque and large changes in spacecraft attitude to maintain Sun-point during the solar encounters, this will require relatively frequent, autonomous momentum dumps during the solar encounter phase (Figure 11). Some momentum dumps will be needed for solar range > 0.25 AU, but they will be few in number and likely commanded in real-time instead of allowed to occur autonomously. Individual momentum dumps will introduce a delta-V on the order of 10 mm/s, per event, but with relatively large uncertainty on each event because the momentum states will be difficult to predict.

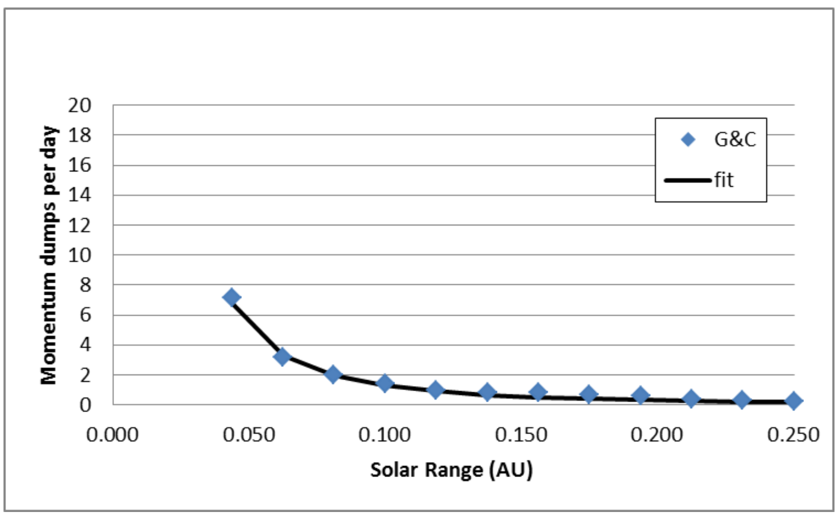

Figure 11. Nominal, autonomous momentum dumps as a function of solar range. Points are from a Monte Carlo analysis by G&C. The solid line is a best fit 1/r^2 curve, where r is solar range.

For solar distances greater than 0.79 AU, it is necessary to use the Sun to warm the dry radiators while keeping bus components within their required temperature limits. This region requires a different pointing strategy referred to as "aphelion attitude". At this attitude, the Sun line is located at 45° from the +Z axis towards the –X axis in the –X, +Z quadrant of the XZ plane.

In addition to the G&C components previously mentioned above, the G&C system also includes a number of Sun sensors that directly measure Sun location relative to the spacecraft. These are not used in nominal operations to maintain relative Sun position, but are utilized to maintain the desired Sun-relative attitude during a safing response. Furthermore, the G&C system also assists with pointing HGA at Earth and controlling the orientation of the two solar arrays relative to the Sun. More information on the attitude control system and associated challenges can be found in References 8 and 9.

Flight Path Control

The PSP reference trajectories are specifically designed to be ballistic for an optimal launch time during every day of the launch window (strictly speaking, they are only ballistic as designed for that specific time). None of the trajectories contain deterministic maneuvers, except for the launch delta-V – all the maneuvers are statistical. In order to shape the trajectory and lower the perihelion to the desired 9.86 R_S for the last few orbits, seven Venus flybys are performed. In other words, the gravity assists provided by the Venus flybys are in lieu of large deterministic delta-V maneuvers that would be needed otherwise.

The maneuver strategy for PSP is to use the TCM opportunities to guide the trajectory back to the reference trajectory via the B-plane targets at the Venus encounters in each reference trajectory. For example, the Venus B-plane targets for V1 through V7 are shown in Figure 12 for the 31 July 2018 launch trajectory. Once the final, seventh Venus flyby occurs, the remaining TCMs are used to target the minimum perihelion desired for the final three orbits. The general placement of the TCMs is such that there are two post-launch TCMs for cleanup of the launch dispersions, two TCMs for each pre-Venus encounter (Venus targeting), one TCM post-Venus encounter (cleanup), and one TCM per solar revolution. This gives a total of 39 TCMs used to target the seven Venus flybys. Now add three TCMs to target the final three, minimum perihelion solar encounters for a total of 42 TCMs.

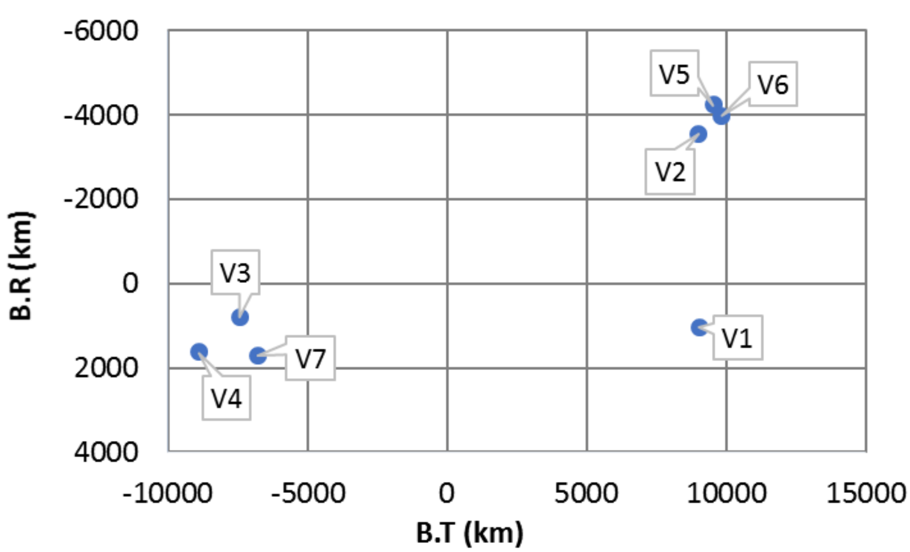

Figure 12. Venus B-Plane targets for 31 July 2018 launch reference trajectory.

There are no specific requirements to achieve the B-plane targets within a certain tolerance. The only explicit requirements as can be seen in Table 1 Req. #22 and #77: a requirement to keep total delta-V for TCMs (i.e., total propellant usage) within 135 m/s and a requirement to target the minimum perihelion orbits to 9.86 R_s within 500 km.

There are several challenges with the maneuver placement for the PSP reference trajectories. First, every launch day has a unique trajectory and set of targets. Also, every trajectory has a unique set of tracking and communication gaps. Because the gaps are dependent upon the particular relative positions of Earth, Venus, Sun, and the spacecraft, they do not simply slide uniformly in time as a function of launch date. Instead the gaps can sometime grow, shrink, and even merge into a larger gap. This means that there is a unique TCM schedule for each reference trajectory that must account for tracking opportunities for OD, time to design the maneuver, uplink opportunities for the TCMs commands, tracking during maneuver execution, and tracking to reconstruct the maneuver delta-V. Every one of these schedules is taken into account for our planning and maneuver analysis

The primary role of the Flight Path Control component of the NAV team prior to launch is to verify the maneuver related requirements (see Table 1). That work as done for the Preliminary Mission Analysis (PMA) cycle is documented in Reference 5; it shows that we meet all maneuver related requirements. A key result of that work is that using the current assumptions, the DV99 is between 79-90 m/s, depending on launch date. This is well under 135 m/s for all launch dates. However, one caveat worth noting is a key assumption being made in order to obtain those results is that an optimization "chain" was used to target each upcoming Venus encounter from V2 through V7. Rather than force every TCM to target the upcoming Venus flyby, the strategy allowed for an optimal division of the delta-V across multiple TCM opportunities leading into a Venus encounter. This reduces the total delta-V needed when compared to a strategy where every TCM is forced to go to the same, fixed Venus target.

And this is just the strategy used for analysis. In operations, a more ambitious strategy will be used that further minimized delta-V costs. Namely, the Mission Design team will be responsible for selecting the ideal delta-V needed to target back to the reference trajectory. But the reference trajectory will be recalculated during the design cycle of every TCM in such a way that all future Venus flyby targets are allowed to vary. Rather than targeting to a static set of Venus targets that were selected for the reference trajectory prior to launch, the Venus flybys, in a sense, will be used as delta-V opportunities that can be adjusted to help minimize TCM delta-V. This means that the DV99 found using the strategies described in Reference 5 should be thought of more as an upper bound for the TCM propellant usage.

SUMMARY

Parker Solar Probe is not only an unprecedented mission to the solar environment, it has some relatively unique navigation challenges compared to previous missions; for example, no other mission has required seven gravity assist flybys before being able to achieve key science observations. Even with the challenges presented by using a new launch vehicle configuration, large gaps in tracking data, the effects of solar plasma on data quality, and flying in an extreme solar environment for the first time, we have shown that all requirements for safely navigating PSP can be met. With the launch of Parker Solar Probe less than one year away, we will continue to re-verify these requirements in the coming months as we obtain updates to the launch trajectories, launch dispersions, spacecraft models, momentum dump predictions, tracking contact schedules, and mission reference trajectories. In particular, special attention will need to be paid to the four extra days of the extended launch period as it will be the first time we have studied those days. Then at the beginning of 2018, we will transition from analysis and into operational readiness for launch and beyond as we prepare for the launch period to open on 31 July 2018.

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