Solar Probe Plus

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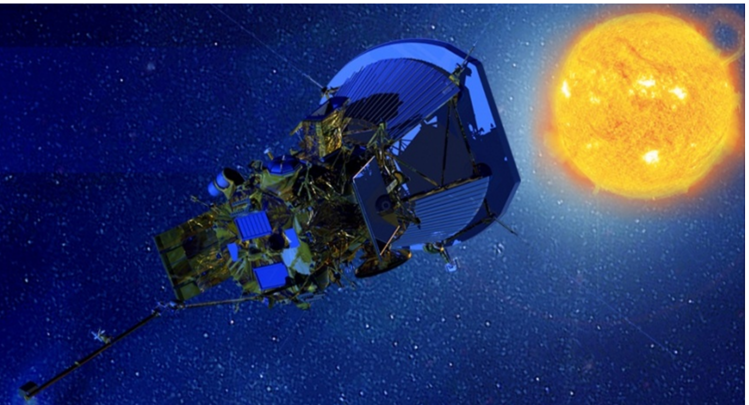

Fault Management Peer Review Day 2

Sanae Kubota

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Agenda: Day 2

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Topic	Speaker(s)	Start Time
Critical Scenarios - Critical Sequence - Critical Faults - Safe Mode Review - Attitude Protection	Sanae Kubota Robin Vaughan	9:00 am 9:20 am
**** break (10 minutes) ****		10:50 am
Solar Array Control overview	Carson Baisden	11:00 am
**** lunch (60 minutes) ****		11:20 am
Solar Array Safing - Overview - System Temperatures - Solar Array Safing Approach	Danielle Marsh	12:20 pm
**** break (10 minutes) ****		1:50 pm
Solar Array Safing, continued - Solar Array Safing Approach, continued - TRL-6 Testing - Future Work	Danielle Marsh	2:00 pm
Preliminary Verification & Validation	Sanae Kubota	3:30 pm
Wrap Up	Sanae Kubota	3:45 pm
Review Board caucus		4:00 pm

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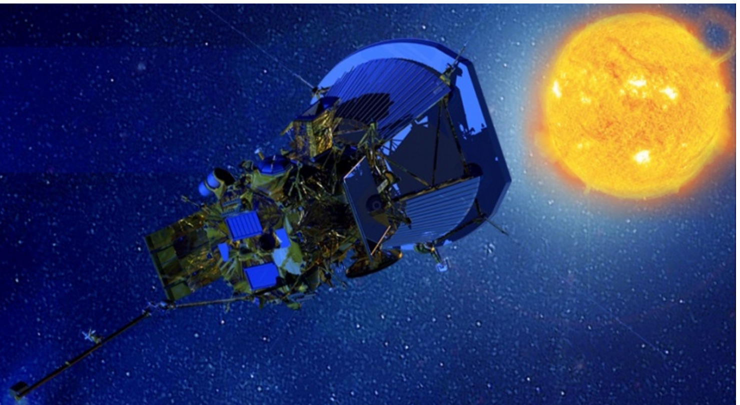

Critical Scenarios

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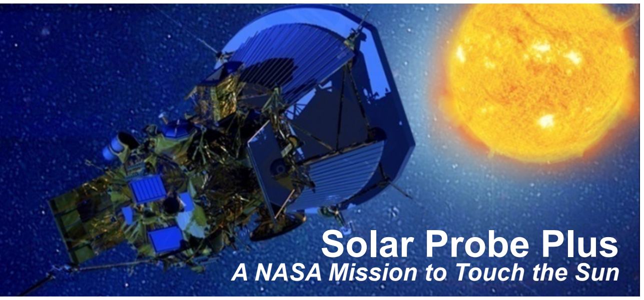
Critical Scenarios

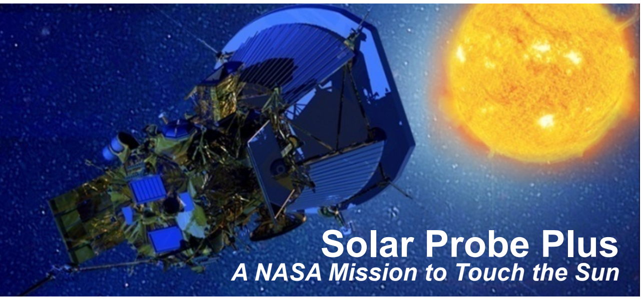


- **Critical Sequence**
  - **Launch until ready for battery recharge**

- **Critical Faults**
  - **Umbra violation – Orange Warning**
  - **Aphelion Thermal Violation**
  - **SA/CS over-temp**
  - **CS system under-temp**
  - **LBSoC**
  - **CLT expiration**
  - **Processor Overcycling**

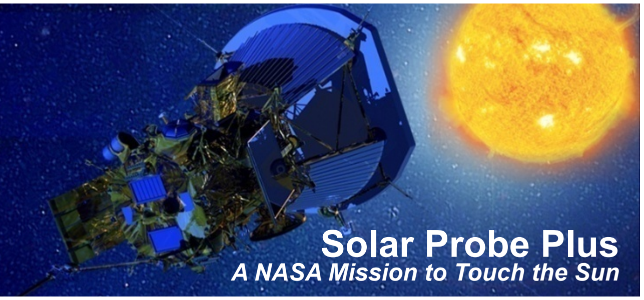
- **Attitude Protection**

Critical Sequence overview



- **An event, or sequence of events, which must be executed within a specified time in order to achieve mission success.**
- **For SPP, the period from launch through initial cooling system activation until ready for battery recharge is a critical sequence.**
  - **The sequence steps will be autonomously executed.**
  - **Ground-based commanding of the sequence is planned as a back-up to the autonomous commanding.**
- **The sequence is time critical to prevent cooling system freezing and LBSoC.**

Critical Sequence steps



- Launch
- 3rd stage separation, detected via redundant breakwires
- Power-on G&C sensors and actuators
- Release solar array launch locks
- Solar array wings commanded to 0 deg flap angle, 90 deg feather angle
- Detumble
- Slew spacecraft to face radiators 1 & 4 toward the Sun
- Heat radiators and solar array wings
- When radiator and array temperature reaches 20C,
  - command cooling system accumulator valve open to release water
  - command pump activation
- Recharge battery

Critical Faults

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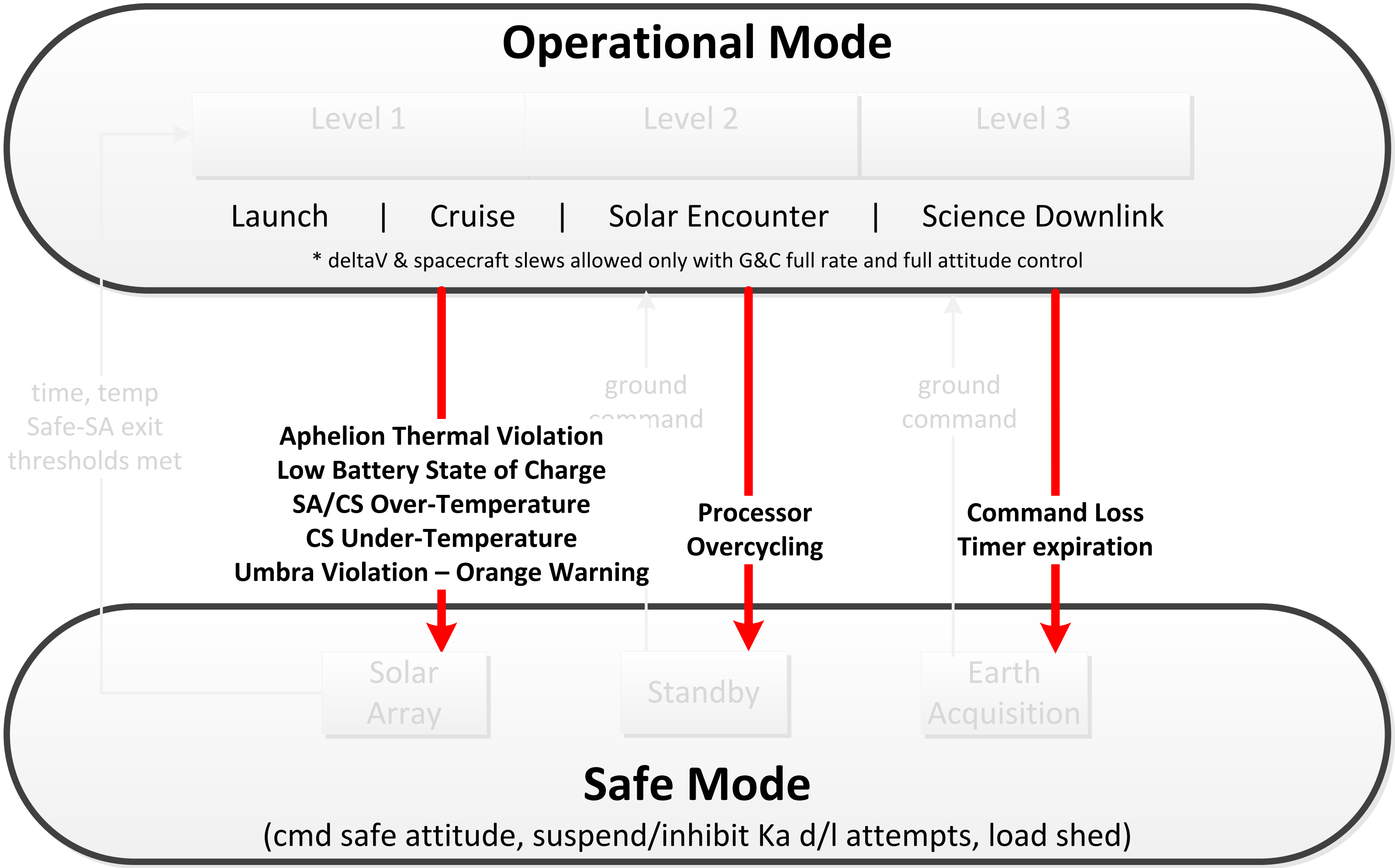

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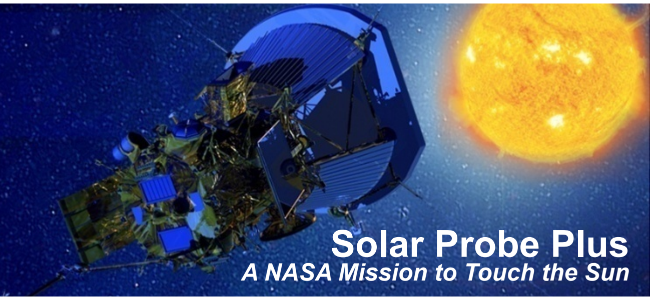
Umbra Violation – Orange Warning



- **Potential causes: *<u>details discussed within Attitude Protection section.</u>***

- **Telemetry used for diagnosis:**
  - **4 redundant cross-strapped solar limb sensor heads**

- **Response: Safe Mode – Solar Array**
  - **Upon initial SLS illumination (yellow warning), G&C will attempt to regain control without initiating safing.**
    - **Keeps G&C software and interfaces online**
  - **If SLS detect > TBD angle (orange warning), autonomy will initiate safe mode.**
  - **Safing the array wings will temporarily provide greater thermal margin while G&C continues to recover control.**

Aphelion Thermal Violation

- **Potential causes: *details discussed within Attitude Protection section.***
- **Telemetry used for diagnosis: 4 redundant cross-strapped solar limb sensor heads, or additional sun sensor heads if needed**
- **Response: Safe Mode – Solar Array**

Solar Array / Cooling System Over-Temperature Causes

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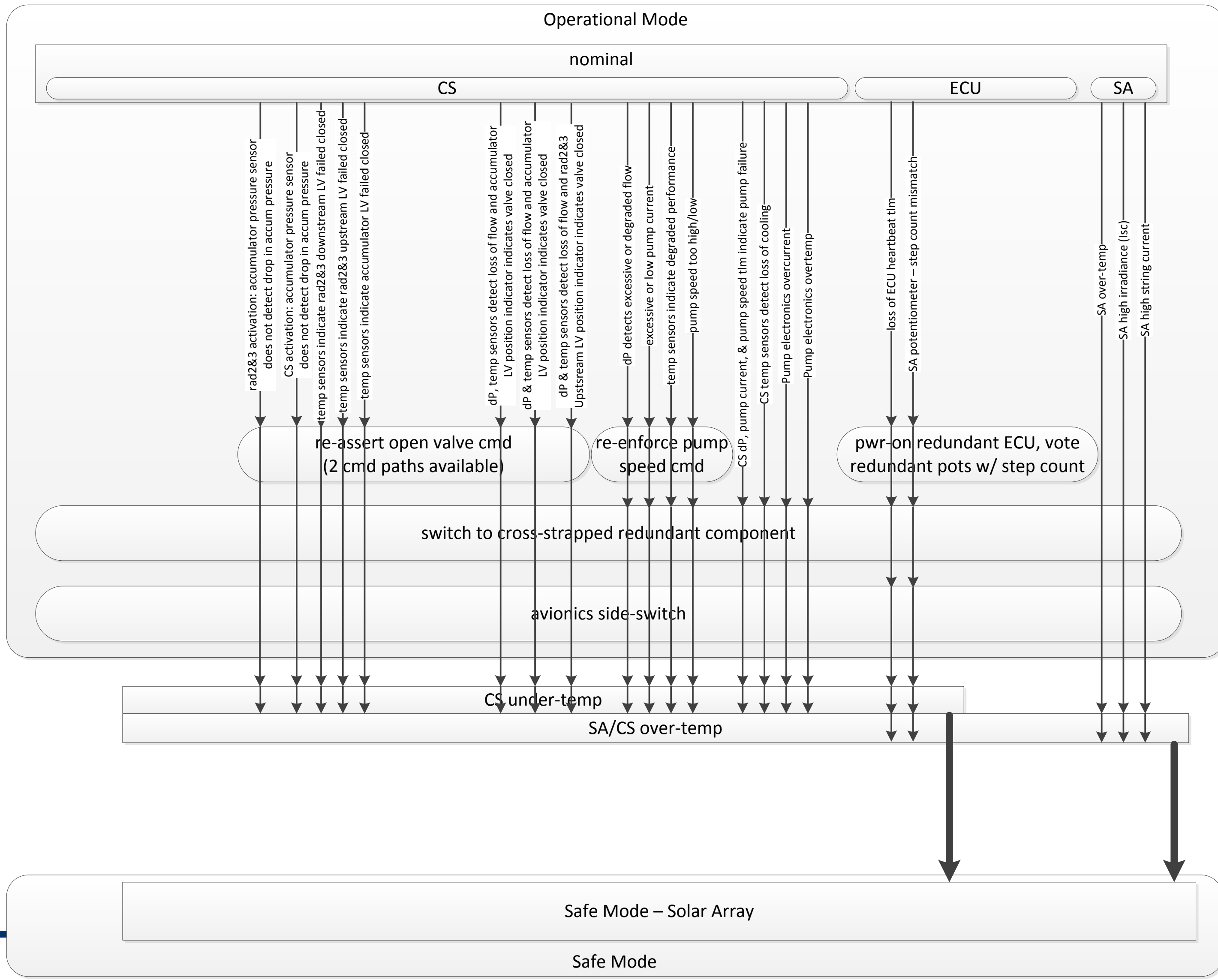

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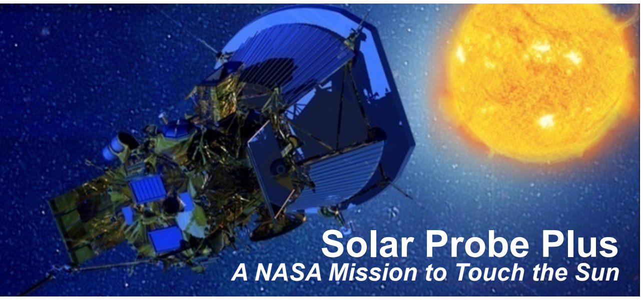
Solar Array / Cooling System Over-Temperature



- **Cause summary: solar array control fault, attitude control fault, cooling system fault**
- **Telemetry used for diagnosis:**
  - **4 redundant pairs of temperature sensors on the back of each cooling system platen**
  - **2 redundant pairs of Isc and Voc sensors on each wing (indicating solar flux and cell temperature)**
- **Response: Safe Mode – Solar Array**
  - **Safing thresholds to be set to allow sufficient margin before max survival temperature for fault detection and safing operation.**
    - ***Details discussed within Solar Array Safing section*.**

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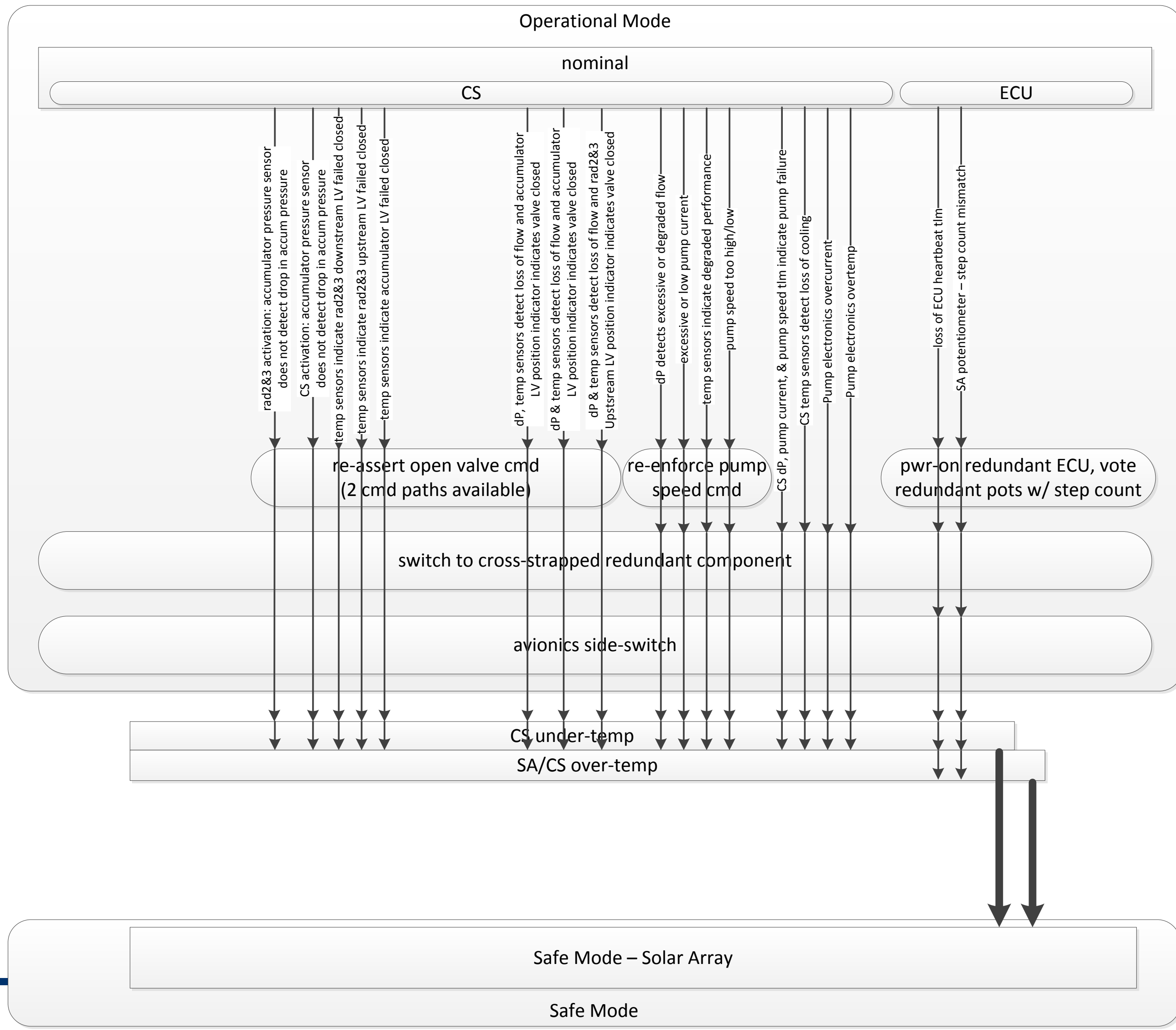
Cooling System Under-Temperature Causes



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Cooling System Under-Temperature

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- **Cause summary: solar array control fault, cooling system fault**
- **Telemetry used for diagnosis:**
  - **2 cross-strapped RIU strings with radiator temperature telemetry available at all times**
  - **4 redundant pairs of temperature sensors on the back of each cooling system platen**
- **Response: Safe Mode – Solar Array**
  - **43 degree TBR safing threshold allows 5 minutes before temperature would reach 20C**
    - **Allows ample time for Prime processor switch and avionics side-switch before resuming autonomous wing control.**
    - ***<u>Details discussed within Solar Array Safing section</u>*.**

Low Battery State of Charge Causes

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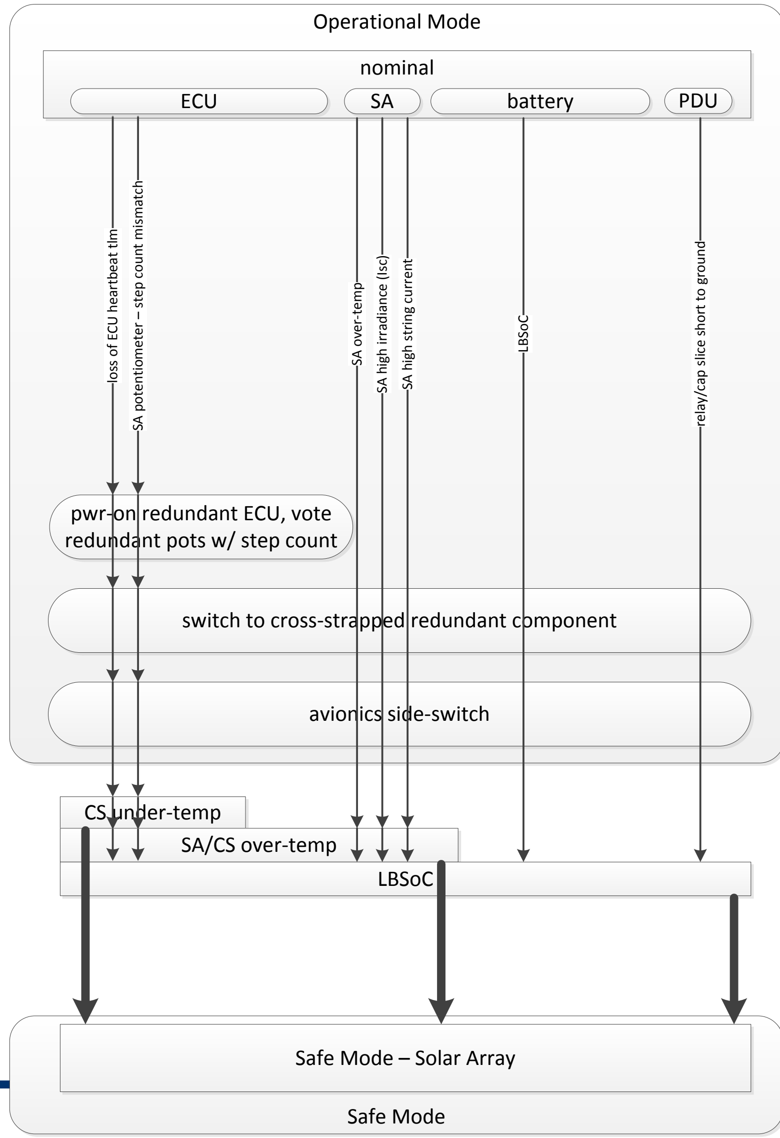

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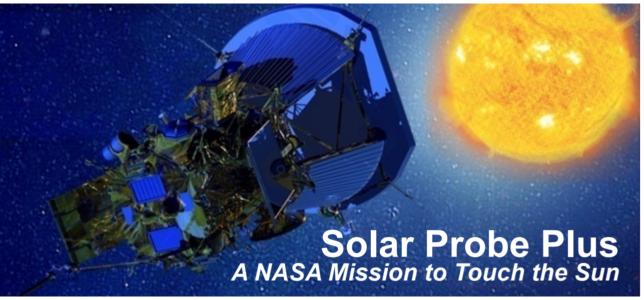
Low Battery State of Charge

- **Cause summary: battery charge control fault**

- **Telemetry used for diagnosis: state of charge estimate included in PSE telemetry**

- **Response: Safe Mode – Solar Array**
  - **LBSoC safing threshold will be set below the minimum expected SoC and with enough margin to ensure battery SoC will not decrease below 140 Wh during solar array safing and recovery.**
  - **This energy margin allows the battery to support a 440 W load (max load w/ margin) for an additional 19 minutes beyond the minimum 140 Wh SoC.**
    - **Conservative, as non-essential loads will be shed in Safe Mode.**

CLT expiration



- **Potential causes:**
  - No/incorrect configuration commands
  - X-band receiver: reduced performance, hard failure, locked/reset, fails to acquire, fails to detect commands
  - No output from LNA
  - No RF input to LNA from filter
  - Failure of filter
  - No uplink signal to filter from diplexer
  - Diplexer failure
  - Loss of uplink signal from switch assembly to diplexer
  - Switch stuck in incorrect/invalid position
  - Antenna degraded performance or mechanical failure

- **Telemetry used for diagnosis: re-programmable software command loss timer (reset only upon receipt of dedicated CLT-reset ground command)**

- **Response: Safe Mode – Earth Acquisition**

Processor Overcycling

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- **Potential causes:**
  - **repeated incorrect time-out of internal watchdog timers of all SBCs as Prime,**
  - **persistent faulty processor telemetry indication (example: Prime overcurrent) causing autonomy commanded self-demotion**
- **Telemetry used for diagnosis: ARC processor transition count**
- **Response: Safe Mode – Standby**

Safe Mode

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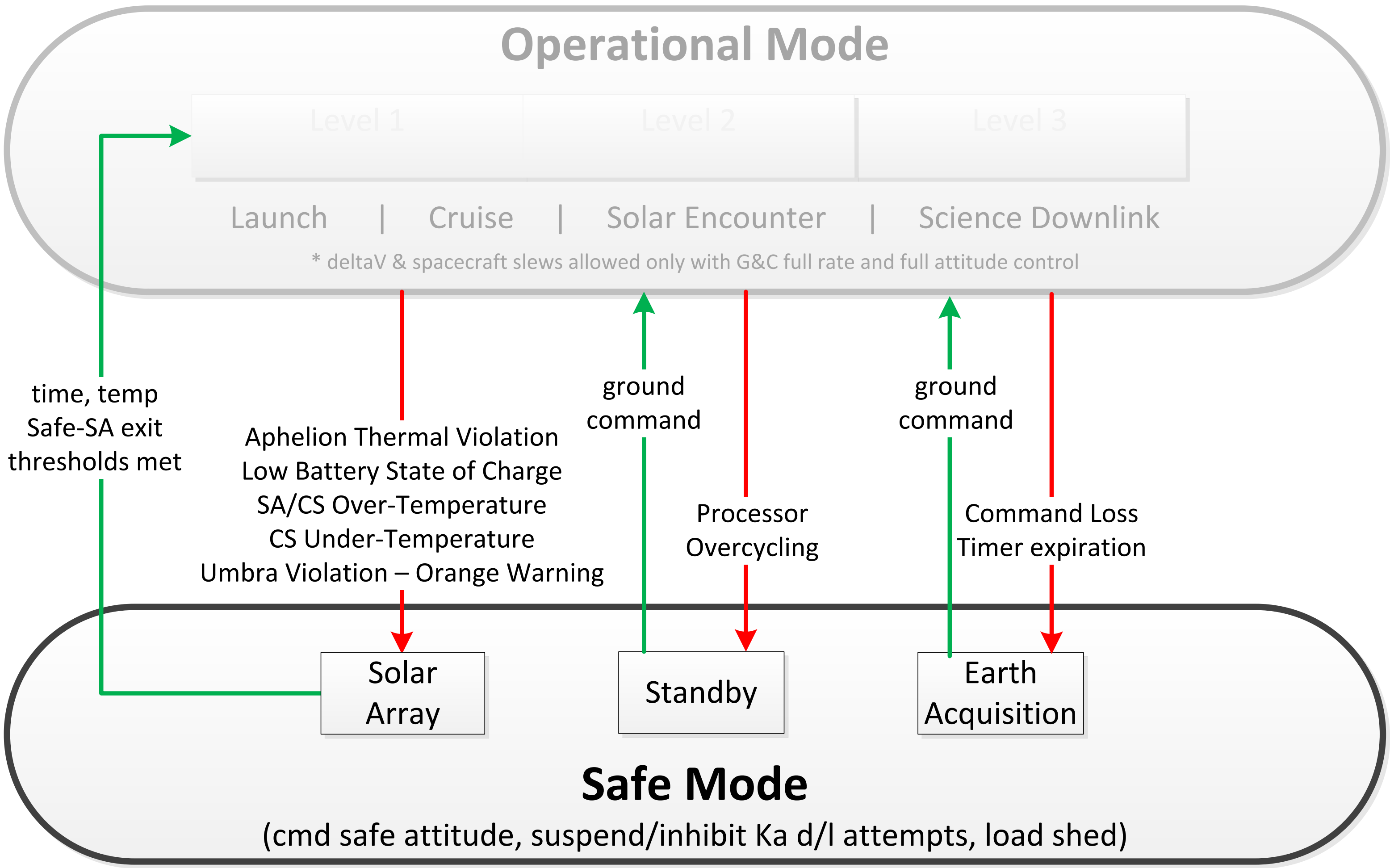
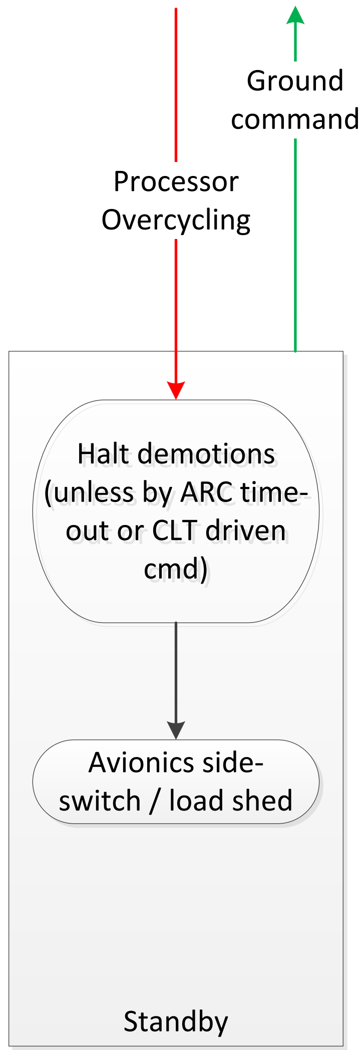


Safe Mode - Standby

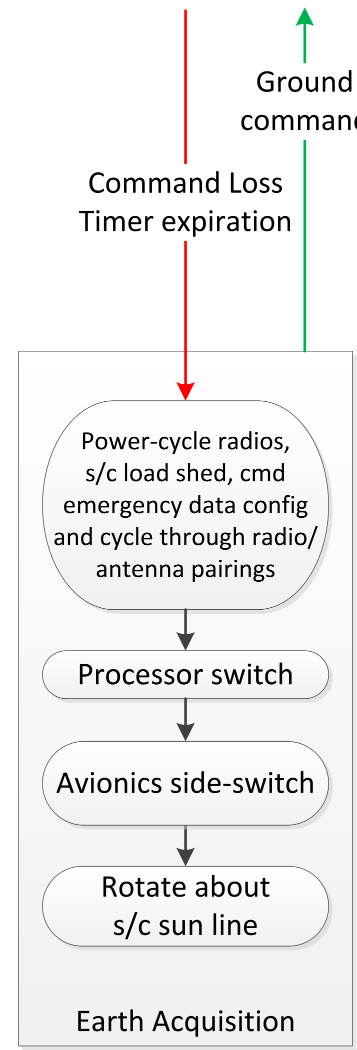
- **Actions:**
  - **Halt Prime processor demotions**
  - **Avionics side switch / load shed**

- **Exit criteria**
  - **Ground command**



Safe Mode – Earth Acquisition

- **Actions:**
  - **Power-cycle radios, s/c load shed**
  - **Command emergency data configuration**
  - **Configure pre-defined radio/antenna pair sets**
  - **Processor switch**
  - **Avionics side/switch**
  - **Rotate about s/c sun line**
    - **Configure pre-defined radio/antenna pair sets**
- **Exit criteria**
  - **Ground command**

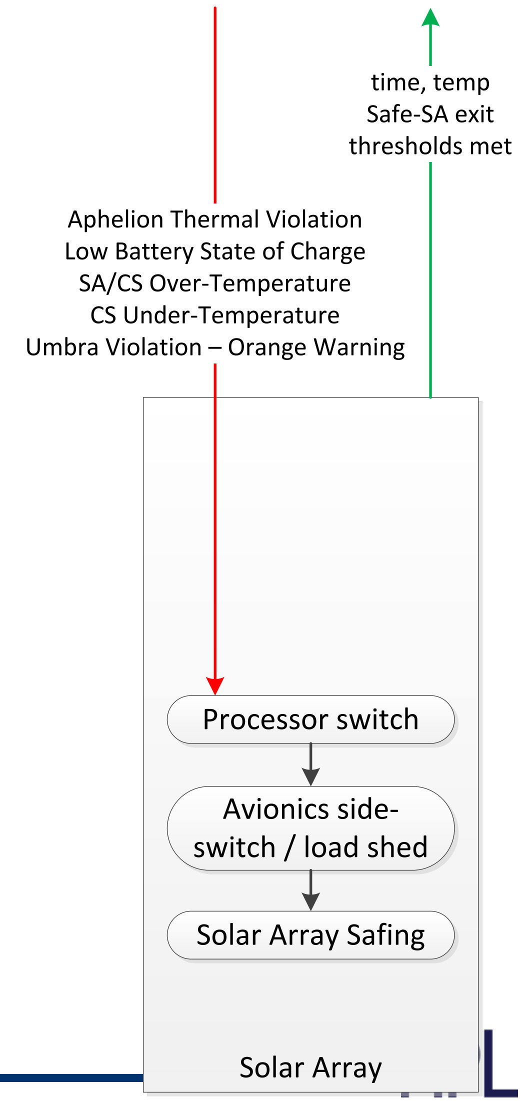


Safe Mode – Solar Array

- **Actions:**
  - **Prime processor demotion**
  - **Side-switch / power-cycle**
  - **Command solar arrays to target safing angle**

Exit criteria:

(> 90 seconds TBR from safing start & < 125C TBR) or 280 seconds TBR from SA safe angle achieved



Safe Mode – Solar Array: timing budget

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Timing budget allocations for fault condition detection and response through..

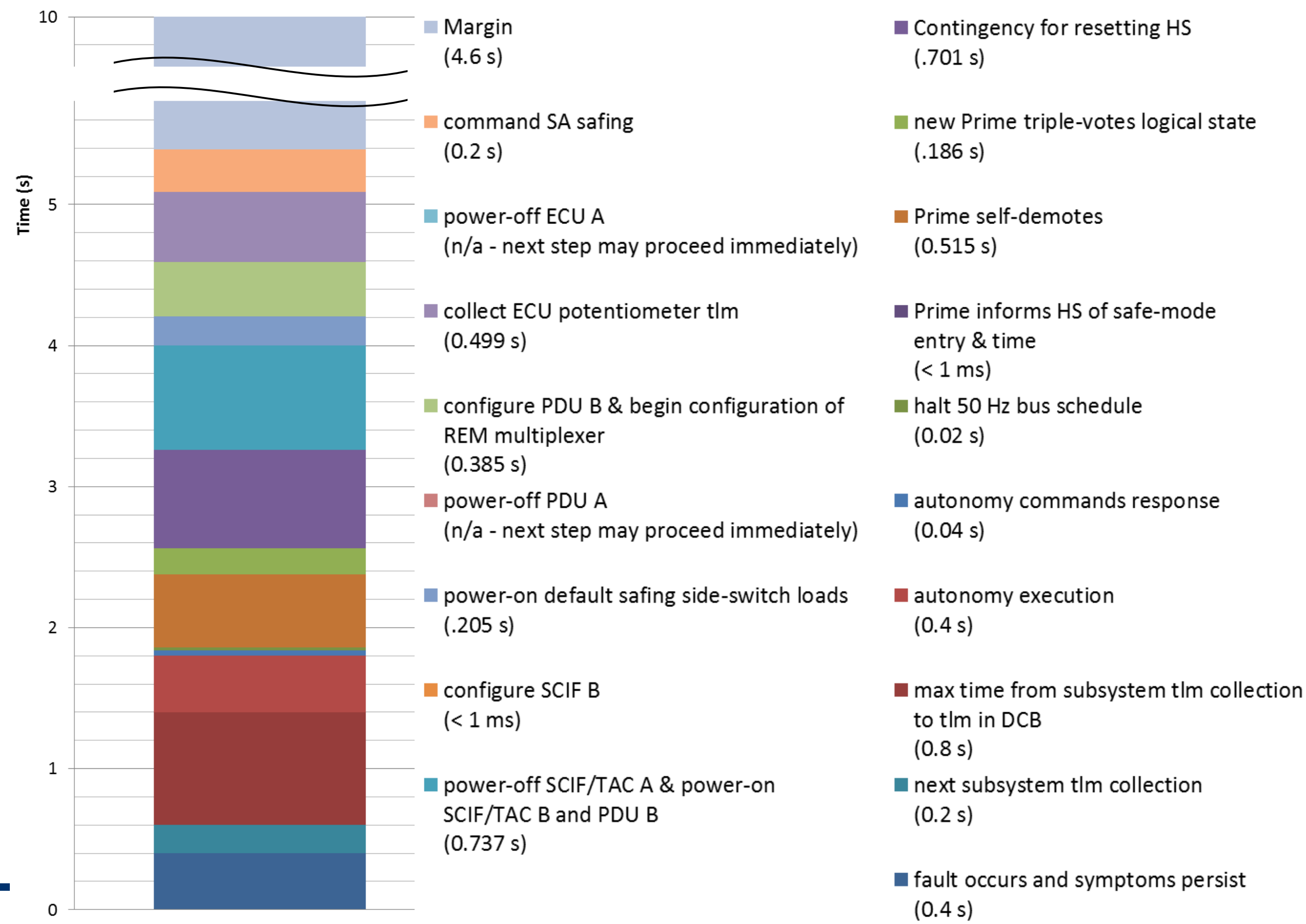
Removal of power from solar array drive (ending potential over-shoot)

- Total is ~ 4.2 seconds
- Time allocation allowed in solar array safe angle determination is 5 seconds.

Commanding of solar array movement to safe angle

- Total is ~ 5.4 seconds
- Time allocation allowed in solar array safe angle determination is 10 seconds.

Timing budget from solar array movement to safe angle through Safe Mode exit is discussed in SA Safing section



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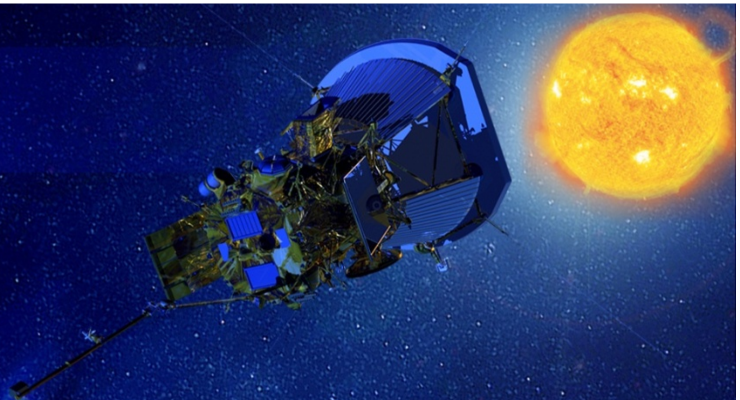

Attitude Protection

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Outline

- G&C system overview
  - Nominal operation: 3-axis stabilized
  - Off-nominal operation: Sun-safe attitude
- Attitude anomalies – causes and mitigations
  - Potential aphelion thermal violation or umbra violation (perihelion)
  - Target attitude and attitude knowledge faults
  - Attitude control faults
  - External/environmental disturbances
- Maintaining Sun-safe attitude with solar limb sensors
  - At perihelion with TPS (+Z axis) to Sun
  - At aphelion with Sun line 45° between +Z and –X axes
- G&C simulations and timing for side switch, processor reset/switch (safe mode demotion)
  - Time limits to umbra violation if control loop broken
  - Ability to recover without umbra violation if control loop restored
- Future Work

G&C System Overview

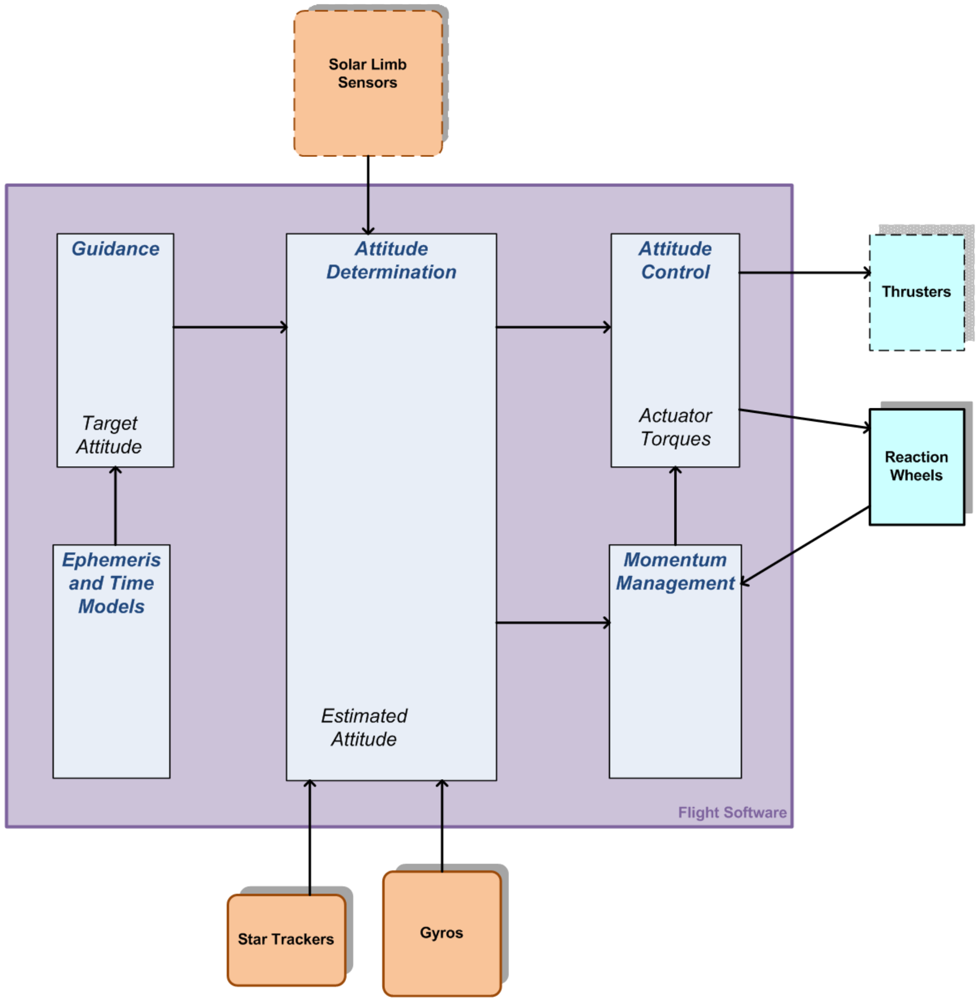
- SPP has a closed-loop attitude control system to maintain 3-axis stabilized spacecraft
- All hardware components are redundant, most are cross-strapped to REM

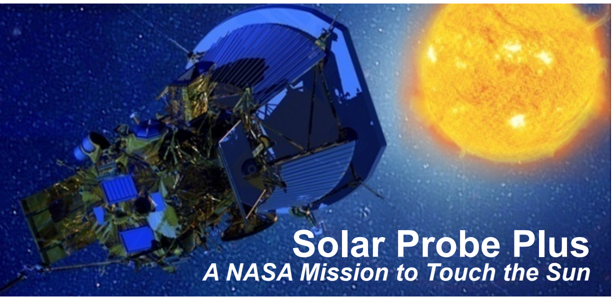
- Sensors (for attitude control):
  - Star trackers provide inertial attitude reference
  - Gyros in IMU provide angular rates
  - Solar limb sensors provide coarse Sun direction

- Actuators (for attitude control):
  - Reaction wheels apply torques for achieving and maintaining desired attitude
  - Thrusters used for attitude control when dumping momentum from the wheels (wheel desaturations)

G&C System Normal Operation

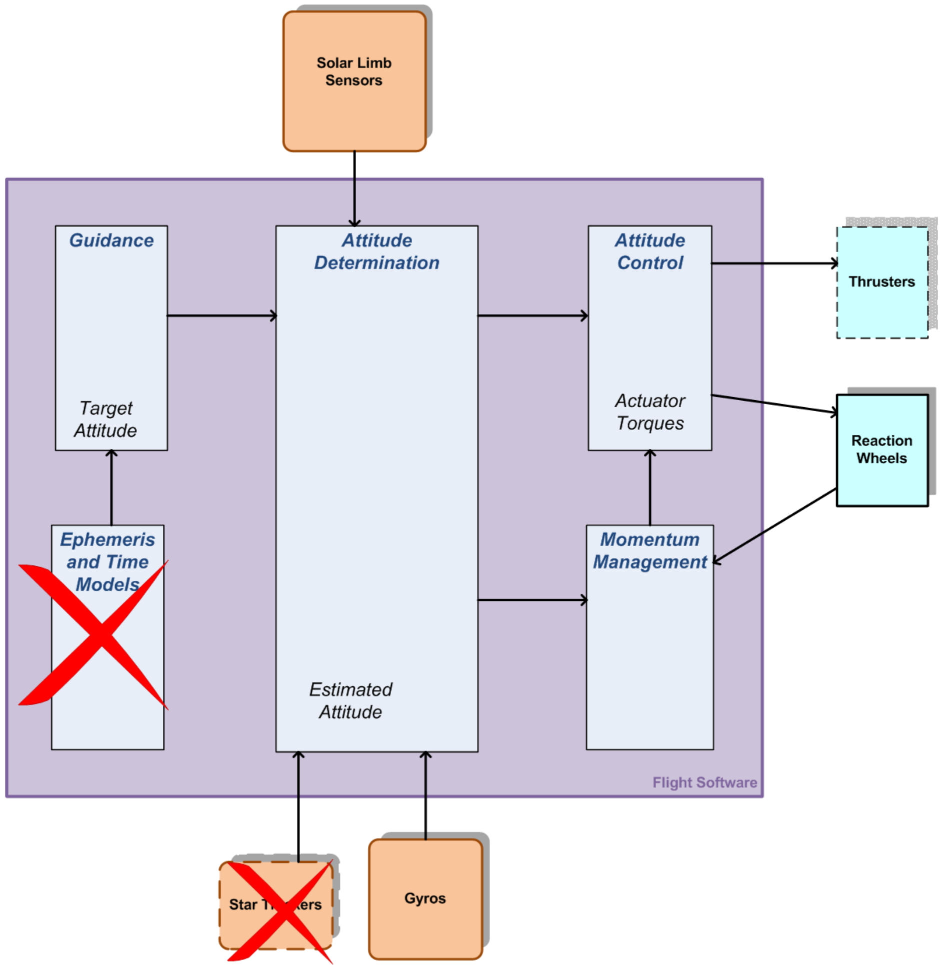
- Normal operating mode:
  - Spacecraft orbit (ephemeris) and time system models in flight software used to compute desired inertial-relative attitude
  - Star tracker and gyros in IMU provide inertial attitude reference and angular rates
  - Reaction wheels apply torques for achieving and maintaining desired attitude
  - Thrusters used for attitude control when dumping momentum from the wheels (wheel desaturations)





G&C System Sun-Safe Attitude

- Sun-safe attitude:
  - Solar limb sensors provide relative Sun direction information, gyros provide angular rates
  - Reaction wheels and thrusters used as for normal operations



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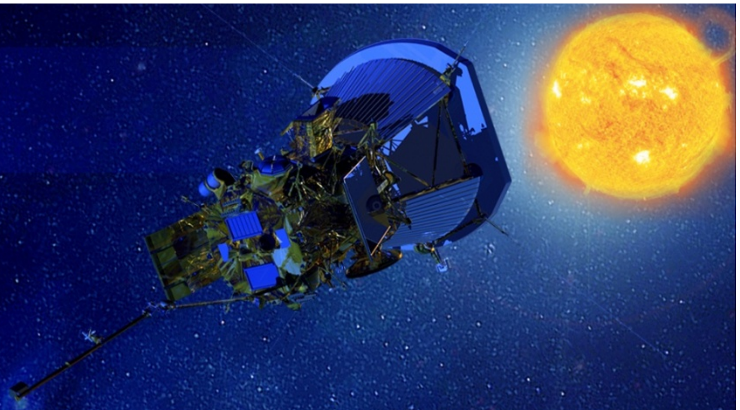


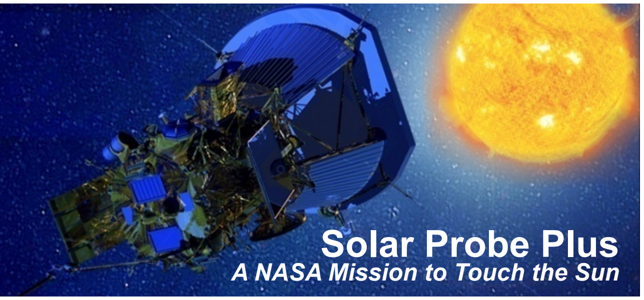
Attitude Anomalies
Causes and Mitigations

Attitude Anomalies
Error Sources for Target Attitude Computation

- Target attitude computed from external reference vectors
  - Sun-Ram attitude at perihelion:
    - +Z axis points along s/c to Sun vector (-s/c orbital position vector)
    - +X axis points as close as possible to s/c orbital velocity vector
  - Tilted attitude at aphelion
    - S/C to Sun vector is 45° from +Z axis towards –X axis
    - +X axis points as close as possible to s/c orbital velocity vector
  - S/C orbital position and velocity (relative to Sun) required to compute target attitude
  - Time knowledge required to compute orbital position and velocity from on-board ephemeris models
    - Convert current time (MET) to dynamic time used for ephemeris models (TDT)

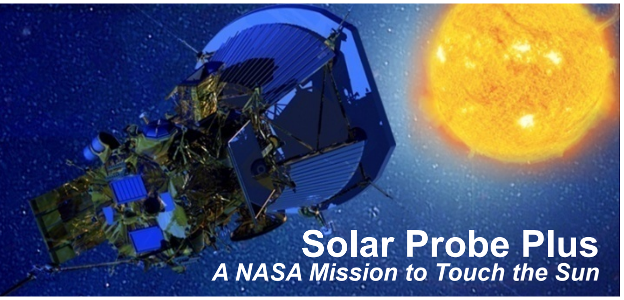
- Anomalies leading to incorrect target attitude include:
  - Errors in ephemeris model data
  - Errors in time knowledge (s/c MET) or time conversion (TDT)
  - Inability to compute time or reference vectors
  - Errors in computing attitude from reference vectors
  - Commanded attitude does not match required attitude for current orbit position (solar distance)

Attitude Anomalies
Incorrect Target (Commanded) Attitude



- Errors in ephemeris model data
  - Actual errors in knowledge of s/c orbit (navigation errors)
  - Errors in fitting on-board ephemeris model to ground navigation solution
  - Errors in transmitting ephemeris model data to s/c
  - Corruption of ephemeris model data once loaded to s/c
  - “Expiration” of ephemeris model – on-board data does not cover current s/c time
- Errors in time knowledge (s/c MET) or time conversion (TDT)
  - Errors in s/c MET - causes and mitigations covered in separate section
  - Errors in knowledge of MET relative to ground time systems (TDT)
  - Errors in transmitting time conversion parameters to s/c
  - Corruption of time conversion parameters once loaded to s/c
- Errors in flight software when computing target attitude from reference vectors
  - TDT incorrectly computed using time model
  - S/C position and/or velocity vector incorrectly computed using ephemeris models and computed TDT
  - Attitude generated incorrectly from vectors
    - Discontinuity in commanded attitude
- Commanded attitude does not match desired attitude for current orbit position (solar distance)

Incorrect Target (Commanded) Attitude Anomalies and Mitigations (1)



Anomaly (Error Source)	**Mitigation(s) Ground**	**Mitigation(s) Spacecraft**
Ephemeris/Time Conversion Model Generation	Tracking schedule Navigation analyses, operational processes and procedures Time-keeping analyses and operational processes and procedures Ground software development process and testing program MOPS procedures for ephemeris and time conversion data generation and testing prior to loading to s/c	n/a (models generated on ground)
Ephemeris/Time Conversion Data Upload	MOPS procedures for ephemeris and G&C parameter management and upload to s/c Load/dump/compare process to confirm correct receipt of intended ephemeris or time data Commands required to move ephemeris or time conversion data to working memory used by G&C flight software	CFDP manages validation of uploads (reject incorrectly formatted messages, etc.)
Ephemeris/Time Conversion Data Storage		Processor memory scrubbing

Incorrect Target (Commanded) Attitude Anomalies and Mitigations (2)

Anomaly (Error Source)	Mitigation(s) Ground	Mitigation(s) Spacecraft
Ephemeris & Time Model Usage (flight software errors)	G&C and flight software development processes and testing/verification programs I&T testing (mission sims, G&C special tests)	G&C flight software “sanity” checks to reject grossly incorrect time values or reference vectors, reject target attitude if large discontinuity from previously computed values (See separate section for details on mitigations for MET errors)
Attitude commanding (operator error)	MOPS procedures for generating and checking s/c sequences MOPS procedures for real-time commanding	G&C software will have “lock” to reject commands to change target attitude during perihelion passages (solar distance < 0.25 AU) (Other checks being considered: G&C software may limit angular rates at which any slews/attitude changes are performed during perihelia passages)
Expired Ephemeris Model (operator error)	MOPS procedures for ephemeris management	Processor and software configured to store ephemeris data covering longest expected communication outage G&C software will continue to use last valid target attitude computed from ephemeris vectors when ephemeris has expired

Attitude Anomalies
Error Sources for Attitude Determination

- Actual spacecraft attitude estimated from sensor data
  - Star trackers provide periodic measurements of orientation relative to inertial reference frame
  - Gyros in IMU provide frequent measurements of body angular rotation rates
  - Attitude determination algorithms combine star tracker and gyro measurements for best estimate of orientation (attitude) and angular rates
    - Best attitude knowledge available with both sensor data types
    - Attitude knowledge degrades when either sensor data type is not available

- Anomalies leading to incorrect estimated attitude include:
  - Errors in star tracker or gyro data
  - Lack of star tracker or gyro data
  - Errors in attitude determination computations
  - Incorrect values for attitude determination parameters

Attitude Anomalies
Incorrect Estimated Attitude

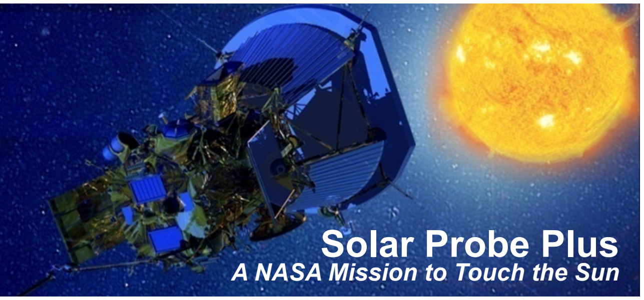
- Errors in star tracker or gyro data
  - Degraded (poor quality) or incorrect measurements
- Lack of star tracker or gyro data
  - Insufficient measurement data available
    - Short-term data drop outs
  - No measurement data available
- Error in or lack of sensor data is most likely due to a hardware fault (in component itself or in spacecraft avionics)
  - See section on subsystem fault responses for details on G&C hardware fault detection and correction
  - Exception is long-term star tracker data outages that are expected in periods of high solar activity (e.g. CME)

- Errors in measurement processing or attitude determination algorithms
- Incorrect parameter values
  - Errors in ground calibration procedures and computations
  - Errors in uploading parameter values to s/c
  - Corruption of parameter values in s/c memory

Incorrect Estimated Attitude Anomalies and Mitigations (1)

Anomaly (Error Source)	**Mitigation(s) Ground**	**Mitigation(s) Spacecraft**
Errors in star tracker or gyro data	Flight unit performance testing by star tracker and IMU vendors	IMU and star trackers typically incorporate internal error checking and will flag any invalid data G&C flight software performs "sanity" checks on measurements to reject bad data: Checks on message validity and integrity as input to software Checks on consistency of measurements with previous attitude state (i.e. reject "outliers") G&C flight software sets flags to request autonomy action to correct possible hardware faults (See section on subsystem fault responses for G&C HW faults & responses)
Lack of star tracker or gyro data	Gyros will be chosen so that errors in attitude propagation using rate data over 24-hour (TBR) period do not exceed packaging umbra violation angle Gyro performance verified by vendor's testing program Star tracker software will be upgraded to permit attitude solutions to be generated with higher background noise (studies performed by potential vendors in phase A); software performance verified by vendor analysis and testing	Star trackers and IMU are redundant (internally or by carrying multiple units) Attitude or angular rates estimated from available sensor data during short-term data drop outs Estimate rate from consecutive star tracker measurements during long-term gyro data outage Estimate orientation by propagating from last available star tracker measurement using angular rates from gyros during long-term tracker data outage G&C flight software sets flags to request autonomy action to restore sensor data (See section on subsystem fault responses for G&C HW faults & responses)

Incorrect Estimated Attitude Anomalies and Mitigations (2)



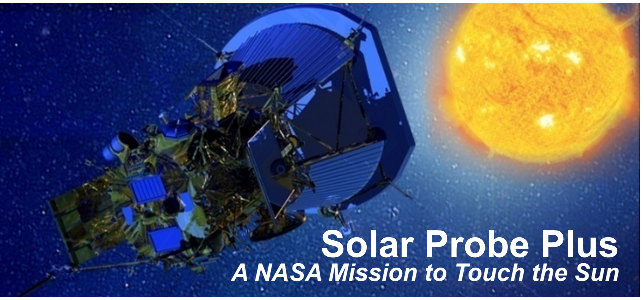
Anomaly (Error Source)	**Mitigation(s) Ground**	**Mitigation(s) Spacecraft**
Errors in measurement processing or attitude determination computations (software errors)	G&C and flight software development processes and testing/verification programs I&T testing (mission sims, G&C special tests)	G&C attitude determination software monitors consistency of attitude solutions and rejects “outliers”
Incorrect attitude determination parameters (operator error)	G&C procedures and processes for system calibration MOPS procedures and processes for G&C parameter management Load/dump/compare process to confirm correct receipt of intended parameter values Commands required to move values to working memory used by G&C flight software	CFDP manages validation of uploads (reject incorrectly formatted messages, etc.) G&C attitude determination software monitors consistency of attitude solutions and rejects “outliers”
Attitude determination parameter storage		Processor memory scrubbing

Attitude Anomalies
Error Sources for Attitude Control

- Spacecraft attitude maintained (or changed) by applying torques from actuators
  - Reactions wheels used for attitude control except during TCMs or momentum dumps
  - Thrusters used for attitude control during TCM or momentum dump
  - Momentum dumps performed autonomously when wheels are near saturation (maximum speed/momentum storage capacity)
    - Wheel speed data needed to correctly track and manage system momentum

- Anomalies leading to incorrect or no attitude control include:
  - Inability to apply necessary control torques
  - Incorrect control torques applied due to
    - Hardware failures
    - Errors in attitude control computations

Attitude Anomalies
Incorrect Attitude Control Action

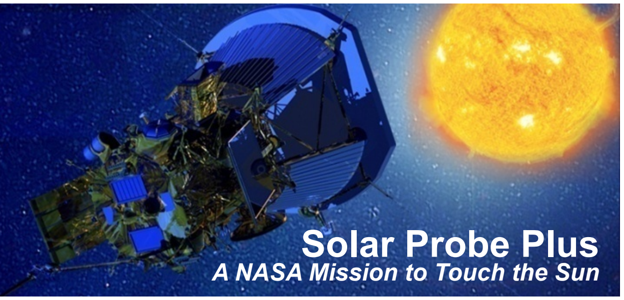


- Inability to apply necessary control torque
  - Momentum dump not performed when needed, allowing wheels to saturate
    - Incorrect or no wheel speed data available, leading to incorrect system momentum estimate
  - S/C not configured to allow commands to flow to actuators (operator error)
- Incorrect control torques applied (torques not following commands from G&C software)

- Inability to apply torque or incorrect torques exerted are most likely due to hardware faults (in component itself or in spacecraft avionics)
  - Wheel speed data missing or incorrect
  - Wheels not following commanded torque profile or thrusters not following commanded firing profile
  - See section on subsystem fault response for details on G&C hardware fault detection and responses
- Most actuator hardware faults are not expected to lead to umbra violation
  - Still assessing ability to prevent umbra violation (or aphelion thermal violation) if one or more thrusters are "stuck on"

- Errors in attitude control algorithms (leading to incorrect control torques)
  - Measurement processing (wheel speed data), momentum estimation, or computation of control action
- Incorrect parameter values
  - Errors in ground calibration procedures and computations
  - Errors in uploading parameter values to s/c
  - Corruption of parameter values in s/c memory

Incorrect Attitude Control Action Anomalies and Mitigations (1)



Anomaly (Error Source)	**Mitigation(s) Ground**	**Mitigation(s) Spacecraft**
Unable to apply control torques Wheel or thruster hardware failure S/C avionics hardware failure	Flight unit performance testing by reaction wheel and propulsion system vendors Avionics performance testing by APL	Wheels, thrusters, and avionics are redundant; wheels cross-strapped G&C flight software monitors wheel performance (response to control commands) when speed data is available G&C flight software sets flags to request autonomy action to correct possible wheel hardware faults G&C flight software will switch to thrusters if 2 or more wheels failed (See section on subsystem fault responses for list of G&C hardware faults & responses) Control can be maintained if 1 thruster fails off; still investigating effect of thruster failing on
Unable to apply control torques Incorrect S/C configuration for actuator commanding (operator error)	I&T testing (mission sims, G&C special tests) MOPS procedures for generating and checking s/c sequences	G&C flight software sets flags to request autonomy action to restore normal wheel response (See section on subsystem fault responses for list of G&C hardware faults & responses)
Unable to apply control torques Momentum dump not performed; wheels saturate	Testing of wheel speed data generation at vendor Testing of wheel data interface in s/c avionics at APL	G&C flight software sets flags to request autonomy action to restore normal wheel data interface if wheel speed data drop out (See section on subsystem fault responses for list of G&C hardware faults & responses)

Incorrect Attitude Control Action Anomalies and Mitigations (2)

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Anomaly (Error Source)	Mitigation(s) Ground	Mitigation(s) Spacecraft
Incorrect control torques applied Wheel or thruster hardware failure S/C avionics hardware failure	Flight unit performance testing by reaction wheel and propulsion system vendors Avionics performance testing by APL	G&C flight software monitors wheel performance (response to control commands) when speed data is available G&C flight software sets flags to request autonomy action to correct possible wheel hardware faults and restore speed data G&C flight software will switch to thrusters if 2 or more wheels failed (See section on subsystem fault responses for list of G&C hardware faults & responses) Control can be maintained if 1 thruster fails off; still investigating effect of thruster failing on
Errors in measurement processing, momentum estimation, or attitude control computations	G&C and flight software development processes and testing/verification programs I&T testing (mission sims, G&C special tests)	
Incorrect attitude control or momentum management parameters (operator error)	MOPS procedures and processes for G&C parameter management Load/dump/compare process to confirm correct receipt of intended ephemeris or time data Commands required to move values to working memory used by G&C FSW	CFDP manages validation of uploads (reject incorrectly formatted messages, etc.)
Attitude control and momentum management parameter storage		Processor memory scrubbing

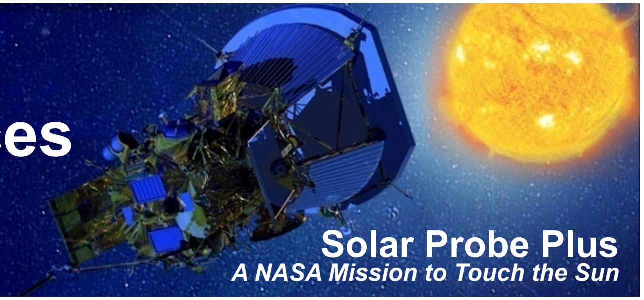
Attitude Anomalies
External Disturbances

- Wheels and thrusters are sized to accommodate the expected environmental disturbances
  - Momentum dumps will occur as needed; time between dumps will increase as solar distance increases (fewer dumps needed)

- Largest environmental disturbance torques are generated by
  - Solar radiation pressure on TPS & SPC with center of pressure (Cp) offset from s/c center of mass (Cg)
  - Thermal radiation from top (Sun-facing) surface of TPS
  - Gravity gradient torque at closest approach for Venus flybys

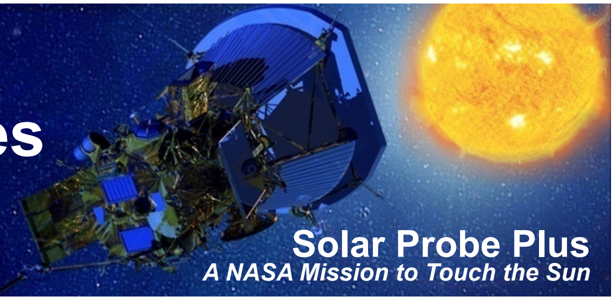
- Analyses have shown other environmental disturbances are negligible compared to the 3 largest contributors
  - Plasma pressure from electrons and protons in the solar wind
  - Thermal radiation pressure from spacecraft components other than TPS
  - Dust impacts
  - Magnetic torques from (minimally) charged spacecraft moving through Sun’s dynamic magnetic field

Torque Comparison
Actuators vs. Environmental Disturbances
Solar Radiation Effects



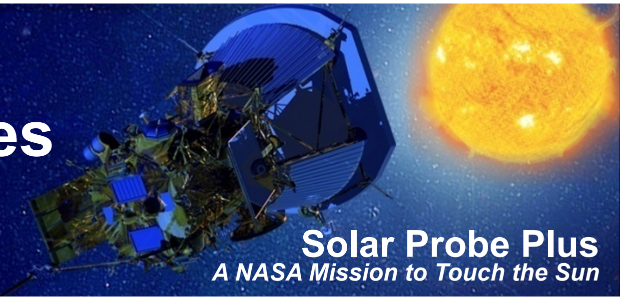
Source(s)	Typical Torque Magnitudes	Comments
Wheels	0.033 Nm	Current best estimate for maximum torque per wheel
Thrusters	0.3 – 3.0 Nm	Varies by body axis and tank pressure
Solar radiation pressure TPS & SPC	3 - 8 x 10^{-4} Nm at 9.5 Rs 1 – 3 x 10^{-6} Nm at 1 AU for Cp-Cg offset of 51 mm (2")	Varies with Cp-Cg offset and solar distance
Solar wind plasma pressure Magnetic torques	at least 1 order of magnitude lower than solar radiation pressure from photons	Generated by populations of electrons and protons emitted by Sun Generated by charged s/c moving through Sun's variable magnetic field

Torque Comparison
Actuators vs. Environmental Disturbances
Solar Dust and S/C Thermal Radiation



Source(s)	Typical Torque Magnitudes	Comments
Wheels	0.033 Nm	Current best estimate for maximum torque per wheel
Thrusters	0.3 – 3.0 Nm	Varies by body axis and tank pressure
Dust Impacts	Maximum 18 x 10^{-10} Nm (TBR)	Taken from pre-phase A study; will be updated with phase B dust modeling results
Thermal radiation pressure TPS Other s/c components	 15 – 30% of solar radiation pressure < 5% of TPS solar radiation pressure	 TPS top surface is an efficient radiator fully exposed to Sun Other surfaces are less efficient radiators and/or not fully exposed (back of TPS, back and front of solar arrays, radiators)

Torque Comparison
Actuators vs. Environmental Disturbances
Gravity Gradient



Source(s)	Typical Torque Magnitudes	Comments
Wheels	0.033 Nm	Current best estimate for maximum torque per wheel
Thrusters	0.3 – 3.0 Nm	Varies by body axis and tank pressure
Gravity Gradient Sun	$3.5 - 8.3 \times 10^{-8}$ Nm $2.3 - 2.9 \times 10^{-11}$ Nm $2.4 - 2.8 \times 10^{-11}$ Nm	At 9.5 Rs with up to 5° Sun offset from +Z axis At 9.5 Rs with Sun on +Z axis At 1 AU with up to 5° Sun offset from 45° line
Gravity Gradient Venus	$1.6 - 8 \times 10^{-4}$ Nm $0.5 - 3.4 \times 10^{-7}$ Nm	Maximum magnitude at closest approach for the 7 flybys ranges Magnitude at 1 hour before and after closest approach (for mission trajectory with minimum perihelia at 9.5 Rs)

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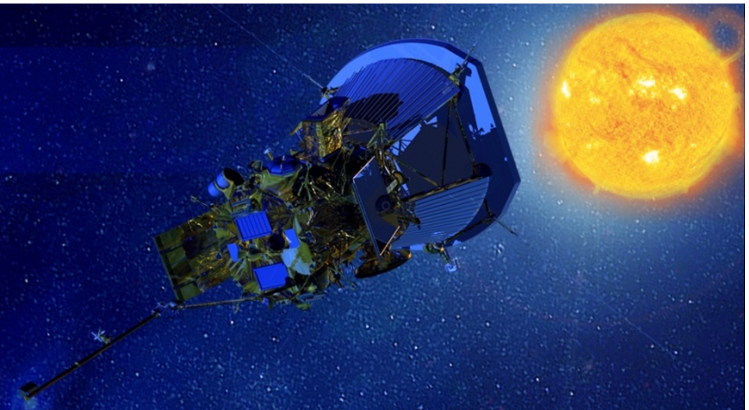
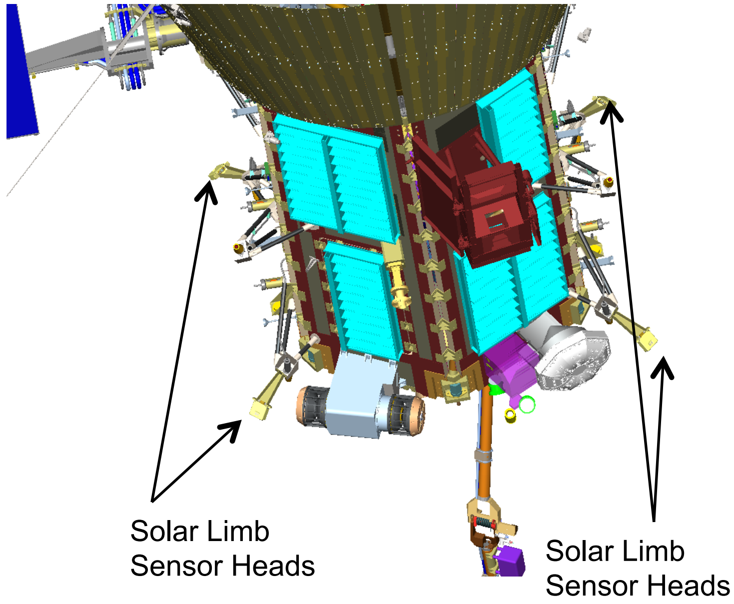
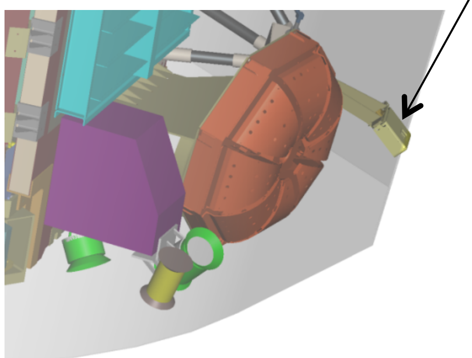


Maintaining Safe Attitude using Solar Limb Sensors

Solar Limb Sensor Overview

- Preceding slides presented “first tier” responses to correct G&C faults
  - Primary sensor or actuator faults, software faults
- G&C system includes a solar limb sensor (SLS) assembly to externally detect incorrect Sun direction
  - Pending umbra violation or aphelion thermal violation
- Solar limb sensor system being developed by Adcole Corporation
  - Flight solar limb sensor (SLS) assembly consists of 4 redundant analog solar limb sensor heads and one redundant electronics box
  - Derived from existing sun sensor techniques and hardware
  - Prototype system currently in development and will be tested to demonstrate TRL 6 by mission PDR
- SLS heads are mounted around the perimeter of the aft end of the spacecraft
  - TPS chamfer corners serve as one boundary for SLS head fields-of-view





Information on the solar limb sensor design is proprietary to Adcole and not to be shared.

Solar Limb Sensor Operation

- Solar limb sensors provide "last ditch" protection from incorrect Sun-relative orientation
  - Intended to play similar role to standard Sun sensors for Sun-safe attitude response
  - Different in operation from standard Sun sensors

- System optimized to provide information required to correct attitude anomalies at perihelion
  - SLS heads placed so that one or two are illuminated for small Sun offsets from +Z axis in any "azimuth" direction out to packaging umbra violation boundary
    - Small tilt of Sun off +Z axis needed for initial illumination (angle determined by TPS penumbra size and radial distance or sensor head from s/c center line)
    - Sun presence and intensity measured at two locations in each head
      - Differential intensity between two locations used to derive offset angle in boresight plane when partial Sun disk is visible (small Sun offset angles)
      - Cross-angle information not provided
      - Only Sun presence is provided at larger Sun offset angles when full Sun disk is visible since intensities at both locations are identical (saturation)

- SLS system does not provide continuous or full 3-D Sun direction information at any spacecraft attitude
  - SLS heads not placed to detect Sun at all directions around spacecraft
    - Most of +Z hemisphere is covered by at least 1 head
  - Sun direction vector in s/c body frame not directly measured

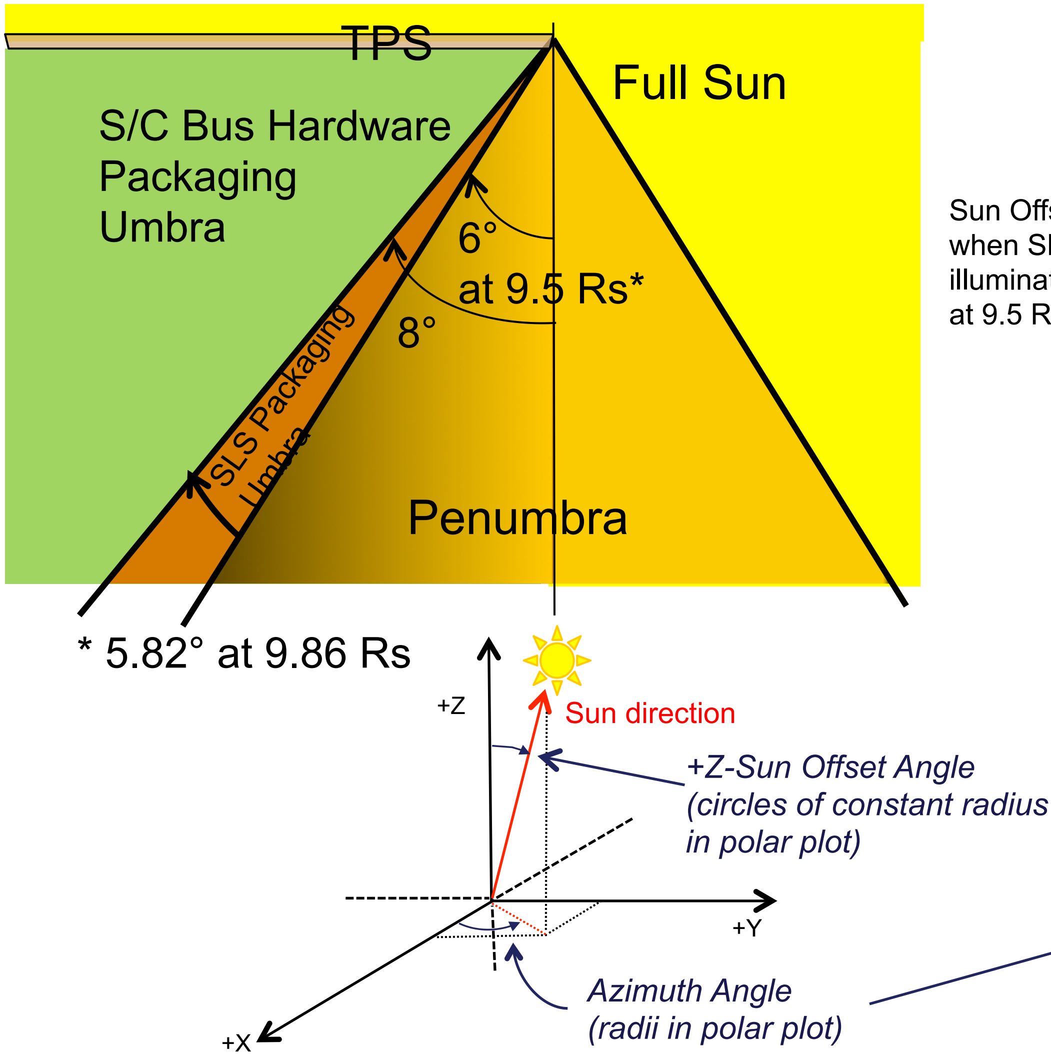
Solar Limb Sensor Operation
Attitude Anomalies at Perihelion Attitude

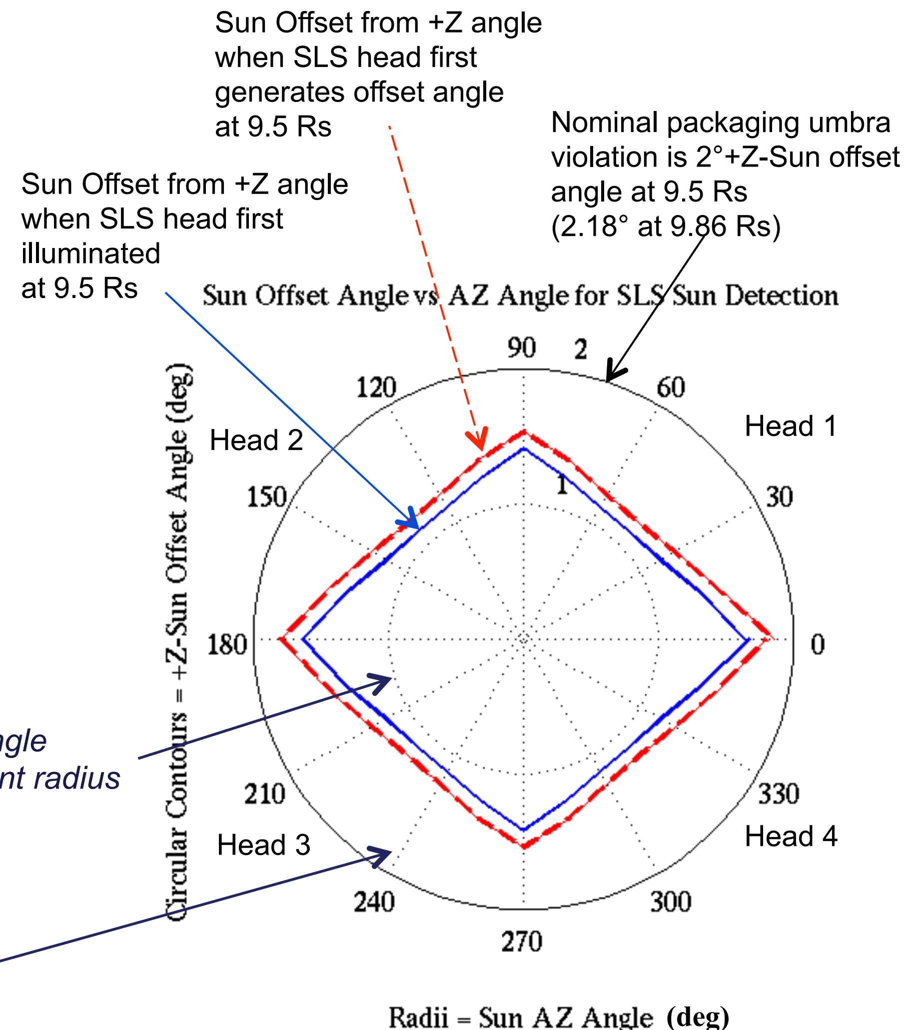
- SLS heads are not illuminated at nominal perihelion attitude
- If the spacecraft off-points from +Z to Sun, then one of the heads may start to be illuminated
  - Sensors placed such that illumination occurs before other s/c bus components are exposed to the Sun

- G&C software will switch to partial attitude-full rate control mode if any SLS head detects Sun presence when at perihelion attitude
  - SLS readings provide attitude reference
    - Star tracker data and ephemeris and time models are ignored
  - Control algorithm maintains Sun direction such that no SLS heads are illuminated (Sun line within ~1° of +Z axis)
    - No active control for secondary attitude reference (+X to ram)
  - Gyro rate data still used to control spacecraft angular rates
    - Turn spacecraft to decrease Sun offset angle while solar limb sensors see Sun
    - Null spacecraft rates once solar limb sensors stop detecting Sun

- Criteria not yet determined for transitioning back to full 3-axis attitude control once using SLS in control loop

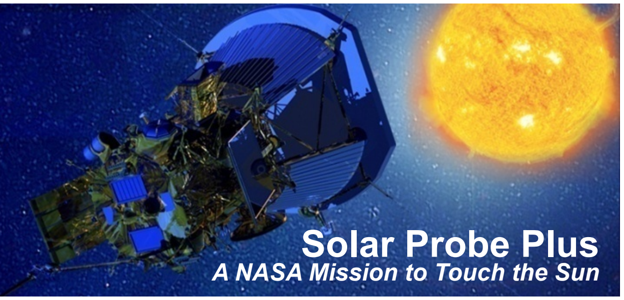
Solar Limb Sensor Operation Coverage at Perihelion Attitude





APL

Solar Limb Sensor Operation
Attitude Anomalies at Aphelion Attitude



- 2 SLS heads are illuminated at nominal aphelion attitude (45° tilt), but full Sun disk is visible
  - Sun presence indication only - no offset angle information
  - Gross attitude errors easily detected (but not expected):
    - Sun illuminating heads on +X side of spacecraft or only illuminating one of two heads that cover –X side or not illuminating any head (Sun in –Z hemisphere)
  - Smaller offsets from nominal 45° tilt are harder to detect, but can pose problems for solar array or cooling system operation
  - May be possible to infer changes in offset angle from changes in intensity readings from SLS heads
- Solar panels are fully extended (flap angle = 0°) and tilted to face the Sun (feather angle = -45°) at this attitude
  - Current and voltage measurements from tips of solar panels may provide indications of off-nominal attitude similar to SLS intensity changes
- If the SLS or solar panel measurements can detect sufficiently small changes in Sun offset angle, will implement control mode that monitors sensed values and rotates spacecraft to stay close to expected values for 45° tilt
  - Currently working with Adcole to determine sensitivity of intensity changes and with power system team to determine sensitivity of panel measurements to Sun offset angle
    - Control will be based on SLS or panel info only; star tracker data and ephemeris and time models are ignored; no control to secondary attitude reference (+X to ram)
- If these measurements are not sensitive enough, will add some type of standard Sun sensor to provide external detection of off-nominal attitudes at larger solar distances

Solar Limb Sensor Operation Coverage at Aphelion Attitude

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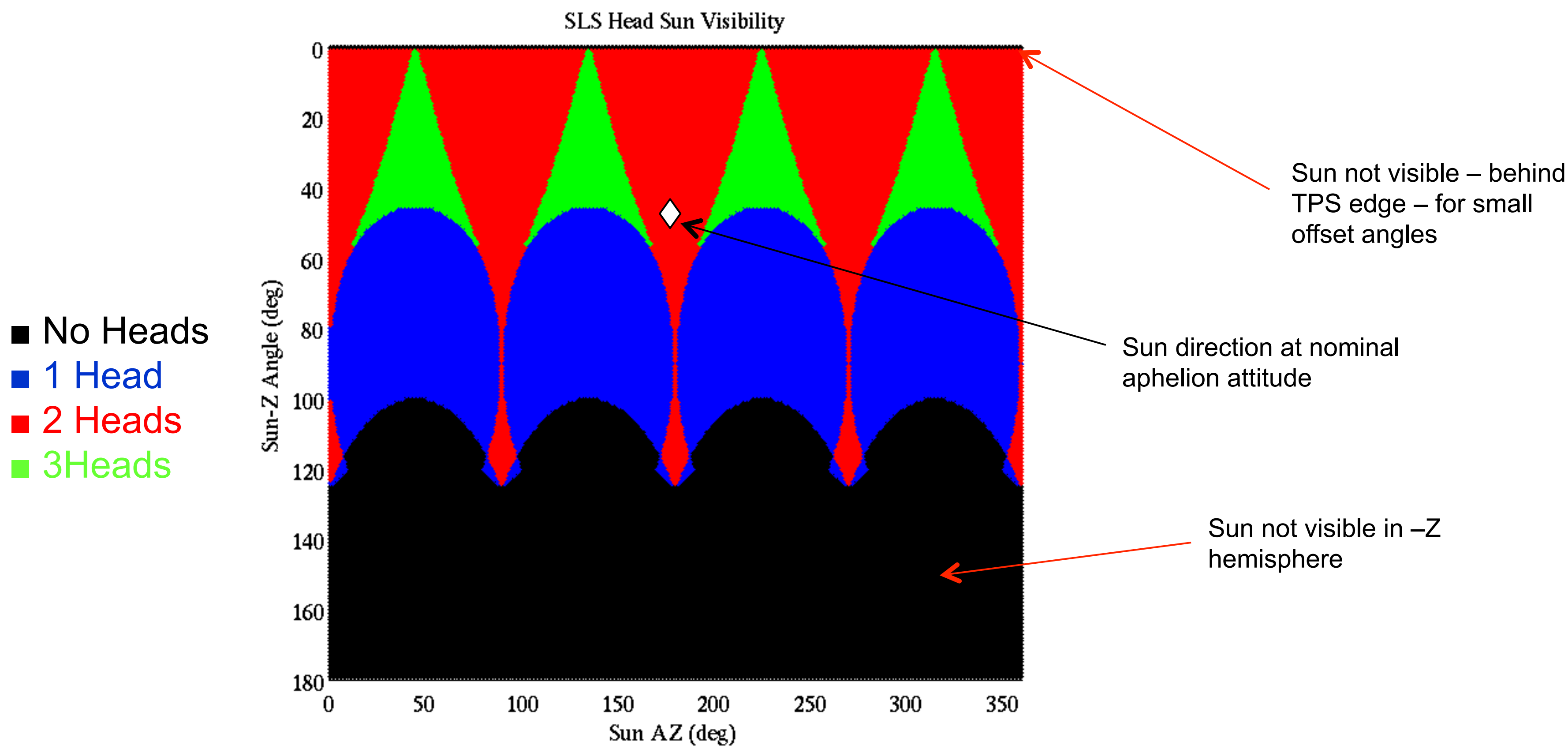
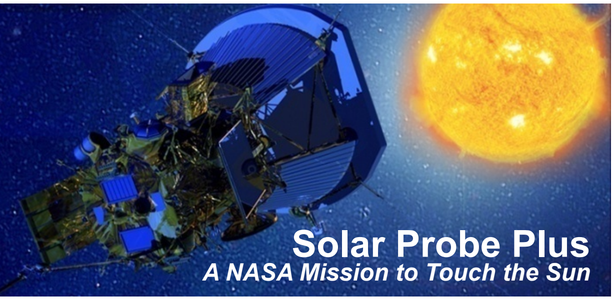


Ignores blockage from spacecraft components

Solar Limb Sensor Faults External/Environmental Sources



- Hardware damage from external/environmental source – sensor heads
  - Dust impacts: probability of no failure is 98.4% for all 4 sensor heads
    - See backup slides for more information
  - Blockage or obscuration of field-of-view
    - Single reticle glass over both sets of solar cell detectors is a single-point failure
    - Glass failure or damage can cause incorrect indication of Sun presence or direction from SLS head
  - Stray light entering field-of-view (leading to false Sun detection)
    - APL will perform stray light analysis
  - Exposure to high intensity solar illumination, radiation, and temperatures at perihelia
    - Adcole thermal analyses and testing of prototype head will demonstrate survival and proper operation of heads at expected flight conditions

- Hardware damage from external/environmental sources – electronics
  - Electronics box mounted inside spacecraft bus
  - No unique conditions compared to other spacecraft electronics boxes
  - Will be designed and tested per SPP standards and requirements

Solar Limb Sensor Faults
Internal Sources – SLS Hardware, S/C Avionics, S/C Flight Software

- SLS hardware failures
  - Adcole will provide standard FMEA and worst-case analysis for prototype system and for flight system
    - Covers materials and parts failures, edges of envelope in required environmental conditions (e.g. radiation exposure)
  - Adcole analyses and performance testing of flight units will demonstrate proper operation over expected flight conditions
- S/C avionics errors in communication with SLS
  - Redundant system, both sides powered at all times
    - One side will provide SLS data to G&C system if other side fails
- Errors in SLS data processing algorithms or parameters
  - Mitigations same as those presented in previous slides for other G&C hardware components
  - Software testing, ground procedures and processes, processor memory scrubbing
- G&C software will attempt to reject “bad” solar limb sensor data
  - Inconsistent readings from each side of one head
  - Sun presence indications inconsistent with known head placement
- Criteria for SLS data checking are TBD, but will act on any valid indication of Sun presence since SLS is “last ditch” means to maintain Sun-safe attitude

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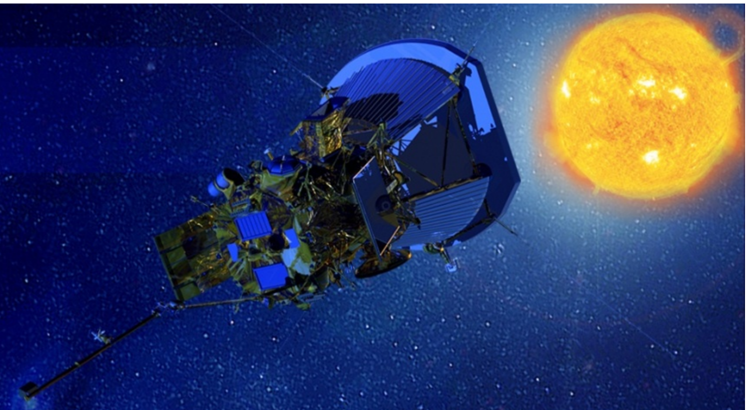

Simulations for Umbra Violation Scenarios

Overview of Simulations for Umbra Violation Scenarios

- Effort to date has focused on:
  - Developing preliminary control algorithms using SLS measurements
  - Assessing effect of breaking the control loop (for processor reset/switch or avionics side switch)
    - Determining time with no control before umbra violation occurs
    - Determining how quickly control must be restored to prevent umbra violation
  - Scenarios used previous trajectory with minimum perihelia distance of 9.5 Rs
    - Conservative compared to new trajectory with minimum perihelia distance at 9.86 Rs

- Simulations span dynamic initial conditions when control loop is broken:
  - System momentum and angular rates
  - Sun line offset from +Z axis

Initial Conditions for G&C Simulations Momentum and Angular Rates

- Spacecraft initial momentum and angular rates when control loop broken:
  - *"Benign" slow drift or rapid attitude drift*
    - Slow drift characterized by low angular rate, holding a slowly varying attitude
      - Accumulating gyro errors after prolonged star tracker outage
      - Sufficiently large MET or TDT time errors that accumulate slowly (not discontinuous large jumps)
      - Incorrect ephemeris models that have slowly accumulating attitude drift
    - Rapid drift characterized by high angular rate, attitude changing unexpectedly
      - Discontinuities in MET or TDT time conversion
      - Discontinuities in ephemeris models (crossing spans, corruption of span memory contents)
        - Rates of 0.01 to 0.3°/s are typical for spacecraft turns using wheels; rate required to track nominal perihelion attitude is 0.0017°/s (at 9.5 Rs)
      - Thruster failure, wheel failure – unintentional self-imposed large torques
  - *Low or high momentum*
      - High momentum in wheels (accumulated by resisting environmental disturbance torques)
        - Just before autonomous dump limit is reached with slowly changing attitude
      - Low momentum in wheels
        - Between momentum dumps with slowly changing attitude
      - High momentum from spacecraft body rates included under rapid drift cases above

Initial Conditions for G&C Simulations
Spacecraft Attitude - Sun Offset Angle

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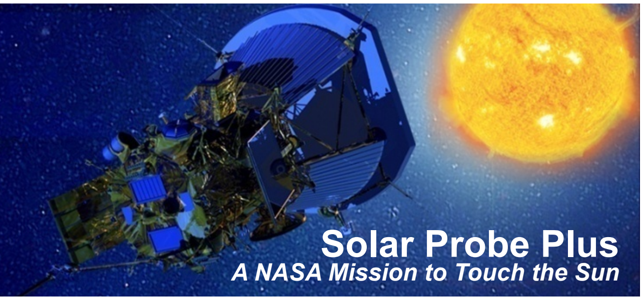
- Spacecraft starting attitude relative to nominal perihelion attitude when control loop broken:
  - *Holding nominal attitude*
    - Sun essentially aligned with +Z axis
      - G&C system performing nominally

  - *Offset at points of first detection of Sun presence by SLS head(s) for all azimuth angles in XY plane*
      - Attitude offset not yet detected by solar limb sensors
      - G&C system not performing nominally, but unaware of problems

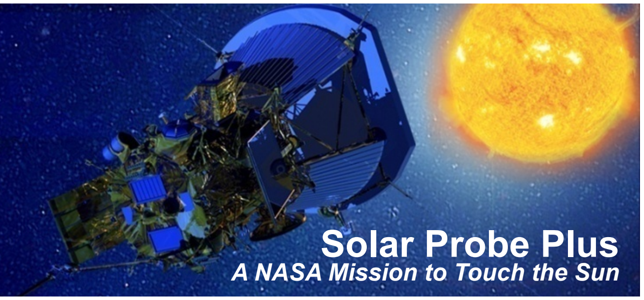
Time to Umbra Violation after G&C Control Loop Broken Starting with +Z Pointing at Sun



Initial Attitude	Initial Momentum	Other Variations	Time to Umbra Violation (s)
+Z to Sun (nominal)	Low (wheels & body, ~0.5 Nms)		30 – 800+
	Auto dump threshold (~2.5 Nms)	Fixed (default) wheel friction Varying wheel friction	35 - 40 30 - 50

- In low momentum case, solar torque dominates; cases with higher Cp-Cg offset reach umbra violation sooner
- In high momentum cases, wheel spin down dominates; cases with momentum aligned with wheel null space and higher wheel viscous friction take longer to reach umbra violation

Time to Umbra Violation after G&C Control Loop Broken Sun at First Detection Limit for SLS



Initial Attitude	Initial Momentum	Time to Umbra Violation (s)
Sun Offset at Sun Presence Limit for SLS Head(s)	Low (wheels & body, ~0.5 Nms)	29.4 - 750+
	Auto dump threshold (~2.5 Nms)	15 - 27
	High body rates (0 - 0.3°/s)	< 5 for angular rates > 0.1-0.14°/s 5 – 50 for angular rates between 0.01 and 0.1°/s 50 – 300+ for rates < 0.01°/s

- Similar conclusions as for nominal attitude case, except that time to umbra violation is shorter when starting offset angle is larger (offset at limit where Sun is first visible to SLS around +Z axis)

Recovery after Umbra Violation

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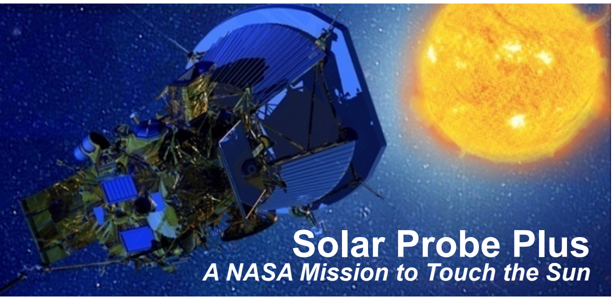
- First set of simulations showed that time to umbra violation after control loop broken is always greater than time budgeted to restore control loop
  - Timing budget for critical fault responses <5 s
  - Umbra violation occurs > 5 s after control loop broken except for cases with high initial angular rates

- Second set of simulations performed with control loop restored 5 seconds after it was broken
  - Determine criteria that separate cases where no umbra violation occurs from cases that still violate umbra despite restoration of control loop

Recovery or Umbra Violation if G&C Control Loop Restored Sun at First Detection Limit for SLS



Initial Attitude	Initial Momentum	% of Cases Leading to Umbra Violation	Reason/Criteria for Umbra Violation
Sun Offset to Sun Presence Limit for SLS Head(s)	Auto dump threshold (~2.5 Nms)	0	Control using SLS data successful in keeping Sun offset below umbra violation threshold in all cases Max Sun offset after control loop restored 1.5 - 1.76° (offset where SLS can determine angle by differential intensity values – giving angle readings instead of just Sun presence)
	High body rates (0 -0.19°/s)	65%	Umbra violation occurs if angular rate > 0.06°/s when control loop restored; Sun offset up to umbra violation limit in other cases.

- Emphasizes need to prevent unplanned s/c attitude changes or actuator failures that can lead to angular rates > 0.06°/s
- Also points out need for further work on SLS control algorithms to try to reduce Sun offset angle past boundary where SLS head is still sensing the Sun

Future Work

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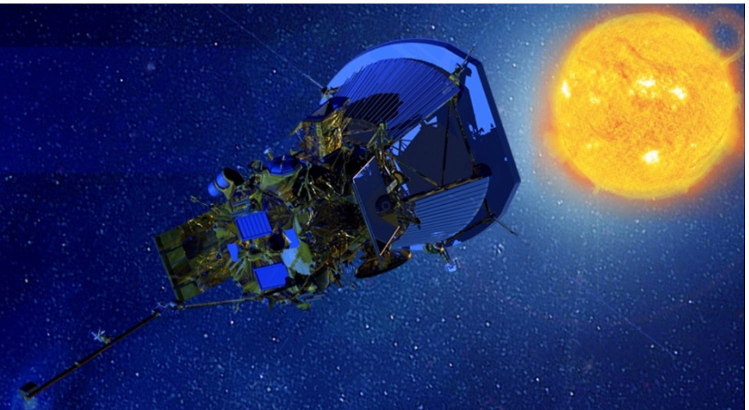
- Continue fault scenario simulations to determine value for “orange warning” Sun offset angle when at TPS-to -Sun attitude

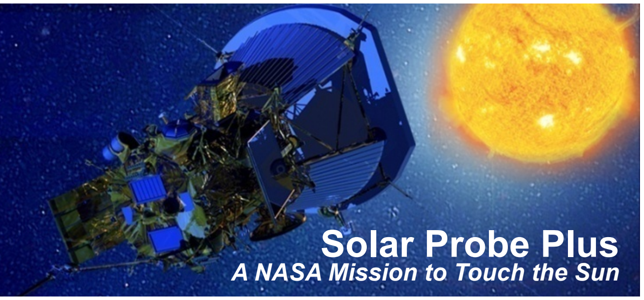
- Refine control algorithms using SLS data
    - Ensure that attitude is corrected to point where no SLS heads are detecting Sun presence (if possible)
    - Investigate switching to thrusters at higher angular rates

- Detailed implementation of G&C hardware and algorithm operational checks
    - Customize fault list and responses for selected flight hardware
    - Perform simulations for hardware fault scenarios



Back up Material

G&C Modes



G&C Mode & Activities	Sensors	Actuators
Full 3-Axis Attitude & Rate		
All normal mission activities		
Change or maintain attitude	star trackers, gyros	reaction wheels
Momentum Dump	star trackers, gyros	thrusters
TCM (+ Momentum Dump)	(star trackers), gyros, accels	thrusters
Partial Attitude & Full Rate		
Maintain Sun-safe attitude	solar limb sensors, gyros	reaction wheels
Momentum Dump		thrusters
Full Rate Only		
Change or maintain angular rates	gyros	reaction wheels
Momentum Dump		thrusters
Partial Attitude/Rate		
Maintain Sun-safe attitude	solar limb sensors	reaction wheels
Momentum Dump		thrusters
No Control	insufficient	insufficient
Sensors or actuators not available		

Interaction of G&C & FM Modes

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FM Mode →

G&C Mode ↓

Operational Level 3	***Solar Array Safe or Standby***	***Earth Acquisition Safe***
Full 3-Axis Attitude & Rate All normal mission activities (after detumble) Full or degraded performance depending on sensor and actuator status	(no SLS Sun detection)	(Immediate Earth point)
Partial Attitude & Full Rate	(SLS Sun detection)	(Delayed Earth point)
Full Rate Only		
Partial Attitude/Rate		
No Control ***Operational Level 1 or 2***		

APL

G&C Block Diagram

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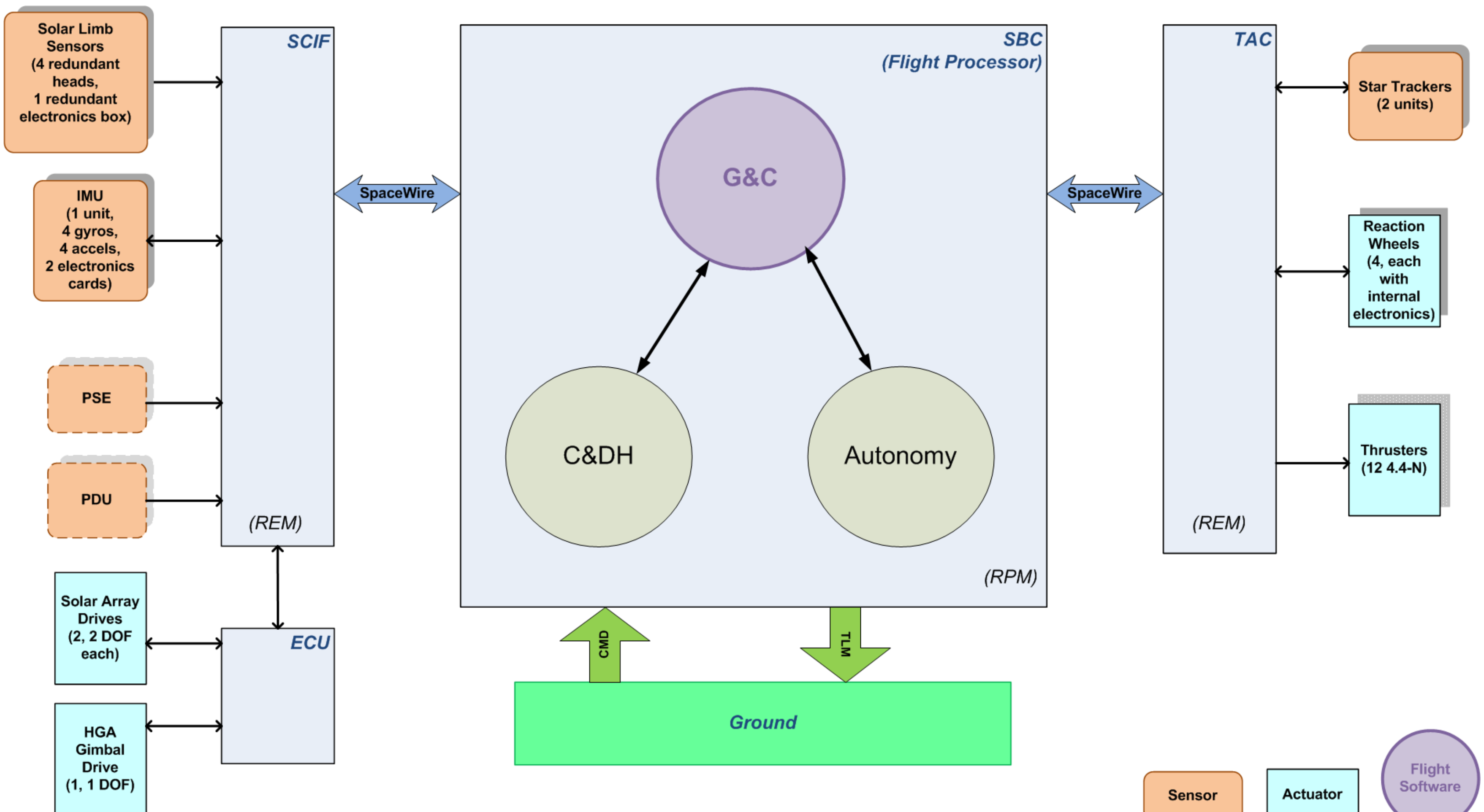

S/C Block Diagram
G&C Components Highlighted

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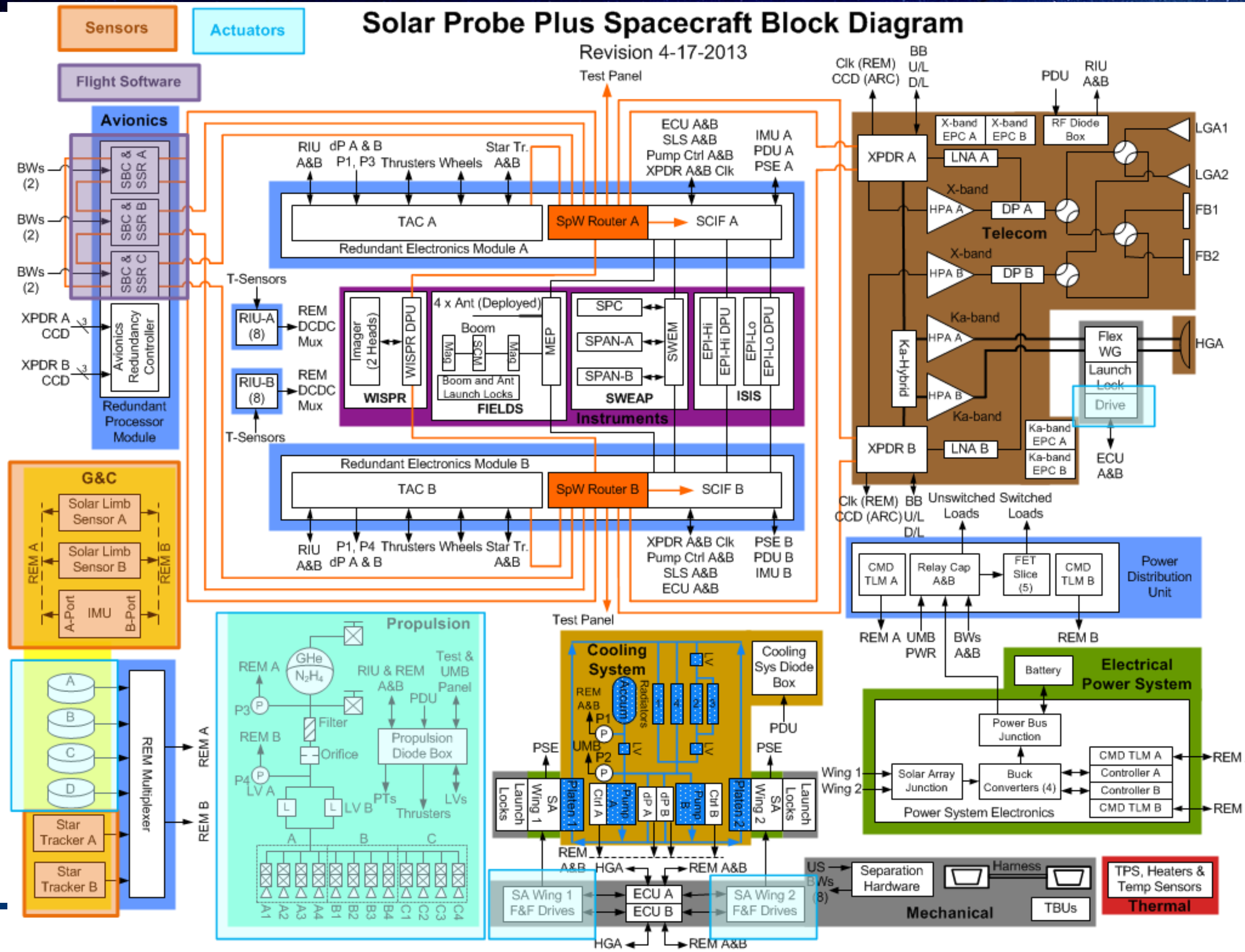
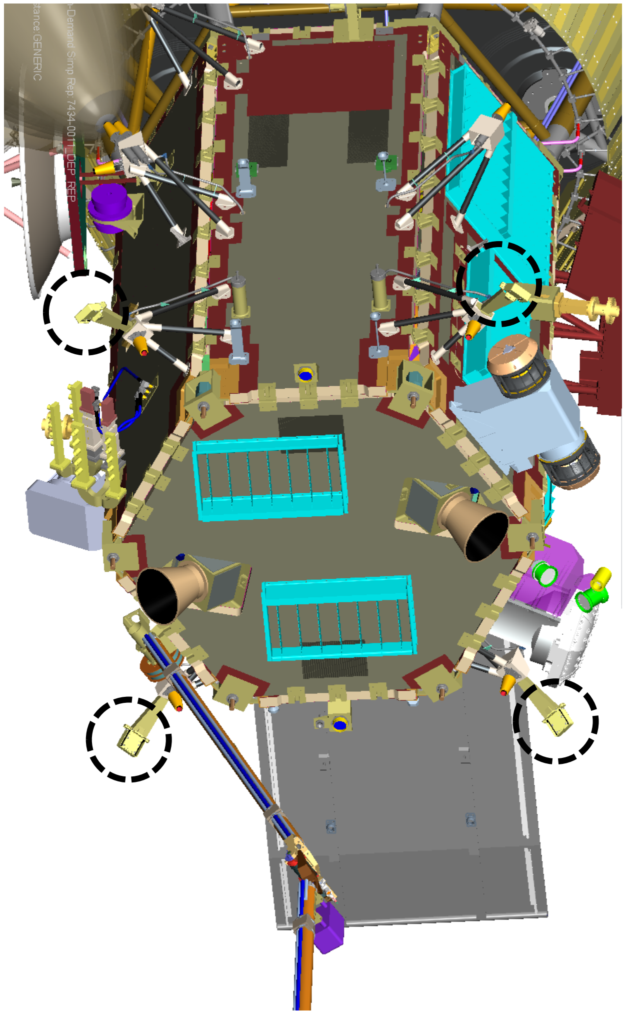
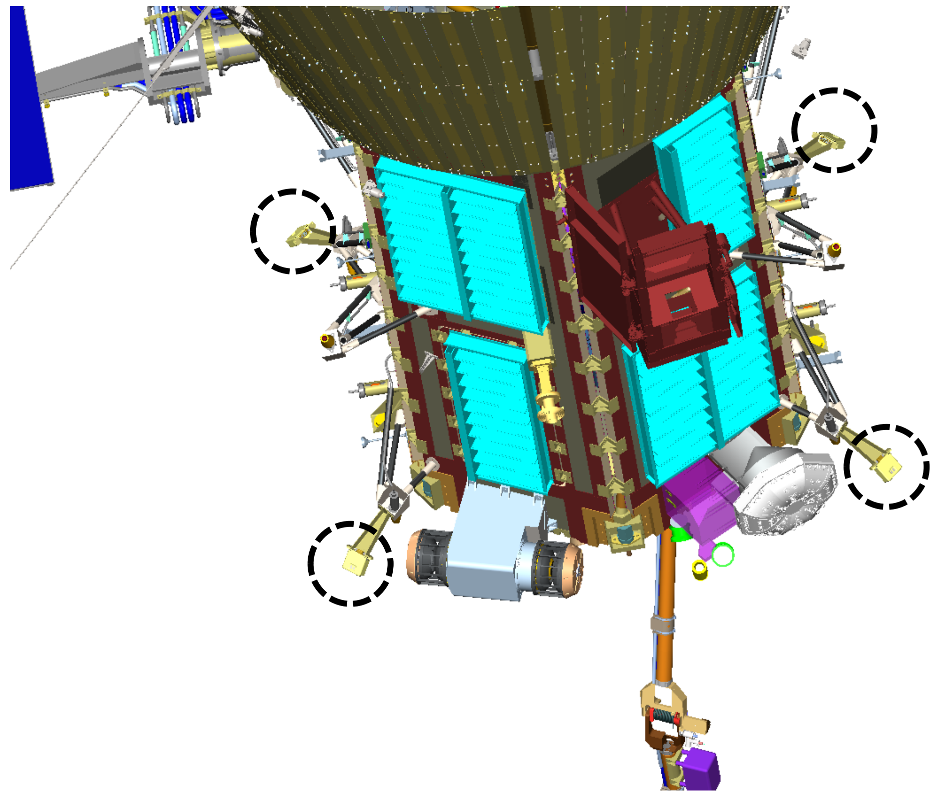
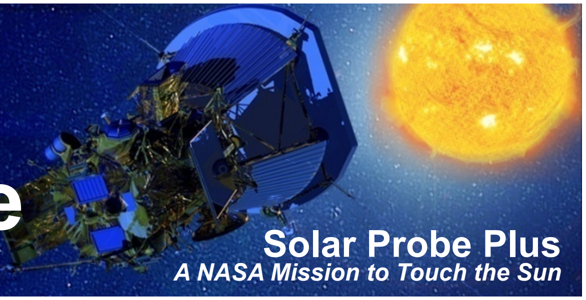


Solar Limb Sensor Placement





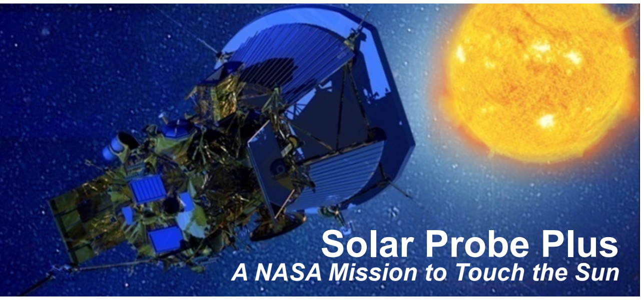
SLS Dust Impacts
Sensor Probability of No Failure



- **The sensor Probability of No Failure (PNF) is found by calculating the probability of each of the external SLS surfaces being hit by a damage particle**
  - The bottom surface is the most vulnerable area
  - Surface damage to the reticle will be in the form of a local pit
  - Failure of one channel assumes penetration of the reticle, cell, and substrate
  - Both channels have to fail to lose the sensor

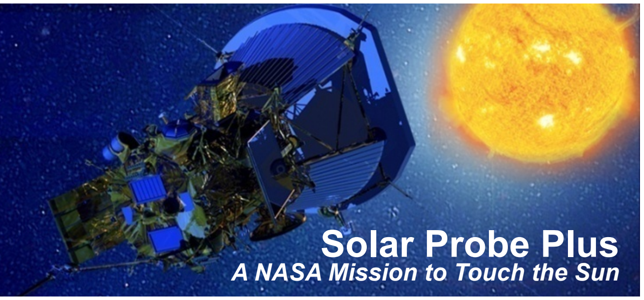
SLS	Component PNF		PNF for all 4 sensors									
	99.6%		98.4%									
	Top area		Cell area		Bottom area		Side		Side		Front side	
	in2	m2	in2	m2	in2	m2	in2	m2	in2	m2	in2	m2
	4.469	2.88E-03	0.062	3.99E-05	4.469	2.88E-03	1.636	1.06E-03	1.636	1.06E-03	1.837	1.19E-03
	PNI	**Top**	**PNI**	**Cell area**	**PNI**	**Bot surf**	**PNI**	**Side - ram**	**PNI**	**Side - anti ran**	**PNI**	**Side - front**
Part dia (µm)	0.999893	315.0	0.999956	131.9	0.996149	128.6	0.999998	538.6	0.99999	538.6	0.99997	325.2
Part vel (km/s)		26.1		26.1		26.2		26.1		26.1		26.1

SLS Dust Impacts Failure Scenarios



- **The solar limb sensors are redundant**
  - Each head has two separate sets of solar cells placed side by side that independently detect the solar illumination
  - Damage to material over the solar cell area would potentially cause stray light or other obscuration that could cause faulty readings
  - Under the windows in the shield, there is a single piece of reticle glass that is common to both sets of detectors
  - If that glass is damaged, it could take out both sides of the head – meaning bad readings or no readings would be generated
  - The two detector sets in each head are connected to separate cards in the electronics box
  - With both sides powered in flight, G&C will get two sets of data from the SLS, which should ideally always be identical
- **The heads themselves are not redundant as a group**
  - The 4 sensors are necessary to provide coverage for all possible Sun offset angle directions
  - Loss of one complete head (both sets of detectors) results in a loss of coverage

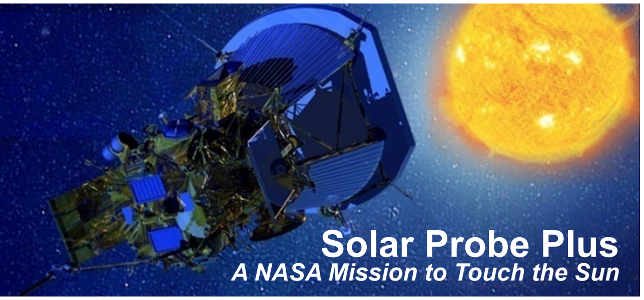
SLS Dust Impact Mitigating Factors



Worst-case and best-estimates:

- **Dust environment**
  - The Collision Model A is being used for the dust environment as a bounding case for the impact damage assessment
  - The best-estimate of the dust environment is probably going to be somewhere between the Collision B and C models
- **Dust particle density**
  - At present the damage scaling with particle density is being done based on kinetic energy scaling
  - The real scaling should be somewhat less
- **Dust particle porosity**
  - At present, the damage modeling is being done using solid particles
  - The most likely estimate of the dust environment is that 50% to 90% of the particles are porous
    - Impacts from porous particles produce lower damage

SLS Dust Impact Shielding Requirements



- **The housing is OK**
  - Even with the use of a worst case dust assumption, the housing survivability is not an issue
- **The solar cell area is OK**
  - Due to the small area and cell redundancy, damage to the aperture does not appear to be an issue
  - Damage to one channel of the sensor assumes penetration through the reticle, cell, and substrate
  - Both channels have to fail to lose the sensor
- **The harness is the next most vulnerable component**
  - Use internal redundancies where possible (parallel connections)
  - Limit the external harness runs
  - Use brackets to shield harness
  - MLI/Kevlar wrap as needed

Parameter Variations for G&C Simulations

- Momentum distribution
  - Magnitude on X & Y axes set to normal distribution with mean value representing low (0) or high (2.5 Nms) momentum limits
  - Direction set by azimuth angle in XY plane (angle from +X axis); varied as uniform distribution between 0 and 360°
  - Magnitude on Z axis set to normal distribution with smaller mean and variation
  - Wheel speeds computed from initial momentum vector
  - Small "bias" speed added to each wheel to represent logic keeping wheels away from zero speed
    - Bias speeds added along "null space" directions so no net contribution to system momentum

- Wheel spin axes directions varied in cones around default axes directions
  - Azimuth angle around cone set to uniform distribution between 0 and 360°
  - Offset angle from default axis (cone centerline) set to normal distribution with 0 mean and 1- σ variation of 1°
  - Each wheel axis varied independently

- Cp of TPS relative to Cg of (dry) s/c set to match direction of momentum build up
  - Magnitude of Cp-Cg offset set to normal distribution with 0 mean and 51 cm (2 in) 3- σ

- S/C bus dry inertia matrix elements varied as normal distribution with default matrix as mean, 10 kg-m^2 1-σ

S/C Coordinate System

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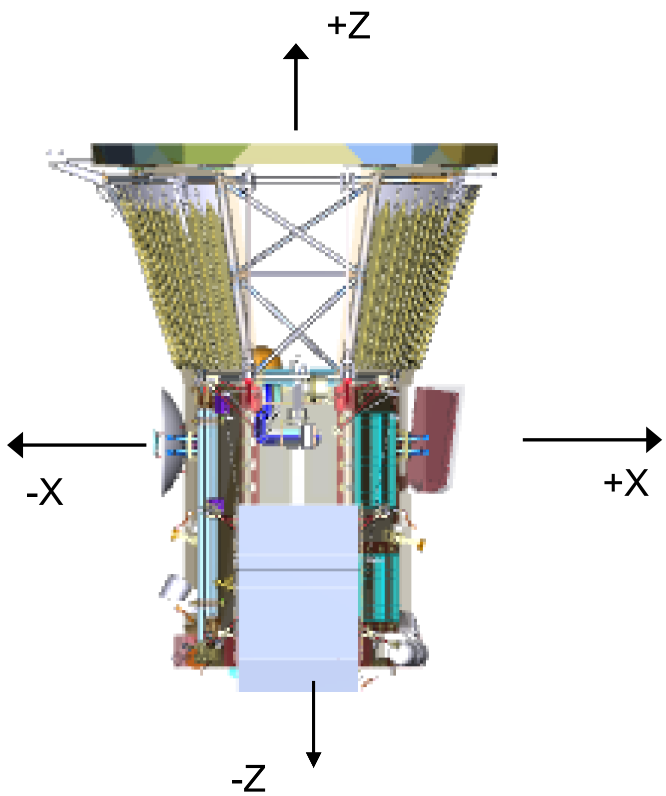

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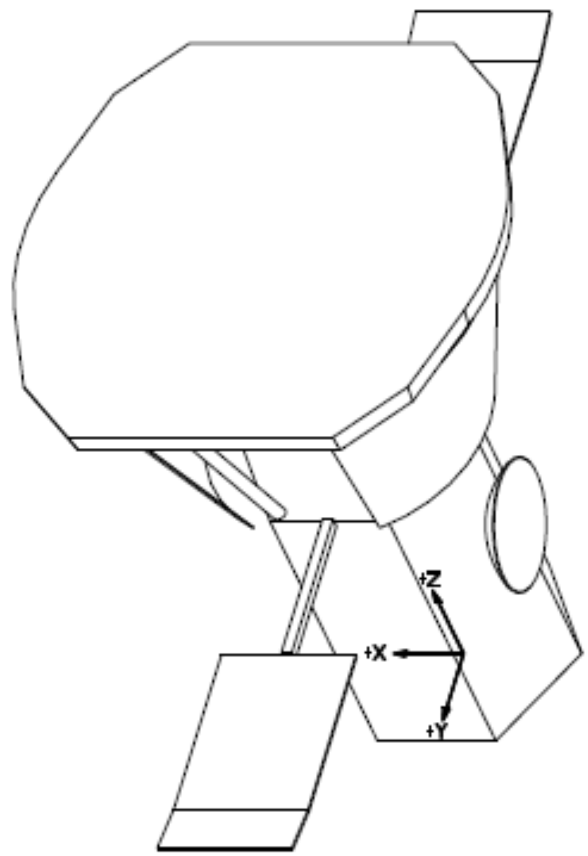

S/C Coordinate System

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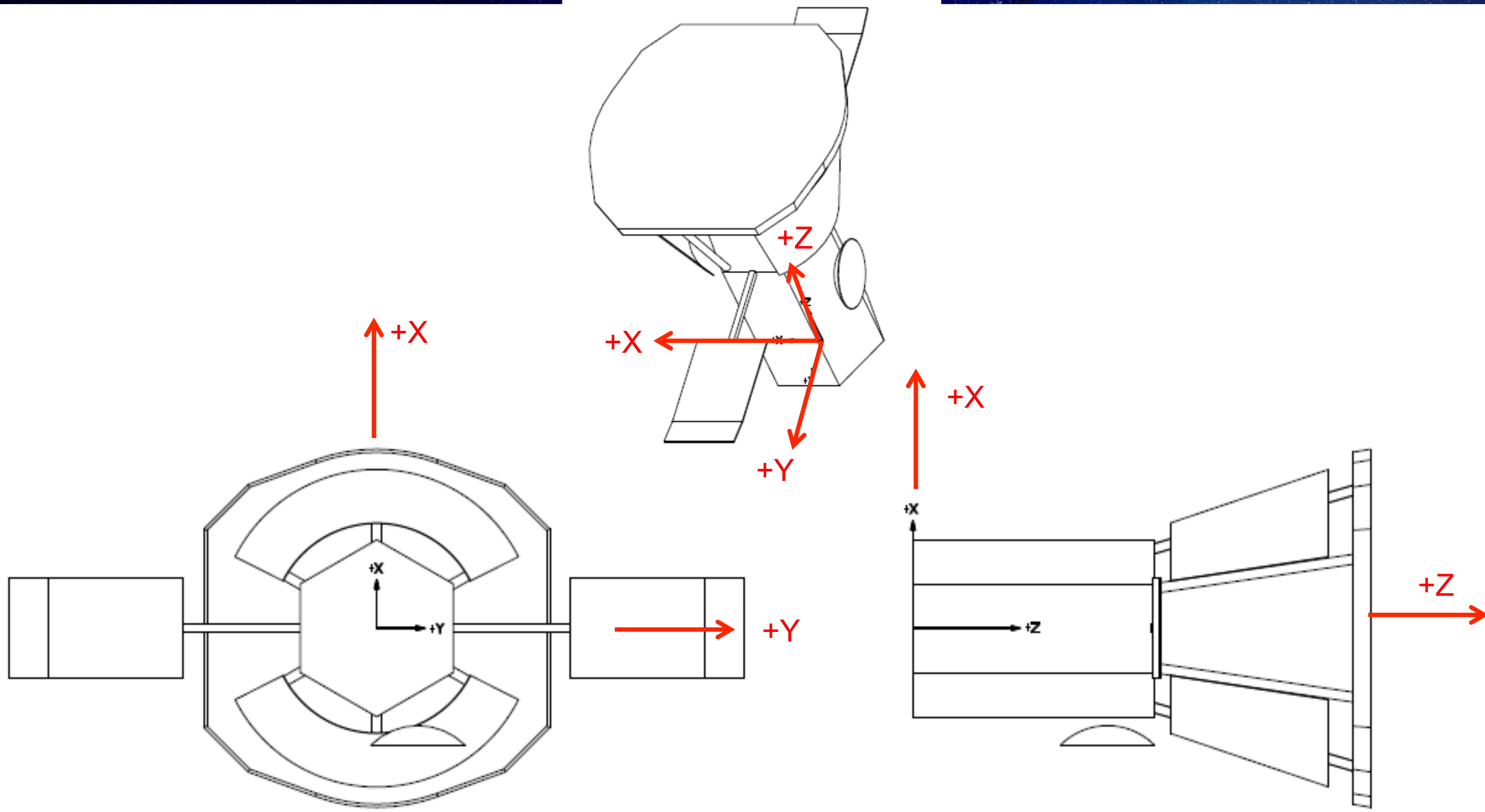
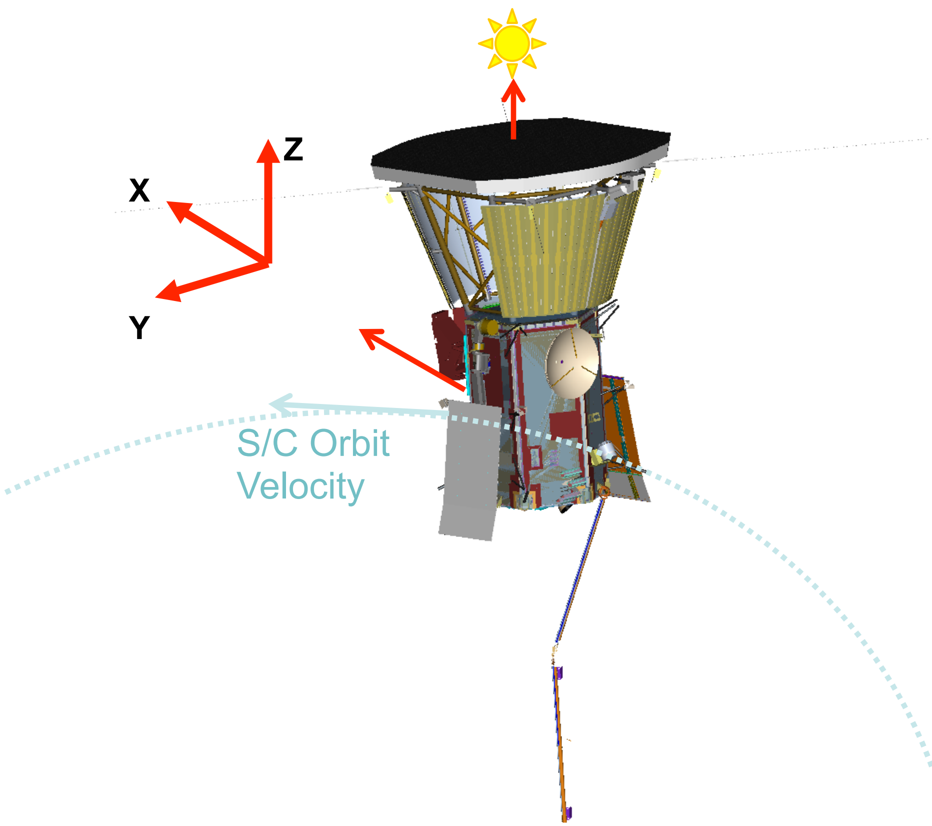
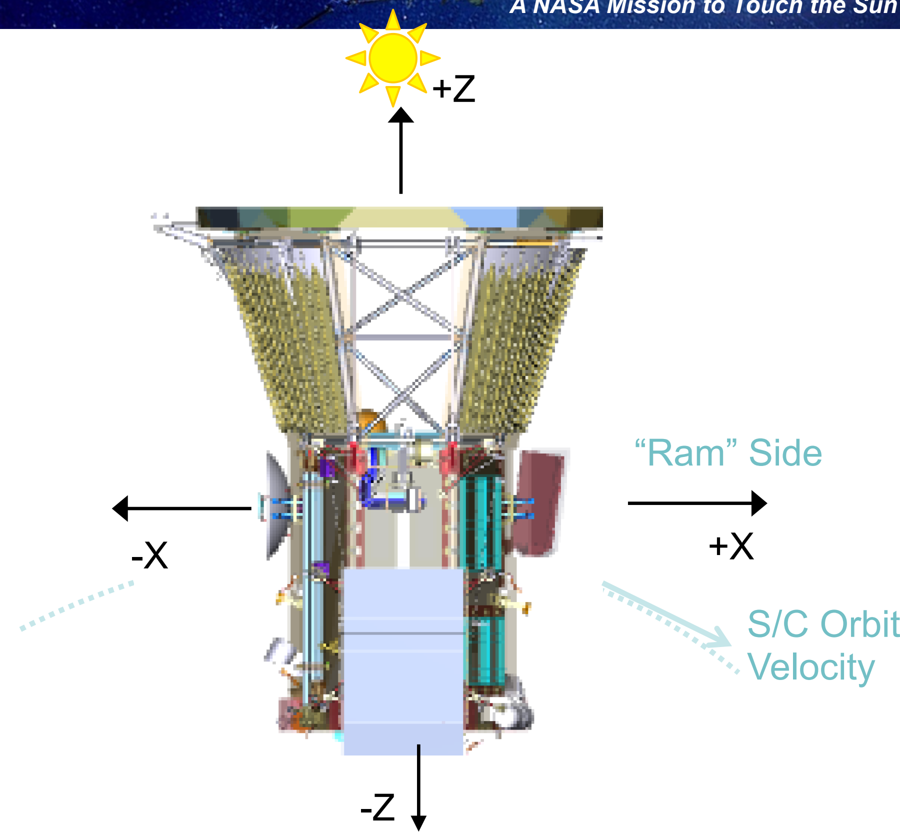


Mission Default Attitude: Perihelion Sun-Ram (TPS to Sun)





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+Z aligned with S/C->Sun direction
+X as close as possible to S/C orbital velocity vector
(velocity vector in +X ,Z half-plane)

Mission Default Attitude: Aphelion
Sun 45° off +Z

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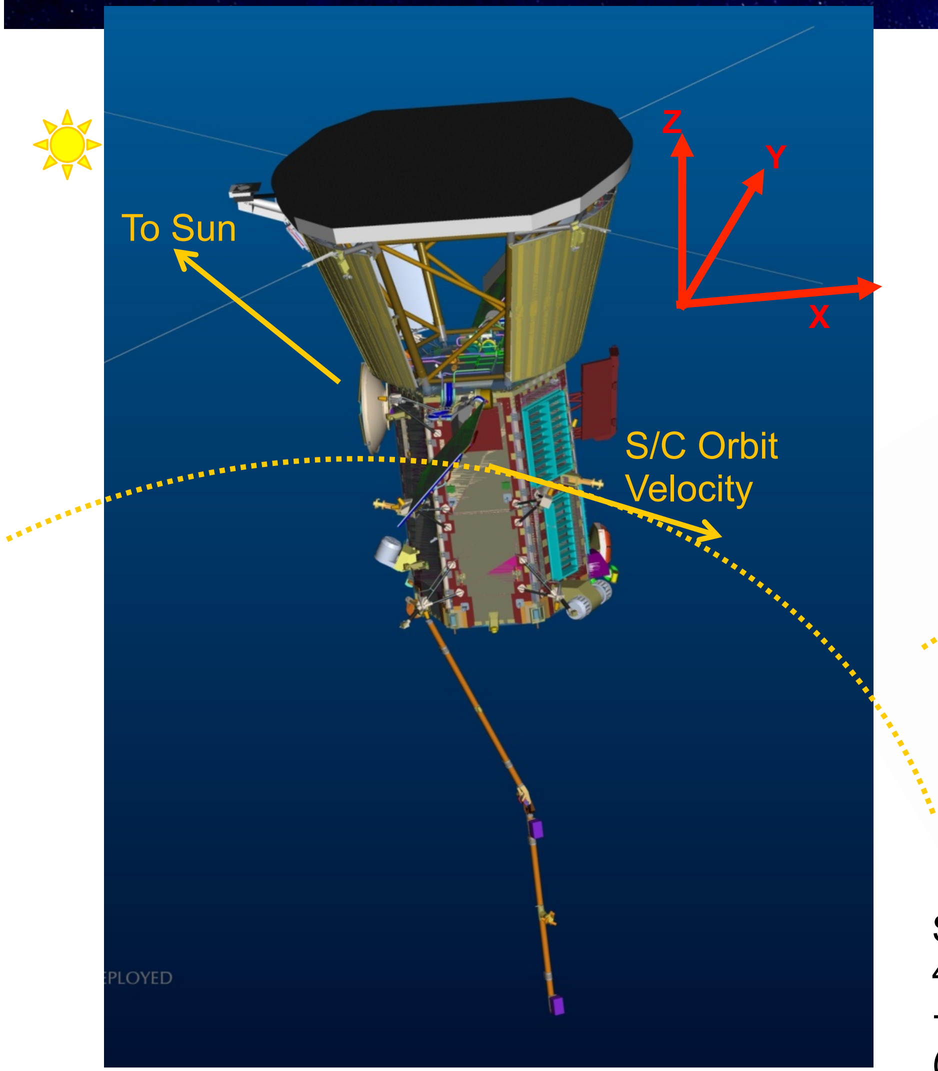

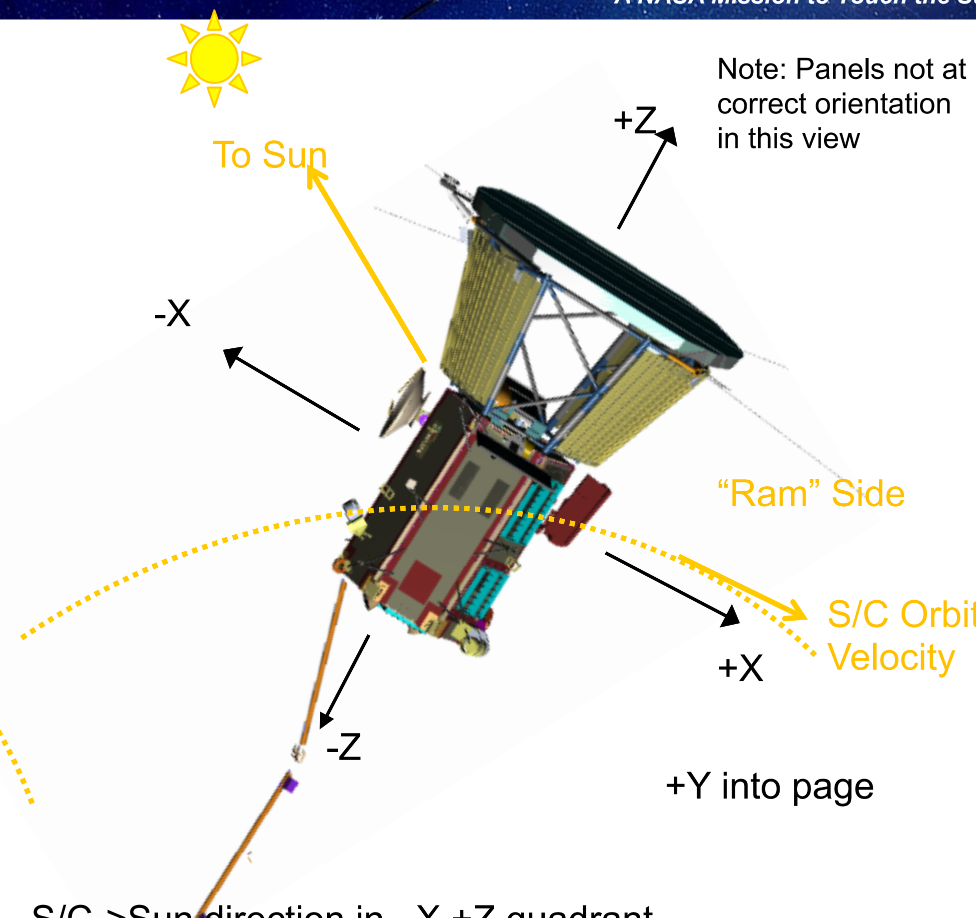

S/C->Sun direction in –X,+Z quadrant,
45 from +Z towards –X axis
+X as close as possible to S/C orbital velocity vector
(velocity vector in +X ,Z half-plane)

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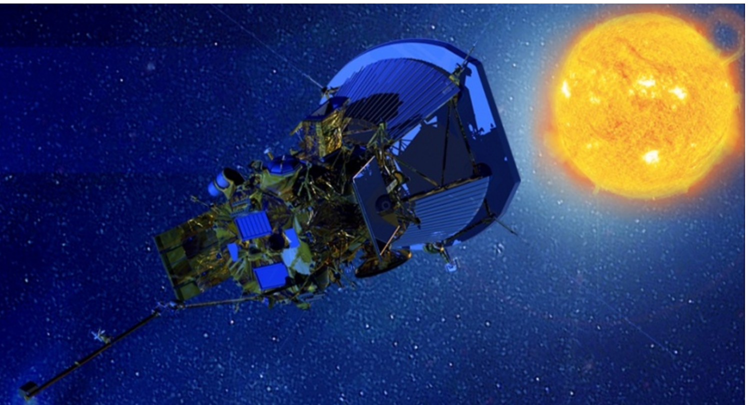

Solar Array Angle Control Overview

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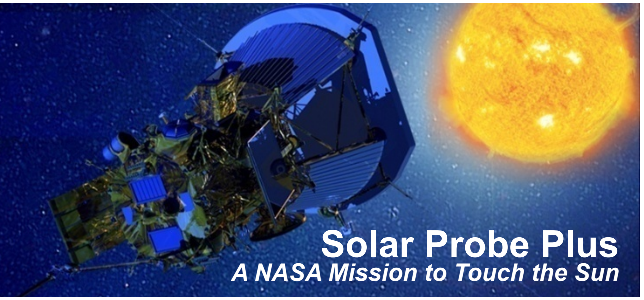
APPLIED PHYSICS LABORATORY

Solar Array Angle Control



- **Solar array (S/A) thermal management:**
  - Water pumped through solar panels (substrates) to radiators
  - Solar array tilted away from sun (cosine and Fresnel reflection)
  - Partial shading behind sunshield (TPS) defined by “flap” angle
    - **Operation in umbra, penumbra and full sun**
- **Purpose: Control solar array “flap” angle during flight**
- **High level requirements:**
  - Provide sufficient power to spacecraft (S/C) loads
  - Do not exceed thermal capability of S/A or cooling system
- **Goals:**
  - Optimize S/A temperature (minimize degradation)
  - Minimize S/A drive motion (power and mechanical wear)
  - Minimize battery cycling (minimize degradation)

Autonomous Close-loop Control

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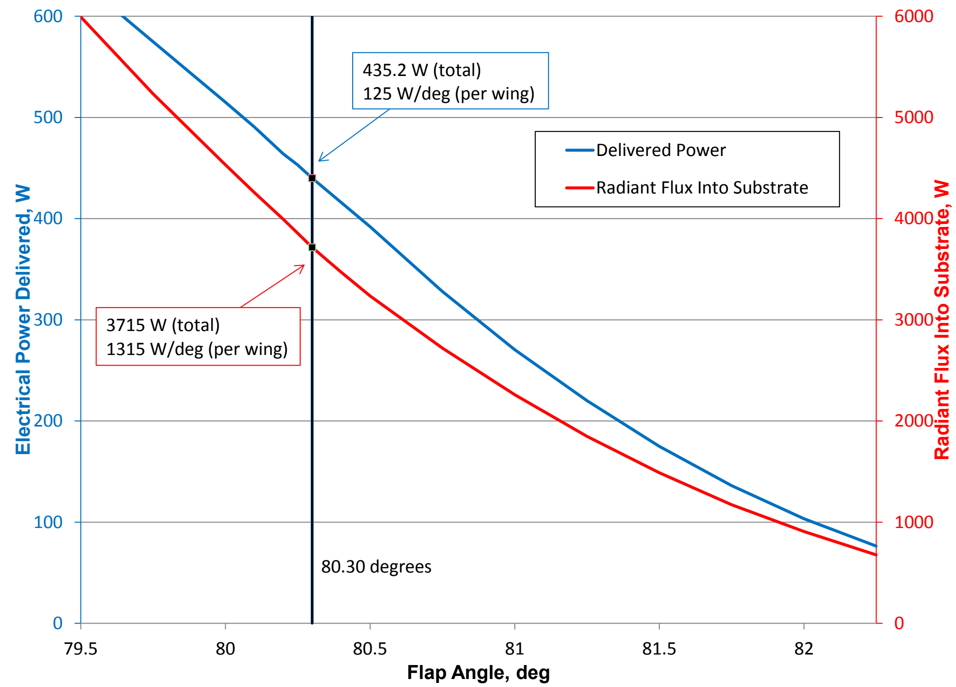
- **Need for an autonomous control**
  - S/A power and temperature very sensitive to angle
  - S/C pointing variations
  - Environmental disturbances
  - S/A wing oscillation and settling
  - S/A power versus angle changes with Sun distance
  - S/A degradation rate uncertainties
  - TPS to wing alignment variations



- **Power Control**
  - Minimize irradiance and temperature on S/A to meet S/C power demands
- **Temperature Control**
  - Achieve a minimum water temperature to prevent freezing
- **The flap angles are independently controlled to equalize power on each wing**

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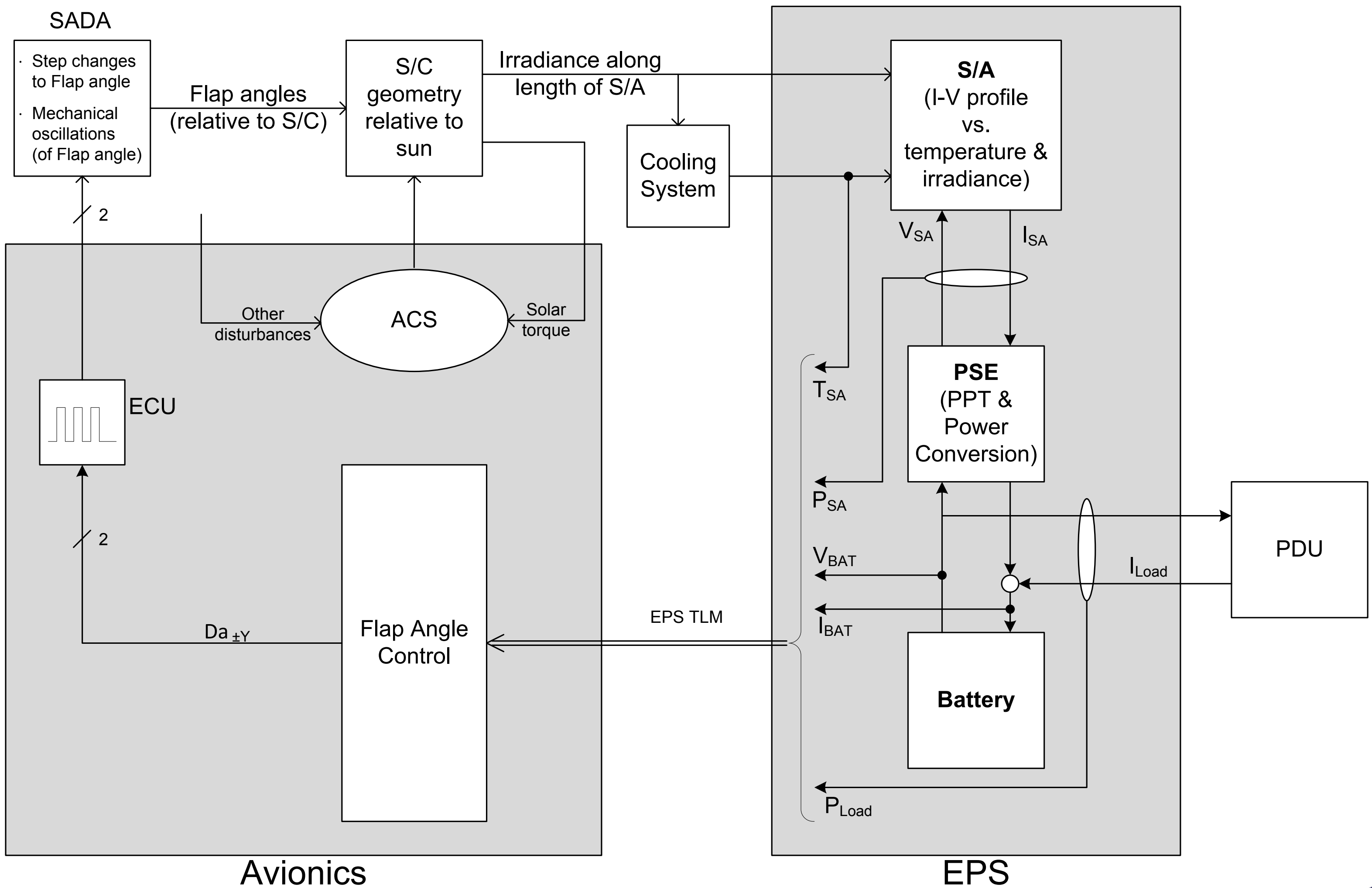
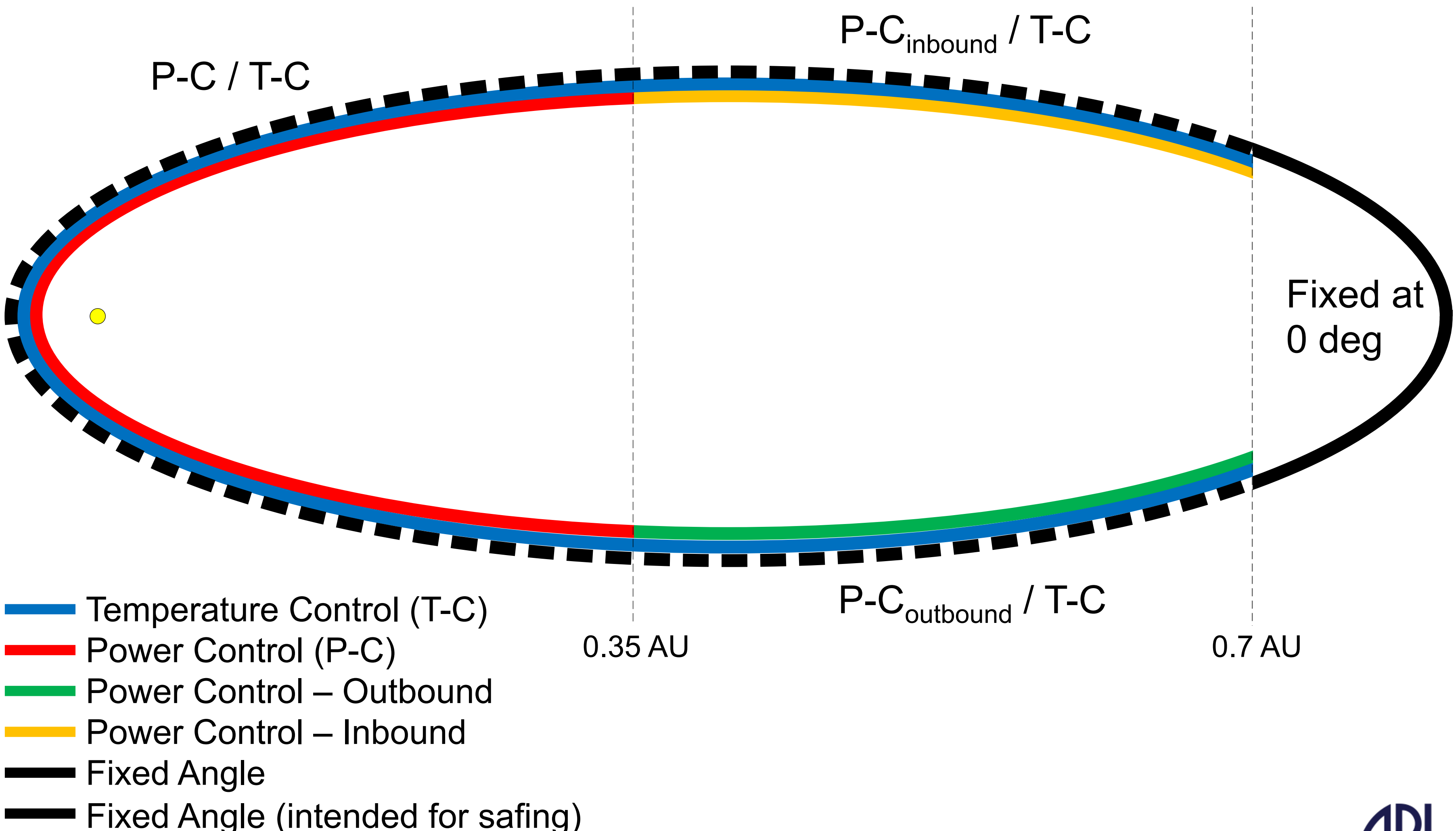
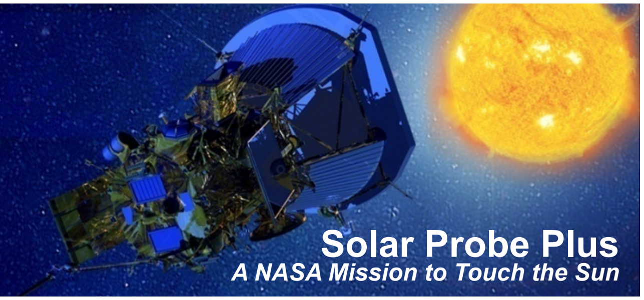
Solar Array Angle Control Block Diagram



S/A Flap Angle Control Modes



Power Control: Inside 0.35 AU

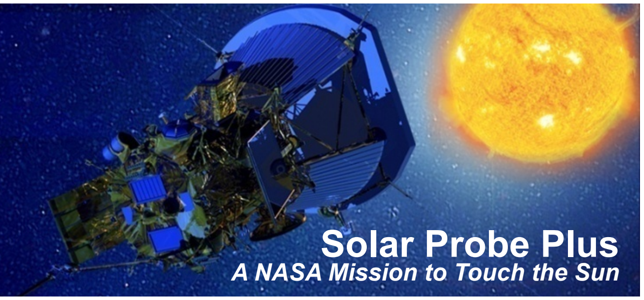


- **Minimum irradiance on wings to achieve S/C power demands**
- **Minimize S/A thermal stress, S/A degradation and cooling system loading**
- **Operation**
  - Adjust a solar array power set-point to maintain battery state-of-charge
    - **Allow battery to serve as a buffer to supply or absorb excess power**
    - **5 minute update rate**
  - Adjust flap angle to achieve the set power from the wings
    - **Wing does not react to short-term changes in S/C load or pointing**
    - **1 minute update rate**
  - Continually peak power track to correlate irradiance to power produced

Power Control: 0.35 – 0.75 AU

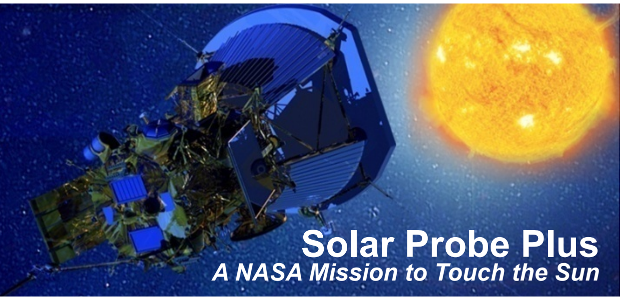
- **Monotonically extend/tuck wings as needed**
  - Minimize S/A drive movements
- **Eliminates need for a priori knowledge of power and thermal margins**
- **Operation**
  - Outbound
    - **Extend wings as needed to compensate increased solar distance**
  - Inbound
    - **Periodically tuck wings to compensate for decreased solar distance**
  - Not peak power tracking
- **Temperature, irradiance and power are minimally affected by S/C slews within the packaging umbra**
- **Load changes will have minimal affect to the monotonic changes of the flap angle**

Temperature Control



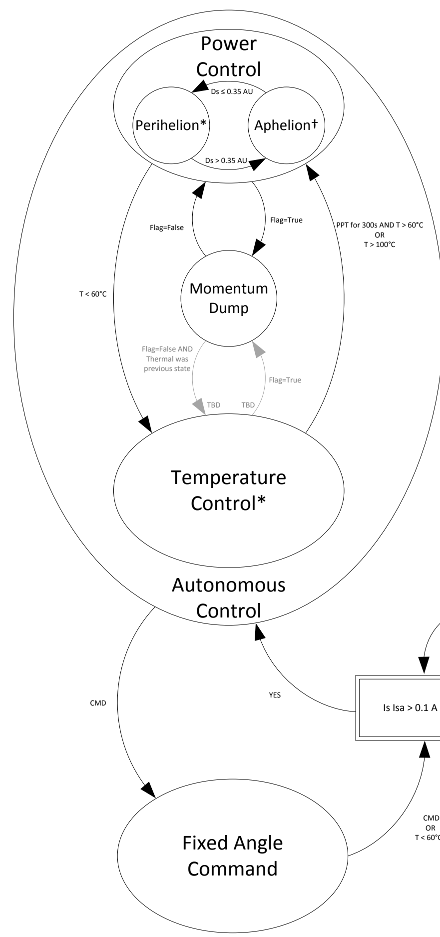
- **Control water temperature to a fixed value, e.g. 65°C**
  - Margin from freezing and over temperature
  - Temperature sensors on S/A platen at outboard edge (water inlet)
- **Compensate for thermal lag**
  - Slower control possible at moderate temperatures
  - Allow the temperature to vary (e.g. +/-5°C)
  - Flap angle does not dither to tightly regulate temperature
- **Operate over a wide range of operating conditions**
  - Thermal parameters, Solar distance, S/C loads, S/A degradation, etc.
- **PSE will not PPT rather draw whatever power from wings as needed by S/C**
  - Flap angle independent of S/C load (and battery) state
- **Operates throughout orbit**

S/A Flap Angle Control Mode Transitions



- **Power vs Temperature Control Transitions**
  - If T_{water} is below 60°C go to T-C
  - If in T-C and T_{water} is above 60°C and PSE is PPT for 300s go to P-C
  - If T_{water} goes above 100°C go to P-C
- **Transition conditions**
  - BOL for S/A will likely be in temperature control
  - If the S/A degrades between 20-45% power control will likely take over
    - i.e. when the S/A produces the required output power at these degradations T_{water} will exceed 60°C
    - The wide range is due to variations in solar distance and efficiency of cooling system
  - If the average S/A loading is less than the requirement the temp. control stays active longer
    - i.e. need higher amount of degradation to transition

Solar Array Flap Angle Control State Transition

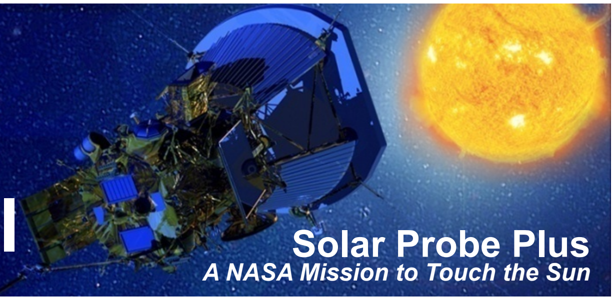


Momentum Dump mode:
*May not be needed for temperature control mode
*It should not need to know previous state

SLS control mode:
TBD

*Battery voltage limit set to reduced value (i.e. voltage below 4.1 V/cell but at or above 65% SoC voltage)
†Battery voltage limit potentially set to a value above 4.1 V per cell

Modeling Capabilities
Integrated G&C/EPS/Thermal Model

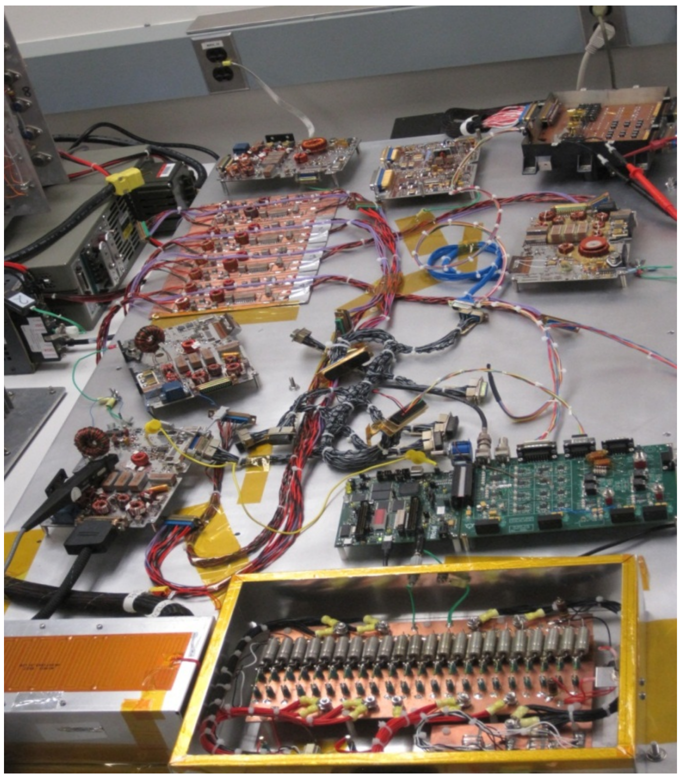


Model Portion	Description	Input Parameters	Outputs
G&C model	Models spacecraft dynamics, Includes closed-loop actuator control	Orbit Spacecraft geometry Mass properties Sensor parameters (noise, gain) Actuator parameters Disturbances	Spacecraft position Spacecraft attitude Spacecraft rates
EPS model	Models irradiance on solar array, Solar array and battery performance, Power conversion model, Includes PPT algorithm	Spacecraft load Solar array string out Solar array degradation Battery parameters Solar array parameters (cell layout, current/voltage characteristics)	Solar array operation, Battery I, V, SoC
Autonomous flap angle control	Models flap angle control modes: power, temperature and fixed angle	Solar array drive rate Solar array drive step-size Control update frequency	Flap angle
Cooling system model	Thermal performance of cooling system, Includes water dynamics	Water cycle time Cooling system parameters Temperature time constants	Water temperature Cell temperature

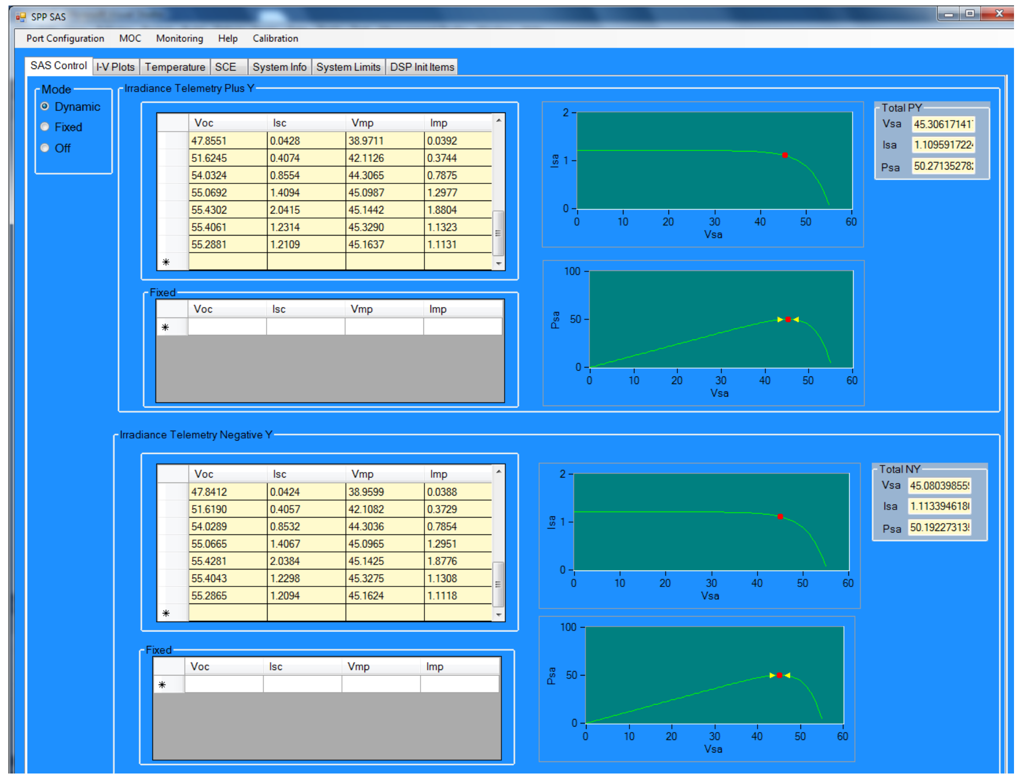
- **All integrated in G&C's Matlab/Simulink model**

Testbed

- **Integrated G&C model with EPS hardware in the loop**
  - EPS hardware includes PSE, S/A simulator and battery

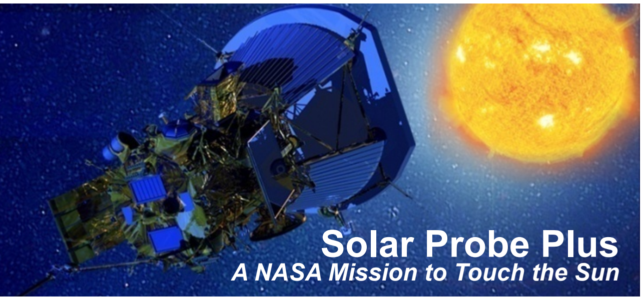


PSE hardware



S/A Simulator User Interface

Future Work



- **Verify thermal parameters of cooling system**
- **Verify control modes and transitions for S/C power load variations**
- **Analyze control laws during anomalous conditions**
  e.g. high S/C rotation rates
- **Ensure quick and stable startup of angle control in all conditions**
- **Optimize parameters and limits**
- **Continue stability analysis**
- **Incorporate entry and exit from safe mode logic in model**
- **Continue to verify control with EPS testbed hardware as models, control and hardware are refined**

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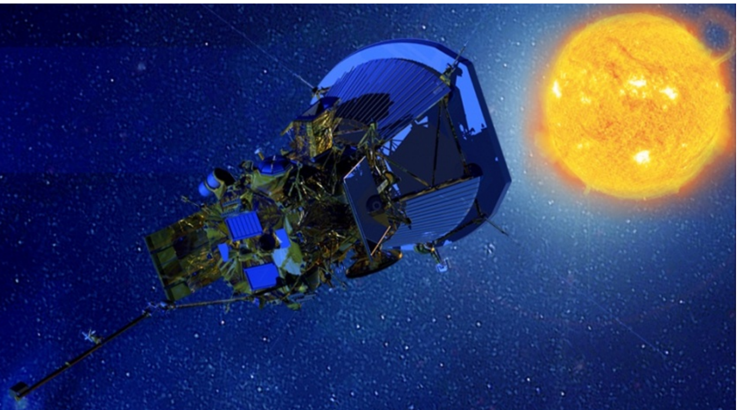

Solar Array Safing

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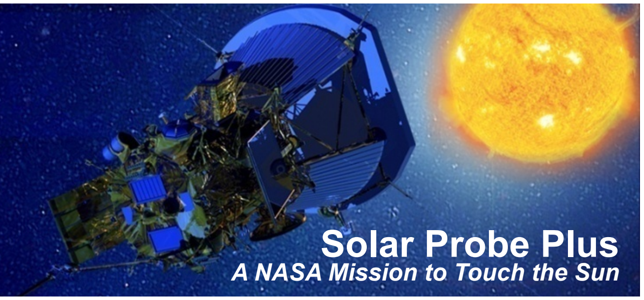
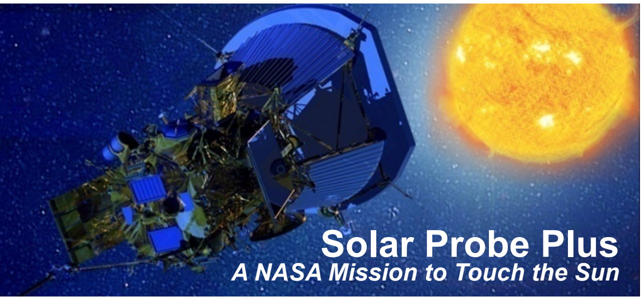
Outline



- Overview
  - Objective
  - Key Questions
  - Safe Mode Recap
  - Key Requirements/Assumptions
  - Solar Array Safing Overview
- System Temperatures
- Solar Array Safing Approach
  - Solar Array Position Sensing
  - Safe Angles
  - Overall Approach for all Critical Faults
  - Solar Array Safing Sensors, Measurements, and Computed Telemetry
- Solar Array Safing Approach (continued)
  - Solar Array/Cooling System Over-Temp
    - Over-Temp Definition
    - Over-Temp Approach
    - Transients by Solar Distance
    - Thermal Analysis
  - Cooling System Low-Temp
    - Low-Temp Definition
    - Low-Temp Approach
  - Exiting Safe Mode
  - Timing Budgets
- TRL-6 Testing
- Future Work
- Backup

Objective



- **Objective: Define operation of solar array in Safe Mode – Solar Array**
  - **Solar array safing occurs in the event of thermal or power critical faults:**
    - **Umbra Violation**
    - **Solar Array/Cooling System Over-Temp**
    - **Cooling System Low-Temp**
    - **Low Battery State of Charge**
    - **Aphelion Thermal Violation**

- **High-level requirements for solar array safing**
  - **Protect from over-temperature of solar array and cooling system**
  - **Protect from freezing of cooling system**
  - **Protect from low battery state of charge**

Key Questions

- **What conditions result in entry into solar array safe mode, how long do they persist, and how are they detected?**
  - **What conditions must solar array and cooling system survive, and for how long?**
- **Upon entry into safe mode, what angle do wings go to, what environment will they see, and how long can they stay there?**
- **When and how does the solar array autonomously return to nominal control?**
- **What analysis and testing is required to show solar array safing approach is feasible?**

Safe Mode Recap

- Nominal autonomous wing angle control is designed to:
  - Correct for over-temp (too much power)
  - Correct for LBSoC (too little power)
  - Correct for low-temp (less than expected solar array degradation)
  - Compensate for spacecraft attitude errors
- In the event of a thermal or power critical fault, system-wide recovery procedure includes processor switch, side-switch/power-cycle (except cooling system pump, SLS, IMU [TBD], star tracker, and new Prime), load shed, solar array safing

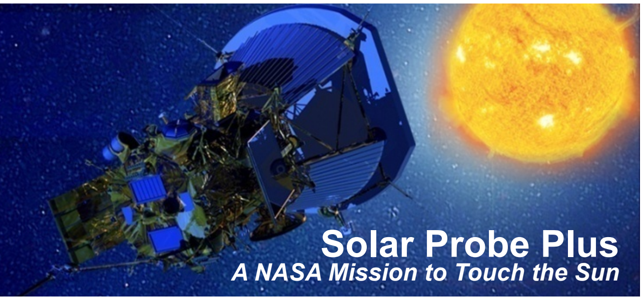
1. Processor switch
   - Allows remaining safing to be commanded from new Prime
2. Side-switch/power-cycle of components required to evaluate current wing position and command wings to safe (PDU, SCIF/TAC, ECU)
   - Allows solar array safing to be commanded from new hardware
3. Wing position evaluated and wings commanded to safe angle
   - Majority vote primary/redundant pots and step-counts
   - Determine desired wing safe position (from MET-based table)
   - Calculate number of steps to move wings
   - Command ECU to drive wings
4. Complete side-switch/power-cycle

Key Requirements/Assumptions

- **Cooling system limits**
  - **Max steady-state capacity: 6,480W**
  - **Min steady-state load to prevent freezing:**
    - **2,350W (yellow limit, 20C steady-state)**
    - **2,050W (red limit, 10C steady-state)**
- **Thermal limits**
  - **Cooling system: 10C – 190C**
  - **Solar array: 240C**
- **T-C control point: 65 +/- 5C**
- **Critical telemetry knowledge:**
  - **Wing angle knowledge:**
    - **0.5 deg (coarse pot only)**
  - **Solar flux knowledge: 6%**
- **Wing flap rotation step-size and rate**
  - **Min step-size: 0.002 deg**
  - **Max rate: 0.5 deg/s**
  - **Max outward rate allowed during nominal operations: 0.1 deg/s**
    - **Exceptions: deploying array after launch, exiting safe mode**
- **Safe mode timing**
  - **Fault detection to power cut to SAD: 5s**
    Fault detection to wings moving to safe: 10s
- **Solar array stow angle: 88 deg**
  - **Safe angle must be shallower than that**
- **Solar array safing angle must accommodate attitude error up to umbra violation**
- **MET is fault tolerant/reliable in fault condition**
- **Solar array safe mode must be entered and exited completely autonomously**

Notes:
-Throughout this presentation, 9.5Rs is defined as a bounding case. New mission architecture perihelion is 9.86Rs. Difference has negligible impact on safe angles, transient conditions, etc.
- 6,480W max capacity corresponds to 9.5Rs, max flux

Solar Array Safing Overview



- Robust set of sensors and computed telemetry used to detect and respond to critical faults
- One solar array safing response for all critical faults, as a function of solar distance and initial temperature
  - Transient safe angle for solar distances < 0.35AU
    - Wings move to a tuck configuration with low heat load into the system
    - Timing budget allows wings to move to safe angle, safing actions to complete, and wings to return to operational before cooling system violates freeze limit
  - Steady-state safe angle for solar distances ≥ 0.35AU
    - Wings move to a configuration with no danger of freezing or over-heating
- Solar array safing approach requires good absolute knowledge of wing angle
- Solar array safing approach requires maintenance and calibration of two tables on-board spacecraft:
  - Safe angles vs. MET
  - Solar Flux ("Suns") thresholds vs. MET

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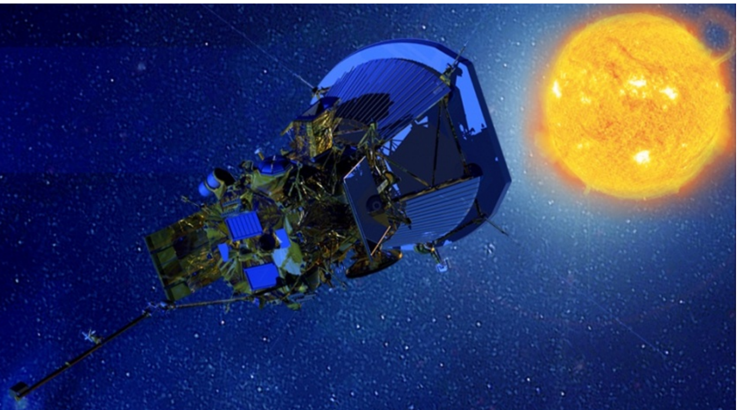

System Temperatures

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System Temperatures

- In order to determine feasible safe angles for solar array safing, identified bounds on system temperatures
  - At what solar distance must wings be normal to Sun in nominal operations?
    - T_{water} < 60C (T-C control point)
  - At what solar distance can wings be normal to Sun in fault condition?
    - T_{water} < 150C (max nominal operating point)
  - At what solar distance must wings be in the penumbra/umbra in fault condition?
    - How long before freeze would occur?

System Temperatures

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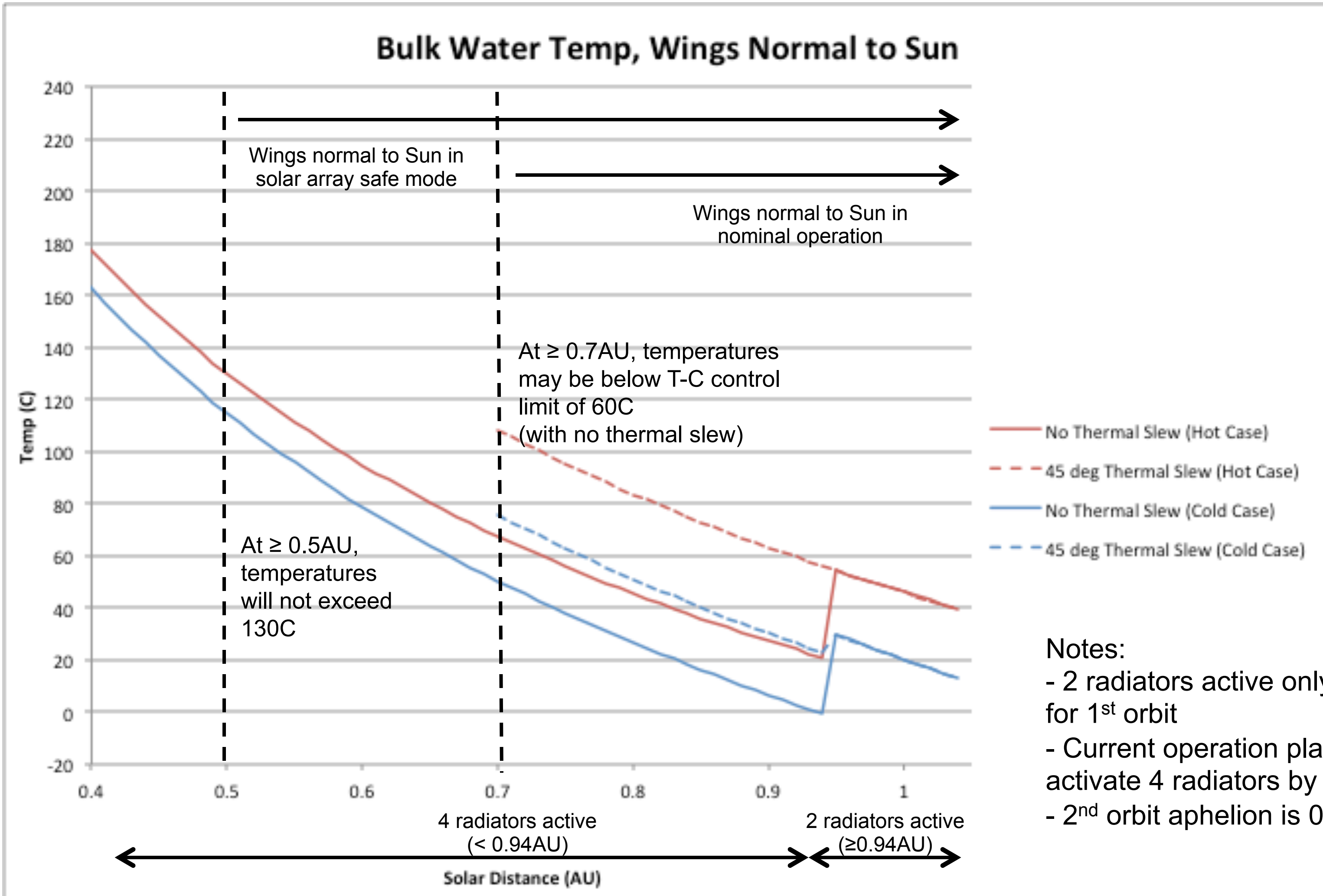

Notes:
- 2 radiators active only relevant for 1st orbit
- Current operation plan is to activate 4 radiators by 0.9AU
- 2nd orbit aphelion is 0.94AU

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System Temperatures

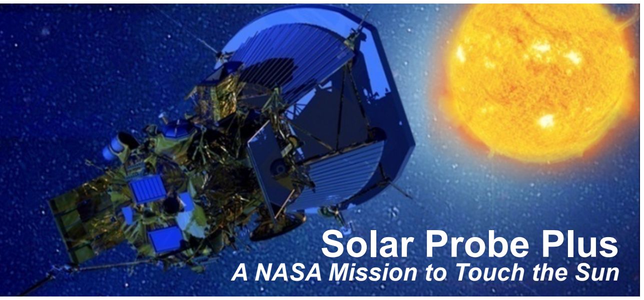
- **At solar distances ≥ 0.7AU, wings will always be normal to Sun in nominal operations**
  - **Water temperatures may drop below T-C control limit of 60C**
- **At solar distances ≥ 0.5AU, wings can be normal to Sun in nominal or fault condition**
  - **Water temperatures will not exceed 130C**
    - **Provides margin on 150C**
- **At solar distances < 0.5AU, off-nominal solar array angle can cause temperatures to quickly and greatly exceed 150C**
- **In fault condition, safest to bring wings into umbra/penumbra**

Freeze Protection

- In order to determine feasibility and time constraints on pulling the wings into the umbra for safing at solar distances < 0.5AU, determined how long wings could stay in full shadow before freezing would occur
  - 20C “yellow” limit
  - 10C “red” limit
- Considered pump operational and pump failed cases
  - Pump operational: 43C provides 5 min to 20C and 8 min to 10C
    - 43C will be min temperature requirement to move wings to full shadow
      - 43C is sufficiently low to bias solar array cold during nominal operations
      - 5 min is sufficient time for wings to move to safe angle, safing actions to complete, and wings to return to operational
  - Pump failed: radiators will cool and wings will heat
    - Radiators will reach 20C in 2.4 min (assuming 43C starting condition)
    - Wings will reach 190C in 20s (assuming 150C starting condition)
    - Pump-failed case is driven by over-temp

43C is min temperature requirement for entering solar array safe mode

System Temperatures



System Temperature	Description
190C	Max over-temp starting condition (defined in later slides)
150C	Max nominal operating temp
130C	Max temp with wings normal to Sun ≥ 0.5AU
125C	Max temp to exit safe mode (defined in later slides)
60C	Min T-C control point
43C	Min low-temp starting condition
20C	Yellow limit for cooling system freeze protection
10C	Red limit for cooling system freeze protection

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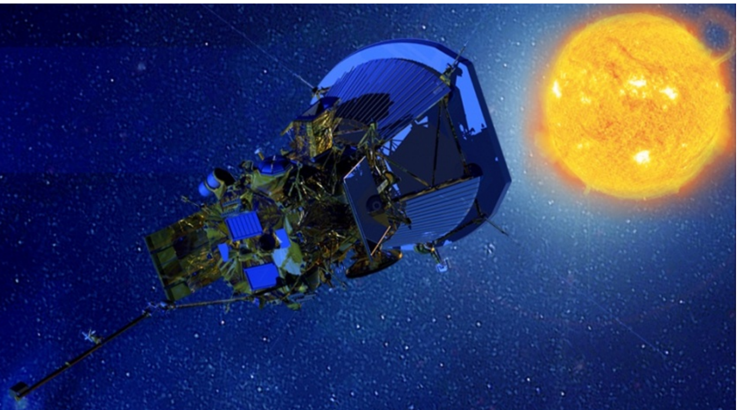

Solar Array Safing Approach

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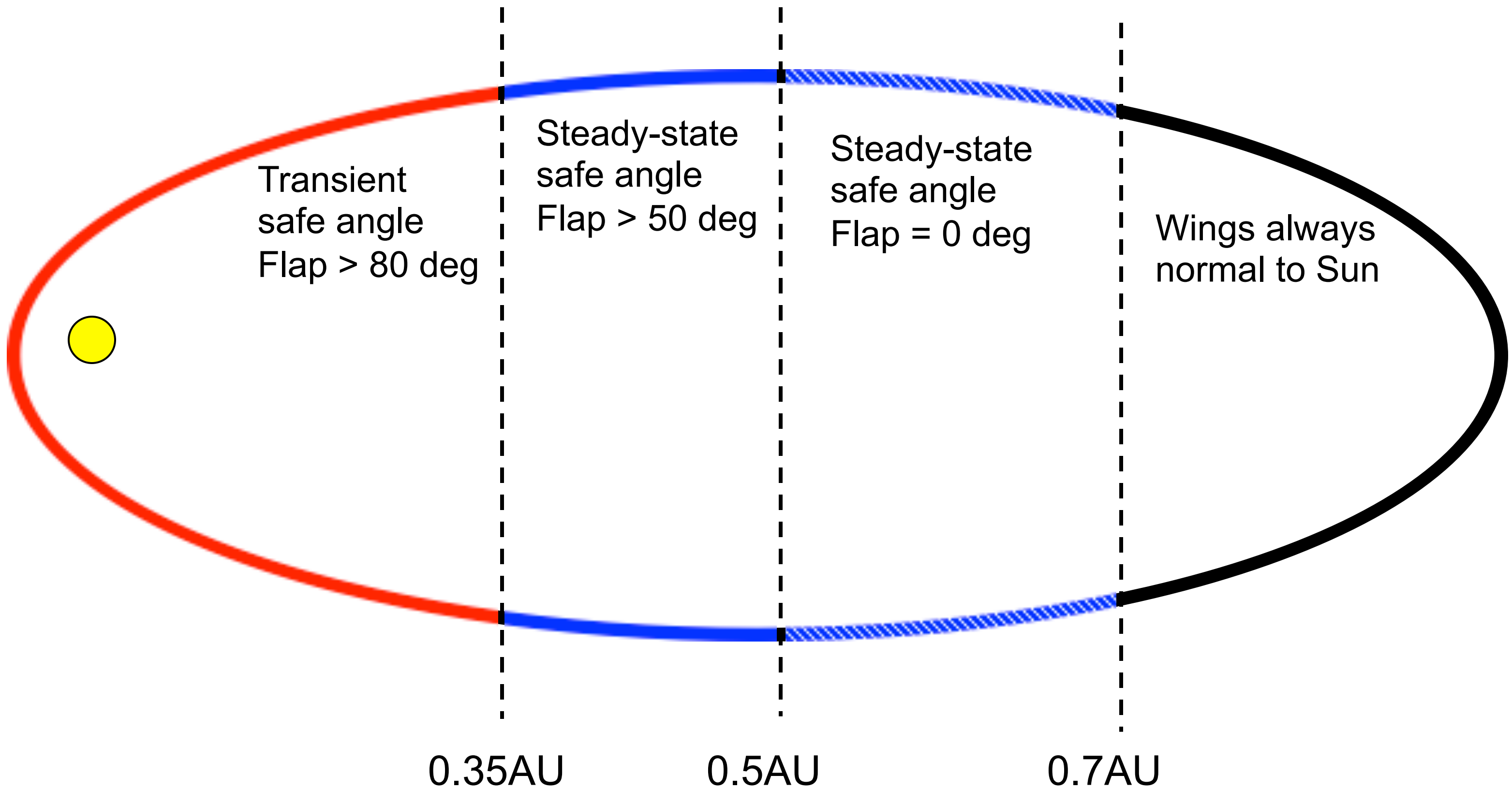
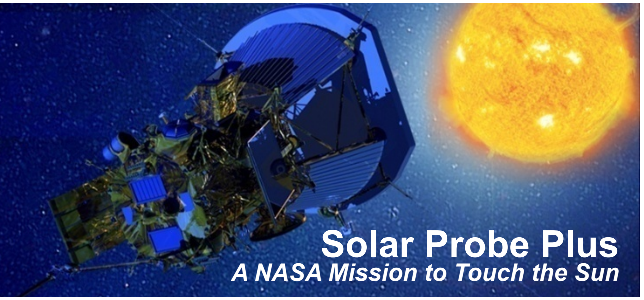
Safe Angles Overview



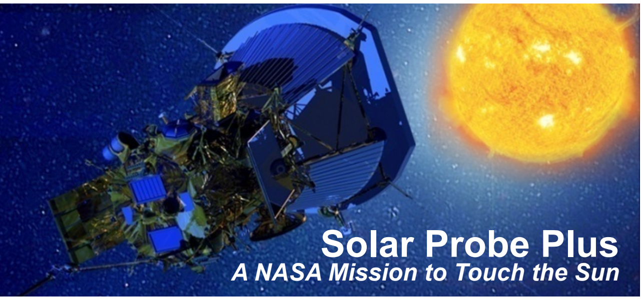
Solar Array Position Sensing



- Solar array safing approach requires good absolute knowledge of wing angle
  - Wings will move to a safe angle defined by MET
- Nominal autonomous wing angle control (P-C or T-C) does not require absolute knowledge of wing angle
  - Algorithm controls solar array power or temperature and moves solar array drive (SAD) a relative quantity of steps

- SAD has as nominal output angle of 0.002 deg/step
  - SAD is commanded via ECU
    - Step-period is command-selectable (idle, 4 ms, 8 ms, 12 ms, …, 352 ms)
      - 4 ms step period = 250 steps/sec = 0.5 deg/s (max rate)
    - Rate accuracy is assumed to be ± 10% (TBR)
  - Wing angle control command to ECU contains: number of steps, step-period (rate), direction
    - Wings will move desired angular distance within desired time

Solar Array Position Sensing



- Angle sensing potentiometers (pots)
  - 2 sets of pots per SAD (2 pots per set, 4 sets per wing)
    - Primary and redundant “coarse” pots
      - Measure angle between SAD output (solar array) and SAD housing
      - Provide wing angle knowledge of ±0.5 deg
    - Primary and redundant “fine pots”
      - Measure angle between stepper motor rotor and SAD housing
      - Rotates 500 times for every one revolution of coarse pot (500:1)
        - Due to 500:1 total gear ratio (0.002 deg output per step)
      - Provide wing angle knowledge of ±0.03 deg when combined with coarse pots
  - Pots are block-redundant to ECUs
    - Reading redundant pots requires activating redundant ECU
  - Counting commanded steps (bi-directional)
    - Used as primary means of tracking array position in nominal operations, for calibration and trending
- Primary pots, redundant pots, and step-count are monitored, compared, and corrected for mismatch in nominal operations

Position Sensing for Safing

- Position sensing for solar array safing
  - Upon power-up of "new" PDU, SCIF/TAC, and both ECUs:
    - Determine current wing position based on majority vote of primary pot, redundant pot, step-count
    - Determine solar array safe angle position (based on MET)
    - Calculate number of steps to move each wing
    - Command ECU to drive wings at max rate (0.5 deg/s) to safe angle
- When entering solar array safe mode, wing angle knowledge is assumed to be valid, to the accuracy of the coarse pots
  - One fine pot could be in deadband and one fine pot failed, so must rely on accuracy of coarse pots for safing
    - Coarse pot deadband not within angular travel of wings
  - Step-count is single fault tolerant to SEU, processor reset (maintained in ECU but also stored in prime processor)
  - Step-count vs. pot mismatch will be caught and resolved as part of normal telemetry checks
- Open trade on potentiometers vs. resolver
  - Assessing resolver for increased reliability on wing angle knowledge

When entering safe mode, wing angle knowledge is assumed to be valid and accurate to 0.5 deg

Safe Angles

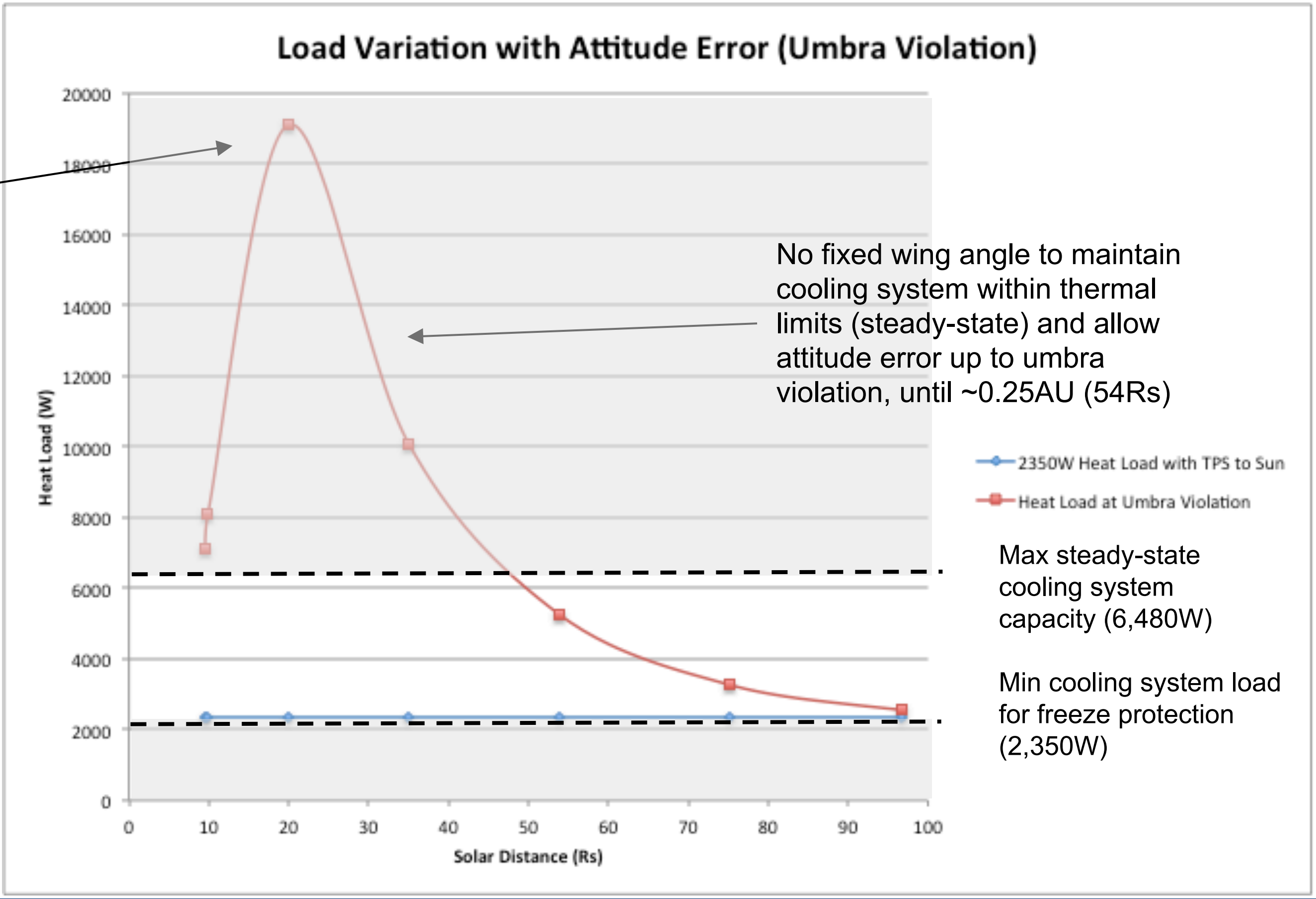
- System temperature analysis shows that inside of 0.5AU, wings must be brought into penumbra/umbra for safing
- < 0.25AU: there is no fixed wing angle that will ***maintain cooling system within steady-state thermal limits*** (2,350W – 6,480W) and ***allow attitude error up to umbra violation***
  - Solar array safing is therefore a transient state for those solar distances
    - Fixed wing angle used for safing will cause system to either freeze or over-heat, steady-state, and therefore must be a temporary position
    - If initial temperature is ≥ 43C, system can tolerate full shadow for at least 5 min before dropping below 20C yellow limit
    - Placing wings in a transient "low load" configuration (< 2,350W) for safing is safer than transient "high load" configuration (> 6,480W)
- 0.25AU – 0.5AU: there are fixed wing angles that will maintain cooling system within steady-state thermal limits (2,350W – 6,480W) and allow attitude error up to umbra violation
  - At 0.25AU, this angle closely approaches cooling system capacity at umbra violation
    - To ensure margin, limit use of steady-state safe angle to ≥ 0.35AU
- ≥ 0.5AU, wings can be normal to Sun and remain below cooling system capacity

Inside of 0.25AU, solar array safing must be a transient state and wings must return to operational before cooling system reaches 20C

Safe Angles

- **To determine feasibility of steady-state safe angles by solar distance:**
  - **Place wings at same angle to generate 2,350W into cooling system with TPS to Sun (blue line)**
  - **Then slew spacecraft to umbra violation (red line)**

Local max due to large increase in attitude error to umbra violation between 9.9Rs and 20Rs

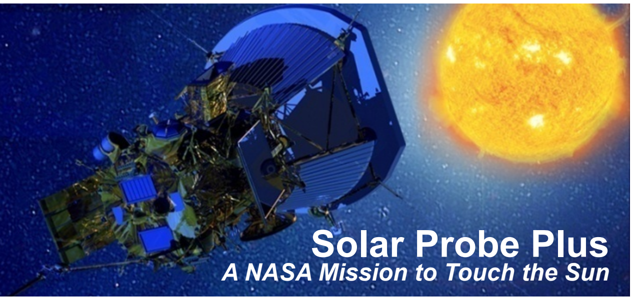


No fixed wing angle to maintain cooling system within thermal limits (steady-state) and allow attitude error up to umbra violation, until ~0.25AU (54Rs)

Max steady-state cooling system capacity (6,480W)

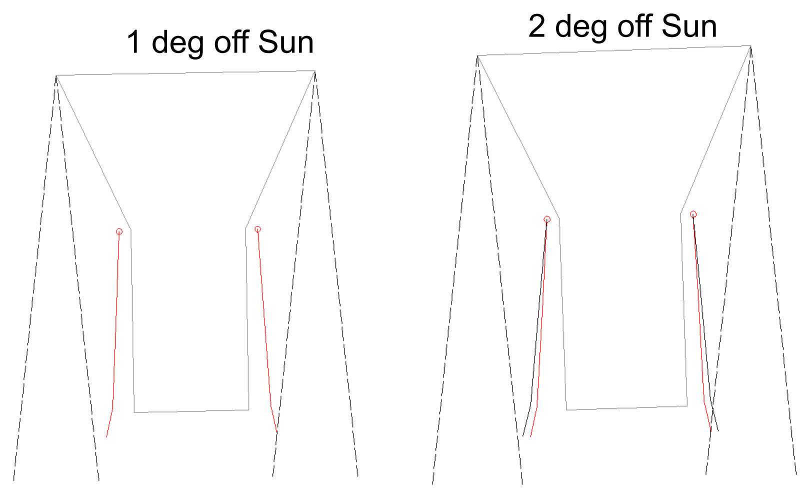
Min cooling system load for freeze protection (2,350W)

Safe Angle Margin



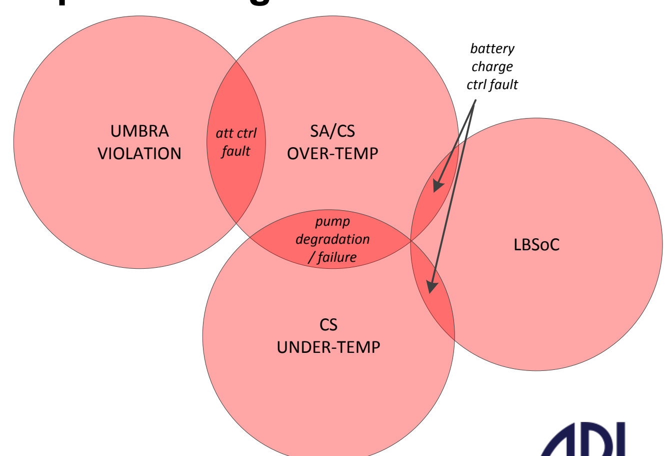
- Solar array safing angle must maintain at least 0.5 deg flap angle margin with solar array stowed position (88 deg)
  - Avoid contact between wings and spacecraft
  - Required margin depends on angle knowledge (accuracy of coarse pots)
  - Fully shadowing the wings during safing and accommodating attitude error up to umbra violation is not feasible
    - Requires a flap angle > 88 deg for all solar distances
    - Wings will therefore see some heat load > 0W during safing

9.5Rs Flap Angle Required to Achieve Full Shadow (0W)	
Spacecraft Attitude	**Flap Angle**
Sun pointing	85.0
1 deg off Sun	86.8
2 deg off Sun (umbra violation)	88.6



Safing Approach

- < 0.35AU: Safing approach *__for all critical faults__* is to move the wings to a transient safe angle, defined by solar distance (MET), that drops the total load into the cooling system to ≤ 2,050W while accommodating attitude error up to umbra violation
  - Thermally safe for at least 5 min
    - Assumes 43C min starting temp
  - Power safe for ~20 min
  - Not feasible or necessary to drop load to 0W (full shadow) during safing
    - Wing contact with spacecraft
    - 2,050W into cooling system allows for sufficient cooldown time in over-temp case
  - Transient safe angle allows completion of safing and recovery actions to complete with wings in known thermally safe configuration
  - One response for all faults results in robust design and protects against situations where critical faults may be combined
    - LBSoC + SA/cooling system over-temp
      - Over-correcting for LBSoC
    - Cooling system low-temp + SA over-temp
      - Pump failure



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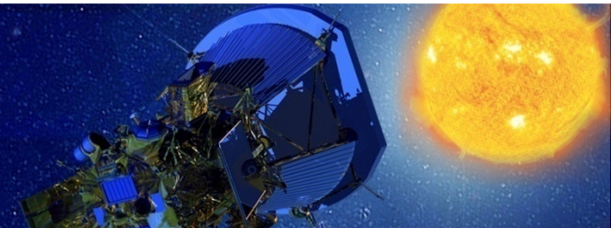
Safing Approach

- **0.35AU - 0.5AU: Safing approach *<u>for all critical faults</u>* is to move the wings to a steady-state safe angle, defined by solar distance (MET), that maintains the total load into the cooling system between 2,350W and 6,480W while accommodating attitude error up to umbra violation**
  - **Thermally safe steady-state**
  - **Power safe for ~20 min**
- **≥ 0.5AU: Safing approach *<u>for all critical faults</u>* is to position the wings normal to the Sun**
  - **Thermally safe steady-state**
    - **Will limit time in this position to minimize solar array degradation**
    - **Able to wait until ground-contact if useful for early ops analysis**
  - **Power safe steady-state**
- **Safe angle table by solar distance includes 3 points and defines feasible overlap points between the three solar distance ranges**

Solar array safing approach is feasible with 3 safe angles defined by MET

Safe Angles



<table>
<tr><th>Solar Distance</th><th>Umbra Violation Slew Angle (deg)</th><th>Min Transient Safe Angle for ≤ 2,050W Into Cooling System (deg)</th><th>Min Steady-State Safe Angle for 2,350W – 6,480W into Cooling System (deg)</th><th>Selected Safe Angle (deg)</th><th>Max Load Into Cooling System at Safe Angle (W)</th></tr>
<tr><td>9.5Rs</td><td>2.00</td><td>84.3</td><td rowspan="5">N/A
(No Steady-State Safe Angle Exists)</td><td rowspan="6">84.3</td><td>2,050W</td></tr>
<tr><td>9.9Rs</td><td>2.18</td><td>84.2</td><td>1,964W</td></tr>
<tr><td>20Rs</td><td>5.13</td><td>83.5</td><td>1,336W</td></tr>
<tr><td>35Rs</td><td>6.36</td><td>82.5</td><td>954W</td></tr>
<tr><td>54Rs (0.25AU)</td><td>6.93</td><td>79.1</td><td>555W</td></tr>
<tr><td rowspan="2">75Rs (0.35AU)</td><td rowspan="2">7.24</td><td rowspan="3">N/A
(Steady-State Safe Angle Exits)</td><td rowspan="2">65.9</td><td>5W</td></tr>
<tr><td rowspan="2">59.6</td><td>4,488W</td></tr>
<tr><td rowspan="2">97Rs (0.45AU)</td><td rowspan="2">7.41</td><td rowspan="2">59.6</td><td>2,554W</td></tr>
<tr><td rowspan="6">N/A
(Wings Can be Normal to Sun)</td><td rowspan="6">0</td><td>8,050W</td></tr>
<tr><td>108Rs (0.50AU)</td><td>7.47</td><td rowspan="5">0</td><td>6,445W</td></tr>
<tr><td>118Rs (0.55AU)</td><td>7.52</td><td>5,259W</td></tr>
<tr><td>129Rs (0.60AU)</td><td>7.56</td><td>4,356W</td></tr>
<tr><td>140Rs (0.65AU)</td><td>7.59</td><td>3,653W</td></tr>
<tr><td>150Rs (0.70AU)</td><td>7.62</td><td>3,096W</td></tr>
</table>

Notes:
- 75Rs overlap case with 54Rs results in min load of 5W at 75Rs (becomes a transient case)
- 97Rs overlap case with 108Rs results in max load of 8,050W at 97Rs (above cooling system capacity). Heat flux is low enough that steady-state temperatures remain below 155C.

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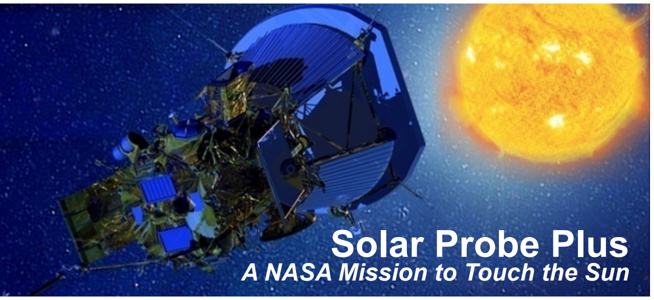
Safing Summary



Solar Distance	Flap Angle	Feather Angle	Min Initial CS Temperature	Total Load into CS	Description
9.5Rs – 0.35AU	Transient safe angle defined by MET	0 deg	43C	≤2,050W	Thermally safe for at least 5 min Power safe for ~20 min
0.35AU – 0.5AU	Steady-state safe angle defined by MET	0 deg	43C	2,350W – 6,480W	Thermally safe steady-state Power safe for ~20 min
0.5AU – 0.7AU	0 deg	0 deg	43C	2,350W – 6,480W	Thermally safe steady-state Power safe steady-state High irradiance increases solar array degradation
≥0.7AU	0 deg	0 – 90 deg	20C	< 3,000W	Thermally safe steady-state Power safe steady-state Wings should nominally always be normal to Sun

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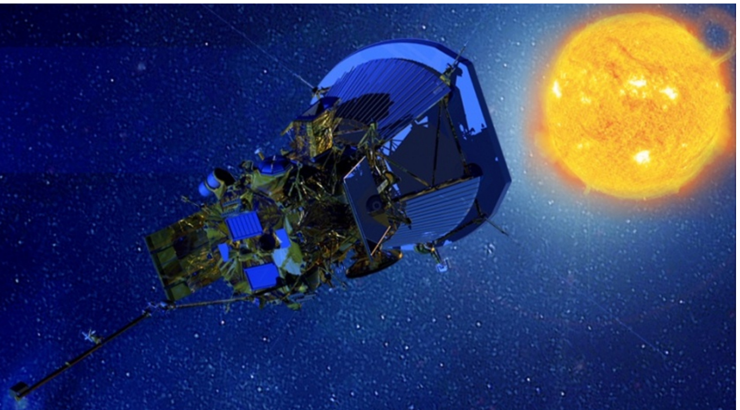

Sensors, Measurements, and Computed Telemetry

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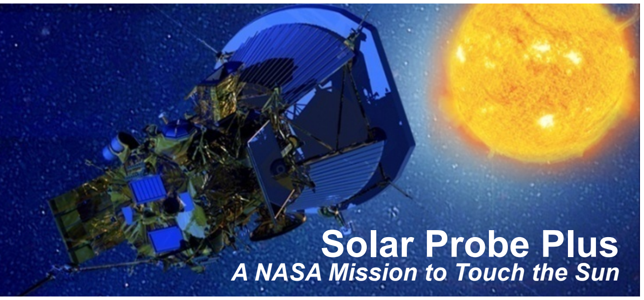
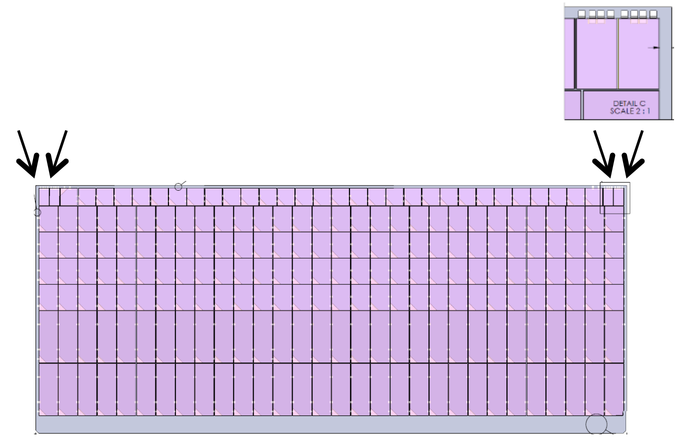
Sensors, Measurements, and Computed Telemetry



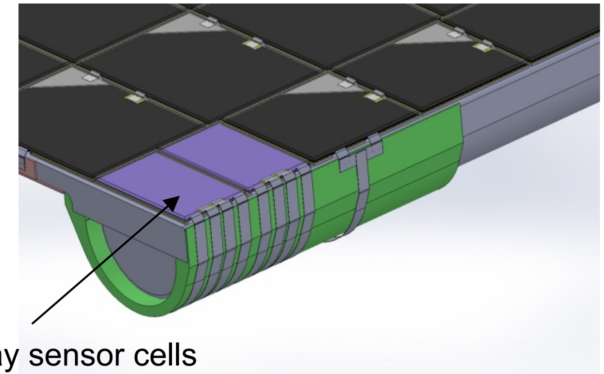
- Robust set of sensors and computed telemetry used to detect and respond to critical faults:
  - Solar array sensor cells
    - Measure Isc and Voc
  - Platen temperature sensors
    - Measure inlet and outlet temperature on back of platen
  - Radiator temperature sensors
    - Measure inlet and outlet temperature of each radiator
  - Computed telemetry from above measurements gives:
    - Absorbed solar flux
    - Absorbed heat load
    - Bulk water temperature
    - Cell temperature

Solar Array Sensor Cells

- 2 primary/redundant solar array sensor cell sets at outboard corner of each wing (4 cells per set, 2 sets per wing, 16 cells total)
  - Measures short circuit current (Isc)
    - Proportional to average solar flux ("Suns") on cell
  - Measures open circuit voltage (Voc)
    - Indicates cell temperature
      - Temp = $K_1 - K_2 * Voc + K_3 * Log(Isc)$
  - Sensor cells calibrated in-flight
    - Solar flux and temperature relationships dependent on solar array degradation
  - Cross-strapped to the PSE
    - Variation between corners of one wing can be large
  - PSE performs I-V sweep of any sensor cell when commanded
    - Used for diagnostics, trending, calibration



Secondary solar array section, outboard edge



Solar array sensor cells to measure "Suns" (outboard edge)

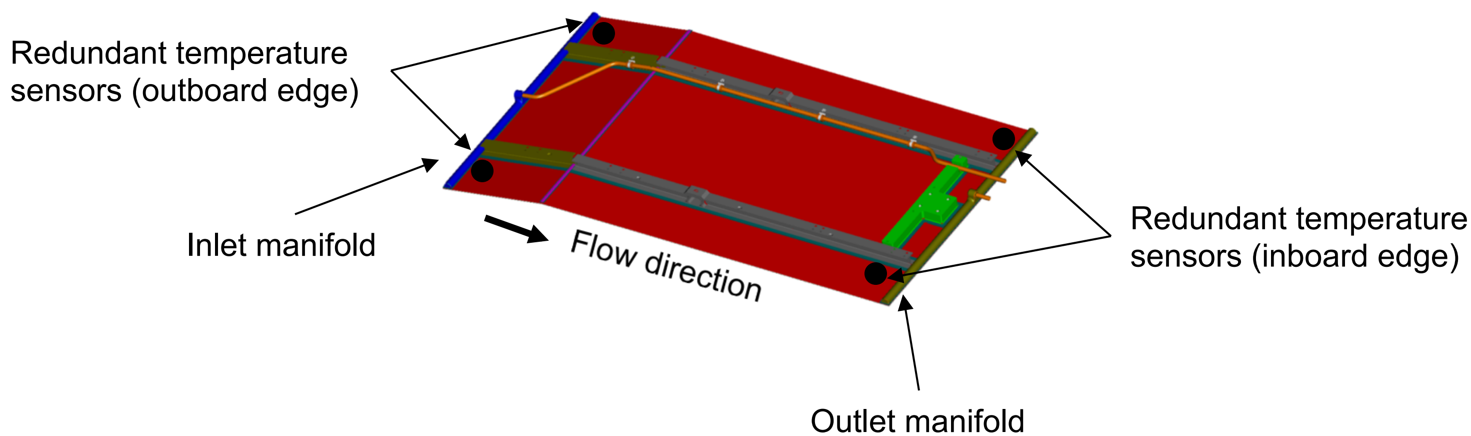
Note: Figures indicate 1 pair of sensor cells/wing corner; flight wing includes 2 pairs/wing corner

Solar Array Sensor Cells

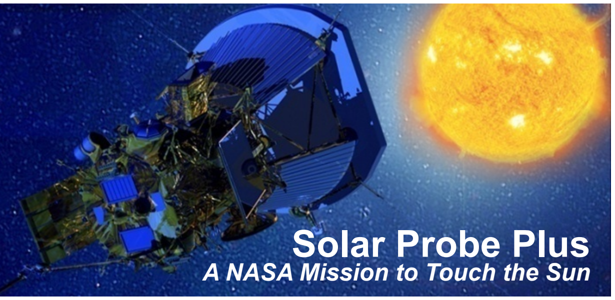
- Calibration of solar array sensor cells performed twice per orbit (TBR)
  - Occurs at approximately 0.5AU, must be under ground contact
    - Min solar distance to exercise full range of wing flap and feather angles
  - Drive solar array to 0 deg flap and use known solar flux as reference for calibration
- Isc telemetry accurate to ±3% (TBR)
  - Computed solar flux accurate to ±6% (TBR)
- Voc telemetry accurate to ±3% (TBR)
  - Computed cell temperature accurate to ±15C (TBR)
    - Given sensitivities and uncertainties in K_1, K_2, K_3
- Circuit development, analysis, and test needed to refine accuracies
  - Accuracy affected by:
    - Sweep rate
    - Wiring resistance (affects ability to approach Isc)
    - Maximum Isc (intensity) and temperature that can be accommodated

Solar Array Temperature Sensors

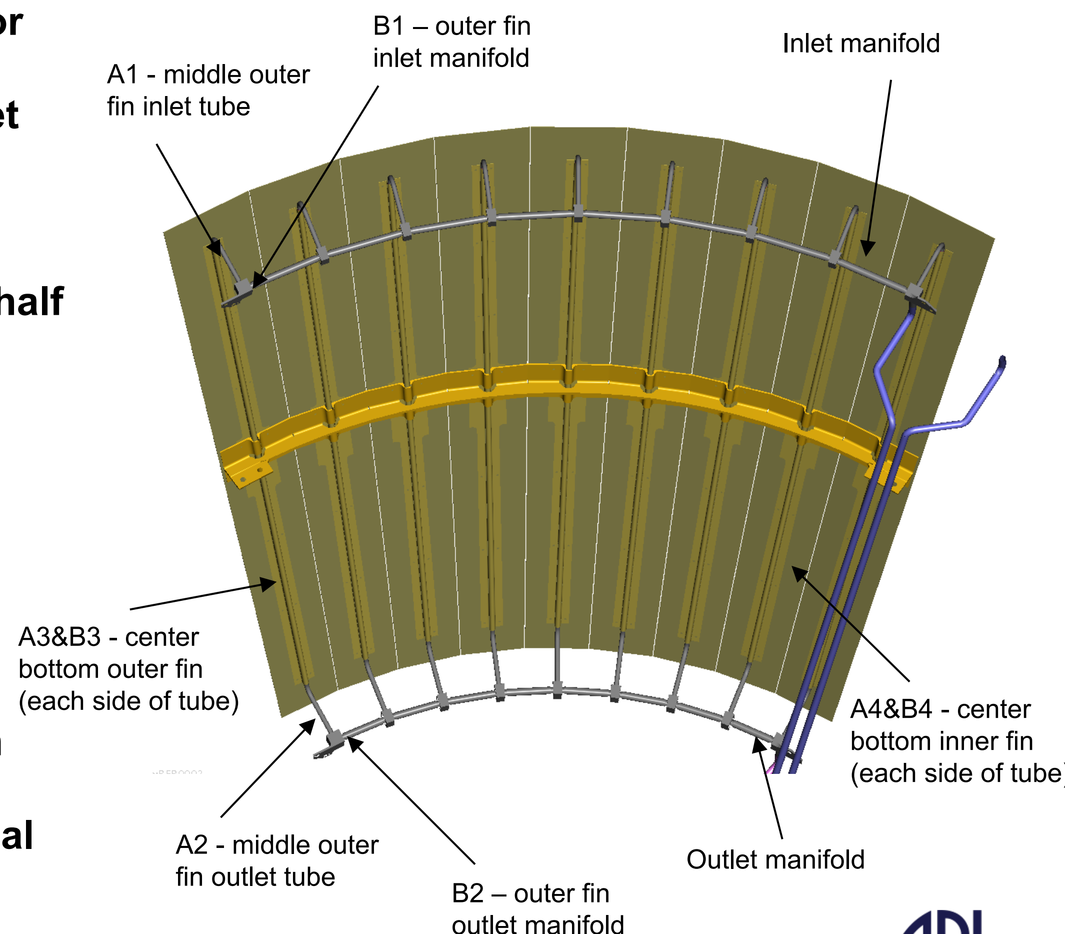
- **4 primary/redundant PT-103 temperature sensor pairs on back of each platen (8 per wing, 16 total)**
  - **Measure inlet and outlet manifold temp**
  - **Block redundant to the PSE**
    - **Variation between corners of one wing small (across inlet corners and across outlet corners), accommodates failed sensor without a side-switch**
  - **Temperature sensor locations notional until TVac**



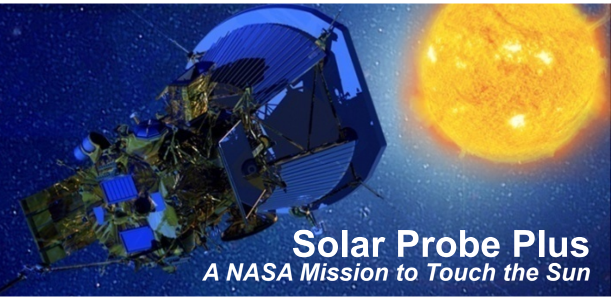
Radiator Temperature Sensors



- **48 total PT-103 temperature sensors allocated to cooling system**
  - **4 primary/redundant pairs per radiator (8 per radiator, 32 total)**
    - **One pair on each inlet and outlet manifold**
      - **Denoted A1&2 and B1&2**
    - **One pair on each radiator inner and outer fin (center of bottom half of fin)**
      - **Denoted A3&4 and B3&4**
    - **Cross-strapped with RIU-A and RIU-B strings to Avionics**
  - **16 single-string sensors**
    - **Multiple locations throughout cooling system**
      - **Pump, lines, etc**
    - **Half on RIU-A string and half on RIU-B string**
  - **Temperature sensor locations notional until TVac**



Computed Telemetry

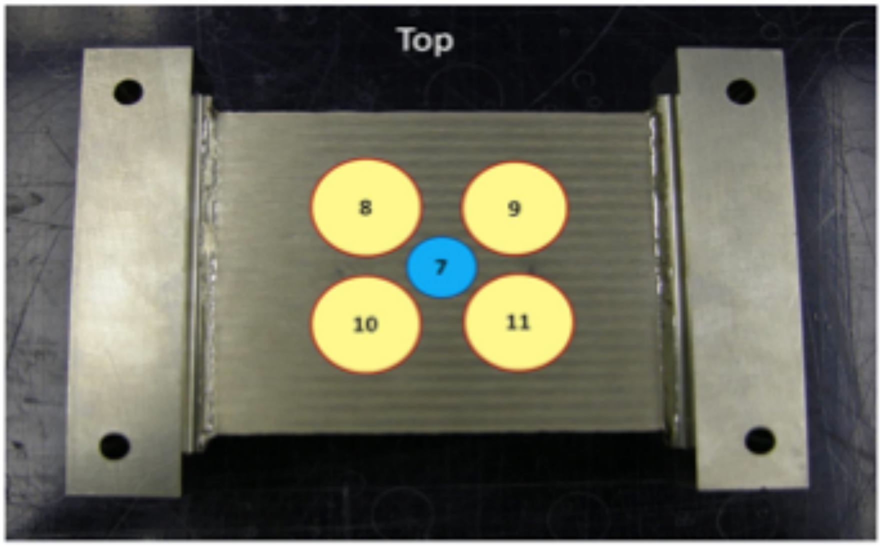


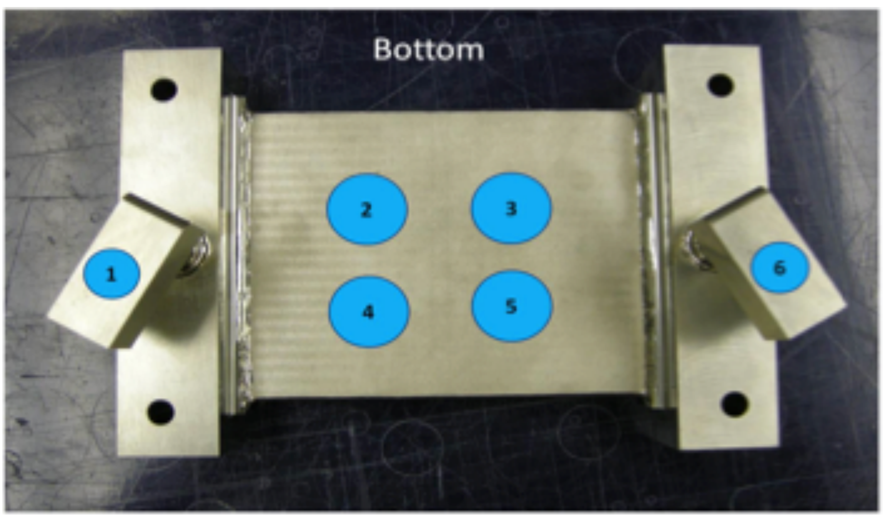
Output Parameters / Input Parameters	Bulk Water Temp	Mass Flow Rate	Cell Temp at Leading Edge (1)	Cell Temp at Leading Edge (2)	Solar Flux at Leading Edge	Heat Load Into Platen	Heat Addition to/ Rejection from Radiators
Pump Speed		x					
Platen Inlet Temp	x			x		x	
Platen Outlet Temp	x					x	
Isc					x		
Voc			x				
Radiator Inlet Temp	x						x
Radiator Outlet Temp	x						x
Radiator Fin Temp	x						
Mass Flow Rate				x		x	x
Bulk Water Temp		x					
Solar Flux at Leading Edge				x			

Measured Telemetry

Computed Telemetry

Cooling System Heat-Exchanger Test





- **Platen qual unit setup used to simulate water flow, water temp, and cell temp across the platen for a given heat input**
  - **Determined absorbed heat load as a function of flow rate and inlet to outlet delta-T**
  - **Determined solar cell base temp as a function of flow rate, inlet temp, and absorbed heat flux**
- **Yellow circles are type-K thermocouples embedded in ceramic heaters**
- **Blue circles are type-T thermocouples surface mounted to titanium platen**
  - **“1” represents inlet**
  - **“6” represents outlet**
  - **Flow is from right to left**
- **Test configuration designed to minimize radiative heat rejection off platen (wrapped in MLI)**
  - **In flight, will have heat rejection off cell side**

Determining Absorbed Heat Load

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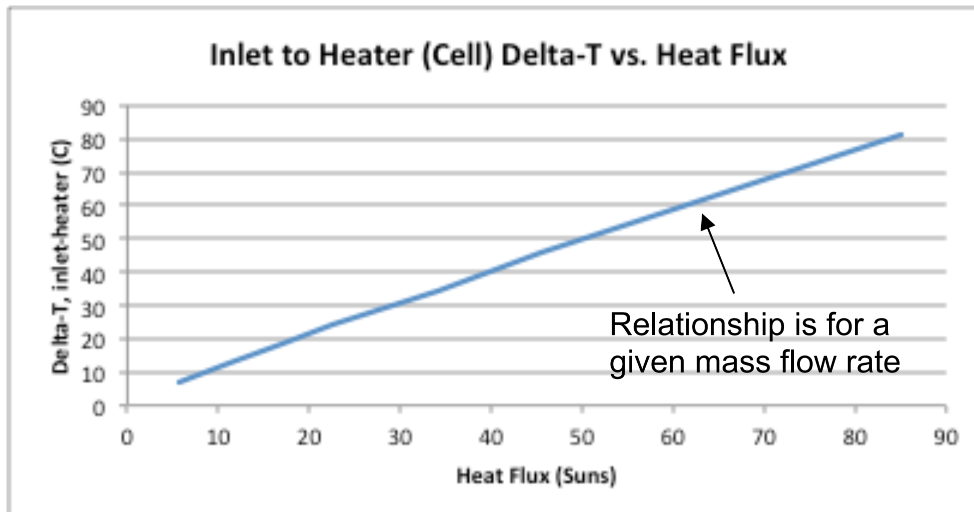
- **Absorbed heat load is a function of mass flow rate and delta-T from inlet to outlet**
- **Inlet and outlet temp are directly measured in-flight, flow-rate is calculated in-flight from pump speed and water temp**
- **Calculated heat load will be used in combination with temperature measurements in high-flux cases to indicate impending over-temperature (see later slides)**
  - **Accuracy is dependent on solar flux (higher solar flux is more accurate)**

	Flow Rate:	**0.3 L/min**		**Targeted Inlet Water Temp:**		**8°C**			
	Q (W/in²)	**5**	**10**	**15**	**20**	**30**	**40**	**50**	**75**
	Q (Suns)	**5.7**	**11.3**	**17.0**	**22.7**	**34.0**	**45.4**	**56.7**	**85.1**
Inlet	TC-1 (°C)	6.8	7.3	7.5	7.6	7.8	7.1	7.6	7.6
	TC-2 (°C)	8.0	9.3	10.4	11.3	12.8	13.9	15.9	19.3
	TC-3 (°C)	8.5	10.4	11.9	13.3	15.5	17.4	20.4	25.7
	TC-4 (°C)	7.7	9.0	9.9	10.6	11.9	12.6	14.3	17.2
	TC-5 (°C)	8.4	10.0	11.3	12.4	14.3	15.7	18.2	22.6
Outlet	TC-6 (°C)	8.3	9.7	10.8	11.8	13.4	14.6	17.0	21.0
	TC-7 (°C)	8.1	9.6	10.8	11.7	13.4	14.6	16.7	20.6
	Htr-1 / TC-8 (°C)	14.0	20.6	26.7	32.6	43.7	54.5	65.8	91.7
	Htr-2 / TC-9 (°C)	13.9	20.5	26.6	32.5	43.5	54.3	65.5	91.3
	Htr-3 / TC-10 (°C)	13.3	19.3	24.9	30.3	40.6	50.7	61.0	85.2
	Htr-4 / TC-11 (°C)	13.4	19.6	25.5	31.0	41.7	52.1	62.7	87.6
	Inlet-Heater Delta-T (°C)	6.8	12.7	18.4	24.0	34.6	45.8	56.1	81.3
	Inlet-Outlet Delta-T (°C)	1.4	2.4	3.3	4.1	5.6	7.5	9.4	13.4
mdot (g/s)		4.995	4.995	4.995	4.995	4.995	4.995	4.995	4.995
cp (J/g/K)		4.18	4.18	4.18	4.18	4.18	4.18	4.18	4.18
calculated heat pickup by H2O (W)	mdot*cp*dT	29.4	50.1	69.5	86.2	117.1	155.5	197.1	279.2
measured heat input (W)	4*Q	20	40	60	80	120	160	200	300
measured/calculated		1.47	1.25	1.16	1.08	0.98	0.97	0.99	0.93

Determining Cell Temperature

- **Delta-T from inlet to heater (inlet to cell) is a function of absorbed heat flux, for a given flow-rate**
- **Inlet temp is directly measured in-flight, heat flux is calculated in-flight from Isc sensors, flow-rate is calculated in-flight from pump speed and water temp**
- **Assumes no heat rejection off platen (upper bound)**
- **Calculated cell temp shows an approximately 1C/Sun relationship from back of platen to cell (conservative)**

Heat Flux (Suns)	Inlet to Heater Delta-T (C) (average)
5.7	6.8
11.3	12.7
17.0	18.4
22.7	24.0
34.0	34.6
45.4	45.8
56.7	56.1
85.1	81.3



Calculations of absorbed heat load and cell temp as a function of measured temperatures and calculated heat flux are validated with early test data

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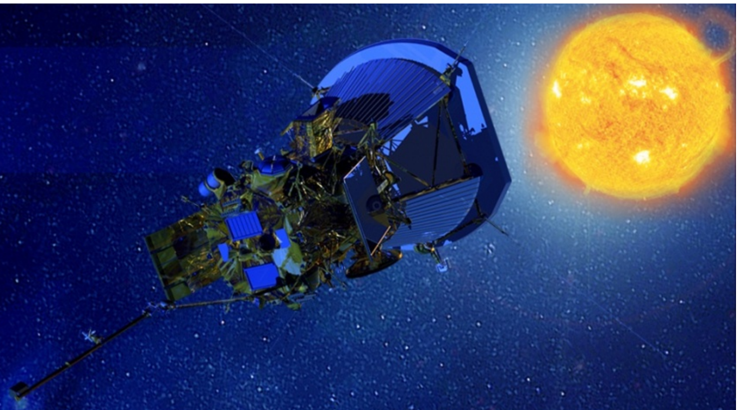

Solar Array/Cooling System Over-Temp

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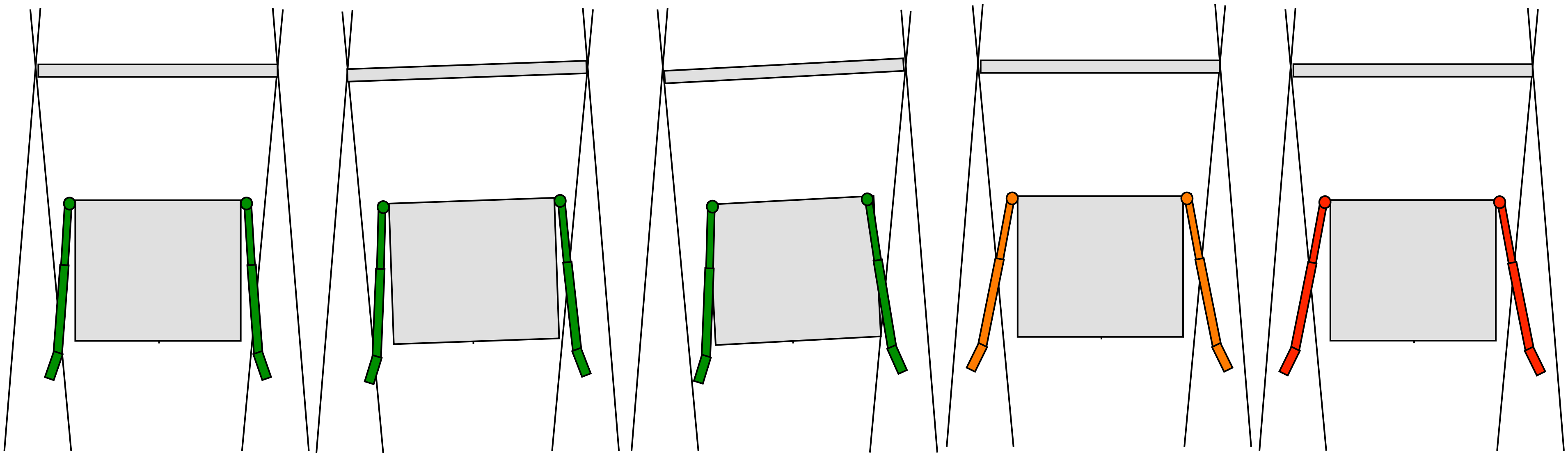
Over-Temp Definition

- **Solar array/cooling system over-temperature is defined as:**
  - **Solar flux (“Suns”) exceeding limits**
    - **Survival limit is dependent on solar distance**
    - **Violation limit is per parametric table**
  - **Cooling system exceeding temperature limits**
    - **Survival limit is 190C**
    - **In distributed flux cases, hottest temp will be at platen outlet (measured)**
    - **In high-flux cases, hottest temp will be in between platen inlet and outlet (not measured)**
      - **Delta between outlet temp and hottest temp could be 10C (based on steady-state analysis)**
    - **Violation limit will depend on combination of measured temperature and calculated heat load into the system, in order to ensure safing occurs in cases where max temp is not at a measured point along the platen**
    - **Thresholds to be determined through further transient analysis (see later slides)**
  - **Solar array exceeding temperature limits**
    - **Survival limit is 240C**
    - **At 190C with high-flux (40 Suns), test data shows that upper bound on cell temp is approximately 230C (~1C/Sun)**
      - **40 Suns is worst-case transient (see later slides)**
      - **Cooling system temperature will be violated first**

Over-Temp Approach

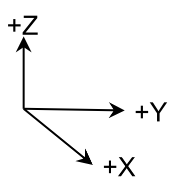


0 deg attitude error 21 Suns into +Y wing 21 Suns into -Y wing 6,480W into CS	1 deg attitude error 30 Suns into +Y wing 8 Suns into -Y wing 6,480W into CS	2 deg attitude error Umbra violation 32 Suns into +Y wing 0 Suns into -Y wing 6,480W into CS *Defines Suns threshold*	0 deg attitude error 26 Suns into +Y wing 26 Suns into -Y wing 8,500W into CS	0 degree attitude error 32 Suns into +Y wing 32 Suns into -Y wing 11,000W+ into CS (plus additional for error in reading, wing overshoot, etc)

↔ Nominal operating points (within cooling system capacity)

↔ Above nominal operating point
Below solar flux threshold
Safe on temp, heat load

↔ Above nominal operating point
Worst-case transient
Safe on solar flux



Note: Example is for 9.5Rs

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Safing on Solar Flux

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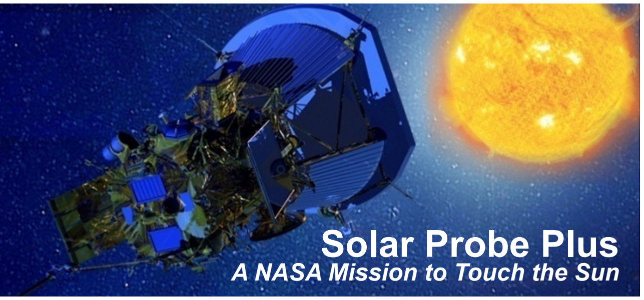
- Calculated solar flux at leading edge (from Isc measurement) is a useful trigger for solar array safing
  - Provides near instantaneous knowledge of an impending over-temp
    - No thermal lag
- For safing, a profile of solar flux thresholds vs solar distance (MET) will be used
  - Amount of solar flux that can be tolerated by the system varies with solar distance and attitude error
    - Investigate setting threshold to max solar flux that can be tolerated by the system at umbra violation, with all heat load coming from one wing (removes attitude error from the problem)
      - One wing illuminated, one wing shadowed -> what solar flux on illuminated wing causes 6,480W into cooling system?
      - Translates into max allowable solar flux on either wing
  - This profile will cause high transients in certain situations (e.g. both wings illuminated with max solar flux)
    - Profile is currently defined to allow max cooling system capacity and full range of attitude error up to umbra violation, before safing occurs

Solar flux thresholds are currently defined with wide bounds, to allow max cooling system capacity and attitude error up to umbra violation before safing

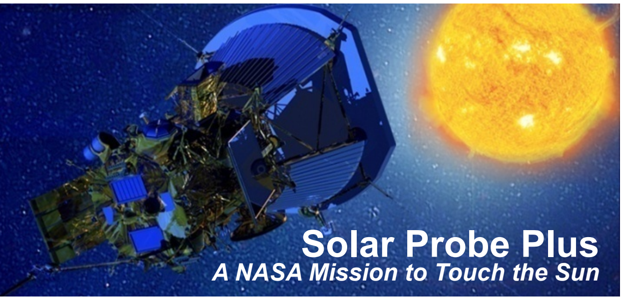
Over-Temp Approach



- **Solar flux will be used as an upper bound for the safing approach**
  - **Defines worst-case transients seen by the system**
  - **Defines worst-case time to safe the wings (min safe mode entry angle)**
- **If solar flux reaches threshold on either wing, immediately trigger safing, regardless of temperature measurements**
  - **Catches scenarios where a fault causes the wings to move out at a high-rate and thermal lag does not keep up**
  - **Safing must occur regardless of temperature measurements**
    - **By the time temperature rises to violation, wings could be beyond the point to get to safe angle in time**
- **If the array is operating above cooling system capacity but below the solar flux threshold, temperature measurements and heat load calculation will trigger safing**
  - **Catches scenarios where a fault causes the wings to be at an angle that is too shallow to be safe steady-state, but not too shallow to trip a solar flux violation**
  - **More work is needed to determine where temperature thresholds will be set in order to bring wings to safe angle in time (see later slides)**

Solar flux will provide an upper bound to the safing approach (for transient loads and time to safe)

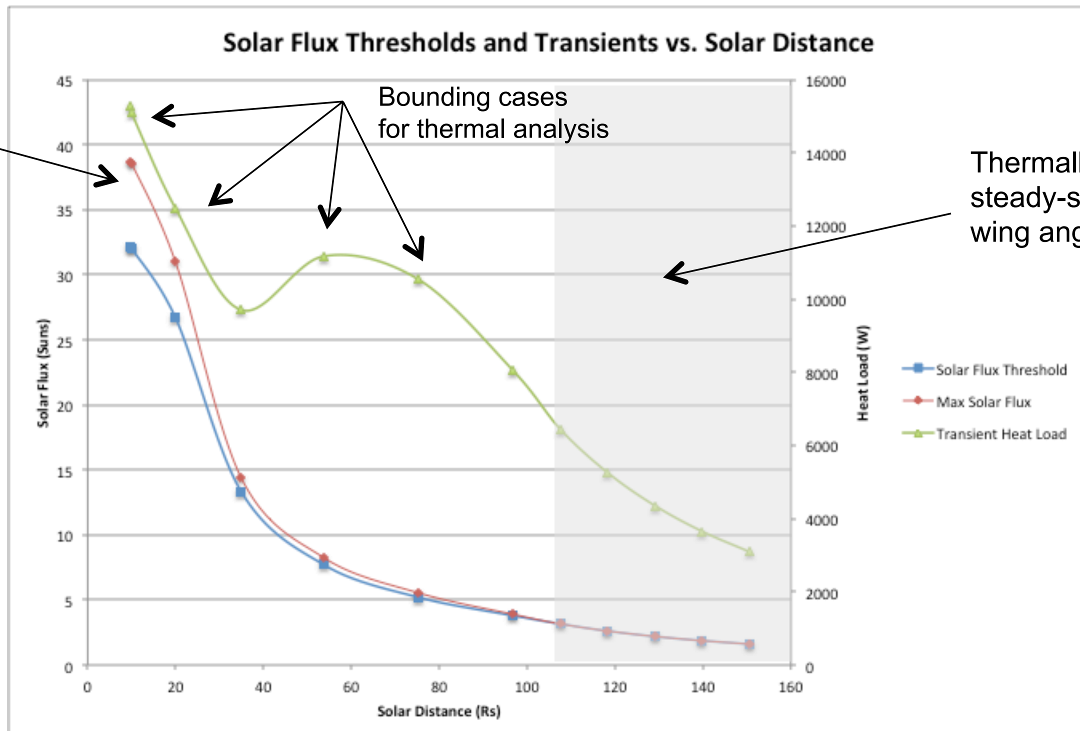
Transients by Solar Distance



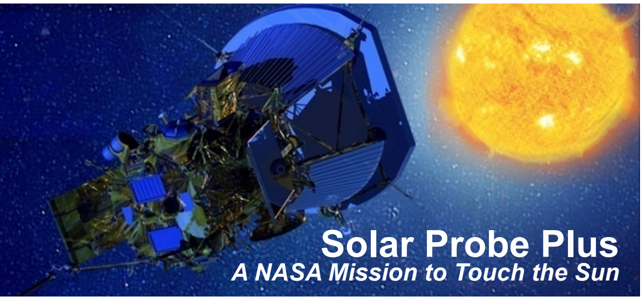
- "Solar Flux Threshold" is currently defined as solar flux that can be tolerated on one wing at umbra violation (heat load = 6,480W), and will be used to instantly trigger safing
- "Max Solar Flux" represents solar flux that will actually be reached on either wing before safing occurs, due to error in the solar flux measurement (6%) and wing overshoot (0.1 deg/s for 5s)
- "Transient Heat Load" represents max load into the cooling system that will be reached, due to max solar flux (red line) occurring on both wings, with TPS to Sun
  - Includes heat load from instruments/TPS

~40 Suns max transient at 9.5Rs

Local min/max due to combination of increased attitude error to umbra violation (higher solar flux), increased solar distance (lower solar flux), and decreased wing angle to reach defined solar flux threshold (increased heat load)



Transients by Solar Distance



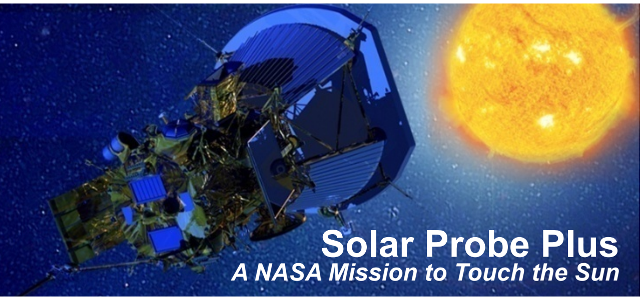
- **"Min Safe Mode Entry Angle" is worst-case and corresponds to wing angle prior to safing if TPS is to Sun and wings are at defined solar flux threshold, with error and overshoot (wing angle that generates red line from previous plot)**
  - **Includes 6% error on solar flux measurement**
  - **Includes 0.1 deg/s wing overshoot for 5s (time until power cut to solar array drive)**
- **"Time to Safe" assumes:**
  - **10s from fault occurrence to wings moving**
  - **0.5 deg error on wing angle knowledge (must target safe angle 0.5 deg steeper)**
  - **0.5 deg/s rate**
  - **10% error on rate accuracy**

Red line from previous plot

Green line from previous plot

Solar Distance	Umbra Violation Slew Angle (deg)	Min Safe Mode Entry Angle (deg)	Defined Safe Angle (deg)	Wing Travel Distance (deg)	Time to Safe (s)	Max Solar Flux (Suns)	Transient Load (W)
9.5Rs	2.00	77.8	84.3	6.5	25.6	38.7	15,274
9.9Rs	2.18	77.3		7.0	26.7	38.6	15,122
20Rs	5.13	71.5		12.8	39.6	30.1	12,482
35Rs	6.36	67.6		16.7	48.2	14.4	9,702
54Rs (0.25AU)	6.93	56.5		27.8	72.9	8.2	11,173
75Rs (0.35AU)	7.24	38.8		45.5	112.2	5.5	10,539
			59.6	20.8	57.3		
97Rs (0.45AU)	7.41	0		59.6	143.6	3.9	8,050

Thermal Analysis



- **Thermal analysis for transient cases that bound solar array safing in over-temp scenarios (using solar flux thresholds) will be used to validate and refine the approach**
  - **Steady-state temperatures**
  - **Temperature response times**
- **Analysis will help answer the following questions:**
  - **Which transient cases will not exceed thermal limits before wings are moved to safe angle?**
    - **These cases are ok to safe on solar flux with currently defined thresholds**
  - **Which transient cases will exceed thermal limits before wings are moved to safe angle?**
    - **These cases will safe on either a reduced solar flux level or on a combination of temperature and heat load measurements**
      - **What are impacts and feasibility of narrowing bounds on solar flux?**
        - **Bounds currently set wider than needed for nominal operations (max cooling system capacity at umbra violation)**
      - **What conditions (solar flux, heat load, and wing angle, as a function of solar distance) will cause steady-state temperatures of 190C and what are response times?**
        - **Will help determine combination of temperature and heat load thresholds that will ensure safing before thermal limits exceeded**

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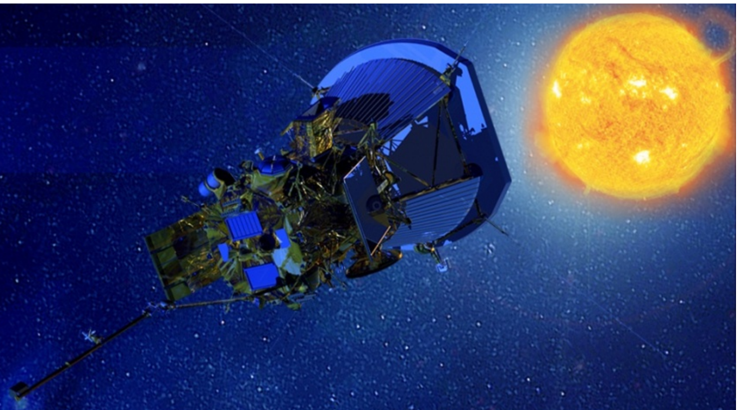

Cooling System Low-Temp

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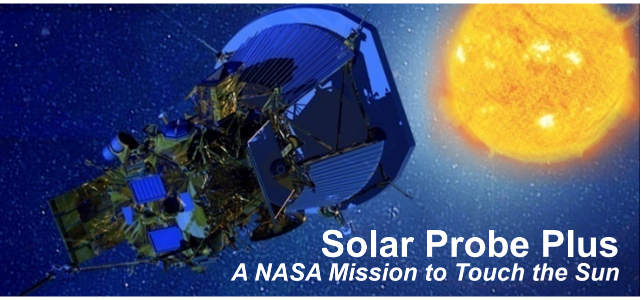
Low-Temp Definition and Approach



- Cooling system low-temperature is defined as:
  - Cooling system dropping below temperature limits at solar distances < 0.7AU
    - Survival limit is 10C
    - Threshold defined to accommodate same solar array safing response for all critical faults
      - Violation limit is ≤ 43C
        - Violation limit chosen for 5 min to 20C yellow limit on freeze protection (assumes wings fully tucked)
        - Coldest temp will be at platen inlet and on radiators (measured)
  - Wing angle too far off normal to Sun and/or solar flux dropping below limits at solar distances ≥ 0.7AU
    - Nominal operating temperatures will approach 20C, and array should always be normal to Sun
      - 43C temperature limit will be inhibited
    - If fault occurs that causes wings to be off normal to Sun, solar array safe mode entered using a combination of wing angle knowledge and known solar flux with wings normal to Sun

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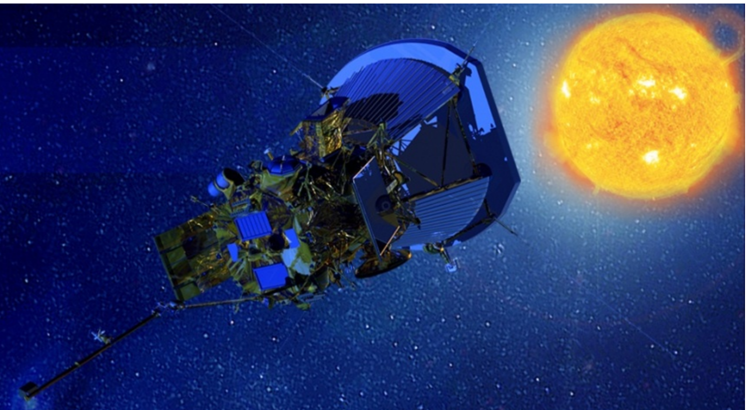

Exiting Solar Array Safe Mode

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Safe Mode Temperatures

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- In order to determine time to safely return wings to operational in over-temp and low-temp scenarios at < 0.35AU:
  - How long for T_{water} to cool from 190C to 125C, assuming 2,050W heat load into system (over-temp cooldown)?
    - 190C provides margin on temp violation thresholds (safing will occur before 190C)
    - 125C provides margin on max nominal operating point (150C)
      - $T_{water} \leq$ 125C to exit safe mode
    - 2,050W provides margin on total heat load into system
      - System will approach 0W when at safe angle and TPS is to Sun
      - System will approach 2,050W when at safe angle and spacecraft is at umbra violation
    - Time shows how long wings must stay at safe angle to cool down within limits
      - Timing budget assumes no cooldown occurs as wings move to safe angle and no cooldown occurs as wings move back out to operational (conservative)
  - How long for T_{water} to cool from 125C to 20C, assuming 0W heat load into system (over-temp freezing condition)?
    - Time shows how long wings will have to return to operational before cooling system violates freeze limit
  - How long for wings to cool from 43C to 20C, assuming 0W heat load into system (low-temp freezing condition, previously discussed)?
    - 43C previously defined as low-temp threshold
    - Time shows how long wings will have to return to operational before cooling system violates freeze limit

Safe Mode Temperatures

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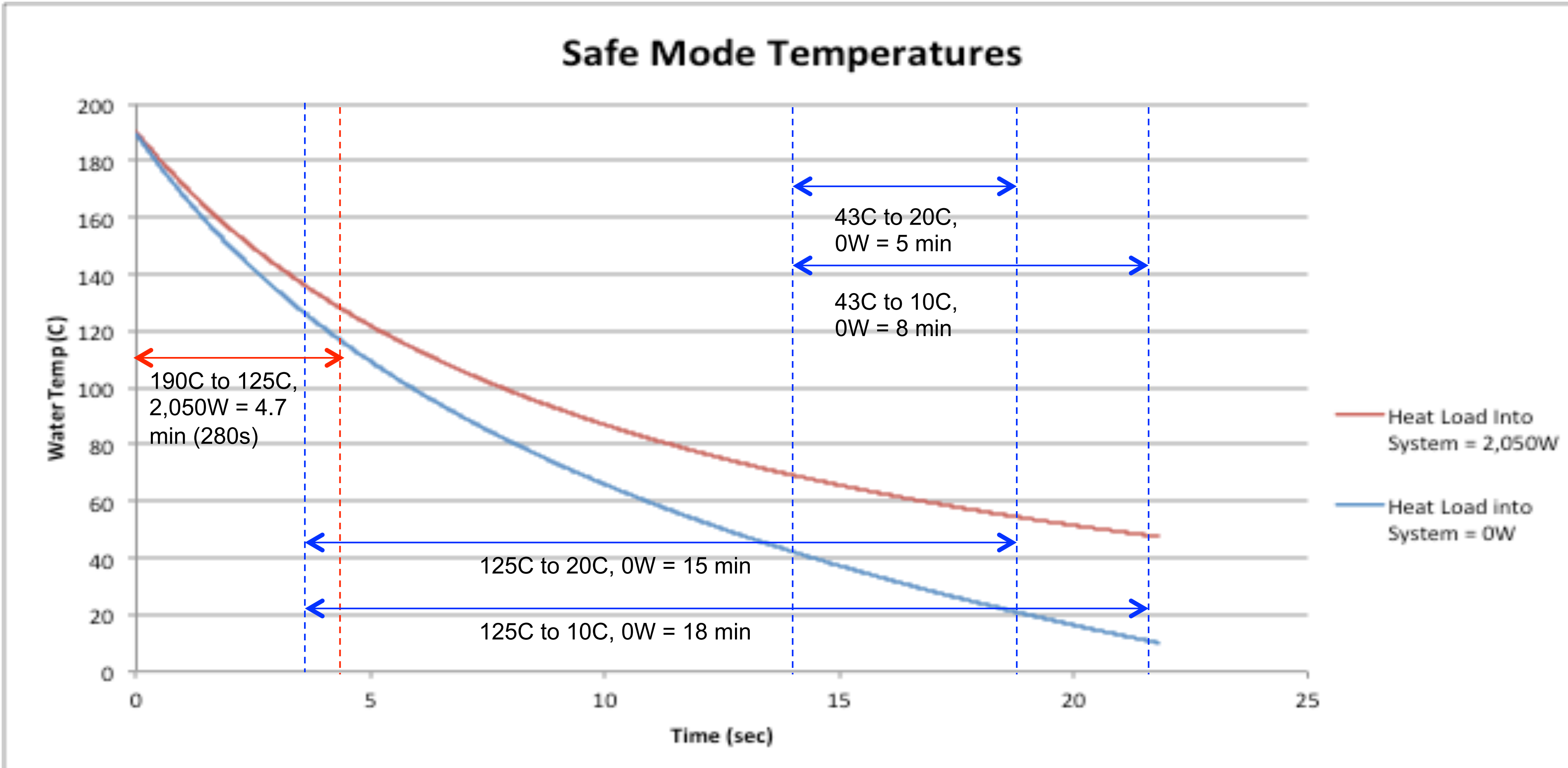

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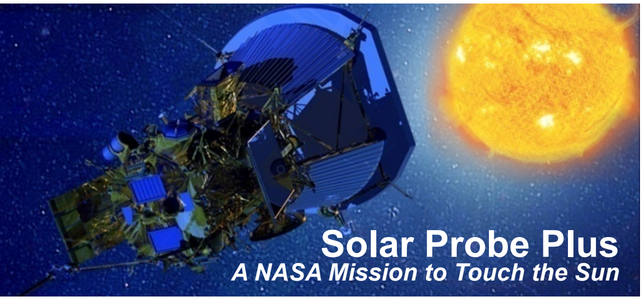
Safe Mode Temperatures



- **Over-temp scenario:**
  - **Wings will require 280s at safe angle to cooldown within limits (T_{water} = 125C)**
  - **When T_{water} = 125C, there will be 15 min before 20C yellow limit reached**
    - **Margin on 15 min will be defined from fault detection (conservative)**
- **Low-temp scenario**
  - **When T_{water} = 43C (min threshold for entering safe mode), there will be 5 min before 20C yellow limit reached**
    - **Margin on 5 min will be defined from fault detection (conservative)**

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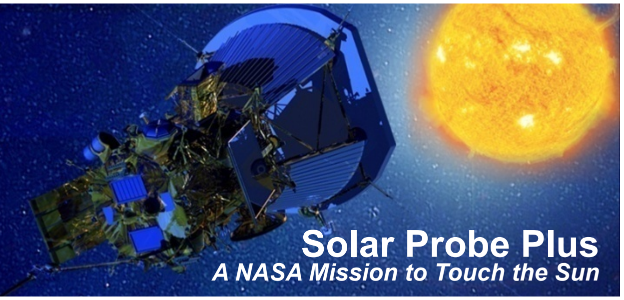
System Temperatures



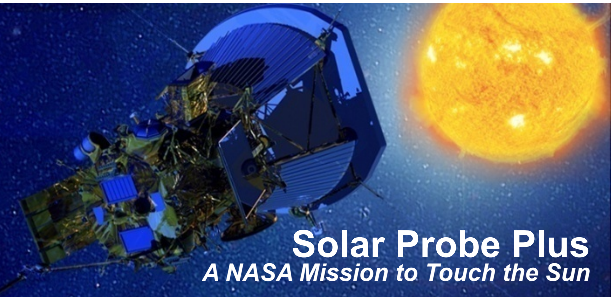
System Temperature	Description
190C	Max over-temp starting condition
150C	Max nominal operating temp
130C	Max temp with wings normal to Sun ≥ 0.5AU
125C	Max temp to exit safe mode
60C	Min T-C control point
43C	Min low-temp starting condition
20C	Yellow limit for cooling system freeze protection
10C	Red limit for cooling system freeze protection

Constraints on Exiting Safe Mode

- **< 0.35AU: wings will be at a transient safe angle with total load into the cooling system ≤2,050W (10C steady-state)**
  - **Timing to exit safe mode is critical in low-temp scenarios**
    - **Wings must be back to thermally safe operation within time to 20C yellow limit (5 min)**
      - **Thermally safe operation defined as 2,350W into cooling system (20C steady-state)**
  - **Timing to exit safe mode is not critical in over-temp scenarios**
    - **Wings will exit safe mode and resume nominal autonomous control after allocated cooldown time, well within time to 20C yellow limit (15 min)**
- **≥ 0.35AU: wings will be at a steady-state safe angle**
  - **Timing to exit safe mode is not critical**
  - **Wings will resume nominal autonomous control**

In low-temp scenarios < 0.35AU, timing to exit safe mode is critical; must show wings can return to thermally safe operation within 5 min of fault detection

Safe Mode Timing



- To show in all critical fault scenarios the wings can move to safe angle, safe mode and recovery actions can complete, and the wings can return to operational without violating thermal or power constraints, the solar array safing sequence assumes two timers:
  - At t = 90s from fault detection:
    - Telemetry check to determine if wings should exit safe mode immediately, or wait the duration of allocated cooldown time
      - If $T_{water} \leq$ 125C, exit safe mode immediately ("low temp path")
        - Wings will return to thermally safe operation within 5 min of fault detection
      - T_{water} > 125C, wait duration of cooldown time ("over-temp path")
        - Wings will return to thermally safe operation within 10 min of fault detection
  - At t = 280s from safe angle reached ("over-temp path"):
    - Allocated cooldown time met, wings exit safe mode immediately
- Telemetry check at 90s is TBR and allows for a set amount of time for wings to move to safe angle (envelopes all solar distances), safe mode actions to complete, G&C to come back online, umbra violation recovery, etc

Safe mode timing budget assumes a timer-based temperature check and a timer-based cooldown time

Exiting Solar Array Safe Mode

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1. Autonomous control will extend the wings at a constant rate (0.1 deg/s TBR) until electrical power meets spacecraft load
   - Rate is a function of solar distance, due to PPT constraints
     - Faster rate likely achievable at further solar distances

2a. If in a low-temp scenario: T-C will take over and continue extending the wings
   - T_{water} < 43C when wings reach required electrical power point
   - If solar array degradation is low or if spacecraft power load is low, electrical power required from wings could result in a heat load < 2,350W into the system
     - Wings might not extend far enough in step 1 to be safe steady-state
   - T-C will eventually reach thermally safe operation at ≥ 2,350W
     - The normal T-C gain profile vs solar distance will be used to achieve the desired performance and ensure stability
       - Preliminary analysis shows T-C will move fast enough to achieve 2,350W heat load before cooling system violates freeze limit, not too fast to overshoot and risk overheating

2b. If in an over-temp scenario: normal P-C/T-C transitions will take over
   - T_{water} > 60C when wings reach required electrical power

Exiting Solar Array Safe Mode (Low-Temp)

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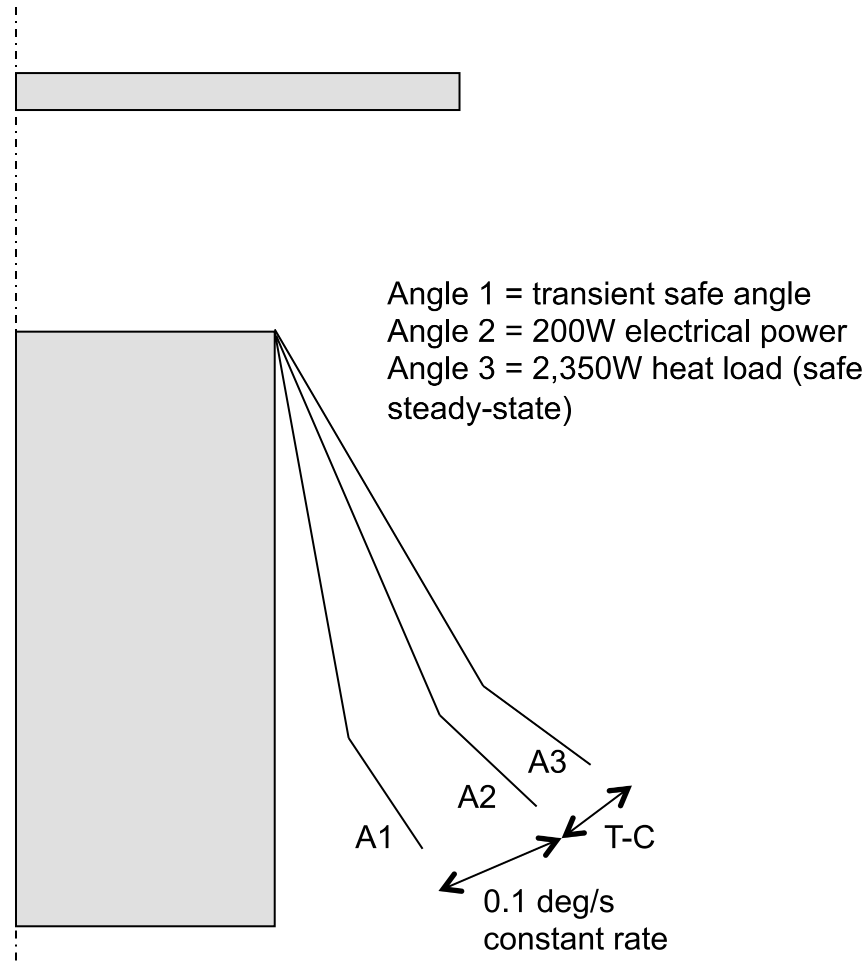
- **Approach for exiting safe mode will:**
  - **Return wings to thermally safe operation before freezing**
  - **Return wings to thermally safe operation without overheating (not too much overshoot)**
- **Approach:**
  - **Thermally safe operation = 2,350W**
  - **Angle 1 = transient safe angle**
  - **Angle 2 = worst-case angle for array to just meet spacecraft load**
    - **Assume min 200W spacecraft load**
    - **Assume no solar array degradation**
  - **Angle 3 = worst-case angle for array to meet 2,350W heat load (target angle)**
  - **Drive wings from Angle 1 to Angle 2 at 0.1 deg/s**
  - **Cover remaining distance from Angle 2 to Angle 3 in T-C**



Note: "Worst-case angle" is min angle (furthest travel distance) and occurs with TPS to Sun (actual angle in-flight will depend on attitude error)

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Wing Angles to Exit Safe Mode

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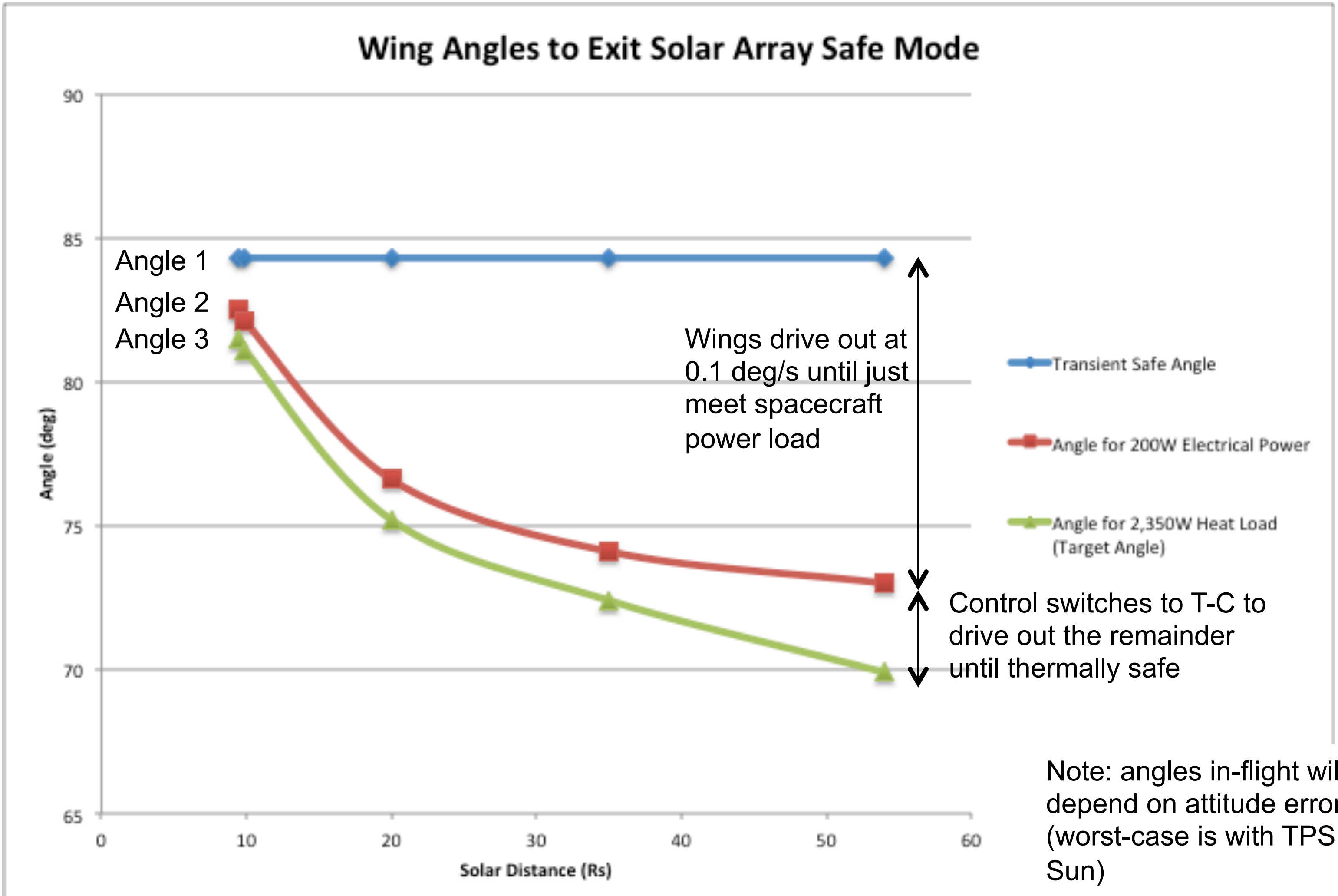

Note: angles in-flight will depend on attitude error (worst-case is with TPS to Sun)

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Wing Angles for Safing

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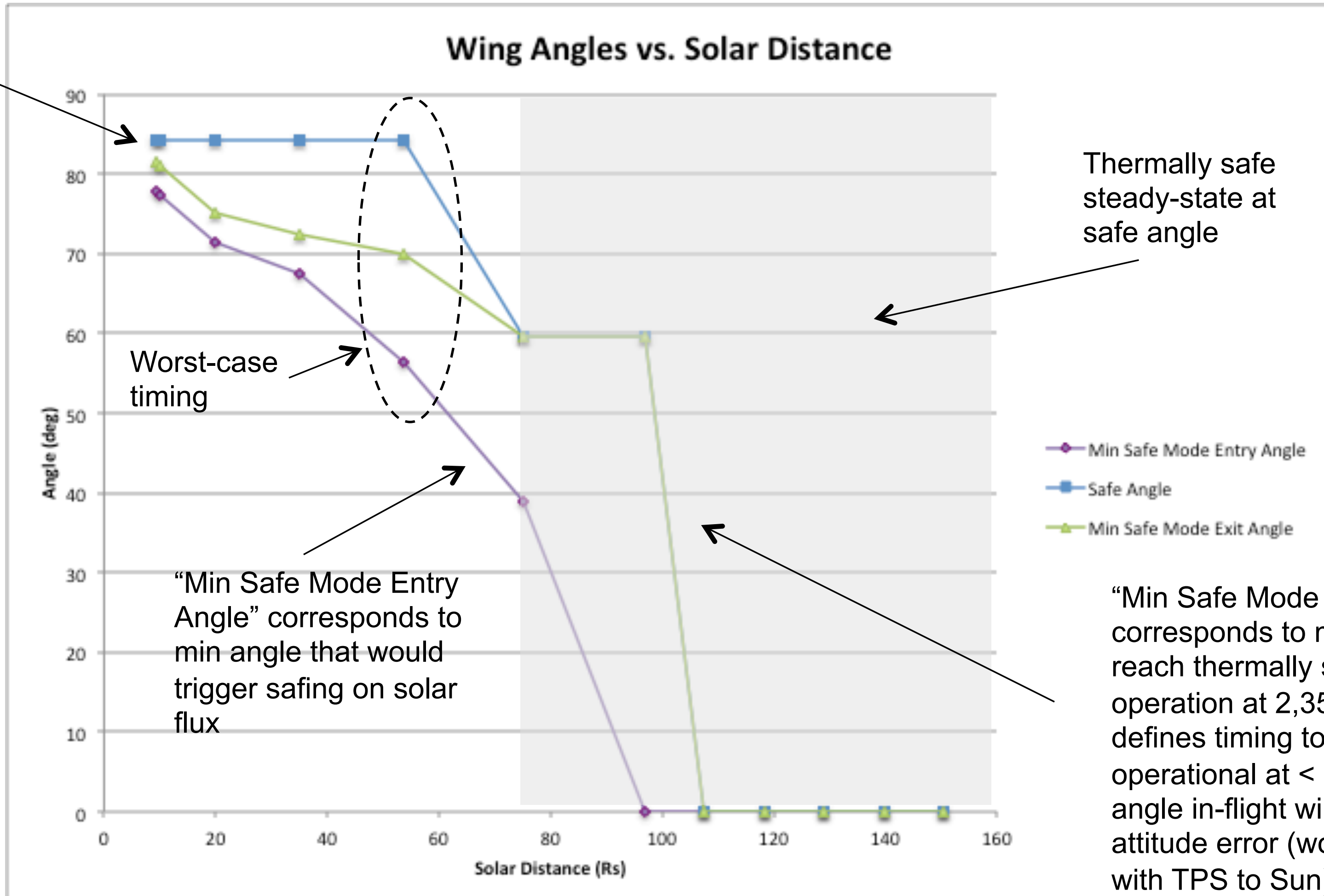
Provides ~3 deg margin before contact with spacecraft at 9.5Rs (within accuracy of coarse pots)



Thermally safe steady-state at safe angle

"Min Safe Mode Entry Angle" corresponds to min angle that would trigger safing on solar flux

"Min Safe Mode Exit Angle" corresponds to min angle to reach thermally safe operation at 2,350W and defines timing to return to operational at < 0.35AU; angle in-flight will depend on attitude error (worst-case is with TPS to Sun)

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Safe Mode Exit at 54Rs

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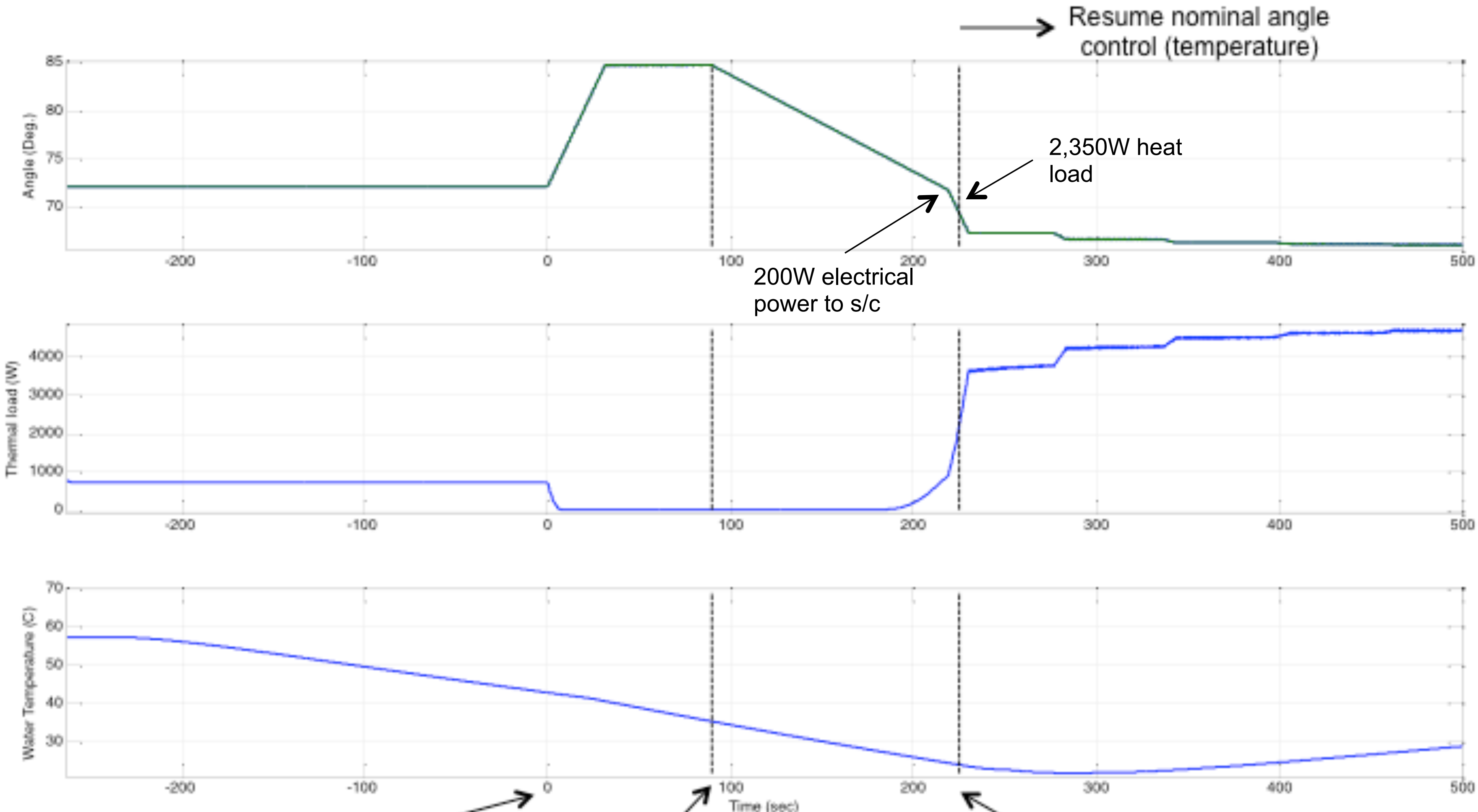


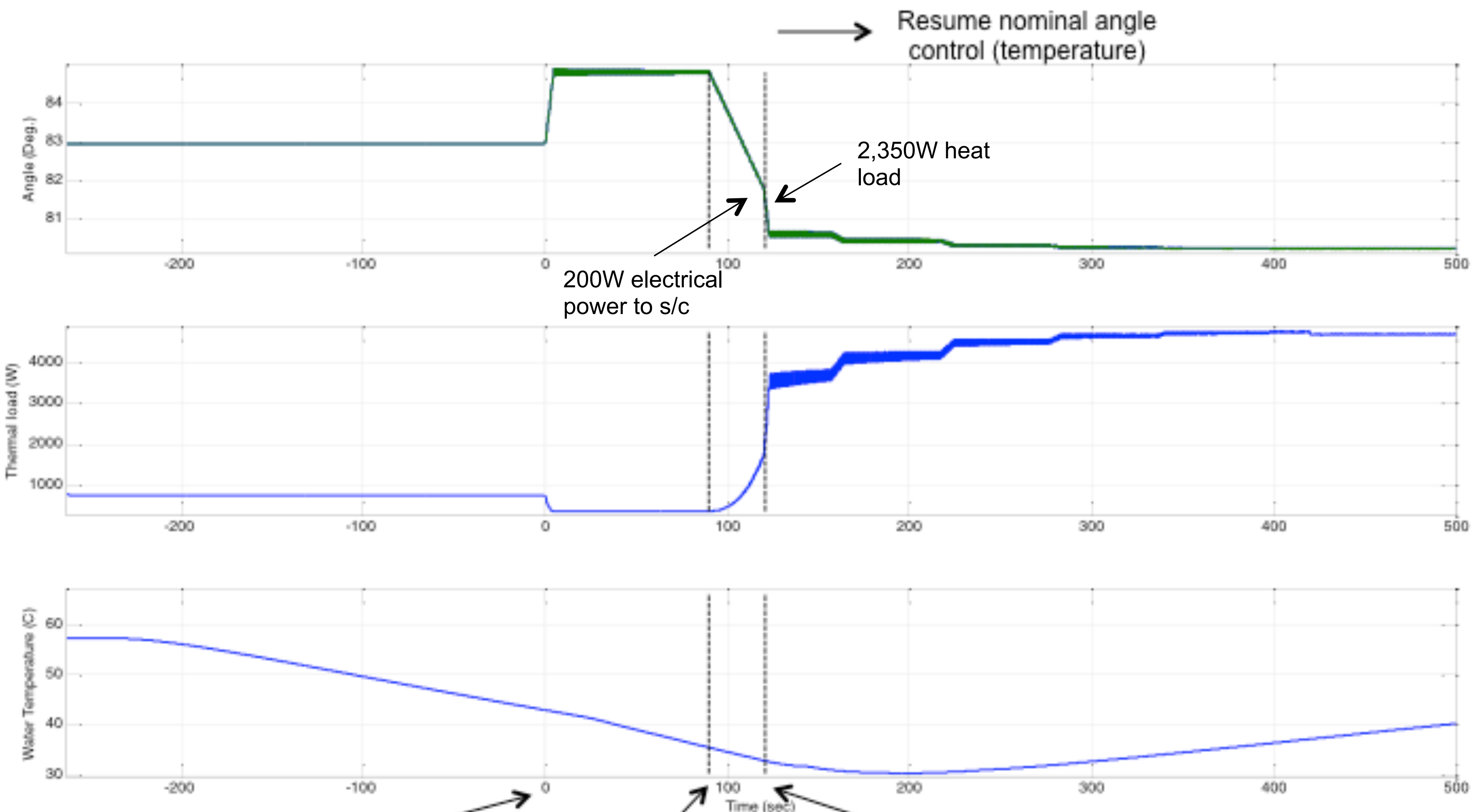
Note: time to thermally safe does not include 10% error on drive rate

Enter Safe Mode t=0s

Exit Safe Mode t=90s

Reach Thermally "safe" operation, t=225s

Safe Mode Exit at 9.5Rs



Note: time to thermally safe does not include 10% error on drive rate

Enter Safe Mode t=0s

Exit Safe Mode t=90s

Reach Thermally "safe" operation, t=121s

Solar Array Safing Flowchart

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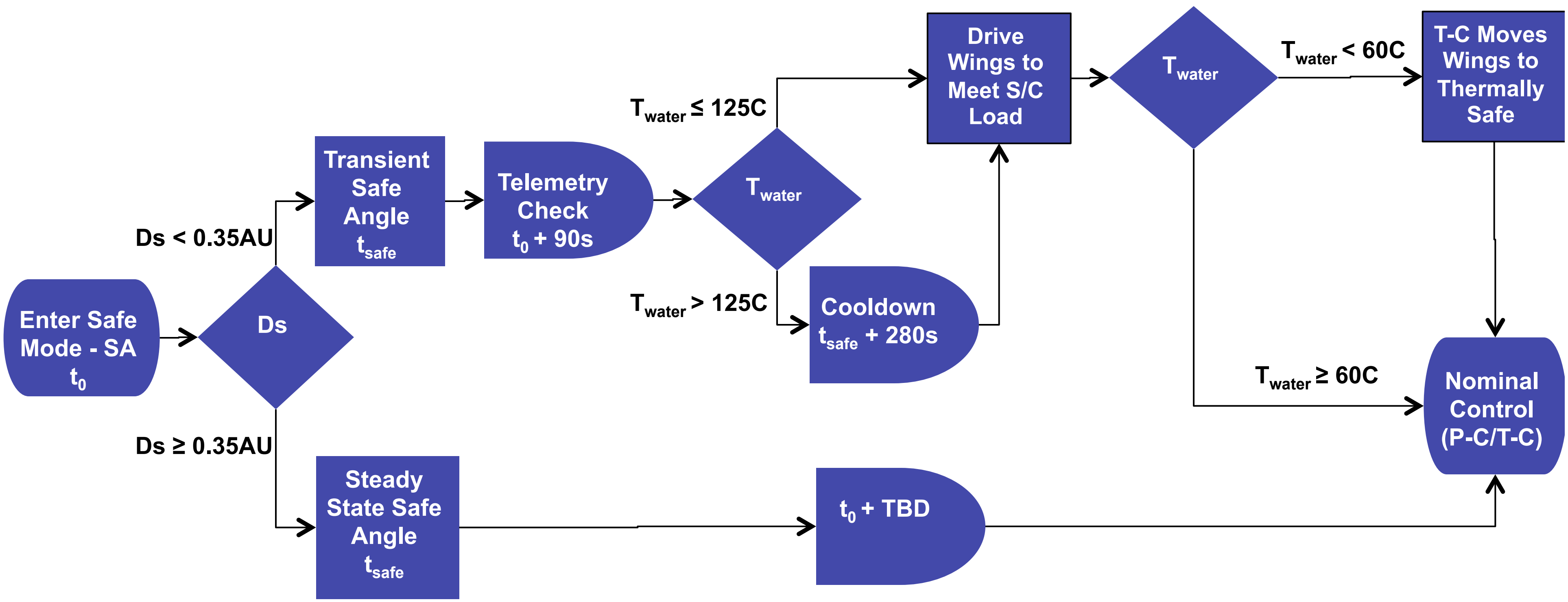

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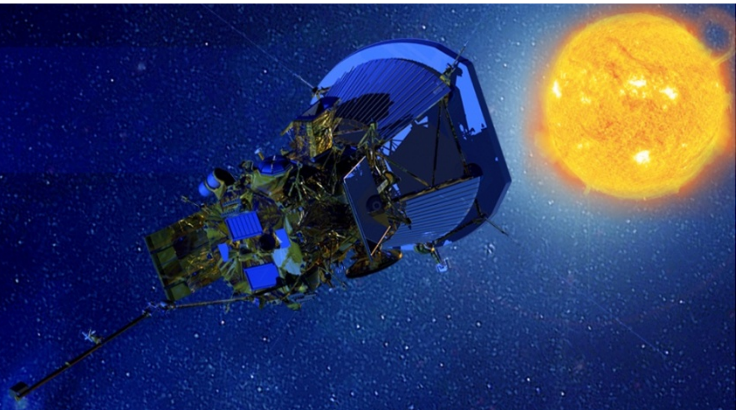

Timing Budgets

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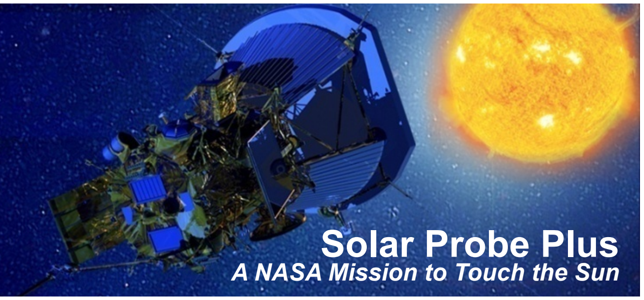
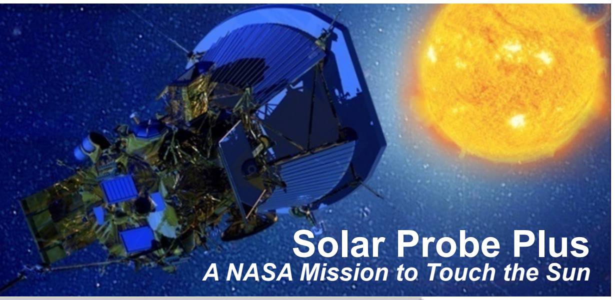
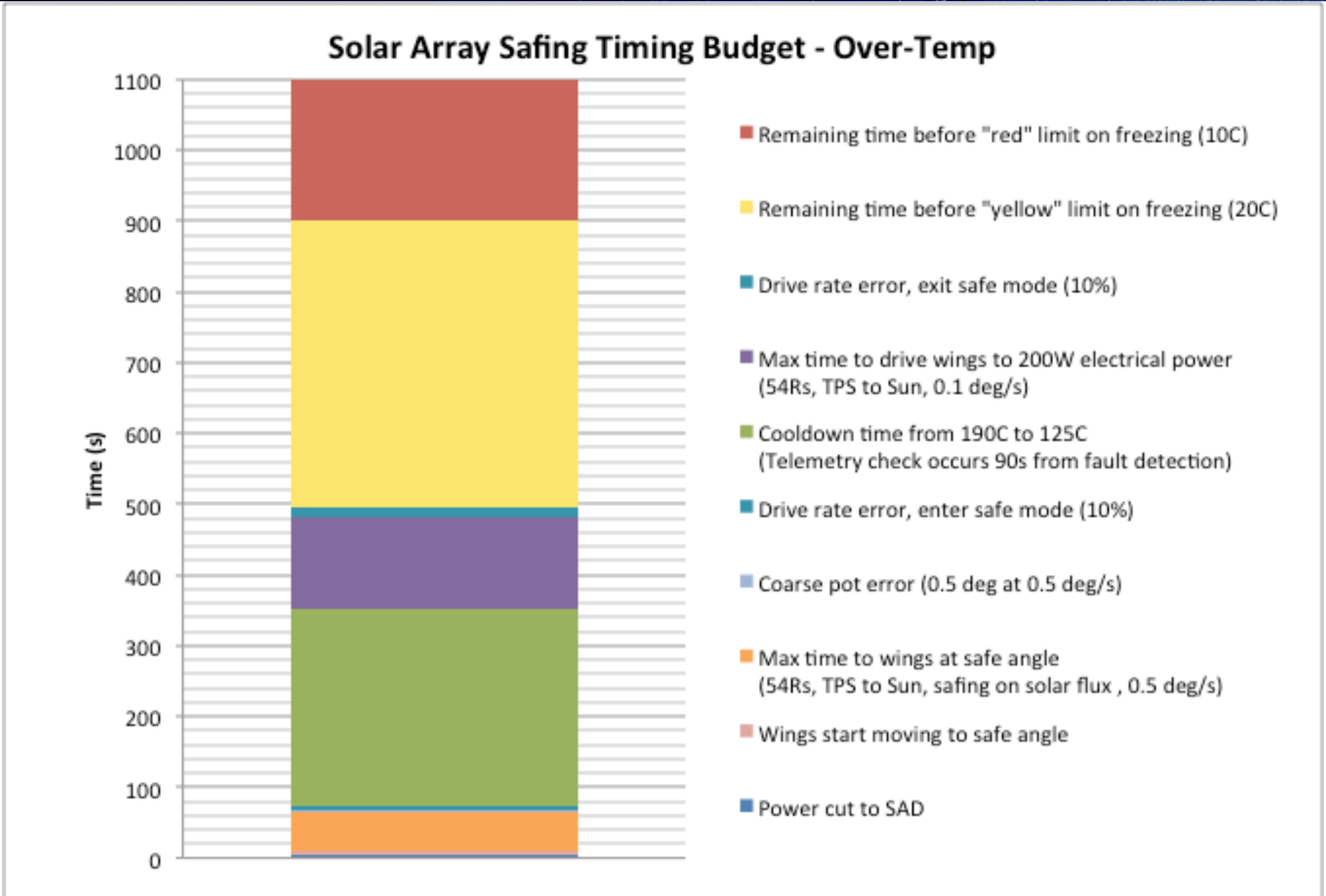
Over-Temp Timing Budget



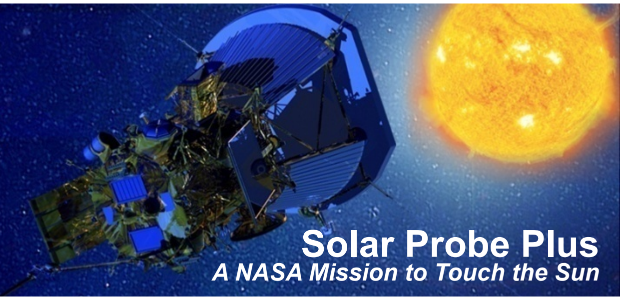
- < 0.35AU: Over-temp timing budget is not critical
  - Wings will be at a transient safe angle and will drive out at 0.1 deg/s until spacecraft power load met (at t = 280s from safe angle reached)
  - Normal P-C/T-C transitions will take over
  - Assuming T > 125C at fault detection and no heat load into the system:
    - 15 min from fault detection to 20C “yellow” limit
    - 18 min from fault detection to 10C “red” limit
  - Assuming T > 125C at 90s telemetry check and no heat load into the system:
    - T_{water} > 60C when wings reach required electrical power
- ≥ 0.35AU: Over-temp timing budget is not critical
  - Wings will be at a steady-state safe angle
    - No danger of freezing or over-heating

Over-Temp Timing Budget



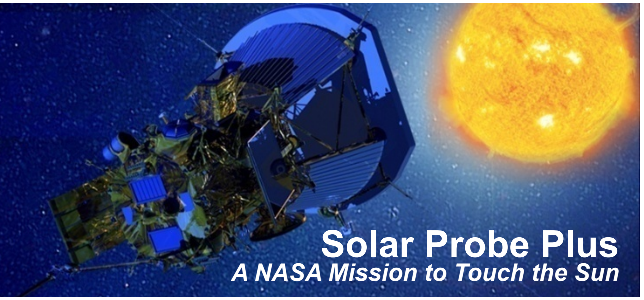


Over-Temp Timing Budget



- **Factors in over-temp timing budget:**
  - **Time to detect fault and cut power to solar array drive (5s, from fault detection)**
  - **Time to begin moving wings to safe angle (10s, from fault detection)**
  - **Time to move wings to defined safe angle at 0.5 deg/s**
    - **Worst-case is 54Rs (56s)**
      - **Assumes starting from solar flux threshold point (“min safe mode entry angle”)**
  - **Error on coarse pot (1s)**
      - **Must target safe angle that is 0.5 deg steeper**
  - **Error on drive rate, entering safe mode (10%)**
    - **Apply to time to move wings to safe angle and to coarse pot error**
  - **Cooldown time (280s, from time at safe angle)**
    - **Assume 190C to 125C**
    - **90s telemetry check occurs within this time**
  - **Time to move wings to 200W electrical power at 0.1 deg/s**
    - **Worst-case is 54Rs (129s)**
    - **Rate will depend on ability to PPT**
  - **Error on drive rate, exiting safe mode (10%)**
  - **Times to thermal limits:**
    - **20C yellow limit (15 min from fault detection)**
    - **10C red limit (18 min from fault detection)**

Low-Temp Timing Budget



- < 0.35AU: Low-temp timing budget is critical
  - Wings will be at a transient safe angle and will drive out at 0.1 deg/s until spacecraft power load met (at t = 90s from fault detection)
  - T-C will take over to return wings to thermally safe operation
  - Assuming T_{water} = 43C at fault detection:
    - 5 min from fault detection to 20C "yellow" limit
    - 8 min from fault detection to 10C "red" limit
- ≥ 0.35AU: Low-temp timing budget is not critical
  - Wings will be at a steady-state safe angle
    - No danger of freezing or over-heating

Low-Temp Timing Budget

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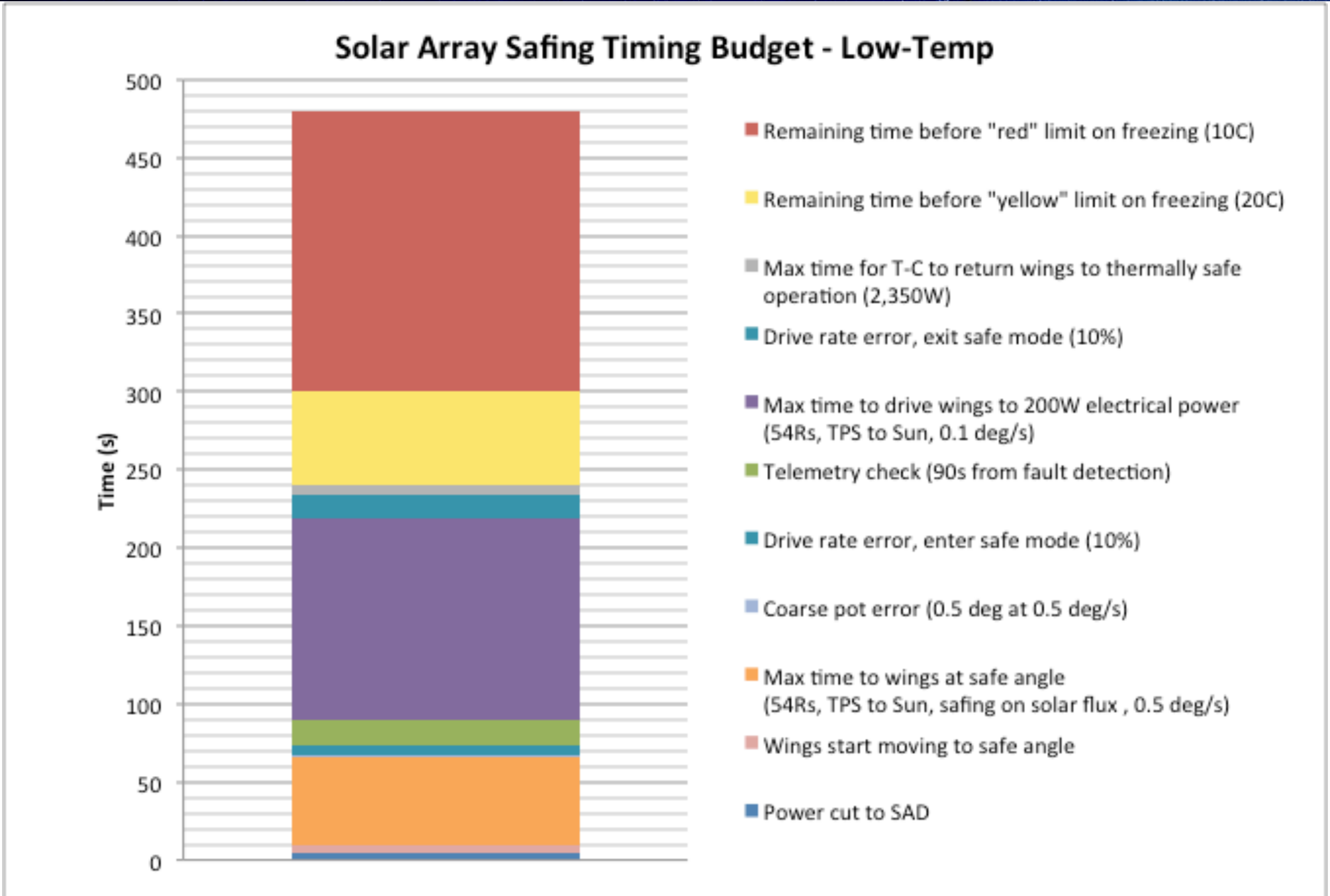
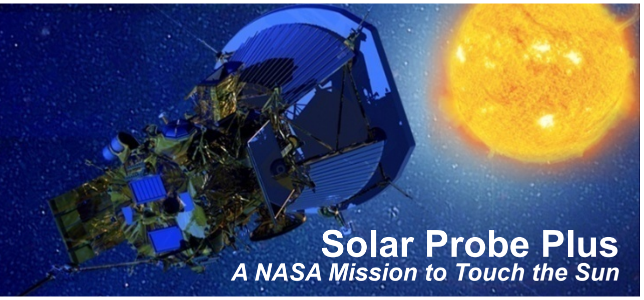


Low-Temp Timing Budget



- Factors in low-temp timing budget:
  - Time to detect fault and cut power to solar array drive (5s, from fault detection)
  - Time to begin moving wings to safe angle (10s, from fault detection)
  - Time to move wings to defined safe angle at 0.5 deg/s
    - Worst-case is 54Rs (56s)
      - Still assume starting from solar flux threshold point (“min safe mode entry angle”), min angle bound not yet defined for low temp (conservative)
  - Error on coarse pot (1s)
      - Must target safe angle that is 0.5 deg steeper
  - Error on drive rate, entering safe mode (10%)
    - Apply to time to move wings to safe angle and to coarse pot error
  - Telemetry check (90s from fault detection)
    - If $T_{water} \leq 125C$, exit safe mode
  - Time to move wings to 200W electrical power at 0.1 deg/s
    - Worst-case is 54Rs (129s)
    - Rate will depend on ability to PPT
  - Time to move wings to 2,350W heat load using T-C
    - Worst-case is 54Rs (6s)
  - Error on drive rate, exiting safe mode (10%)
    - Apply to time to move wings to 200W electrical power and time to move wings to 2,350W heat load

LBSoC and Umbra Violation Timing Budgets

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- Timing budget for LBSoC, umbra violation, and aphelion thermal violation scenarios are enveloped by over-temp and low-temp scenarios
  - Depending on initial temperature, these scenarios will either exit safe mode at 90s ("low temp path") from fault detection or at 280s ("over temp path") from safe angle reached
    - With worst-case starting SoC, battery can support spacecraft load for ~20 min
      - In any scenario, wings will be back out and generating sufficient power to meet the spacecraft load well within 10 min of fault detection
        - 54Rs over-temp is bounding case
    - Telemetry check at 90s before exiting safe mode keeps wings safe in umbra violation scenario as long as possible

Timing budgets allow safing and recovery actions to complete with wings in a known configuration and without violating constraints on cooling system or battery

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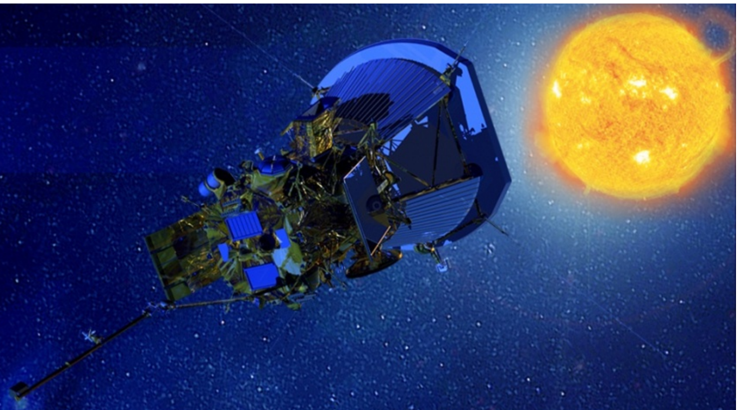

TRL-6 Testing

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Cooling System Test

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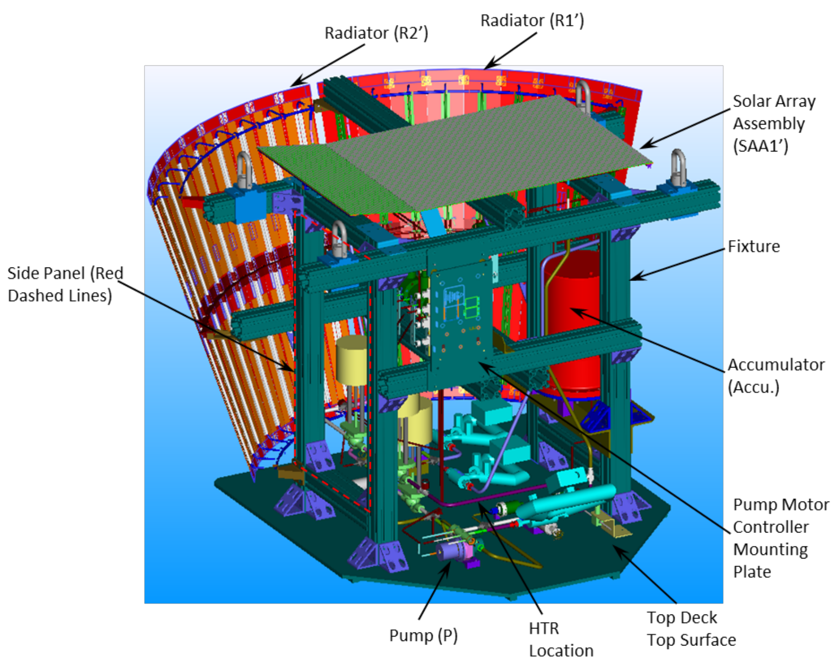
- **HSSSI fabricated one-half size cooling system using full-scale components**
  - **2 full-scale radiators**
  - **1 full-scale platen**
  - **Full size pump and controller electronics**



Cooling System TRL-6 thermal prototype (MLI not shown)

- **Verify critical mission conditions through test**
  - **Steady state operation**
    - **Near Earth - half wet/half dry radiators**
    - **Near Earth - fully wet radiators**
    - **Venus - hot communication slew**
    - **First mission perihelion (35Rs)**
    - **Minimum mission perihelion (9.86Rs) for nominal and stacked worst case heat loads**
  - **Transient operation**
    - **Launch/wet the system**
    - **Venus eclipse**
    - **High Suns anomaly cases**
- **Data collected**
  - **Input power for heaters and electronics**
  - **Volume flow rate**
  - **Component and GSE temperatures (type-T thermocouples)**
- **Results will be incorporated into modeling and development of safing strategy (e.g. temperature time constants, validation of solar flux thresholds)**
- **Occurring Aug 2013**

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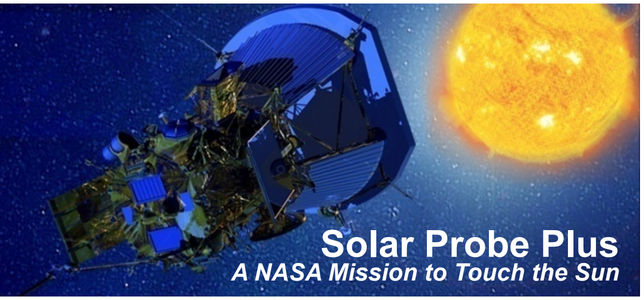
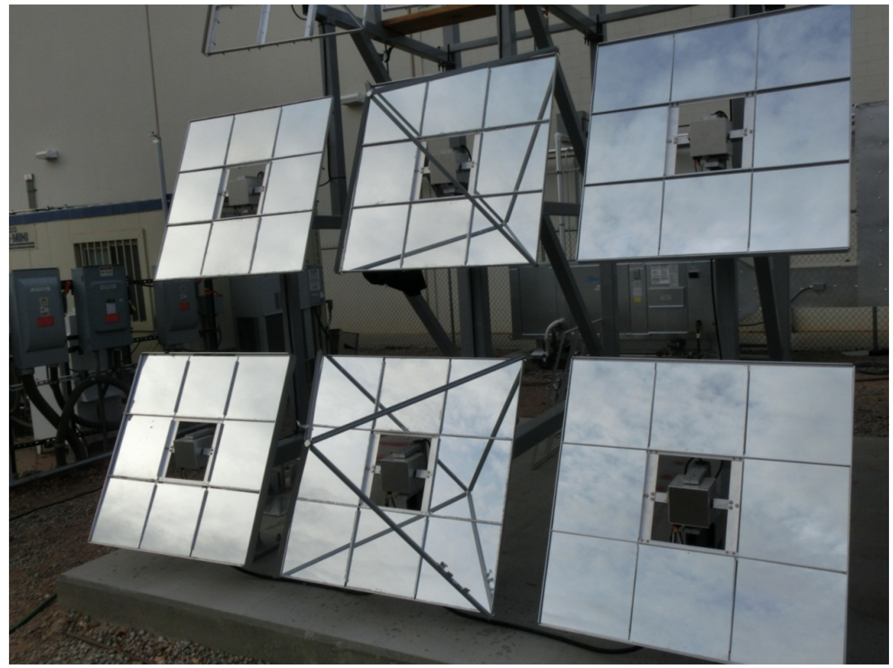
Solar Array Test



- Test article is a full-scale secondary wing fully populated with all part types the flight wing will carry
- Functional testing before and after each exposure includes electrical characterization using a large area pulsed solar simulator and heliostat
- TRL-6 exposures
  - Humidity
  - Thermal vacuum bake with TQCM
  - Forty-one thermal vacuum cycles with TQCM
  - High irradiance (~34 suns) for 45 hours using the substrate's cooling capability
  - Irradiance simulating misalignment between TPS and wing edges using the substrate's cooling capability
  - Non-nominal high irradiance exposure (~77 suns) using the substrate's cooling capability
- Subsequent exposures and tests
  - Arc sensitivity
  - Long duration high irradiance high temperature (174 days) using the substrate's cooling capability
  - Arc testing to failure
- Occurring June – Oct 2013

Solar Array Test



Heliostat Field – shown not fully populated with mirrors (does not need to be fully populated for TRL-6 test, will be for flight tests)

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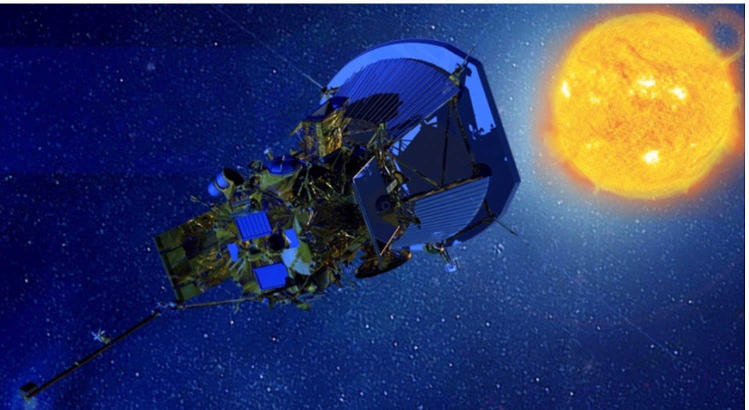

Summary and Future Work

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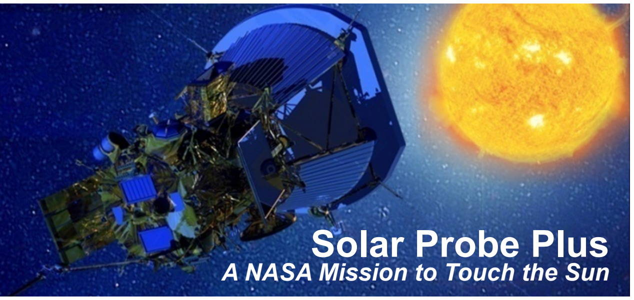
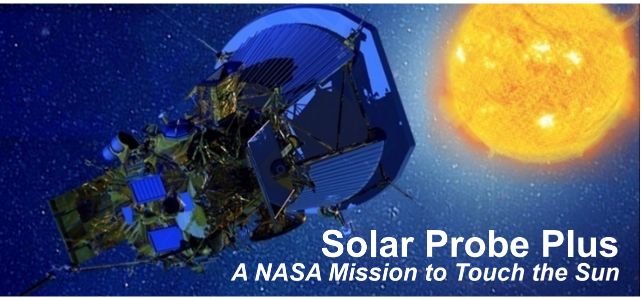
Summary

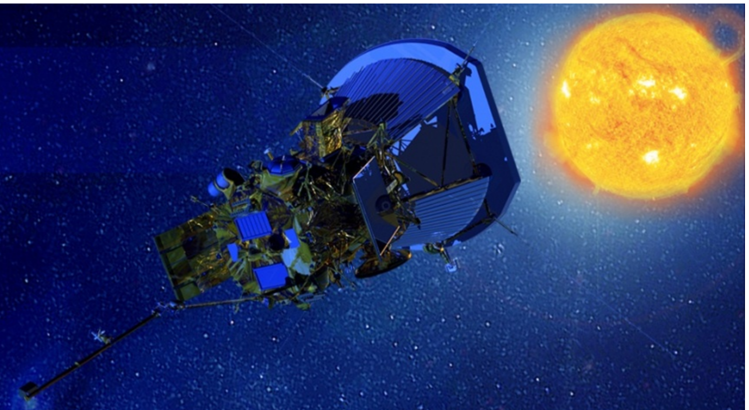


- **Preliminary analysis shows that one solar array safing response, as a function of solar distance and initial temperature, will work for all critical faults, without constraining the design**
  - **Transient safe angle for solar distances < 0.35AU**
    - **Wings move to a tuck configuration with low heat load into the system**
    - **Timing budget allows wings to travel to safe angle, safing and recovery actions to complete, and wings to return to thermally safe operation before cooling system violates freeze limit**
  - **Steady-state safe angle for solar distances ≥ 0.35AU**
    - **Wings move to a configuration with no danger of freezing or over-heating**
- **Solar array/cooling system over-temp will be detected by calculated solar flux and by a combination of measured temperature at platen outlet and calculated heat load**
- **Cooling system low-temp will be detected by measured temperature at platen inlet and on radiators**
- **Solar array safing strategy requires maintenance and calibration of two tables on-board spacecraft:**
  - **Safe angle vs. MET (3 points)**
  - **Suns thresholds vs. MET (TBD points)**
- **Bounding over-temp cases identified for further analysis and testing**

Future Work



- Steady-state and transient thermal analysis
  - Initial steady-state analysis cases run
  - Bounding transient cases for safing on solar flux identified
  - Identify additional transient and steady-state cases to support analysis for safing on temperature and heat load
- Refine solar flux thresholds based on transient analysis and based on analysis of additional solar distance points within 0.35AU
  - Group thresholds by solar distance to define discrete points in table
  - Determine when and how to calibrate table in-flight
- Update approach for solar array position sensing, based on pots vs. resolver trade
- Identify transient cases for TRL-6 cooling system test, incorporate results into modeling and development of safing strategy (e.g. temperature time constants, validation of solar flux thresholds)
- Develop plan for verification
  - Modeling of solar array safing scenarios (integrated G&C/EPS/Thermal model)
  - EPS testbed (G&C model with EPS hardware in the loop)
- Refine Level III Solar Array Operation and Safing Requirements, derive Level IV requirements



Backup

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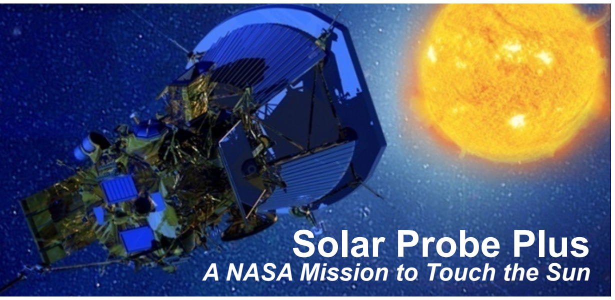
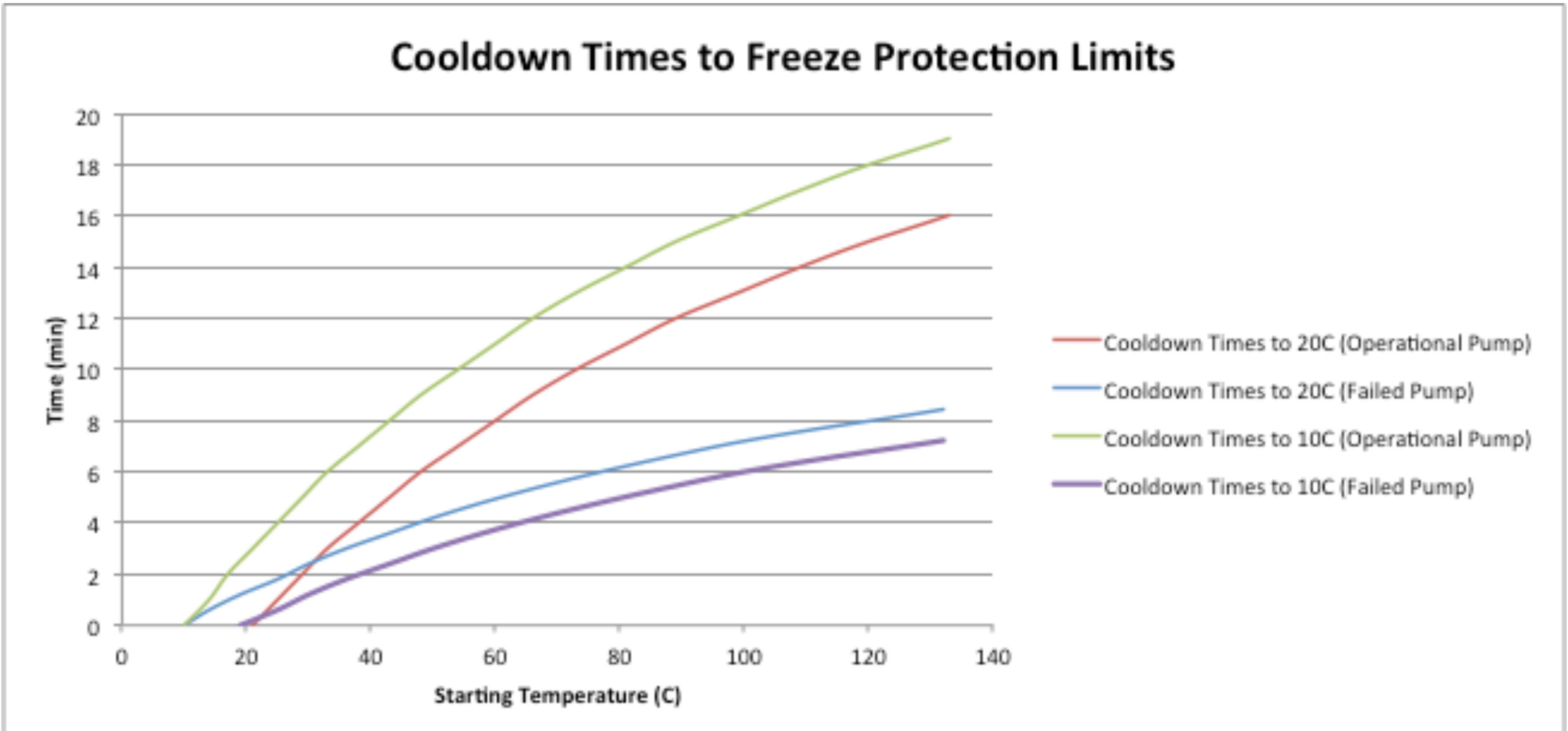
Freeze Protection



Operational Pump		
Starting Temp (C)	Time to 20C (min)	Time to 10C (min)
133	16	19
120	15	18
109	14	17
99	13	16
89	12	15
81	11	14
73	10	13
66	9	12
60	8	11
54	7	10
48	6	9
43	5	8
38	4	7
33	3	6
29	2	5
25	1	4
21	0	3
17		2
14		1
10		0

Failed Pump		
Starting Temp (C)	Time to 20C (min)	Time to 10C (min)
132	8.4	7.2
115	7.8	6.6
100	7.2	6.0
88	6.6	5.4
77	6.0	4.8
67	5.4	4.2
58	4.8	3.6
50	4.2	3.0
43	3.6	2.4
36	3.0	1.8
30	2.4	1.2
25	1.8	0.6
19	1.2	0.0
14	0.6	
10	0.0	

Freeze Protection



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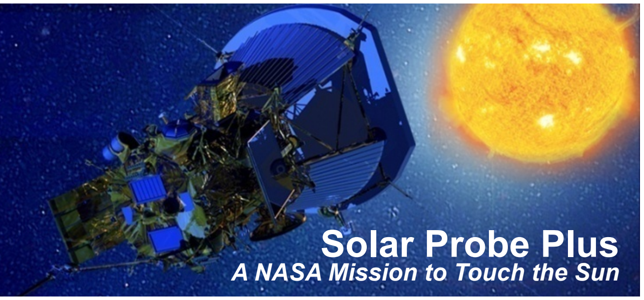
Integrated G&C/EPS/Thermal Model

- **Modeling and simulation done using Simulink**
  - **Capability to run nominal or transient simulations using a set of parameters**
  - **Capability to run Monte Carlo simulations over a range of parameters**
- **Model contains**
  - **G&C model**
  - **EPS model**
  - **Autonomous flap angle control**
  - **Cooling system model**

Integrated G&C/EPS/Thermal Model

Model Portion	Description	Input Parameters	Outputs
G&C model	Models spacecraft dynamics, includes closed-loop actuator control	Orbit Spacecraft geometry Mass properties Sensor parameters (noise, gain) Actuator parameters Disturbances	Spacecraft position Spacecraft attitude Spacecraft rates
EPS model	Models irradiance on solar array, Solar array and battery performance, power conversion model, includes PPT algorithm	Spacecraft load Solar array string out Solar array degradation Battery parameters Solar array parameters (cell layout, current/voltage characteristics)	Solar array operation, Battery I, V, SoC
Autonomous flap angle control	Models flap angle control modes: power, temperature, fixed angle	Solar array drive rate Solar array drive step-size Control update frequency	Flap angle
Cooling system model	Models thermal performance of cooling system, includes water dynamics	Water cycle time Cooling system parameters Temperature time constants	Water temperature Cell temperature

Calibration of Potentiometers



- Calibration of potentiometers performed twice per orbit (TBR)
  - Occurs at approximately 0.5AU, must be under ground contact
    - Min solar distance to exercise full range of wing flap and feather angles
- Calibration of flap angle
  - 1. Activate redundant ECU to read redundant pots (in addition to primary pots)
  - 2a. Drive solar array into TPS umbra; monitor pots, solar array power, sensor cells
  - 3a. Use solar array power and sensor cell drop-off as a reference for calibration
  - 2b. Drive solar array to 0 deg flap; monitor pots, solar array power, sensor cells
  - 3b. Use known solar flux as reference for calibration
  - Provides verification of pot position and counted steps
  - Requires good spacecraft sun-pointing knowledge
- Calibration of feather angle
  - 1. Activate redundant ECU to read redundant pots (in addition to primary pots)
  - 2. Drive solar array to 0 deg flap
  - 3. Feather the wing angle; monitor pots, total current, current of two leading edge strings, and sensor cells
  - 4. Use known cosine effect with current and sensor cell measurements as reference for calibration
    - If pots do not match, known cosine effect will tell which pot is “better”

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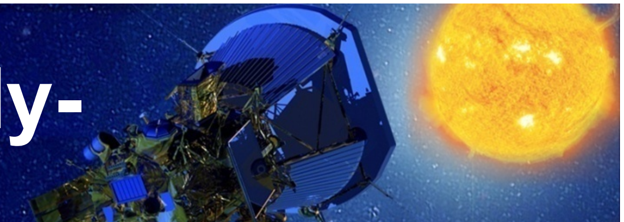
Worst-Case Off-Nominal Steady-State Analysis Results

- **Steady-state analysis run for 9.5Rs, 20Rs, 54Rs, and 75Rs transient cases from safing on solar flux**
  - **Bound both total load and wing travel time to safe**
- **Results show in which cases the cooling system and cell temperatures will exceed thermal limits**
  - **≥ 75Rs, steady-state temperatures remain below limits**
  - **9.5Rs, 20Rs, and 54Rs, steady-state temperatures exceed thermal limits**
    - ***These results are used to determine which cases need further transient analysis, and are not indicative of conditions that will be seen in-flight***

Worst-Case Off-Nominal Steady-State Analysis Results



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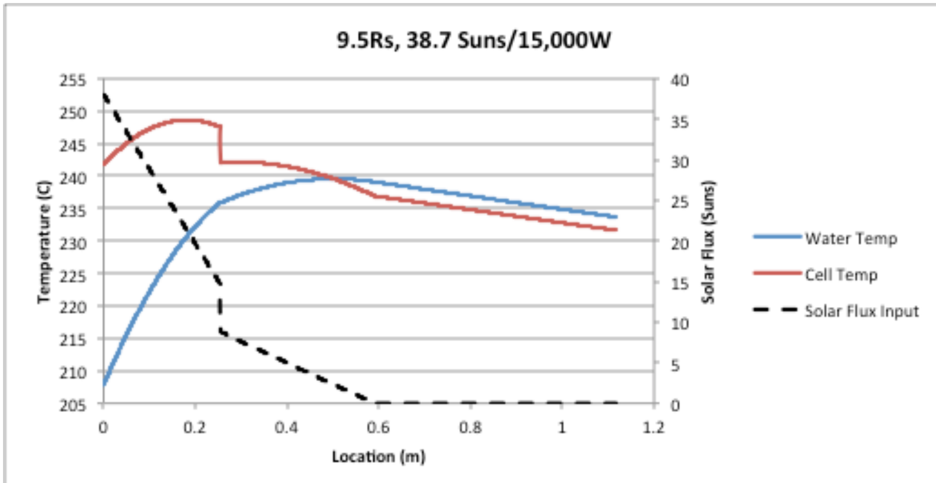

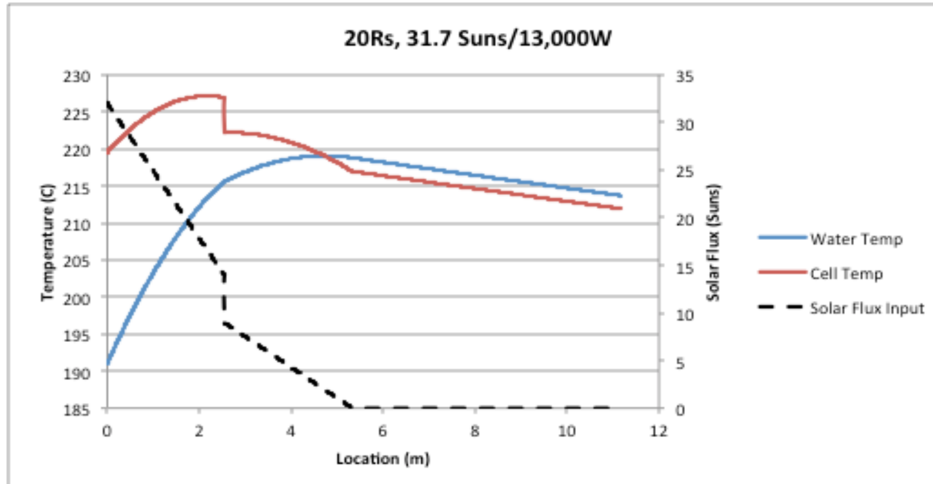

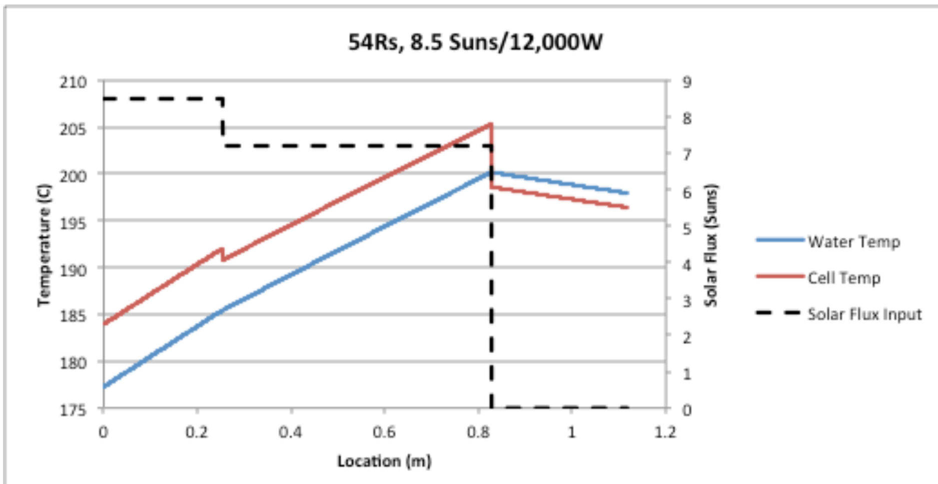

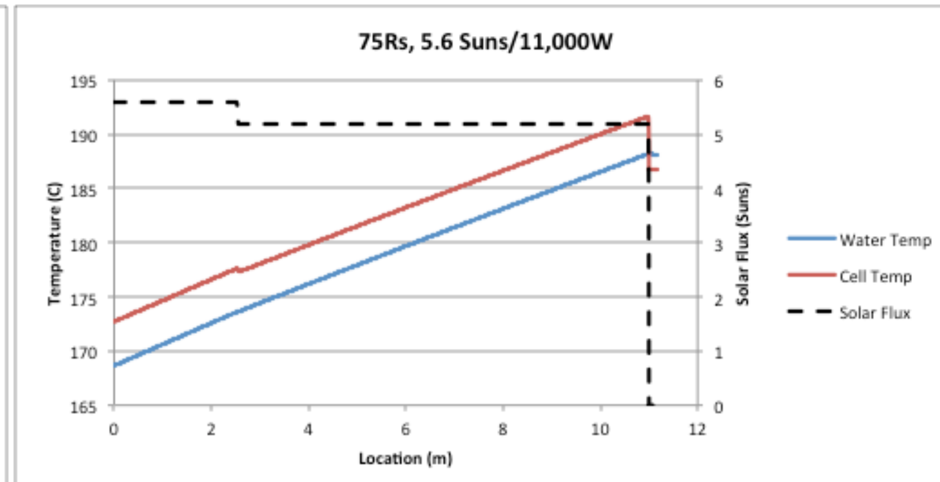

Note: Steady-state analysis results used to determine transient cases for analysis; actual temperatures in flight will not exceed 190C on platen (water) and 240C on cell

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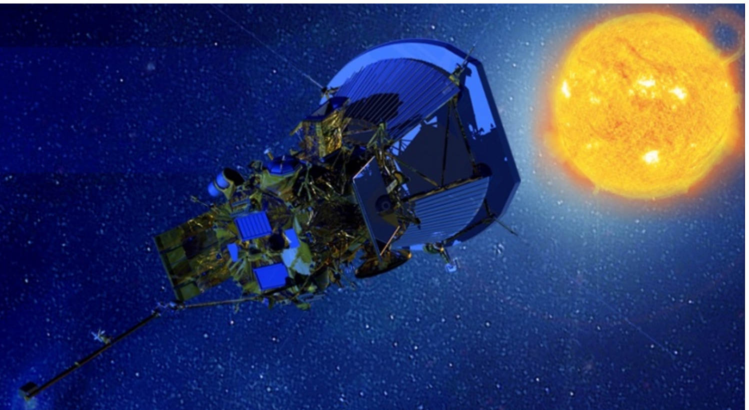

Preliminary Verification & Validation Plans

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Topics

- FM V&V Overview
- Documentation
- FM System-Level Testing
- Near-Term V&V Work

FM V&V Overview (1 of 2)

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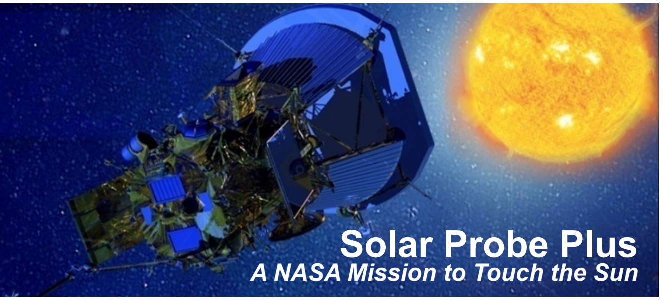
- FM V&V adheres to 7434-9099 SPP System Validation & Verification Plan
- FM requirements are distributed among various levels; the V&V of these requirements is correspondingly distributed
  - FM lead is responsible for V&V of L2 & L3 FM requirements.
  - Subsystem leads are responsible for V&V of FM requirements at L4 and lower levels.
    - FM lead is responsible for ensuring these requirements are adequately validated and verified.

FM V&V Overview (2 of 2)



- **Validation of FM comprised of three activities:**
  - **FM requirements validation**
    - Accomplished via the formal requirements review process
    - On-going process which is concurrent with the cyclical refinement of the FM concept, architecture, and design
  - **FM design validation**
    - Accomplished with FM timing, interference, and coverage analyses during design and peer review process
  - **FM end-product validation**
    - Accomplished with FM scenario testing and “day in the life” scenarios during mission simulations

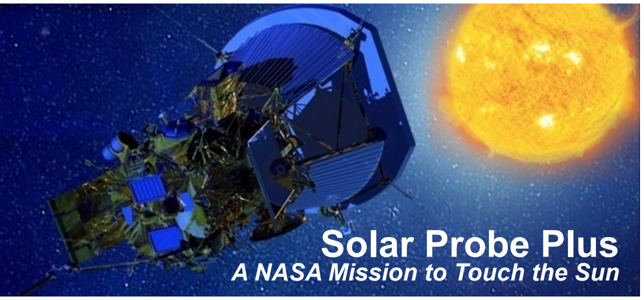
- **Verification of FM requirements may be accomplished by: Test, Analysis, Demonstration, or Inspection**
  - GOAL: Verify by test when possible
- **Verification of L2, L3, and L4 FM requirements tracked in DOORS**

Verification and Test Documentation

- **7434-XXXX Fault Management Verification and Test Plan (preliminary release prior to CDR)**
  - Describes verification and test philosophy
  - Describes test platforms to be utilized
  - Outlines SPP FM test campaign
  - Identifies list of scenario tests
  - For each test, describes starting conditions, high-level test outline, requirements verified
  - Includes requirements-to-test allocation matrix
  - Identifies any non-testable requirements which require analysis and exceptions to test-as-you-fly

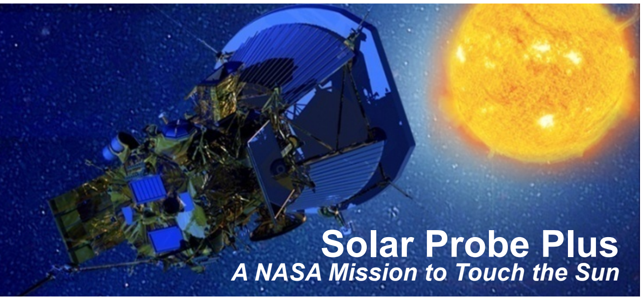
- **7434-9397 – 7434-9427 Fault Management Test Procedures (released prior to and during I&T)**
  - Individual test procedures developed for each scenario test
  - Describes detailed information necessary to run the test on the spacecraft
  - Serves as the ‘as-run’ document

FM System-Level Testing



- **FM scenario tests are:**
  - Black-box, requirements based tests
  - Objective is to verify mission and element-level FM requirements
  - Designed and performed by FM team
  - Similar to MSIMs (scenario based) except one or more faults are injected during the simulation
- **FM scenario test must prove that:**
  1) Spacecraft can perform the scenario correctly (i.e., without fault injection)
  2) Spacecraft can autonomously recover to nominal operations when required within time constraints
- **Majority of L2 and L3 FM requirements verification accomplished via scenario testing, however, may be tested via other system-level spacecraft tests to take advantage of test schedule and personnel**
  - MSIMs
  - CPTs
  - Autonomy path testing

Near-Term V&V Work



- **Validation of FM requirements is on-going via requirements reviews and FM design validation analyses**
- **Continue to identify verification method for each FM requirement**
- **Further develop FM test philosophy**
  - **Test campaign encompasses both FM testing and autonomy testing**
    - Many FM requirements are levied on the autonomy subsystem
    - FM leverages the autonomy path testing for scenario testing with a goal of testing all paths on spacecraft prior to FM scenario testing
  - **Coordinate schedule for use of test platforms (shared resource)**
  - **Identify plan for re-test and regression testing**
  - **Identify preliminary FM test list and incompressible test list**

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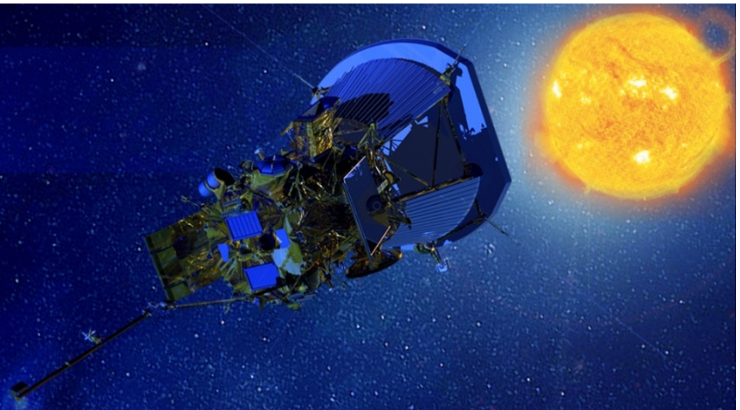

Wrap-Up

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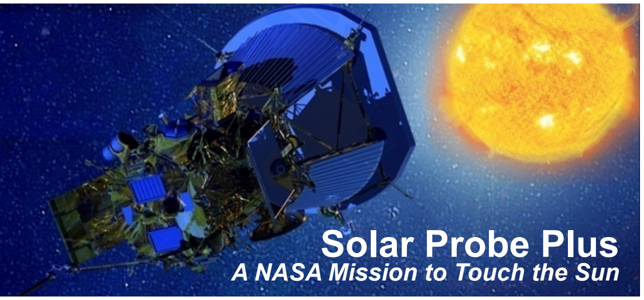
Wrap-up



- **Forward Work**
- **Upcoming milestones/schedule**
- **Review of action items**
- **Comments from review team**

Forward Work

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- **Refine / iterate fault response development**
- **Refine / iterate on Level 4 requirements development**
- **Define aphelion thermal violation detection approach**
- **Critical sequence development**
- **V&V planning**

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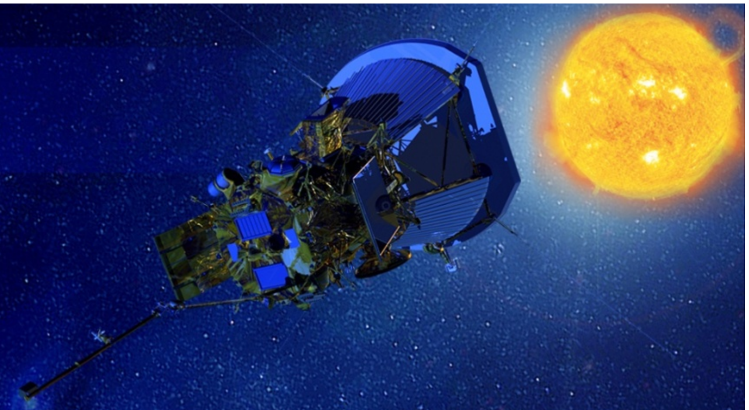

BACK-UP

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