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Post-Launch and Early Mission Thermal Performance of Parker Solar Probe through the First Two Solar Orbits

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Parker Solar Probe (PSP) will explore the inner region of the heliosphere through in situ and remote sensing observations of the magnetic field, plasma, and accelerated particles. PSP will travel closer to the sun [9.86 solar radii (RS)] than any previous spacecraft to obtain repeated coronal magnetic field and plasma measurements in the region of the sun that generates the solar wind. The mission will entail 7 years from launch on 12 August 2018 until the completion of the 24th orbit, projected to be on 19 June 2025. During its lifetime, the spacecraft will be exposed to wide-ranging thermal environments, from the cold of Venus eclipse to exposures to the sun's corona that produce a mission minimum perihelion of 9.86 RS and equivalent solar constant in excess of 480 suns. Spacecraft power is generated using photovoltaic solar arrays that are actively cooled by the SACS (Solar Array Cooling System manufactured by Collins Aerospace). This paper will discuss the thermally critical post-launch SACS activities and also provide an overview of the SACS and spacecraft thermal performance through the mission's first two solar orbits that each have identical perihelion of 35.7 Rs (38 suns).

Nomenclature

AFT	=	allowable flight temperature
APL	=	Johns Hopkins University Applied Physics Laboratory
AR	=	anomaly report
AU	=	astronomical unit (the distance between the center of the Earth and the center of the sun)
ATM	=	analytical thermal model
BOL	=	beginning of life
CSPR	=	cooling system primary radiator
CV	=	check valve
DSS	=	digital sun sensor
EDT	=	Eastern Daylight Time
FBA	=	fan-beam antenna
FIELDS	=	Electromagnetic Fields Investigation instrument suite
GSFC	=	Goddard Space Flight Center
HGA	=	high-gain antenna
IMU	=	inertial measurement unit
ISO	=	latching-type isolation valve (designated 1, 2, or 3)
ITVT	=	integrated thermal vacuum test

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LGA = low-gain antenna
m = meter
MEP = FIELDS Main Electronics Package
MESSENGER = MErcury Surface, Space ENvironment, GEochemistry, and Ranging
MLI = multilayer insulation
MOC = Mission Operations Center
O-1 = solar orbit-1
O-2 = solar orbit-2
P-1 = perihelion-1 (35.7 R_S)
P-2 = perihelion-2 (35.7 R_S)
P-3 = perihelion-3 (35.7 R_S)
Pa = Pascal
PSE = power systems electronics
psia = pressure, absolute
psid = pressure, differential
PSP = Parker Solar Probe
RF = radio frequency
RIU = remote interface unit
R_S = solar radii
RWA = reaction wheel assembly
SA = solar array
SACS = Solar Array Cooling System
SAP = solar array platen
SLS = solar limb sensor
SOC = Science Operations Center
SPAN = Solar Probe Analyzers
SPC = Solar Probe Cup
SSR = solid-state recorder
ST = star tracker (1 and 2)
TEC = thermoelectric cooler
TPS = thermal protection system
TWT = traveling-wave tube
WAC = wing angle control
WISPR = Wide-field Imager for Solar Probe

I. Introduction

PARKER Solar Probe (PSP) was launched on 12 August 2018 at 03:31 a.m. EDT from Cape Canaveral Air Force Station on a Delta IV expendable launch vehicle, including a third stage. Immediately after separation from the third stage, the spacecraft successfully began the post-separation sequence, which included spacecraft orientation relative to the sun and Earth, solar-array (SA) deployment, and partial activation of the cooling system (two platens and two of the four radiators). The time to first perihelion was devoted to early operations, including:

- Launch correction maneuver
- Subsystem checkouts
- Deployments
- Instrument checkouts and in-flight calibrations
- Warm-up and activation of the remaining two radiators
- Preparation for first solar encounter period
- First of seven Venus flybys to target the first solar perihelia (non-eclipsing)

Approximately 3 months after launch, PSP conducted the first of 24 solar encounters, with the perihelion of this first orbit at 35.7 solar radii (R_S) occurring on 5 November 2018. The remaining six Venus flybys planned for the mission will decrease the perihelion of subsequent orbits, leading to an eventual minimum orbit of 9.86 R_S for the final three encounters (Figure 1). During three of these final six Venus flybys, PSP will fly through Venus shadow and experience approximately 11 minutes of Venus eclipse.

PSP is a three-axis-stabilized spacecraft (Figure 2), and its most prominent features are the thermal protection system (TPS) designed to protect the spacecraft bus and most of the payload within its umbra during the multiple solar encounters and the Solar Array Cooling System (SACS). The TPS will always be pointed toward the sun, except during the cooling system activation, communications, thermal control, specified instrument calibrations, pre-Venus eclipse maneuvers, and the trajectory-correction maneuvers that occur at solar distances > 0.7 AU. Figure 3 illustrates the various operational steady-state and transient attitude modes utilized to maintain the proper thermal environments for the observatory and SACS radiator activation. Inside of 0.70 AU, the TPS is *always* maintained normal to the sun (+Z to the sun).

The central feature of each solar orbit will be the solar encounter period, centered roughly ±5.5 days around perihelion when the observatory is within a solar distance of 54 R_S. During this time, the observatory will primarily be devoted to the scientific measurement campaigns. Because communications with the observatory will be limited during solar encounter, the science data and the bulk of housekeeping data will be stored on a solid-state recorder (SSR). After each solar encounter (solar distance > 0.25 AU), mission highlights include cruise/downlink segments, science data downlinks, spacecraft-to-ground communications, and flight-path correction maneuvers.

The Deep Space Network will be used to communicate with PSP to collect data required for navigation. Mission operations will be conducted at the Johns Hopkins University Applied Physics Laboratory (APL) from a single Mission Operations Center (MOC). The MOC will be responsible for the operation of the spacecraft and for providing the necessary data to the instrument teams, such as attitude, ephemeris, and precise time. PSP uses a decoupled approach that allows each instrument team to manage its own instruments, including commanding and telemetry management. The MOC is responsible for transmitting commands provided by the Science Operations Centers (SOCs) to the spacecraft and providing science telemetry data to the SOCs in a timely manner. This decoupled approach was successful during previous spacecraft operations controlled from APL (TIMED [Thermosphere, Ionosphere, Mesosphere Energetics and Dynamics], MESSENGER [MErcury Surface, Space ENvironment, GEochemistry, and Ranging], STEREO [Solar TErrestrial RElations Observatory], and Van Allen Probes programs), allowing for simpler interfaces between spacecraft and science operations mission configurations.

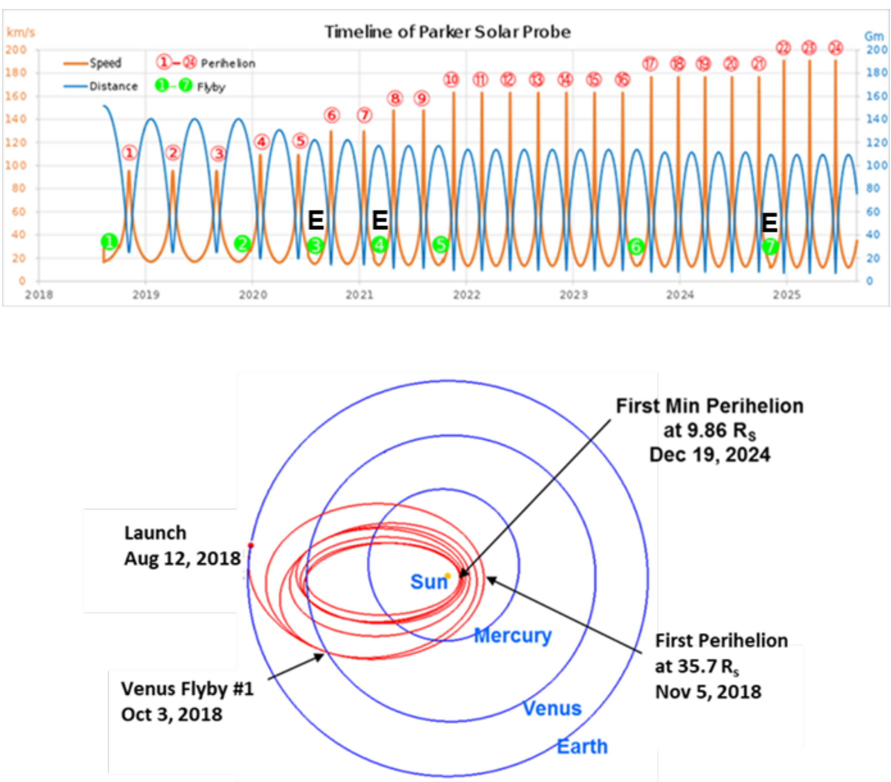


Figure 1. The mission timeline of showing the 24 gradual decreases in perihelion associated with the seven Venus flybys, and orbit geometry highlighting a few of the key events. The three flybys that have 11 minute eclipses are denoted by “E”.

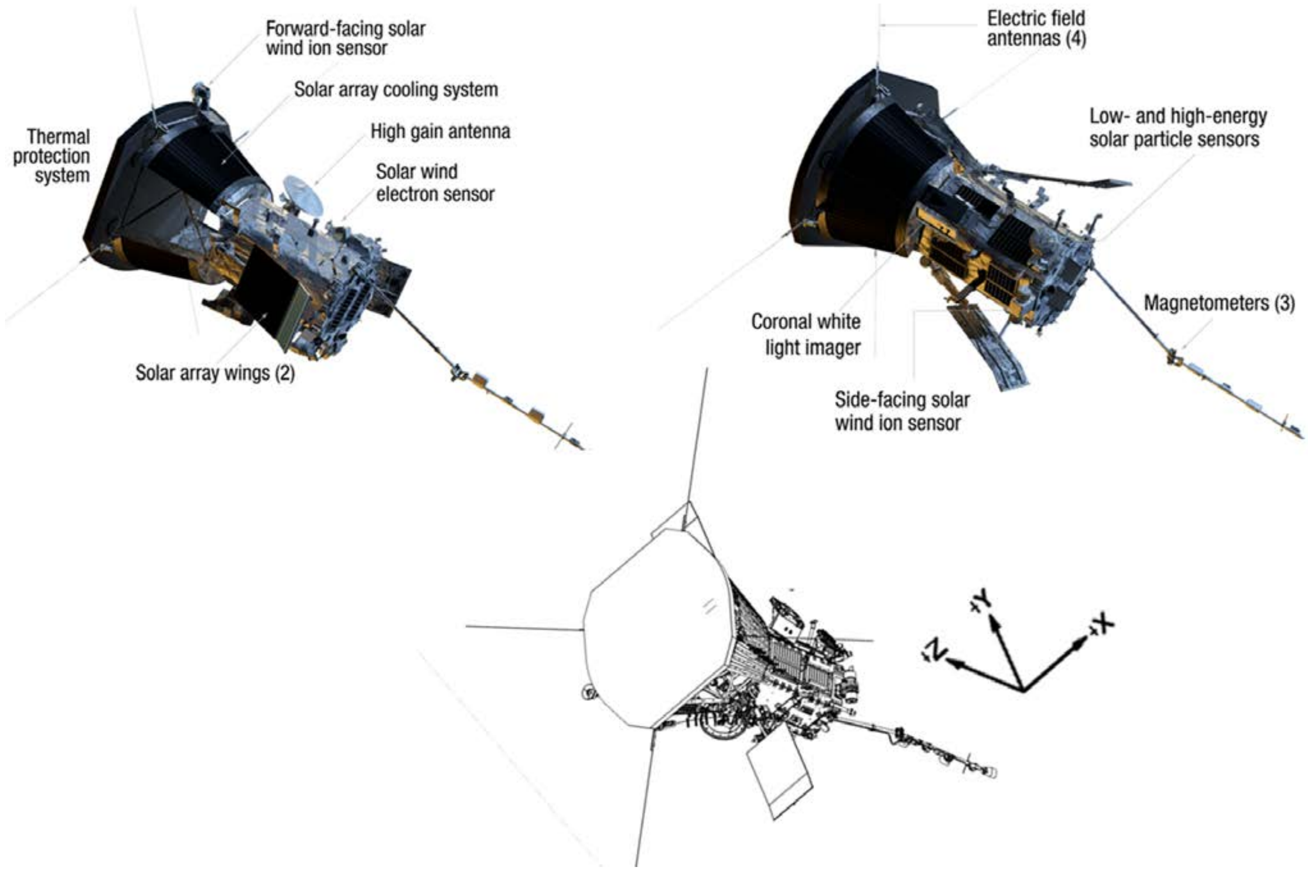


Figure 2. The PSP spacecraft flight configuration and the vehicle coordinate frame.

A - Steady State Orientations: Normal Operation

Solar Distance	Description / View from Sun
1.02 AU to 0.82 AU	Aphelion **(+Z to –X: 45°)**
0.82 AU to 0.7 AU	Aphelion-Umbra Variable **(+Z to –X: 0° to 45°)**
0.7 AU to 9.86Rs	Umbra/ Encounter

B - Transient Orientations: SACS Activation

Name	View from Sun	Solar Distance	Duration
Activate Radiators 1 and 4	**(+X)**	1.02 AU	~ 1 hr
Activate Radiators 2 and 3	**(-X)**	0.9 AU to 0.89 AU	< 1 hr

Figure 3. The PSP flight (A) and SACS activation (B) orientations. During aphelion attitude (A), the spacecraft is tilted to the maximum allowable of 45° from +Z and is maintained in the X-Z plane.

II. SACS/Solar Arrays

The primary requirement of the Solar Array Cooling System (SACS) is to provide SA cooling from 9.86 R_S to 1.02-AU solar distances. The system will provide this cooling with an operating fluid (deionized water) temperature of +10°C (test minimum) to +150°C (test maximum/platen) depending on heat load and mission timeline. The system is designed for a survival fluid temperature of +200°C. A custom-designed accumulator is used to store the water from launch until initial system activation (~90 minutes after launch) as well as maintain a pressure cap on the system to prevent boiling for temperatures up to 210°C. At 9.86 R_S, the cooling system must be able to accommodate ~5900 W of solar load over two solar-array platen (SAP) "wings." The maximum platen surface temperature at that heat load cannot exceed 150°C at the platen surface where the solar cells will mount. The highest portion of this heat load will occur on the tips of the solar platen; the heat load is equivalent to 35 suns. A second cooling capacity case occurs at 0.7 AU during the communications slew; in that case, the spacecraft is slewed 45° toward the sun, imparting additional heat load to cooling system primary radiators (CSPRs) 2 and 3.

The major components of the SACS are the four custom-designed CSPRs, two diffusion bonded SAPs, and the SACS flight components located on both sides of the spacecraft top deck. The SACS top-deck components consist of the following: redundant pump package, total and redundant delta pressure transducers, three latching valves, and the accumulator. The three latching valves allow for the initial system activation and the strategic wetting of the final two radiators. Figure 4 gives an abbreviated pictorial description of the SACS layout with a few of the main components that are visible being called out.

More detailed explanations on the SACS operation; temperature limits; hardware; and measured, tested, and predicted system performance can be found in Refs. 1, 2, and 3. As shown in Ref. 1, the SACS with connected SAs behaves as a nearly isothermal system, and the worst-case system delta-T of ~10°C will occur when the spacecraft is at 9.86 R_S when the SAs are experiencing the maximum solar flux. Also, as described in Ref. 1, an excessive heat leak from the SACS into the spacecraft simulator was discovered during hot case testing, and an engineering fix was made after testing and prior to SACS integration. This fix was verified to be adequate during the spacecraft-level thermal vacuum test where the SACS and TPS simulator were operated to 125°C and 325°C, respectively, and the underlying spacecraft components stayed under their maximum allowable temperatures when at steady-state conditions.

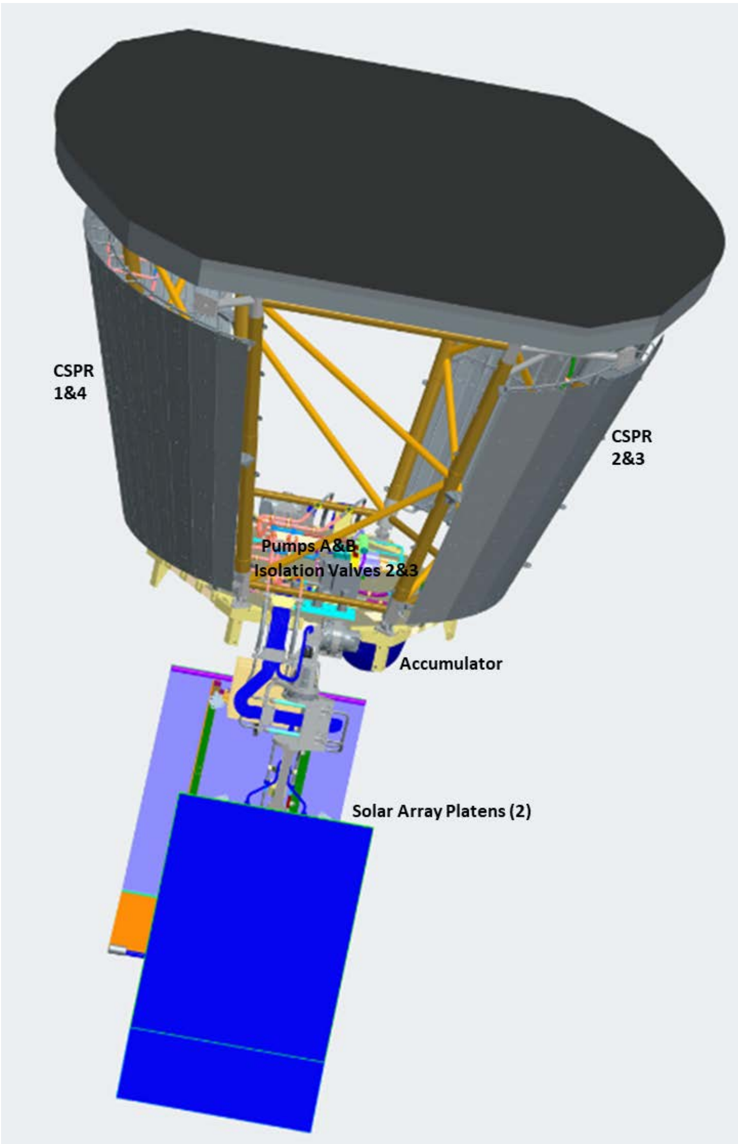


Figure 4. The SACS with a few of the visible main components highlighted. Further description and hardware layout can be found in Ref. 1.

A. Post-Launch and System Activation

PSP was designed to maintain the SACS water temperature above its freezing temperature during the period between launch and SA wings deployment by launching the system dry and strategically activating the system as heat load became available and launch correction attitude uncertainty was reduced. All the SACS water was stored in the accumulator, which is mounted on the underside of the PSP top deck. Utilizing Delta IV ground support equipment umbilical power, accumulator heaters, and thermostats, the water temperature was controlled between +45°C and +50°C before launch to overcome any cold spots in the inlet/outlet tubing when the system is initially activated after launch. The accumulator heater was powered by the launch vehicle starting at L-24 hours, terminating at L-4 minutes. The remainder of the SACS was evacuated and isolated from the accumulator by the first isolation valve, as indicated by ISO1 in Figure 5. After launch and fairing jettison, the SACS was exposed to the cold space, and its temperature began to drop. After de-tumbling, the SAs were deployed; PSP was slewed to +X to the sun to have the SAs, CSPR1, and CSPR4 in the sun-facing orientation (Figure 3); and the solar heating of the SAs and CSPRs began. After approximately 45 minutes in this attitude, the temperatures of the SAPs and CSPRs were verified as acceptable, and the water was released from the accumulator, wetting the SAPs, CSPR1 and CSPR4, and the pump. At this solar distance (~1.02 AU), the solar load is not high enough to maintain the SACS temperature at the safe level if the water were released to all four CSPRs, which is why only two of the four CSPRs are flooded at this stage. After the first activation was successfully completed, PSP was slewed to the sun attitude of 45° from +Z toward −X (aphelion attitude) to have CSPR2 and CSPR3 in the sun-facing orientation (Figure 3). With the solar heating, the dry CSPR2 and CSPR3 temperatures were maintained well above their −150°C dry survival temperature. Thirty-three days later when the spacecraft reached 0.90 AU, the spacecraft was slewed to −X to the sun, and the final SACS activation was successfully executed with the wetting of CSPR2 and CSPR3 (Figure 3). Figure 6 illustrates the CSPR temperatures as measured by the 32 temperature PT103 temperature sensors (eight per radiator) during the two activation events. The thermal “spike” at the beginning of each CSPR activation represents the orientation illustrated in Figure 3. Both activation sequences were nominal, and there were no spacecraft problems or anomalies during either of the events.

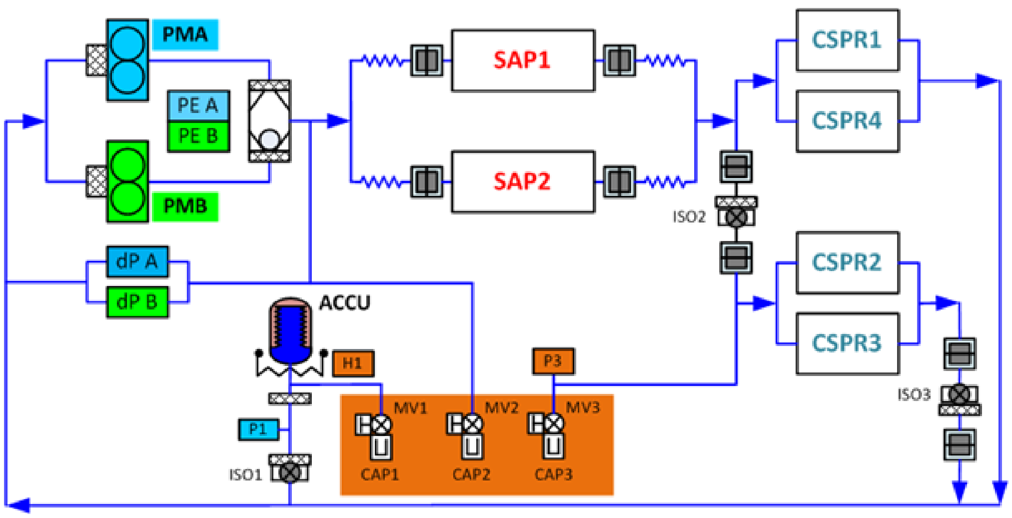


Figure 5. The PSP SACS block diagram. Key components illustrated are the accumulator, block redundant pumps (PM) with electronics (PE), the cross-strapped redundant delta-P sensors (dP), SAs (SAP), radiators (CSPR), and the isolation latching valves (ISO).

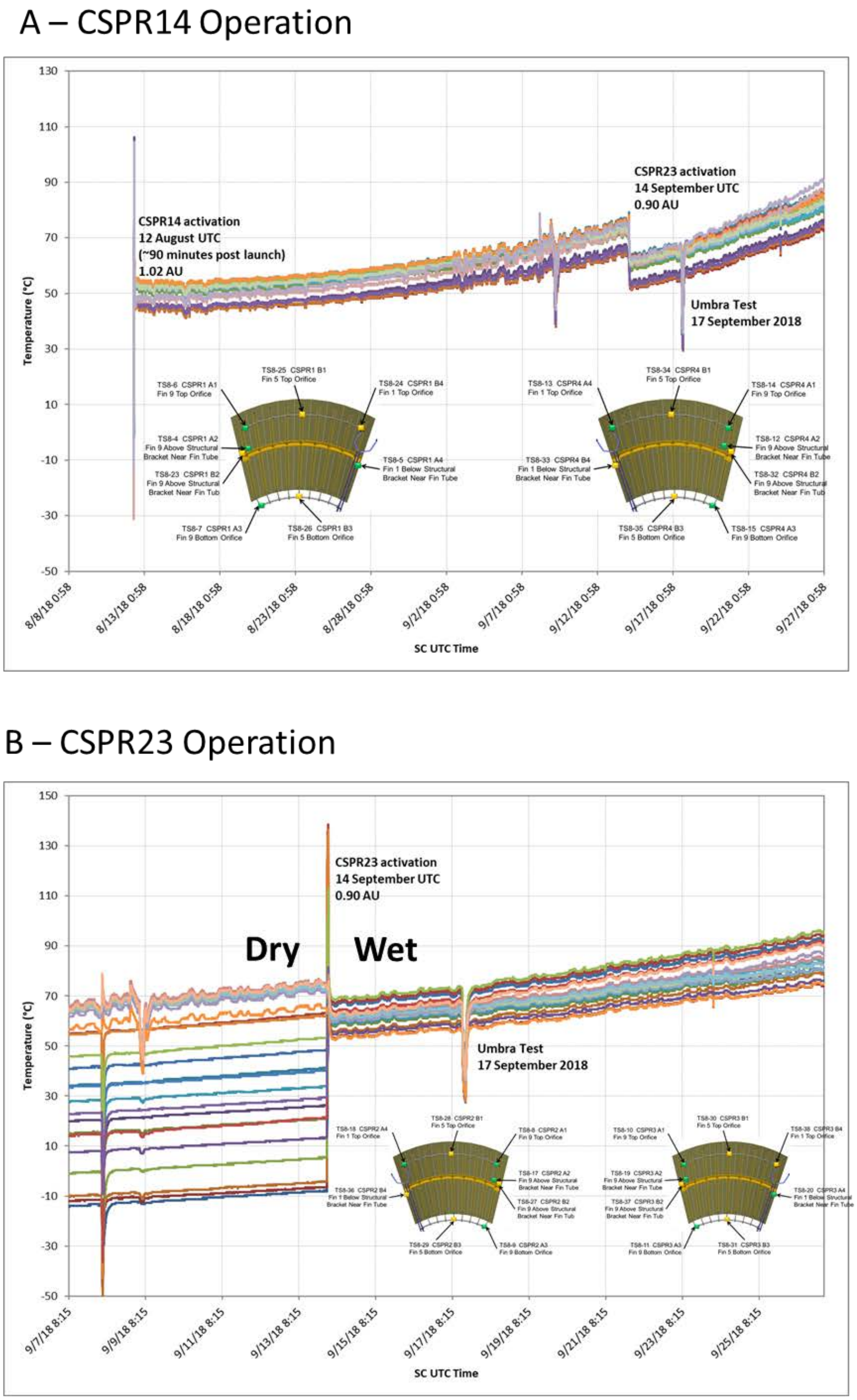


Figure 6. Shown are the two stages of SACS activation and operation. (A) Post-launch and initial system operation with two active radiators. (B) Subsequent activation of the final two radiators 30 days after launch. The 16 PT103 temperature sensors per radiator pair indicate successful SACS activation and operation. Evident in Plot A is the abrupt 20°C step-down in system temperature when CSPR2 and CSPR3 were activated. Because of the 45° aphelion tilt attitude, CSPR2 and CSPR3 also provided an additional ~640 W to the system upon activation.

B. SACS Commissioning

During the first 45 days of the mission (launch to 0.70 AU), the spacecraft subsystems and instruments went through a commissioning period where expected performance was verified and any anomalies were resolved. There were two commissioning events for the SACS:

- the SA 40° tilt test (8 September 2018)
- the umbra test (17 September 2018)

The SA tilt test was used to confirm/verify that the entire SACS heat load was being exclusively absorbed by the SAs and that there was no secondary heat path. At solar distances greater than 0.70 AU, the SAs are held normal to the sun by adjusting the flap (rotation about X axis/motion in the Z direction) and feather angles (rotation about Y axis/parallel to boom long axis) to compensate for spacecraft attitude (Figure 2). For the duration of the tilt test, the SAs were rotated 40° off normal using the feather drive. Based on the following relationship:

$$T_{40} = \text{cosine}\,(40)^{1/4} \times T_i,$$

where Ti = 338 °K (65°C), the steady-state SACS temperature was predicted to be T_{40} = 43.2°C. After ~2.5 hours at the 40° tilt, the measured steady temperature was 44°C, confirming that the SACS heat load is exclusive to the SAs.

On 14 September 2018, just prior to wetting CSPR2 and CSPR3, the SACS heat load based on the measured pump check valve (CV) temperature, 70°C, was estimated to be 1900 W using the correlated SACS thermal model.[1] Three days later, the umbra test was performed, where the heat load from the recently wetted CSPR2/CSPR3 was reduced to zero due to the umbra attitude, and the heat load to the SACS came exclusively through the SAs. Correcting for the decrease in solar distance, the 1900 W predicted on 14 September 2018 (0.90 AU) became 2033 W (0.87 AU). After approximately 3 hours in umbra attitude, the measured steady-state temperature was ~33°C. This lined up very well with the model prediction for the 2033-W power input and four active radiators. In flight, there is no way to independently or directly measure SACS input power, so it must be estimated based on temperature. Figure 7 illustrates early mission SACS performance along with some of the key events that took place during the first 45 days. During O-1, transition to umbra pointing was done on 29 September 2018 (0.78 AU), and the spacecraft crossed over the 0.70 threshold 6 days later on 6 October 2018. As shown, when inside of 0.70 AU, the SA control system performs wing angle control (WAC) to maintain the temperature between 60°C and 65°C.

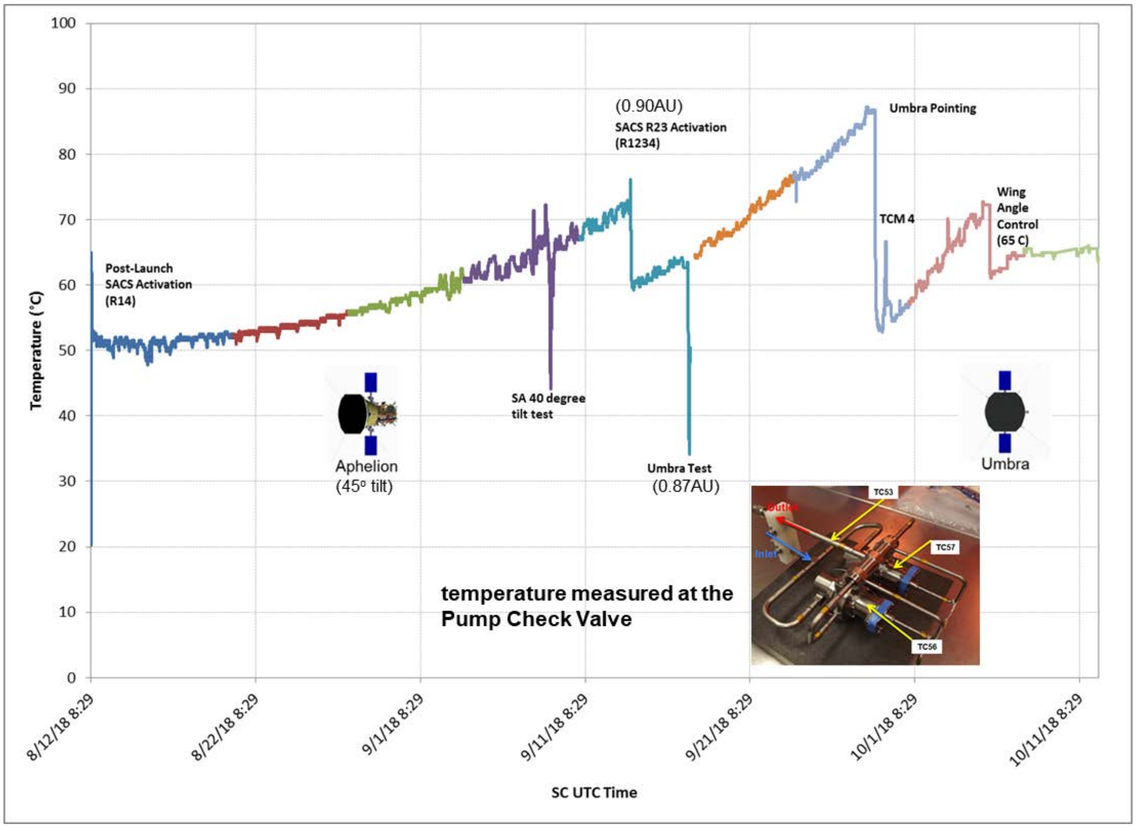


Figure 7. Shown is the SACS system temperature, defined by the pump CV temperature, during the early mission and commissioning. Highlighted are the radiator activations, the tilt and umbra tests, and the first demonstration of SA WAC. Note: The line color change segments are a function of the 1-week data blocks that are processed and are automatically generated by the plotting code. This color change will be evident in some other plots throughout this paper. TCM, trajectory-correction maneuver.

C. SACS In-Flight Performance

The SACS and SA flight performance to date has been very stable, as illustrated in Figure 8. Temperatures and pressures have been nominal and are matching predictions very well. The system delta-P increased by the expected ~13,790 Pa (~2 psid) when CSPR2 and CSPR3 were activated, and system pressure has tracked accumulator temperature perfectly. Figure 9 is an example of the SACS flight telemetry screen that summarizes the key performance parameters: motor speed and control duty cycle (PWM), SA and accumulator temperatures, and total and delta system pressures. Overall, the SACS is working as designed, and the performance is matching measurements taken during thermal vacuum testing for similar conditions. Figure 10 shows the various operating points, with both two and four radiators active, achieved so far during the mission compared to SACS thermal model predictions. As described in Ref. 1, the SACS was comprehensively calibrated over the operating temperature range (referenced at the pump CV) as a function of input power during the integrated thermal vacuum test (ITVT) in March 2017. The SACS thermal model developed for the ITVT was correlated against the test data and was used and adjusted during observatory thermal vacuum test in early 2018. As described above, the SACS thermal model was verified in flight using an estimated heat load prior to CSPR2 and CSPR3 activation, correcting that heat load based on solar distance, and then predicting the correct operating temperature during the umbra test.

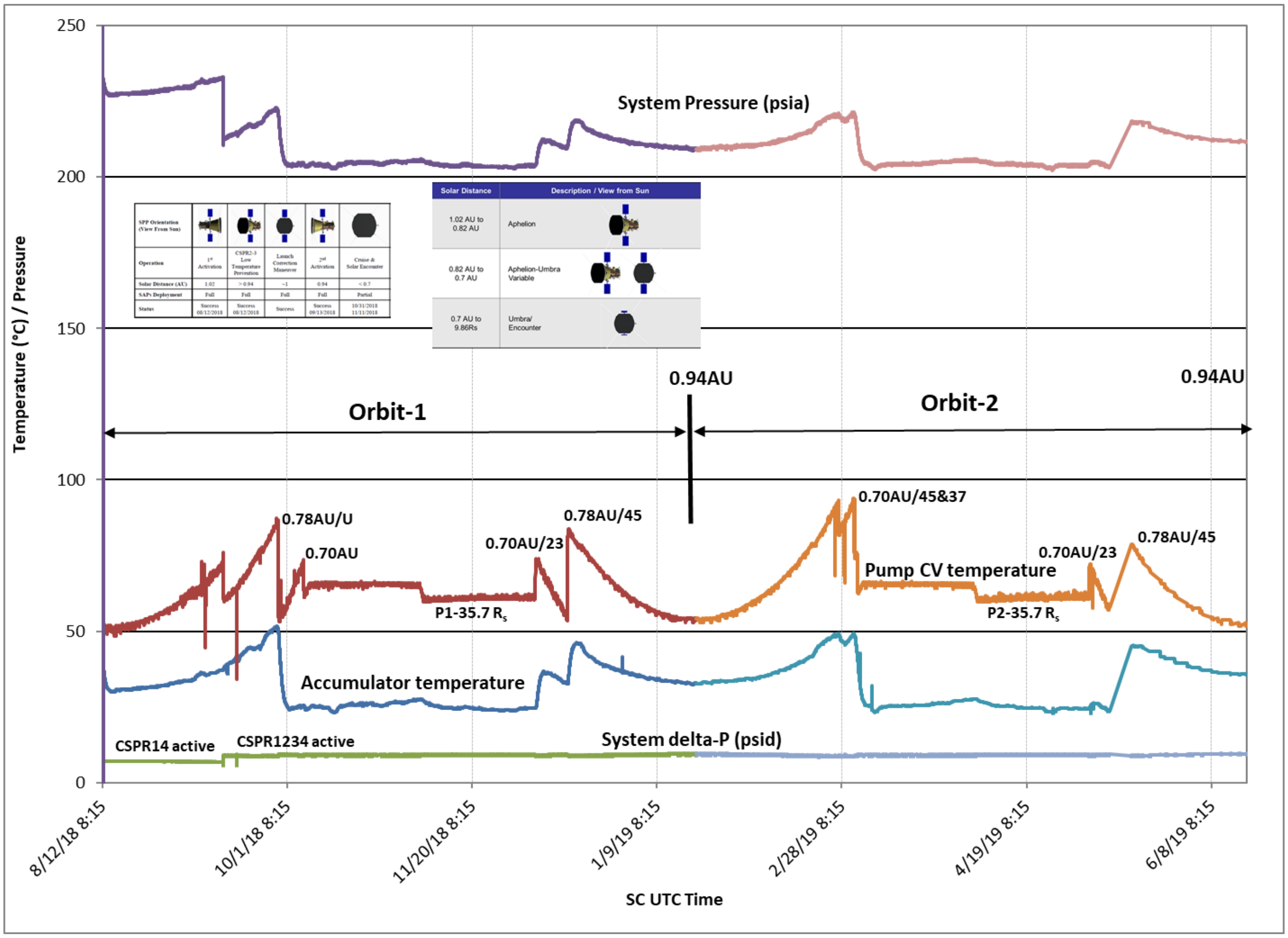


Figure 8. SACS flight performance through O-2 (17 June 2019). Shown are the pump CV and accumulator temperatures (°C) as well as the system total pressure (psia) and delta-P (psid). To date, the system has performed as designed. As shown, when inside of 0.70 AU the solar array flap angle is adjusted as a function of solar distance to keep the SACS operating temperature between 60 °C and 65 °C.

Figure 9. SACS system telemetry screen (1 March 2019): 37° tilt/0.73 AU). Shown are SA temperatures (°C), system total pressure (psia) and delta-P (psid), and pump speed (rpm). The 5271-rpm represents the SACS "high speed" and is the default speed when the CV (system reference) temperature above 50°C. When the system temperature is below 50°C, the default speed is 4200 rpm.

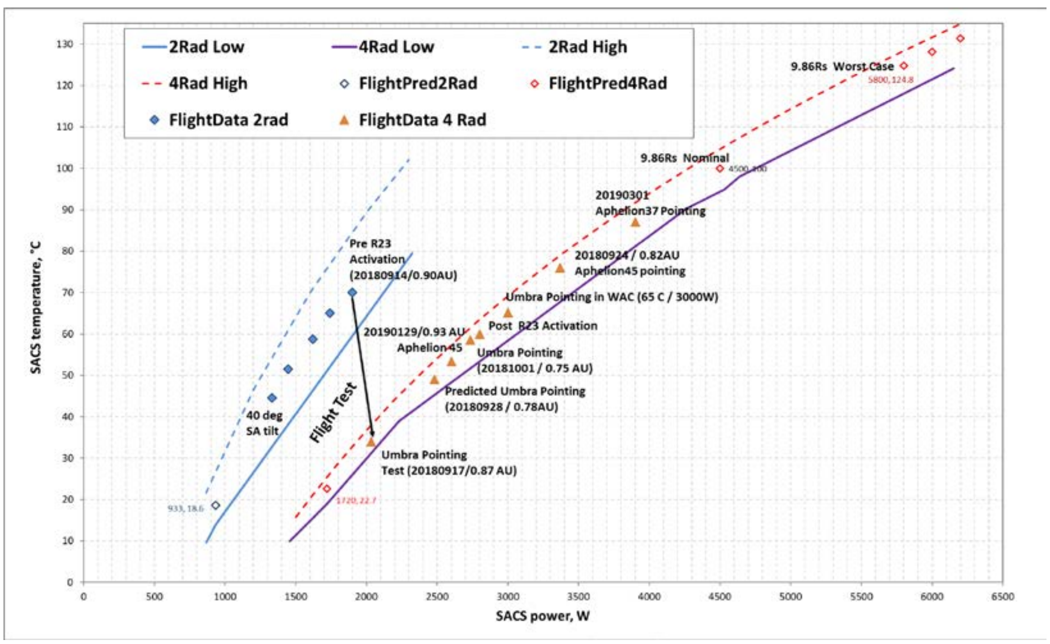


Figure 10. Measured SACS CV (system reference) temperature and corresponding SACS heat load are within the boundaries of the preflight predictions for two and four active radiator operation indicated by 2Rad and 4Rad low and high.

III. Spacecraft

So far in the mission, the spacecraft has experienced one of its two hot cases: during O-2 when near 0.70 AU and in aphelion-variable attitude while tilted 37° (1 March 2019) for KA-band downlink using the high-gain antenna (HGA). During this period, the externally mounted components on the −X side of the spacecraft experienced near-mission-maximum temperatures (0.70 AU/45° tilt), and some the internally mounted components experienced mission-maximum temperatures as well. These conditions are dependent on sun angle and will most likely repeat several more times as the spacecraft adjusts its attitude to allow proper HGA pointing for KA-band downlink. In the second and more severe hot case, predicted for the mission minimum perihelion (9.86 R_S), the external components will stay relatively cold and the temperature gradient inside of the spacecraft will be from top to bottom (+Z to −Z) instead of from side to side (−X to +X) so the internal components that were warm during this hot case will be a bit cooler during the perihelion hot case and vice versa. The cold case happened during the first umbra attitude and will be repeated during each orbit when the spacecraft is inside of 0.70 AU.

A. Spacecraft Packaging and Thermal Design Overview

The spacecraft (excluding the SACS) is a passive thermal design that utilizes louvers, multilayer insulation (MLI), and heaters along with waste electronics heat dissipation to maintain the core bus temperature between +10°C and +50°C. The internally mounted SACS and propulsion components (the propellant tank and the accumulator, pressure transducers, latching valves, and fill and drain valves) are thermally coupled to the bus and rely on the bus bulk temperature to keep their respective temperatures above freezing (both hydrazine and water freeze at nearly the same temperature) during cold spacecraft conditions. Two 20-blade and three 10-blade louvers are utilized to help minimize bus heater power and maintain the bulk bus temperature above 10°C. The battery is thermally isolated from the bus and uses a seven-blade louver and software-controlled heaters to maintain its nominal temperature between 0°C and 15°C. The majority of the high-powered radio frequency (RF) components are located on or near the −Z aft deck and utilize two of the 10-blade louvers to reduce bus heat leak when the RF system is powered off. Spacecraft louver locations are shown in Figure 11.

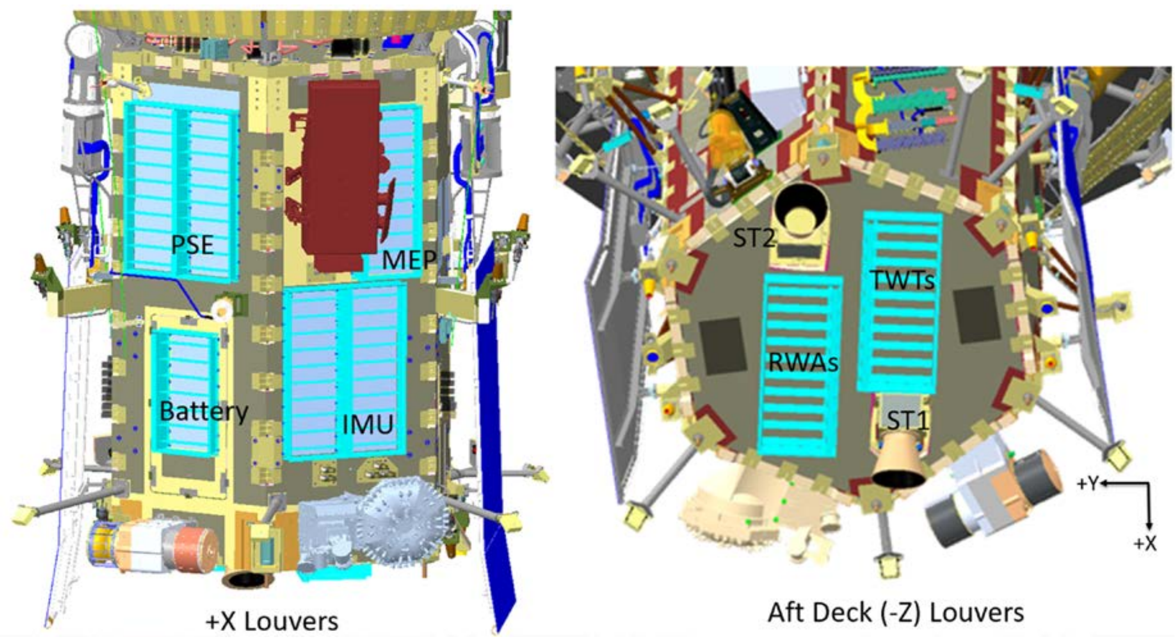
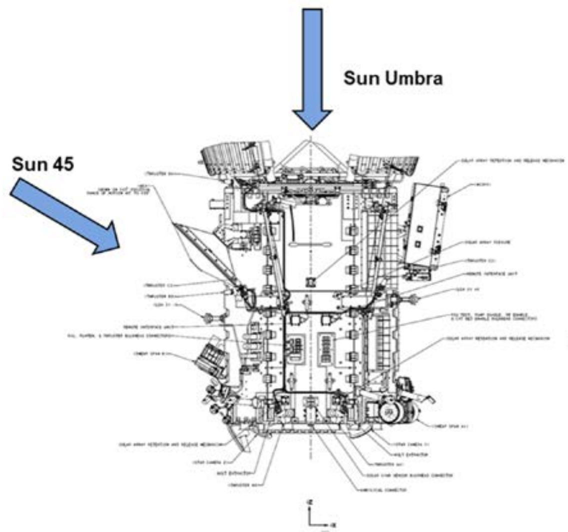


Figure 11. Spacecraft louver locations. Other than for short transients, all louvers are maintained in solar shadow. The flight louvers were manufactured by the Sierra Nevada Corporation, Louisville, CO. Also visible are ST-1 and ST-2.

The body-mounted instruments are thermally isolated from the bus and, with the exception of Solar Probe Analyzer (SPAN)-B, are located with the louvers on the "cold side" of the spacecraft (+X). Excluding short transients, this side of the spacecraft and the aft (−Z) deck are always maintained in solar shadow during aphelion attitude. The truss structure assembly-mounted instruments, the four Electromagnetic Fields Investigation instrument suite (FIELDS) antennas, and the Solar Probe Cup are completely isolated from the bus and are the only instruments designed to withstand the full solar constant when at minimum perihelion. The FIELDS magnetometers are located on a 3.4-m boom and also are thermally isolated from the bus (Figure 1).

B. Aphelion/Aphelion-Variable Attitude: Hot Case

During aphelion operation (outside of 0.70 AU), the spacecraft is tilted so as not to exceed 45° from +Z toward −X to allow for X-band (fan beam) and KA-band (HGA) communications. Inside of 0.82 AU, this angle can be adjusted anywhere between umbra pointing and 45° to allow for proper HGA pointing toward Earth and also to relax the thermal input into the SACS, the externally mounted bus components, and the bus as long as the thermal attitude does not interfere with HGA-KA-band operations. To date, when inside of 0.82 AU, the spacecraft has maintained umbra attitude (solar orbit-1 [O-1]/0.78 AU/inbound), 23° (O-1/0.70 AU to 0.78 AU/outbound), and 37° (solar orbit-2 [O-2]/0.75 AU/inbound). Figure 12 illustrates the external components illuminated during aphelion attitude. The sunlit external components consist of the fan-beam antennas (FBAs); SPAN-B; low-gain antenna (LGA)-2; digital sun sensor (DSS)-1 and DSS-2; solar limb sensors (SLSs) 2, 3, 6, and 7; the HGA and its actuator; and thrusters A2, A3, B1, B2, B3, B4, C2, and C3. Everything else either is under MLI or is nonfunctional.



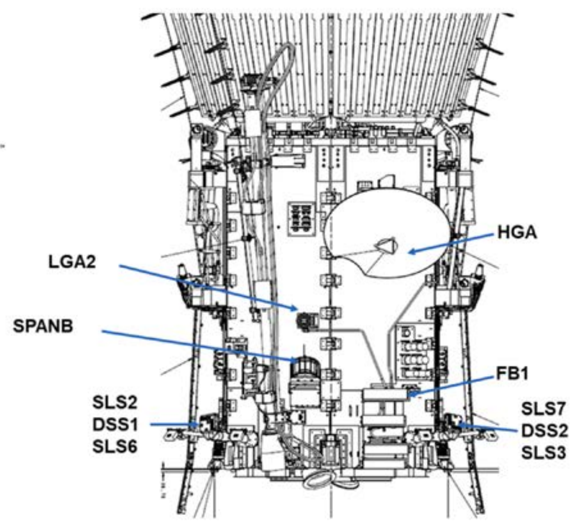


Figure 12. Sun-side geometry and the externally mounted components illuminated during aphelion attitude (>0.80 AU) and aphelion-variable attitude (0.70 to 0.80 AU). At solar distance less than 0.70 AU, the spacecraft flies in umbra attitude.

C. SP-AR-844: The FBA-1, DSS-1, and Star Tracker-2 Anomaly Description and Path Forward

During aphelion attitude, 37° tilt, of O-2, the externally mounted FBA-1 and the DSS-1 exceeded their allowable flight temperature (AFT) hot limits by 7°C and 14°C, respectively. Early mission temperature measurements of these components indicated that they were running hotter than the pre-launch predictions using the analytical thermal model (ATM) when in aphelion attitude. An empirical/heuristic model was developed to re-predict the worst-case temperatures for these and the other external sun-side components when at 45° tilt and 0.70 AU, as shown in Figure 13 for FBA-1. During O-1, the spacecraft went into umbra attitude at 0.78 AU to mitigate the temperature problems with these components because there were no KA-band downlinks scheduled during that period. As can be seen in Figure 13, the ATM very much underpredicts the FBA-1 temperature, whereas the heuristic model (H37 and H45) is very accurate; once a "seed" temperature is measured for constant sun angle and a known solar distance, the remaining temperature profile for that component as a function of solar distance can be computed for that sun angle. From the heuristic model predictions at the 45° tilt, it is expected that FBA-1 will reach 126°C (16°C > AFT) and DSS-1 will slightly exceed 100°C (15°C > AFT). The heuristic predictions also indicate that remaining sun-side components will stay below their respective AFT limits when in the maximum tilted (45°) condition. For FBA-1, it is believed that there is ~2 W of thermal trapping between the open radome end and the gold-plated antenna cups that is not being properly resolved by flight ATM (Figure 14).

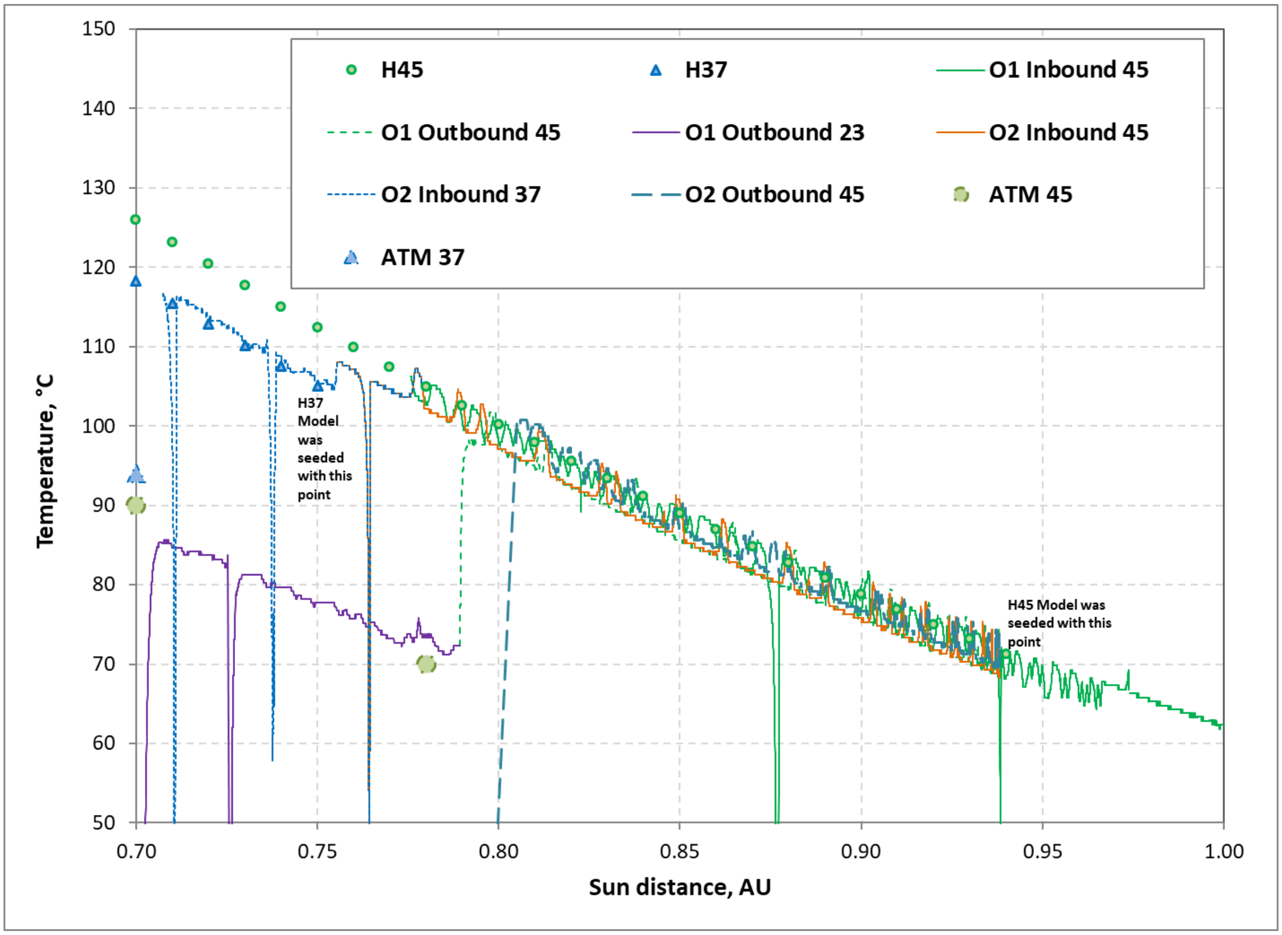


Figure 13. Shown here are results for the FBA-1 antenna, through O-2, using the flight ATM and the heuristic model (open symbols) for 37° and 45° tilts as compared to the inbound and outbound flight data (solid and dashed lines). The heuristic model predictions line up almost perfectly with the measured flight data, and the ATM results are the single-point outliers.

Based on packaging symmetry (Figure 12), it was expected that DSS-1 and DSS-2 would run at nearly the same temperature and both would be below the AFT at maximum tilt when at 0.70 AU. However, as shown in Figure 15, DSS-1 is running ~18°C hotter (equivalent to 25% higher heating) than DSS-2, and the two companion SLSs 2 and 6 co-located with DSS-1 are running warmer than the two companion SLSs 3 and 7 co-located with DSS-2. From the optical property degradation analysis shown in Figure 16, the AZ-93 white paint used on the SLSs and DSSs is degrading in family, currently increasing ~3% per orbit, and nothing abnormal is being observed. However, asymmetric spacecraft reflections combined with small attitude error could be factoring into these temperature anomalies. These temperature outages are being formally carried as a spacecraft anomaly (SP-AR-844), and the plan forward to resolve the anomaly will consist of refining the heuristic model to include data that represent in-flight characterization of two additional intermediate tilt angels, 30° and 40°, so that predictions that are made between 23° and 45° can be interpolated across the smaller angular differences and produce smaller errors in resulting temperature predictions. Also, as part of the path forward, the AFTs for the FBAs and DSSs will be increased to reflect qualification instead of flight hardware acceptance test temperature limits. The FBAs are of MESSENGER heritage that were acceptance tested to 150°C, and the DSSs, which were manufactured by the Adcole Corporation, can be associated by design similarity to units that were tested above 125°C. Also, to further reinforce the AFT change for the FBA, temperature qualification testing using the flight-spare PSP FBA is also planned, and the limits of the test will reflect those that were used for MESSENGER (−100°C to +150°C). This plan is still a work in progress, and the goal is to have the proper changes in place prior to the next hot KA-band downlink season projected to occur in February 2020.

A second part of the anomaly report (AR) is the operational current (power) exceedance of star tracker-2 (ST-2). During the same period, when the spacecraft was in highly tilted aphelion-variable attitude, there was an increase in operational power for ST-2 that was coincident with KA-band traveling-wave tube (TWT) operation, as shown by Figure 17, while the other aft deck components were fairly unaffected. This power increase was directly related to ST-2 thermoelectric cooler (TEC) operation due to the increasing delta-T between the ST housing and the optical element that is being controlled to 0°C. ST-2 exceeded the maximum operating power limit for autonomy rule 294 and was powered off during this Ka-band period when the input power reached 11.1 W. This input power correlated exactly to the power needed by the TEC to maintain the ~50°C delta between the housing and optical element (Figure 18). Operationally, the STs were tested to a housing temperature of +50°C so the correlation between ST-2 temperature and required TEC power matched perfectly. To be clear, this condition is the combination of two elements that make "the perfect storm": highly tilted aphelion-variable attitude when inside of 0.75 AU combined with KA-band operation. During the outbound portion of O-1, the aphelion-variable attitude was set to 23° between 0.70 and 0.75 AU. During this period, KA band was used almost continuously (offloading ~2 months' worth of data from the SSR) without any problems with ST-2, as shown in Figure 19.

Moving forward, there are three possible solutions to remedy this situation: (1) limit ST-2 usage during KA-band operation when inside of 0.75 AU and highly tilted, (2) increase the optical element control temperature from 0°C to say 5°C or 10°C to decrease the control delta-T and related TEC thermal output, or (3) raise the AFT to say 55°C and proportionally increase the allowable current (power) draw to be consistent with a 0°C control temperature for the optical elements. Option 1 would impose operational constraints as well as potentially impacting redundancy, so it is not a desirable option. However, based on the Galileo AA-STR technical data sheet, the advertised upper operational temperature limit is 60°C for this tracker series (the PSP units were acceptance tested to 50°C), and the power cost to maintain a 60°C delta-T would be 12.6 W as compared to 11.2 W measured by PSP for ~50°C delta-T. The best in-flight solution is probably a combination of options 2 and 3 where the control set point is raised, for example, by 5°C and the AFT upper limit is also increased by 5°C. This would keep the operational delta-T and maximum TEC power draw the same as the current flight configuration. As with FBA-1 and DSS-1, corrective action is still a work in progress, and the plan is to have resolution before February 2020.

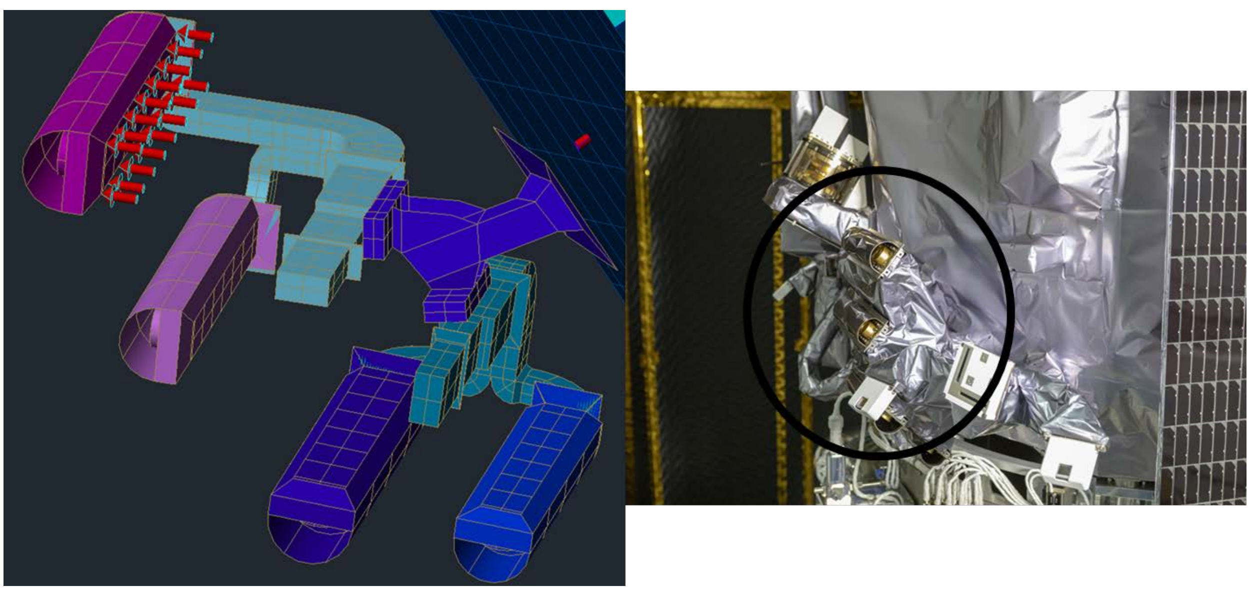


Figure 14. Per the shown analysis, it is suspected that solar trapping is occurring between the open radome end and the gold-plated antenna cups, resulting in an approximately 2-W increase that is not being correctly resolved by the flight ATM.

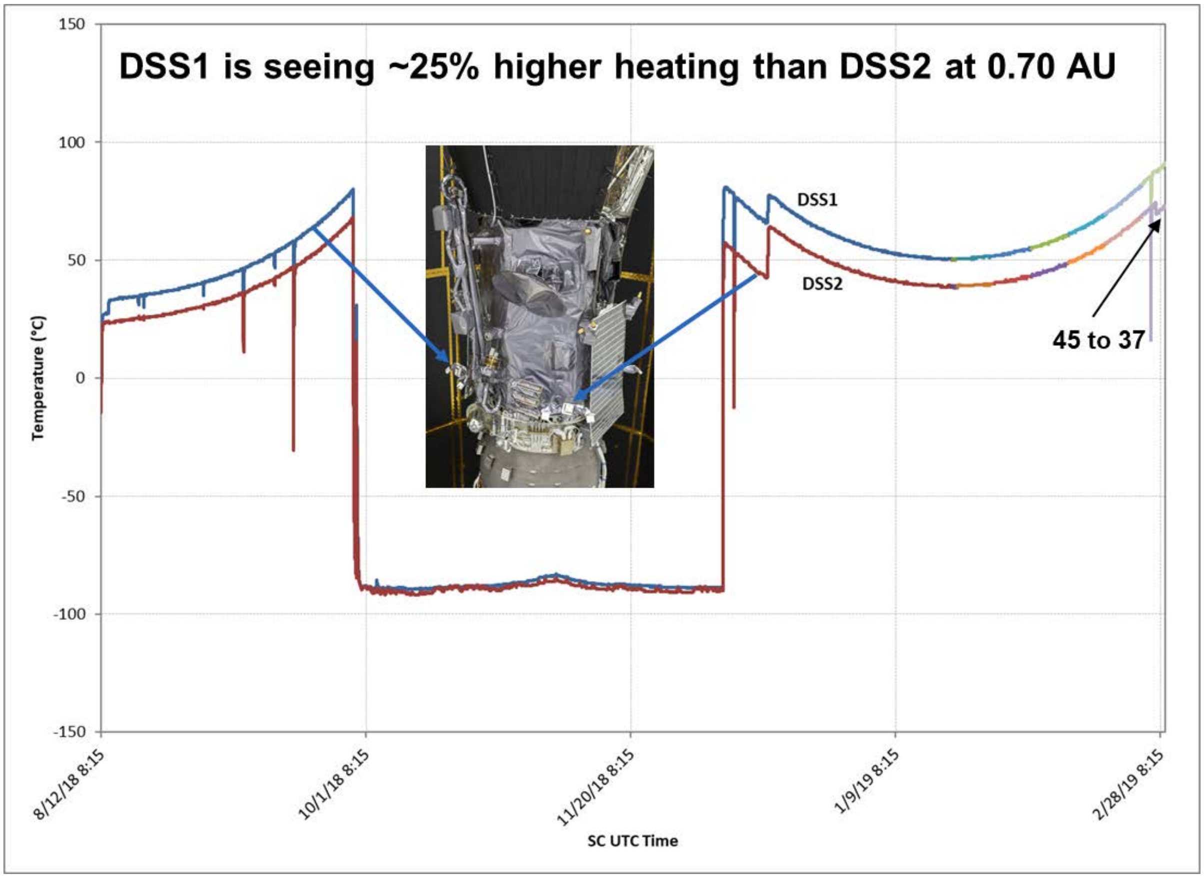


Figure 15. To date, DSS-1 has run 11°C to 18°C warmer than the symmetrically positioned DSS-2 when in aphelion attitude. The temperatures are nearly identical when in umbra attitude. Sharing a common bracket with each DSS is a pair of SLSs.

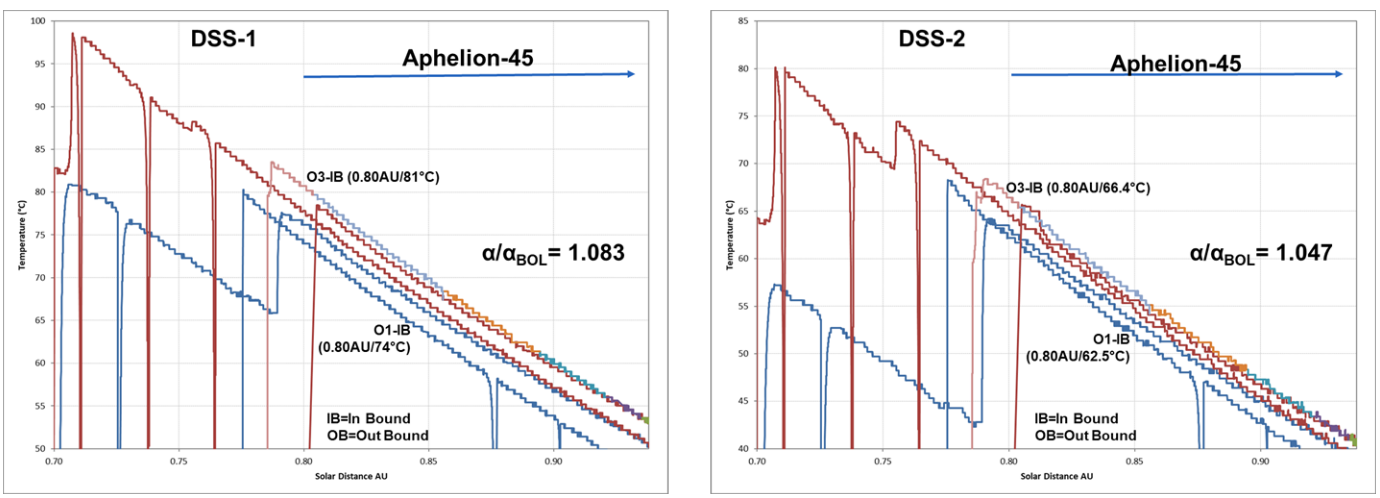


Figure 16. DSS and sun-side SLS optical property degradation have been in family and are now between 5 and 8% higher than beginning of life (BOL). As seen here, the high DSS temperature difference experienced so far cannot be solely attributed to extreme optical property degradation.

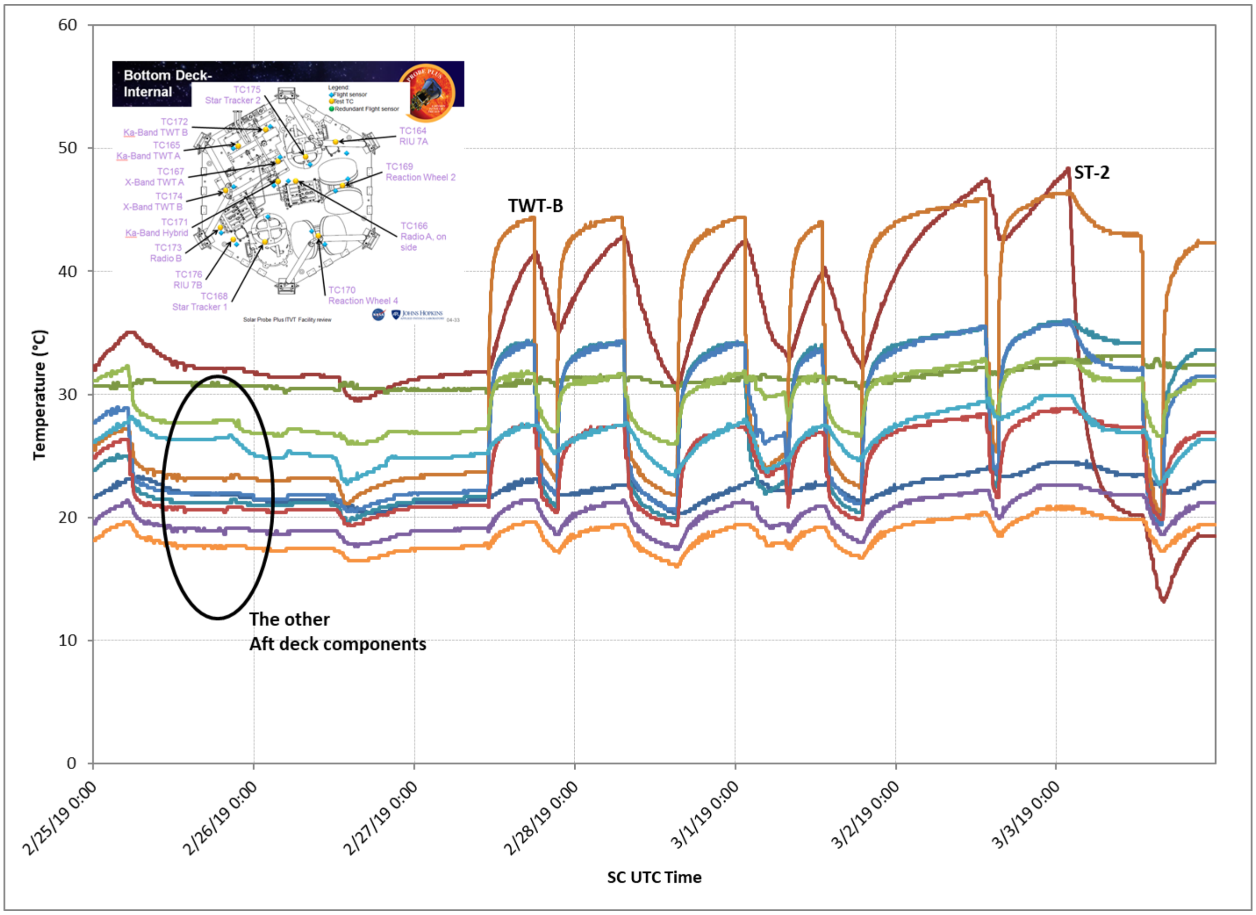


Figure 17. On 3 March 2019, ST-2 was powered off by spacecraft autonomy when the input power exceeded 11.1 W. As shown, the major influence on its temperature is the operation of the KA-band TWT. All other components of the spacecraft aft deck were not overly affected by KA-band operation.

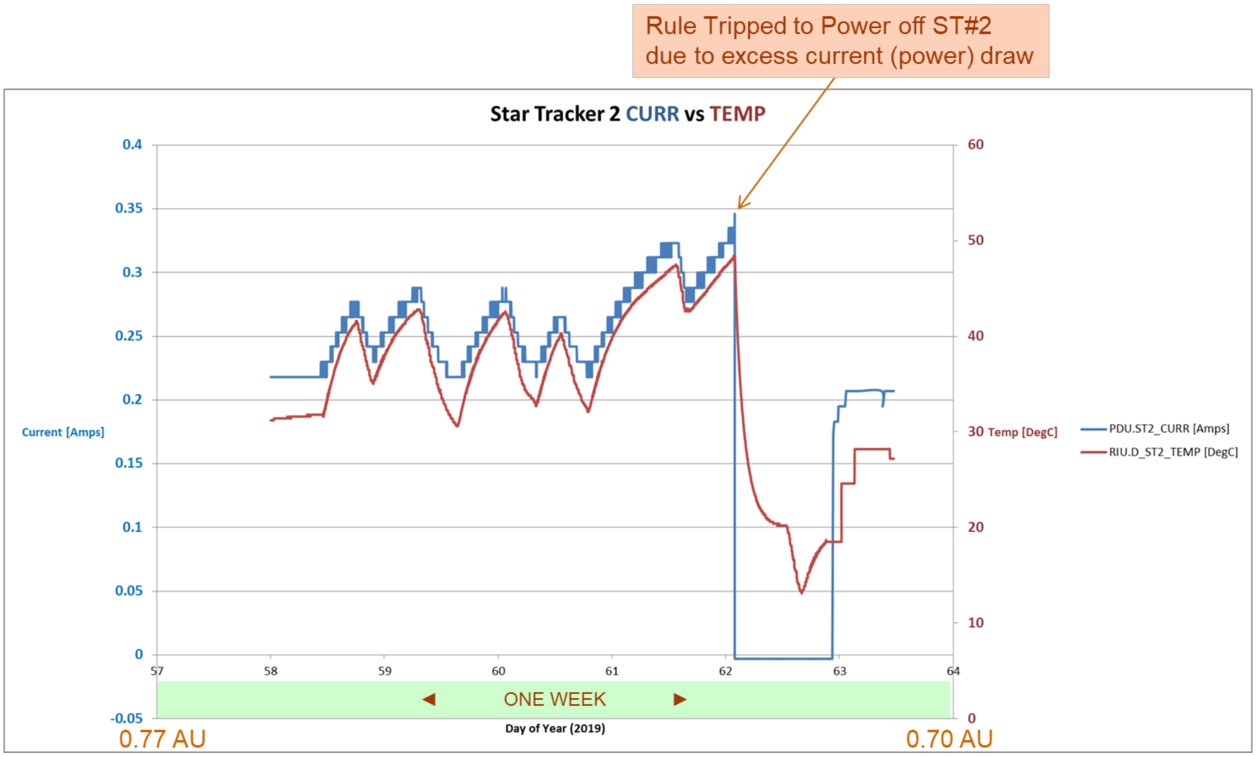


Figure 18. Shown is the direct correlation to TEC power draw and ST-2 temperature increase caused by maintaining the nearly 50°C delta-T. This overage was exacerbated by KA-band TWT operation inside of 0.75 AU when in aphelion-variable 37° tilt attitude.

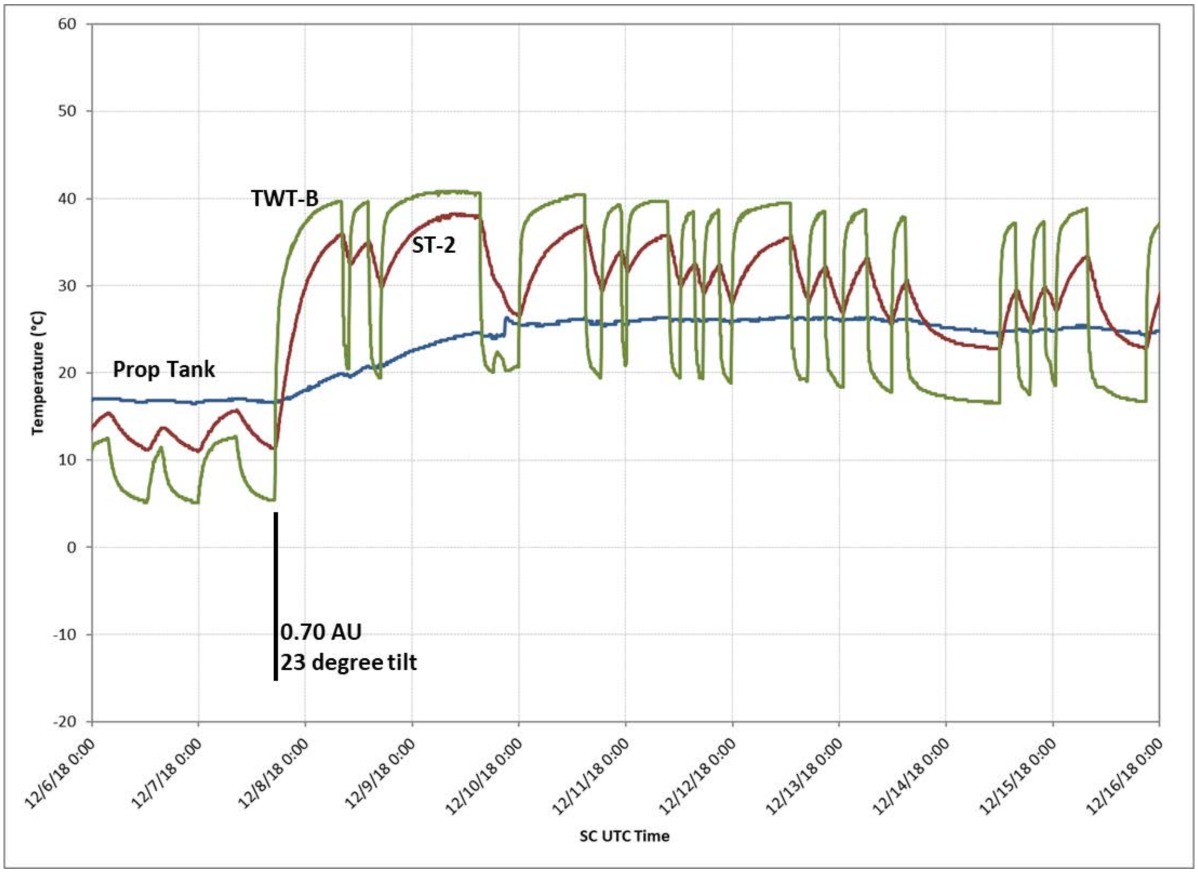


Figure 19. At the shallow 23° aphelion-variable tilt of 23°, ST-2 performed without problems when inside of 0.75 AU during heavy KA-band TWT operation.

D. Umbra Attitude

On 4 March 2019, PSP crossed 0.70 AU and was autonomously transitioned into umbra attitude. SA WAC was invoked to maintain the average SA temperature between 60°C and 65°C. During the final three orbits, 22–24 (minimum perihelion orbits), the umbra attitude will represent both the extreme hot and cold spacecraft thermal conditions. Currently, however, it only represents the extreme cold conditions for the internally and externally mounted bus components that are in the umbra created by the TPS. During O-1 perihelion-1 (P-1) and O-2 perihelion-2 (P-2), the maximum solar constant approached 40 suns but was well attenuated by the TPS and was not noticed by the underlying spacecraft. Figure 20 shows the thermal effects as seen by the spacecraft barrier blanket PT103 temperature sensors of the quickly increasing and decaying solar constant as the spacecraft moved toward and then away from encounters with P-1 and P-2. It should be noted that since there was/will be no Venus flyby during O-3 then perihelion-3 (P-3) will be identical to P-1 and P-2, and the thermal performance for O-3 is expected to be the same as those shown in Figures 20–22 and Table 1 for O-1 and O-2.

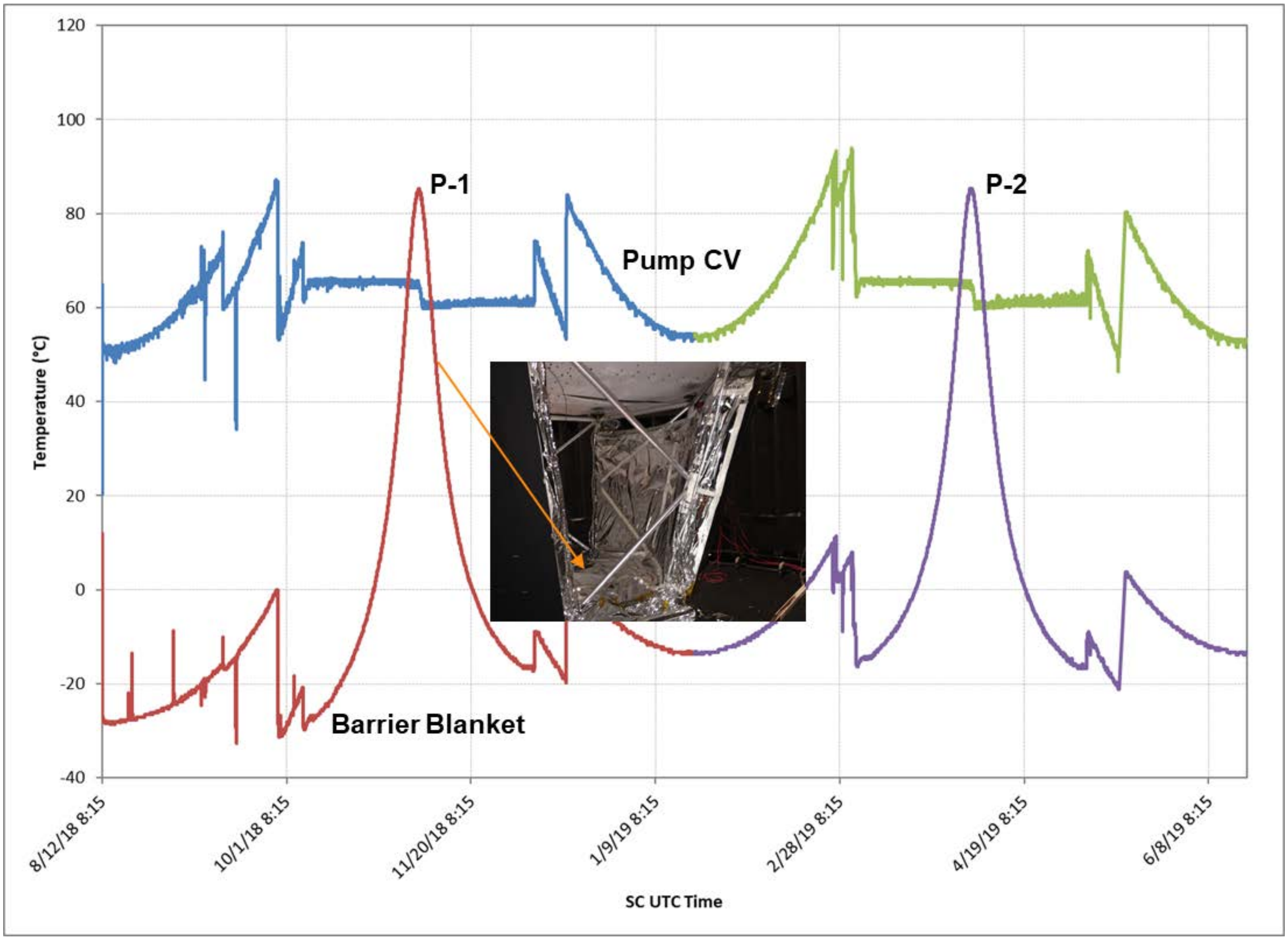


Figure 20. On 6 November 2018 and 5 April 2019, PSP reached its first (P-1) and second (P-2) of 24 perihelion conditions (35.7 R_S/38 suns) as indicated by the temperature sensors on the barrier blanket. It is expected that the barrier blanket temperature sensors will reach a maximum of ~250°C when at minimum perihelion (9.86 R_S) in December 2024. Also shown is the SACS CV temperature in WAC mode, being maintained between 60°C and 65°C when inside of 0.70 AU.

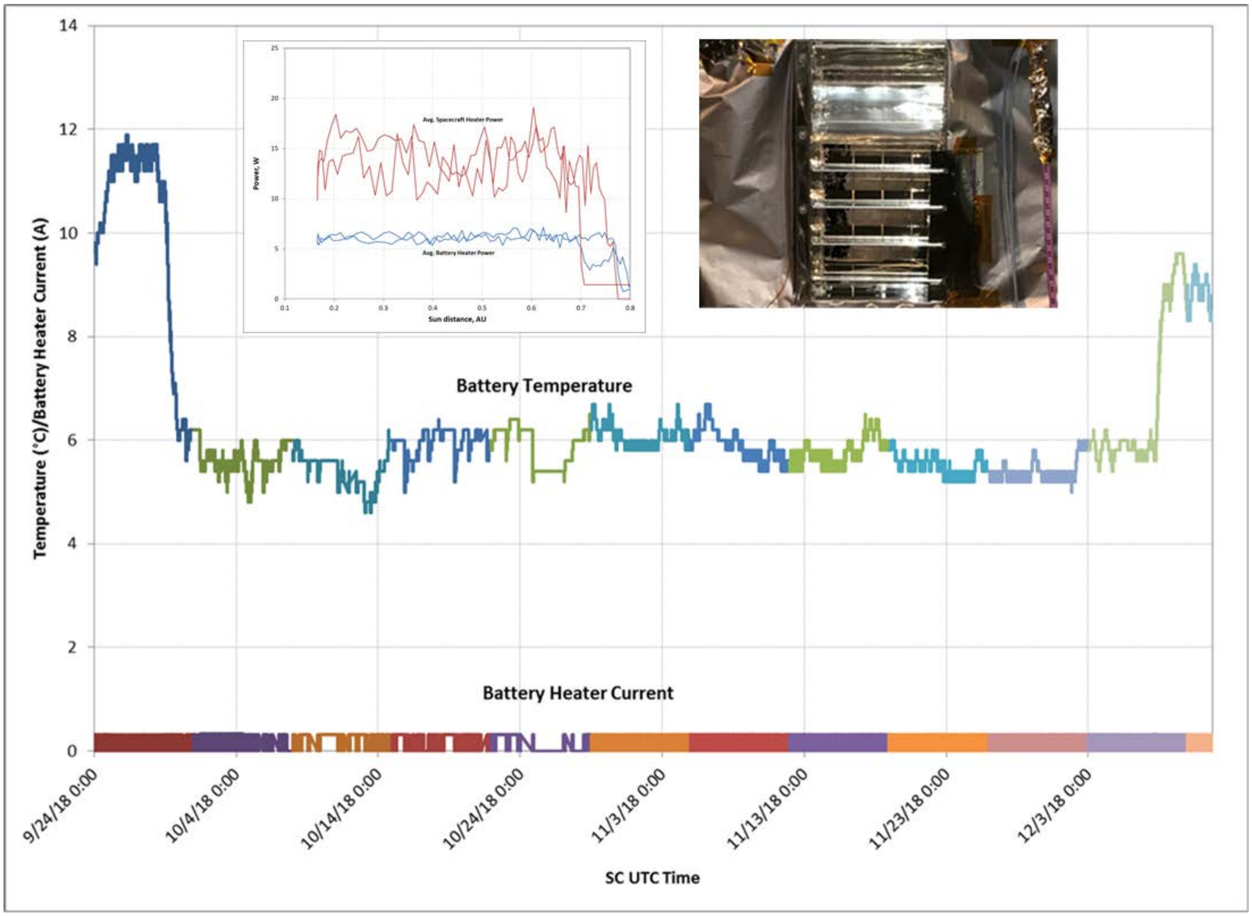


Figure 21. Shown is the battery temperature and associated heater current during O-1 umbra conditions (0.78 AU inbound to 0.70 AU outbound). Because of the highly attenuated solar heating, the battery temperature and heater current are nearly constant during umbra attitude and are independent of solar distance. Note louver and heater power inlays: During spacecraft thermal balance testing, it was determined that the battery temperature was higher than desired by ~15°C. The flight fix, verified during spacecraft thermal-cycle testing, pinned four of the seven louver blades fully open to mitigate the hot condition and keep the heater duty cycled below 75% during the umbra cold case, as shown. Maximum battery heater power is 10.5 W, and the maximum calculated duty cycle is 62%.

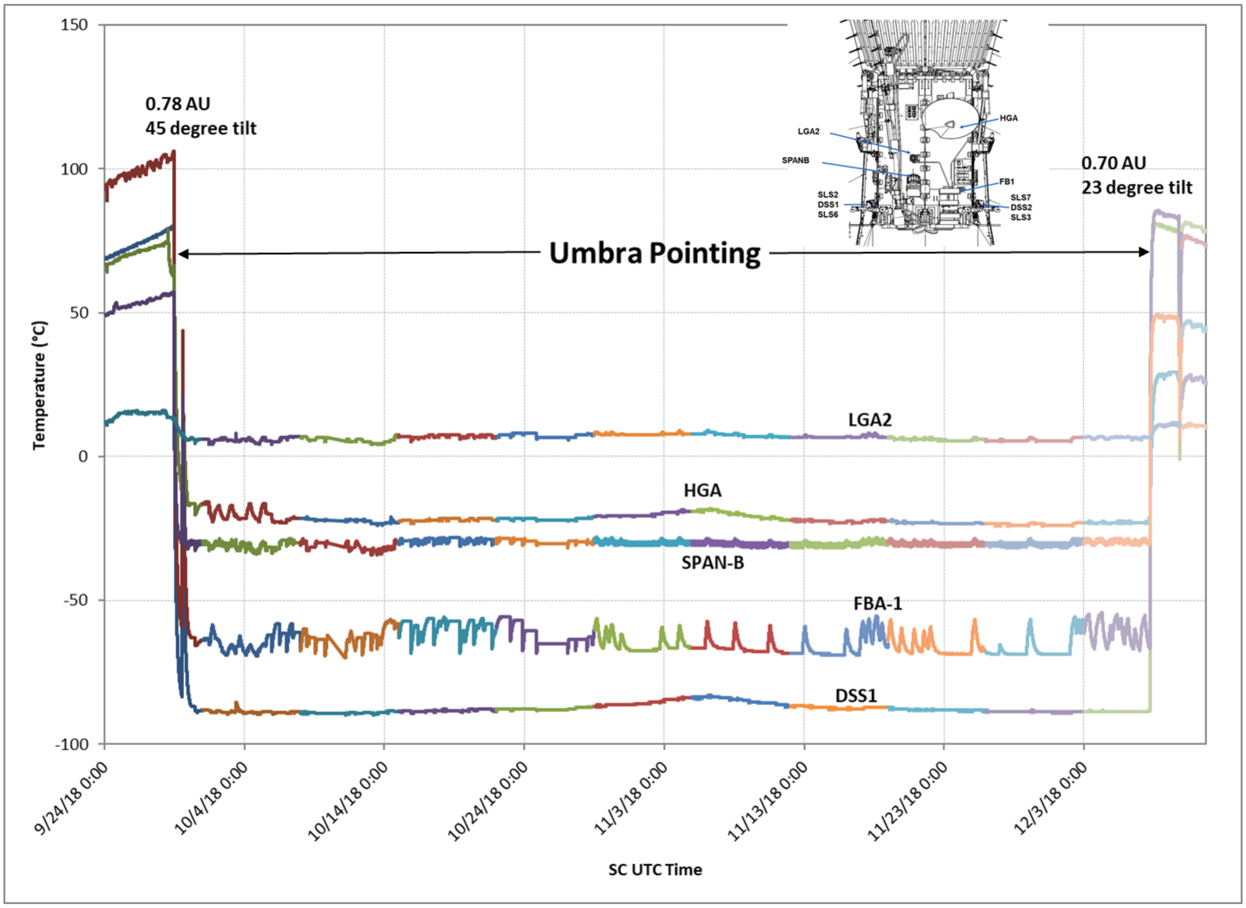


Figure 22. Shown are a few of the external sun-side (−X) components during O-1 umbra attitude. As illustrated by the nearly constant temperatures, the 38-sun solar environment is being well attenuated by the TPS and were repeated during O-2. The small temperature spikes for FBA-1 are due to X-band operation.

Table 1. Shown here are spacecraft minimum and maximum component temperatures that were recorded during O-1 umbra attitude. Evident are the small temperature excursions, mostly due to electrical power changes, in spite of the large solar constant change.

	Flight data		AFT		Margin	
Item	**Min**	**Max**	**Cold**	**Hot**	**Cold**	**Hot**
Telecommunications						
HGA Dish	-24	-18	-170	160	146	178
Ka TWT	1	14	-25	85	26	71
Ka EPC	-3	12	-25	65	22	53
X TWT	5	20	-25	85	30	66
X EPC	6	18	-25	65	31	47
Fan beam	-70	-52	-120	110	50	162
LGA	-1	9	-100	110	99	101
RF switch plate	0	12	-25	65	25	54
Radio	7	25	-25	55	32	30
Guidance and Control						
IMU	18	22	-10	60	28	38
Star tracker	-7	17	-30	50	23	33
Wheels	20	34	-20	60	40	26
SSE	20	26	-25	65	45	39
DSS	-92	-83	-120	85	28	168
Power						
PSE	20	26	0	55	20	29
Battery	5	7	5	35	0	28
Solar Array Cooling System (SACS)						
Pump chk valve	59	67	10	135	49	68
SACS elect	21	26	0	60	21	34
Accumulator	23	28	20	60	3	33
Fill/drain vlv	33	39	10	90	23	51
TotalP Sensor	28	33	10	75	18	42
DP sensor	27	34	10	65	17	31
Avionics						
RPM	22	27	-25	60	47	33
REM	21	28	-25	65	46	37
PDU	12	19	-25	60	37	41
RIU	5	30	-25	65	30	35
Propulsion						
Tank	15	24	10	50	5	26
Lines	14	28	10	75	4	47
Pressure trans	13	18	10	75	3	57
Latch valve	15	19	10	50	5	31
Service valve	12	14	10	50	2	36
Thruster valve	19	31	10	110	9	79

	Flight data		AFT		Margin	
Item	**Min**	**Max**	**Cold**	**Hot**	**Cold**	**Hot**
Mechanical						
SA actuator	-15	11	-25	85	10	74
HGA actuator	-21	-15	-40	85	19	100
ECU	16	21	-25	65	41	44
Instrument Electronics						
FIELDS MEP	17	27	-25	60	42	33
SWEAP SWEM	11	18	-25	65	36	47
WISPR DPU	13	21	-25	55	38	35
Fields						
Fields Pre Amp	-76	-23	-83	91	7	114
SPC Pre Amp	-36	-24	-40	81	4	105
SPAN A/B						
SPAN A Ebox	-39	-23	-40	50	2	73
SPAN B Ebox	-40	-17	-40	85	1	102
SPAN A Pedestal	-22	-15	-90	65	68	80
SPAN A Top Ana	-69	-62	-90	65	21	127
SPAN B Pedestal	-34	-28	-40	85	6	113
SPAN B Top Ana	-45	-39	-70	115	25	154
WISPR						
WISPR Cam Elec	-49	-38	-55	60	6	98
WISPR ERM	-87	-79	-120	55	33	134
WISPR In T DRB	-49	-39	-55	65	6	104
WISPR In T LBA	-56	-40	-60	60	4	100
WISPR Out T DRB	-46	-36	-55	65	9	101
WISPR Out T LBA	-50	-29	-57	60	7	89
EpiLo/Hi						
EpiLo A	-37	-29	-43	62	6	91
EpiLo B1	-37	-28	-43	62	6	90
EpiLo B2	-36	-27	-43	62	7	89
EpiHi Box 1,2	-29	-16	-40	60	11	76
EpiHi HET	-34	-23	-40	60	6	83
EpiHi LET1	-34	-23	-40	60	6	83
EpiHi LET2	-33	-23	-40	60	7	83

IV. Conclusion

To date, PSP has performed essentially as expected, and the to-date temperature performance, ATFs, and margins are summarized by Table 2. Other than the previously discussed anomalous behavior of FBA-1, DSS-1, and ST-2, the spacecraft temperatures for the electronics, propulsion, instruments, and SACS have been nominal and without problems. Critical activation events for the SACS were also nominal, and for the most part, thermal models have been accurate regarding SACS and internal bus behavior. Even though temperature limits were violated for FBA-1 and DSS-1 during O-2, engineering was completely involved with the decision to keep KA-band downlink attitude and to offload the spacecraft SSR because the perceived hardware risk was minimal based on vendor input and heritage testing from the MESSENGER program. As the mission progresses, umbra attitude will not be as benign as shown here, but that is to be expected. Overall, PSP remains healthy and is ready to continue to explore the inner solar system where no spacecraft has ever gone before. Figure 23 shows PSP prior to final fairing encapsulation.

Table 2. PSP thermal performance summary to date (1 July 2019). Other than what was described in the anomaly section, the remaining spacecraft temperatures have been nominal.

	Flight data		AFT		Margin	
Item	**Min**	**Max**	**Cold**	**Hot**	**Cold**	**Hot**
Telecommunications						
HGA Dish	-25	79	-170	160	145	81
Ka TWT	1	47	-25	85	26	39
Ka EPC	-4	45	-25	65	21	20
X TWT	5	36	-25	85	30	49
X EPC	4	47	-25	65	29	18
Fan beam	-70	117	-120	110	50	-7
LGA	-1	92	-100	110	99	18
RF switch plate	-1	41	-25	65	24	24
Radio	6	33	-25	55	31	22
Guidance and Control						
IMU	17	33	-10	60	27	27
Star tracker	-7	48	-30	50	23	2
Wheels	18	51	-20	60	38	9
SSE	20	56	-25	65	45	9
DSS	-92	99	-120	85	28	-14
Power						
PSE	18	41	0	55	18	14
Battery	4	12	5	35	-1	23
Solar Array Cooling System (SACS)						
Pump chk valve	33	94	10	135	23	41
SACS elect	20	42	0	60	20	18
Accumulator	23	52	20	60	3	8
Fill/drain vlv	27	59	10	90	17	31
TotalP Sensor	27	53	10	75	17	22
DP sensor	27	51	10	65	17	14
Avionics						
RPM	21	45	-25	60	46	15
REM	21	49	-25	65	46	16
PDU	12	32	-25	60	37	28
RIU	4	58	-25	65	29	8
Propulsion						
Tank	15	43	10	50	5	7
Lines	14	61	10	75	4	15
Pressure trans	13	36	10	75	3	39
Latch valve	14	37	10	50	4	13
Service valve	11	42	10	50	1	8
Thruster valve	18	79	10	110	8	31

	Flight data		AFT		Margin	
Item	**Min**	**Max**	**Cold**	**Hot**	**Cold**	**Hot**
Mechanical						
SA actuator	-17	72	-25	85	8	13
HGA actuator	-22	79	-40	85	18	6
ECU	16	52	-25	65	41	13
Instrument Electronics						
FIELDS MEP	16	37	-25	60	41	23
SWEAP SWEM	11	52	-25	65	36	13
WISPR DPU	12	39	-25	55	37	16
Fields						
Fields Pre Amp	-76	33	-83	91	7	59
SPC Pre Amp	-37	32	-40	81	3	49
SPAN A/B						
SPAN A Ebox	-40	-4	-40	50	0	54
SPAN B Ebox	-41	61	-40	85	-1	24
SPAN A Pedestal	-22	0	-90	65	68	65
SPAN A Top Ana	-70	-4	-90	65	20	69
SPAN B Pedestal	-34	64	-40	85	6	21
SPAN B Top Ana	-45	87	-70	115	25	28
WISPR						
WISPR Cam Elec	-50	-37	-55	60	5	97
WISPR ERM	-87	-38	-120	55	33	93
WISPR In T DRB	-50	-33	-55	65	5	98
WISPR In T LBA	-57	-34	-60	60	3	94
WISPR Out T DRB	-47	-18	-55	65	8	83
WISPR Out T LBA	-51	-29	-57	60	6	89
EpiLo/Hi						
EpiLo A	-37	-25	-43	62	6	87
EpiLo B1	-37	-28	-43	62	6	90
EpiLo B2	-36	-27	-43	62	7	89
EpiHi Box 1,2	-29	-15	-40	60	11	75
EpiHi HET	-35	-21	-40	60	6	81
EpiHi LET1	-35	-21	-40	60	5	81
EpiHi LET2	-34	-21	-40	60	6	81

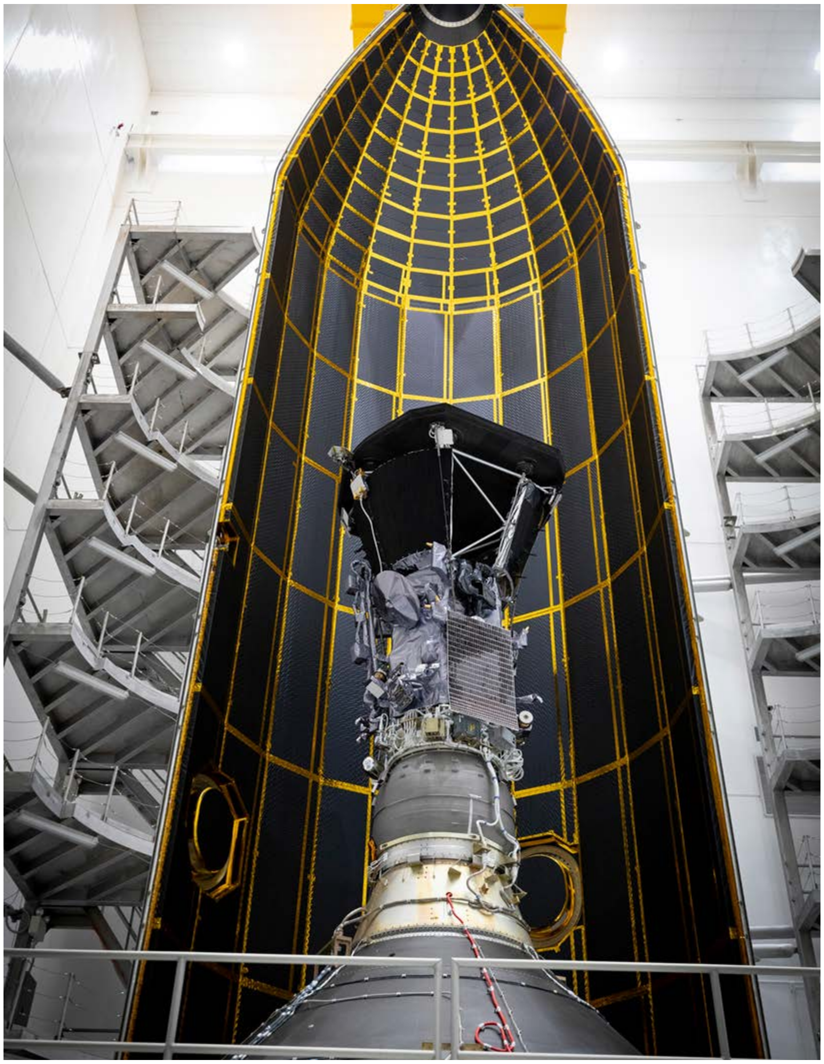


Figure 23. PSP is shown prior to final encapsulation while at Astrotech Space Operations.

Acknowledgments

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