Solar Probe Plus

A NASA Mission to Touch the Sun

Wide-Field Imager for Solar PRobe Plus (WISPR)

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SPACE SCIENCE DIVISION

APL

The Johns Hopkins University

APPLIED PHYSICS LABORATORY

Contents

Science Objectives

- **SPP Level-1 Science Objectives**
- **Trace the flow of energy that heats and accelerates the solar corona and solar wind.**
- **Determine the structure and dynamics of the plasma and magnetic fields at the sources of the solar wind.**
- **Explore mechanisms that accelerate and transport energetic particles.**
- **To address these objectives, WISPR will:**
  - **Derive the 3D structure of the solar corona through which the in-situ measurements are made to determine the sources of the solar wind.**
  - **Provide density power spectra over a wide range of structures (e.g., streamers and pseudostreamers, equatorial coronal holes) for determining the roles of turbulence, waves, and pressure-balanced structures in the solar wind.**
  - **Measure the physical properties (speed, density jump) of SEP-producing shocks and their CME drivers as they evolve in the corona and inner heliosphere.**

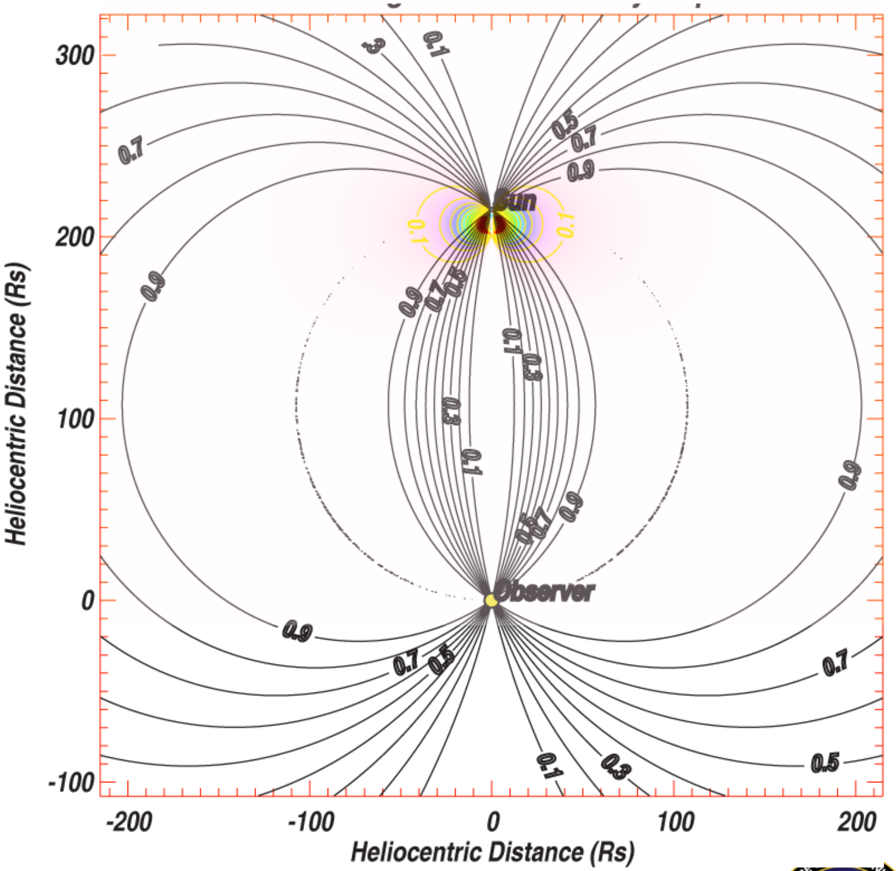
Simulation of WISPR Observations during a 10Rs SPP Perihelion

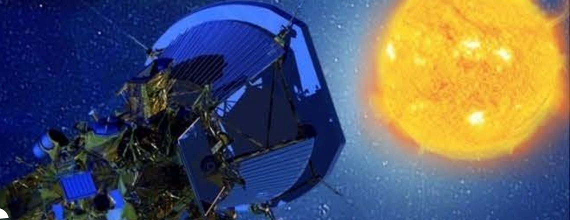
Based on STEREO/SECCHI observations from 1 AU. Frame speed: 2.5 days/sec.

WISPR Unique Science

- **The Varying Heliocentric Distance Transforms WISPR From a Remote (at Aphelia) to a Local (at Perihelia) Imager**
- **WISPR Is the First Imager to Provide Density Power Spectra at Rates Similar to *in-situ* Instruments (< 60 sec) but at Multiple Locations at Once**
- **WISPR Will Provide the First 3D Coronal Density Maps through Tomography.**
- **WISPR Images Contain Scattering from Dust. Although NOT Level 1 Science, WISPR**
  - **Will be the First Imager to Prove/Refute the Existence of a Dust –Free zone around the Sun.**
  - **Will Image the final moments of Sungrazing Comets.**

Sensitivity to Thomson Scattering Emission at 0.05 AU compared to an instrument at 1AU.



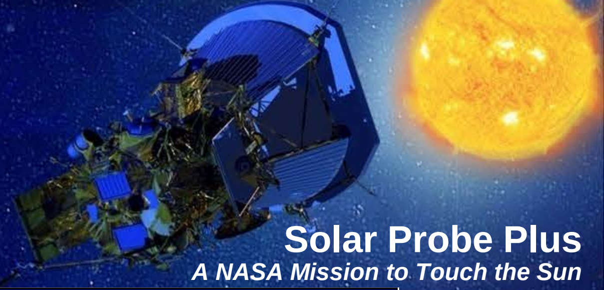


Primary Measurement Requirements

		Science Measurement Reqt	
Reqt ID	**Reqt Title**	**Baseline**	**Threshold**
MRD-95.1	**Wavelength Range**	Visible broadband	N/C
MRD-95.2	**Field of View**	≥ 76° radial x ≥ 20° transverse at 14° elongation to ≥ 44° transverse at 90° elongation	≥ 74.75° radial x ≥ 20° transverse at 15.25° elongation to ≥ 44° transverse at 90° elongation
MRD-95.3	**Inner FOV Boundary (Solar elongation)**	≤ 14°	≤ 15.25
MRD-95.4	**Spatial Resolution**	≤ 6.4 arcmin	≤ 7.5 arcmin
MRD-95.5	**Photometric Accuracy (Pixel Signal to Noise Ratio)**	≥ 20	≥ 8
MRD-95.6	**Cadence**	≤ 16.5 min	≤ 22.5 min

N/C= No Change

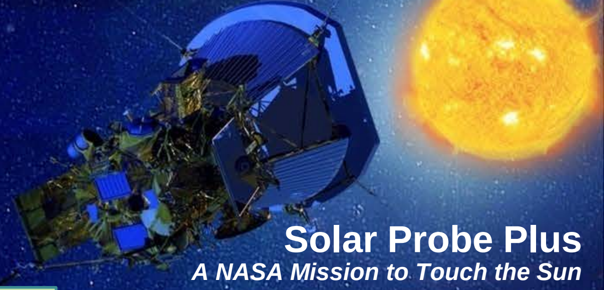
WISPR Driving Requirements



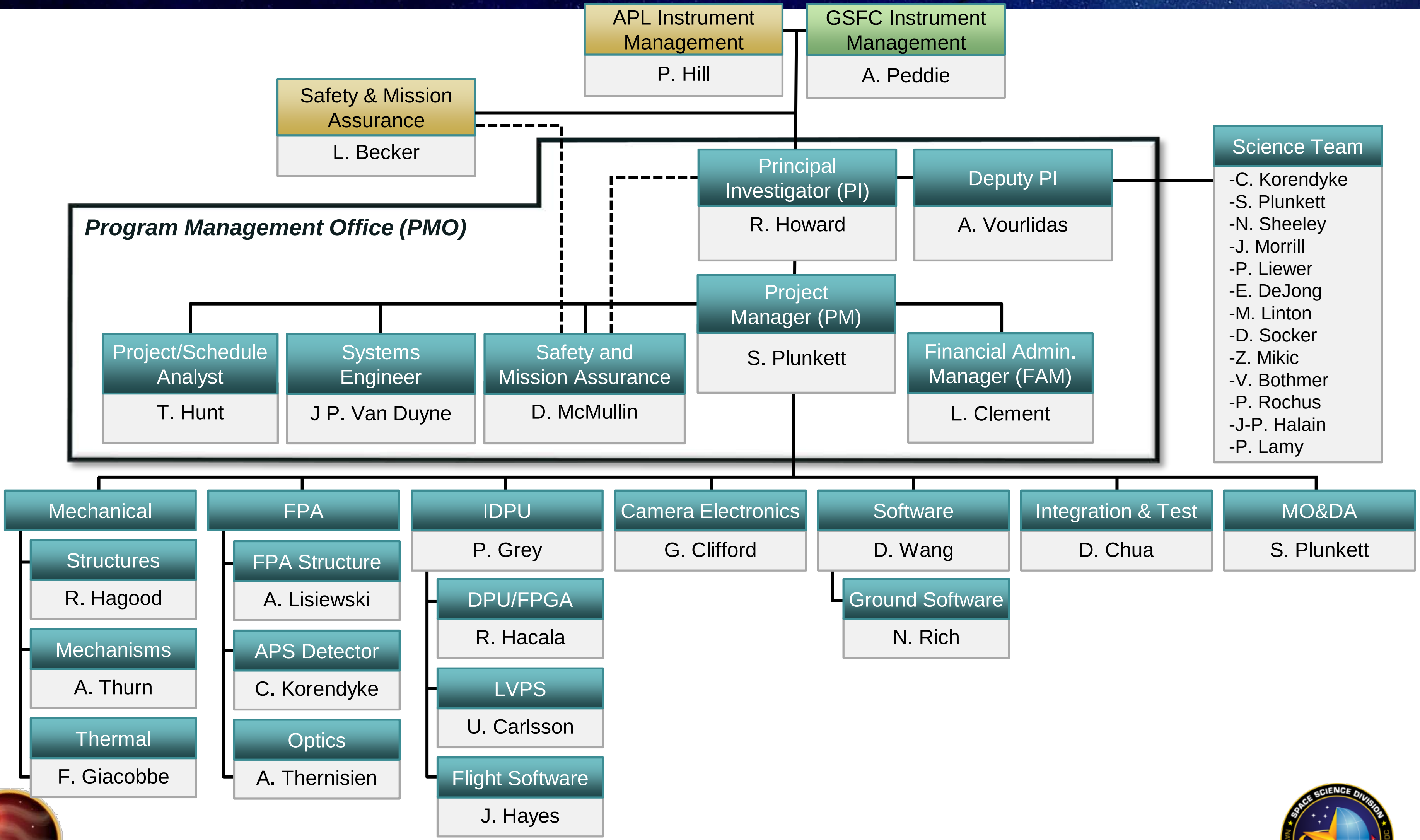
Science Objective	**1. Trace the flow of energy that heats and accelerates the solar corona and solar wind.**			**2. Determine the structure and dynamics of the plasma and magnetic fields at the sources of the solar wind.**			
Science Question #	**1a**	**1c**		**2a**	**2b**		**2c**
Science Question	How is energy from the lower solar atmosphere transferred to, and dissipated in, the corona and solar wind?	How do the processes in the corona affect the properties of the solar wind in the heliosphere?		How does the magnetic field in the solar wind source regions connect to the photosphere and the heliosphere?	Are the sources of the solar wind steady or intermittent?		How do the observed structures in the corona evolve into the solar wind?
Science Measurement Objective	Time history of velocity, brightness of small scale features in coronal holes and streamers	Location, morphology of the stream interface boundaries, and wave turbulence		Map morphology of solar structure to SPP orbit	Time history of velocity, brightness of solar wind features, and wave turbulence		Velocity, acceleration and mass density of evolving structures
Science Measurements	Height-time plot and mass measurements of solar wind features	Height-time plot and mass measurements of solar wind features	Power spectra of density fluctuations at different heliocentric distances	Images of coronal and heliospheric solar wind structures in visible	Height-time plot and mass measurements of solar wind features	Power spectra of density fluctuations at different heliocentric distances	Height-time plot and mass measurements of solar wind features
Measurement Priority	**S**	**R**	**R**	**R**	**R**	**R**	**R**
Observation Requirements							
Image Type	Visible broadband			Visible broadband			
Scene Radial Coverage	14.0° to 90°	14.0° to 100° ^{1} 14.0° to 90° ^{2,3,4}	14.0° to 20.0°	14.0° to 100° ^{1} 14.0° to 90° ^{2,3,4}		14.0° to 20.0°	14.0° to 100° ^{1} 14.0° to 90° ^{2,3,4}
Scene Transverse Coverage	25° ^{7a} to 55° ^{7c}		12°	25° ^{11a} to 55° ^{11c}		12°	25° ^{11a} to 55° ^{11c}
Solar Latitude Coverage	-45° to +40° ^{7a}; -33° to +10° ^{7b}		-25° to +15°	-45° to +40° ^{11a}; -33° to +10° ^{11b}		-25° to +15°	-45° to +40° ^{11a}; -33° to +10° ^{11b}
Image Spatial Resolution (arcmin)	≤ 6.4^{1,2,3a} ; ≤ 12.8^{3b} ≤ 19.2^{3c,4a} ; ≤ 25.6^{4b}		≤ 6.4	≤ 6.4^{1,2,3a} ; ≤ 12.8^{3b} ≤ 19.2^{3c,4a} ; ≤ 25.6^{4b}		≤ 6.4	≤ 6.4^{1,2,3a} ; ≤ 12.8^{3b} ≤ 19.2^{3c,4a} ; ≤ 25.6^{4b}
Photometric Accuracy (Pixel Signal to Noise Ratio)	≥ 20 ^{5}, ≥ 5 ^{6}		≥ 20	≥ 20 ^{5}, ≥ 5 ^{6}		≥ 20	≥ 20 ^{5}, ≥ 5 ^{6}
Cadence (min)	≤ 40 min ^{1,2,3} ≤ 80 min ^{4}	≤ 2.5 min ^{1a} ≤ 4.5 min ^{1b} ≤ 9 min $^{1c, 2a, 3a}$ ≤ 16.5 min ^{2b,3b,4a} ≤ 40 min $^{3c, 4b}$ ≤ 80 min ^{4c}	≤ 4 sec	≤ 40 min ^{1,2,3} ≤ 80 min ^{4}	≤ 2.5 min ^{1a} ≤ 4.5 min ^{1b} ≤ 9 min $^{1c, 2a, 3a}$ ≤ 16.5 min ^{2b,3b,4a} ≤ 40 min $^{3c, 4b}$ ≤ 80 min ^{4c}	≤ 4 sec	≤ 18 min ^{1,2} ≤ 40 min ^{3}, ≤ 80 min ^{4}
Spacecraft Distance from Sun	0.046 to 0.25 AU		0.046 to 0.07 AU	0.046 to 0.25 AU		0.046 to 0.07 AU	0.046 to 0.25 AU
Daily Observing Period	24 hrs		≥ 4 hrs*	24 hrs		≥ 4 hrs*	24 hrs
Orbital Observing Period (days	10		1.5	10		1.5	10
Baseline Mission Observing Period (days)	240		15	240		15	240

WISPR Driving Requirements

Science Objective	**3. Explore mechanisms that accelerate and transport energetic particles.**		**G1. Explore dusty plasma phenomena in the near-Sun environment and their influence on the solar wind and energetic particle formation.**	
Science Question #	**3a**	**3c**	**G1a**	**G1b**
Science Question	What are the roles of shocks, reconnection, waves and turbulence in the acceleration of energetic particles?	How are energetic particles transported radially across magnetic field lines from the corona to the heliosphere?	What is the dust environment in the inner heliosphere?	What is the nature of dust-plasma interactions and how does dust modify the spacecraft environment close to the Sun?
Science Measurement Objective	Location, morphology and speed of shocks near the Sun	Morphology, velocity, acceleration of CMEs and shocks out to SPP orbit	F-corona brightness, morphology and variability as a function of heliocentric distance	Location, morphology of CMEs and coronal evolution along SPP orbit
Science Measurements	High cadence height-time plots and density measurements of CME fronts	High cadence height-time plots and density measurements of CME fronts	Image of F-corona during the orbit	Image and height plots of the corona ahead of SPP passage
Measurement Priority	**R**	**R**	**R**	**R**
Observation Requirements				
Image Type	Visible broadband		Visible broadband	
Scene Radial Coverage	14.0° to 60°	14.0° to 90°	14.0° to 100° [1, 2, 3] 14.0° to 90° [4]	
Scene Transverse Coverage	25° [11a] to 55° [11c]		25° [11a] to 55° [11c]	
Solar Latitude Coverage	-45° to +40° [11a]; -33° to +10° [11b]		-45° to +40° [11a]; -33° to +10° [11b]	
Image Spatial Resolution (arcmin)	≤ 6.4		≤ 6.4[1,2,3a]; ≤ 12.8[3b] ≤ 19.2[3c,4a]; ≤ 25.6[4b]	
Photometric Accuracy (Pixel Signal to Noise Ratio)	≥ 20 [5], ≥ 5 [6]		≥ 20 [5], ≥ 5 [6]	
Cadence (min)	≤ 5 min	≤ 5 min [1a, 1b] ≤ 10 min [1c]	≤ 80 min	≤ 40 min [1,2,3] ≤ 80 min [4]
Spacecraft Distance from Sun	0.046 to 0.07 AU		0.046 to 0.25 AU	
Daily Observing Period	24 hrs		24 hrs	
Orbital Observing Period (days	1.5		10	
Baseline Mission Observing Period (days)	15		240	



WISPR Team



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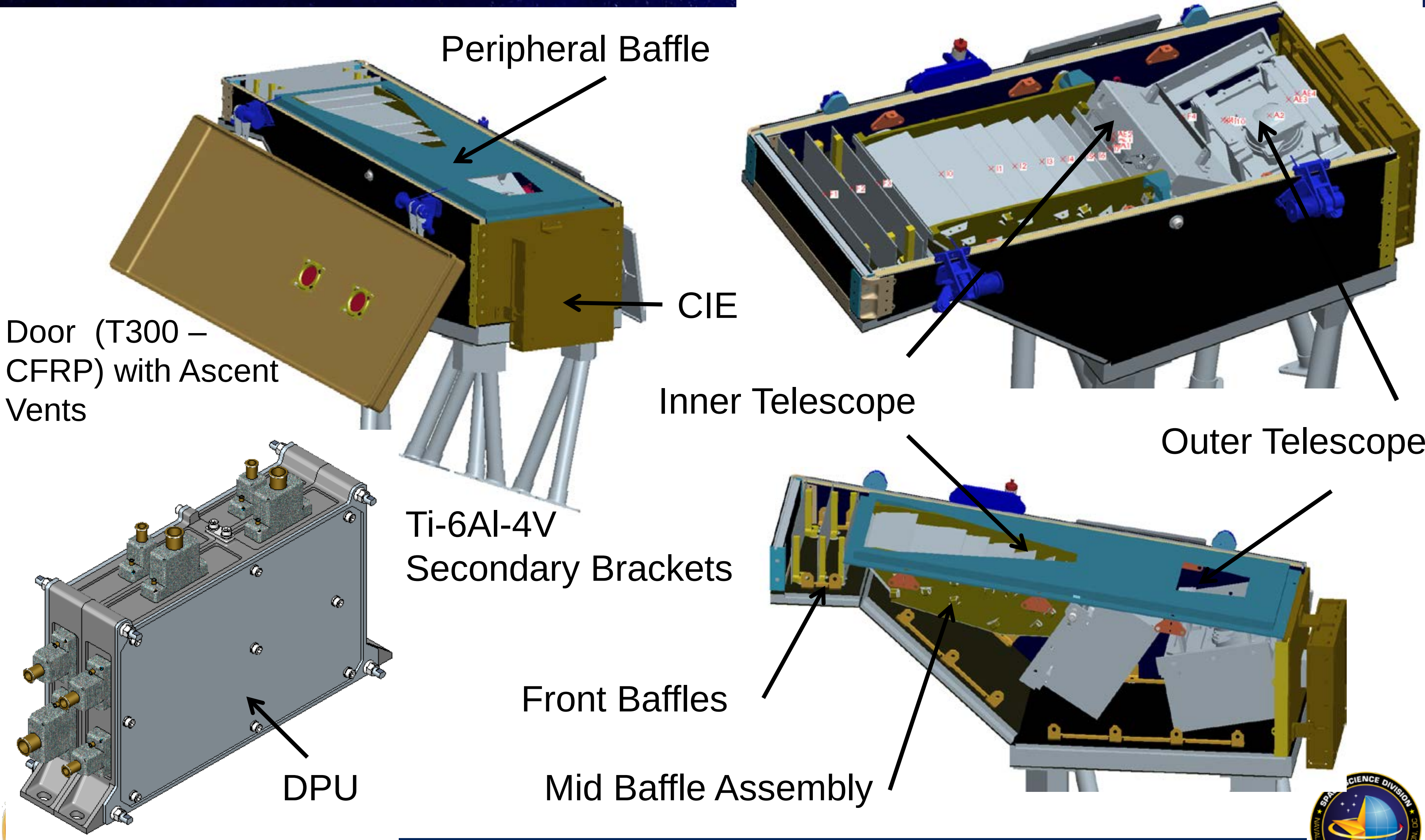
WISPR Instrument Configuration



Peripheral Baffle

CIE

Door (T300 – CFRP) with Ascent Vents

Inner Telescope

Outer Telescope

Ti-6Al-4V Secondary Brackets

Front Baffles

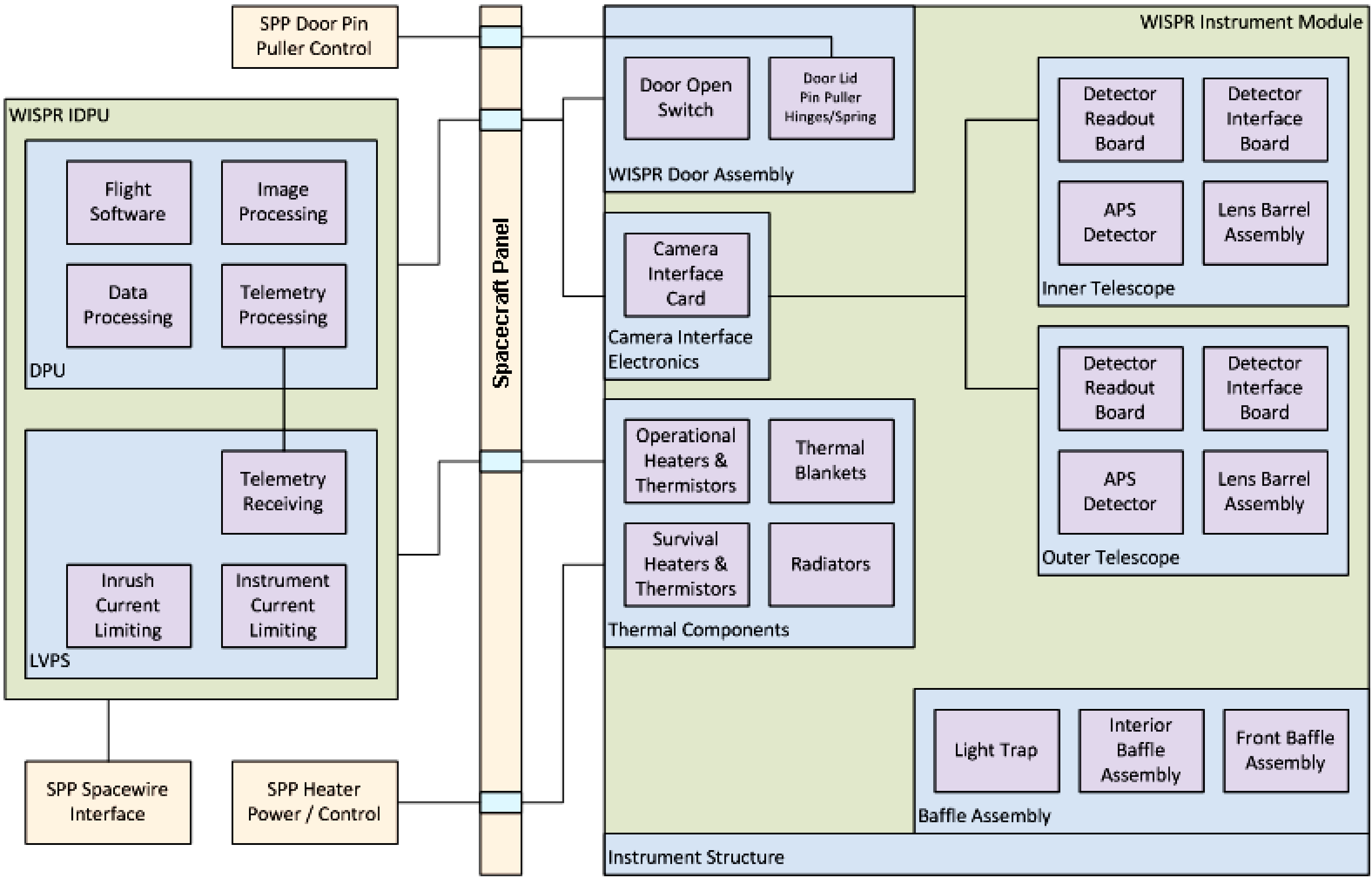
DPU

Mid Baffle Assembly

Technical Changes Since SRR/MDR

Change since SRMDR	Reason for Change	Impact on Resources
Dual Telescope	**To Meet the L1 Science Requirements by Mitigating the Increased Stray Light Sources at the Fields Antennae in the WISPR Field of Regard**	**Mass: Modest** **Power: Minimal**
Internal Bulk Memory	**To Buffer the TM Flow to the S/C**	**Mass: Negligible** **Power: Modest**

Physical Block Diagram



SPP Door Pin Puller Control

WISPR IDPU

- DPU
  - Flight Software
  - Image Processing
  - Data Processing
  - Telemetry Processing
- LVPS
  - Telemetry Receiving
  - Inrush Current Limiting
  - Instrument Current Limiting

SPP Spacewire Interface

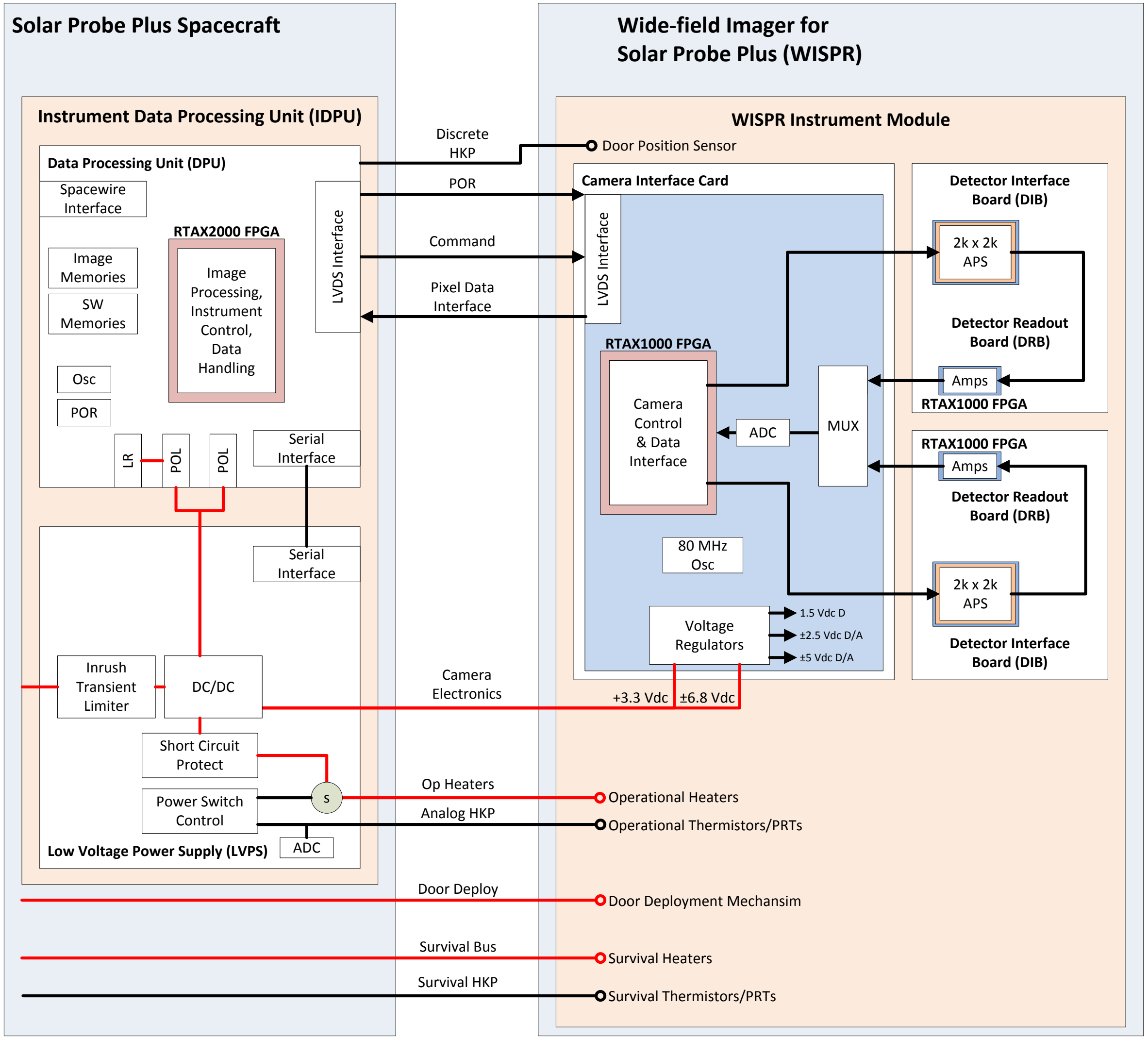
SPP Heater Power / Control

Spacecraft Panel

WISPR Instrument Module

- WISPR Door Assembly
  - Door Open Switch
  - Door Lid Pin Puller Hinges/Spring
- Camera Interface Electronics
  - Camera Interface Card
- Thermal Components
  - Operational Heaters & Thermistors
  - Thermal Blankets
  - Survival Heaters & Thermistors
  - Radiators
- Inner Telescope
  - Detector Readout Board
  - Detector Interface Board
  - APS Detector
  - Lens Barrel Assembly
- Outer Telescope
  - Detector Readout Board
  - Detector Interface Board
  - APS Detector
  - Lens Barrel Assembly
- Baffle Assembly
  - Light Trap
  - Interior Baffle Assembly
  - Front Baffle Assembly
- Instrument Structure

Electrical Block Diagram



Solar Probe Plus Spacecraft

Instrument Data Processing Unit (IDPU)

Data Processing Unit (DPU)

Spacewire Interface

Image Memories

SW Memories

Osc

POR

RTAX2000 FPGA

Image Processing, Instrument Control, Data Handling

LVDS Interface

LR

POL

POL

Serial Interface

Serial Interface

Inrush Transient Limiter

DC/DC

Short Circuit Protect

Power Switch Control

S

ADC

Low Voltage Power Supply (LVPS)

Discrete HKP

POR

Command

Pixel Data Interface

Camera Electronics

Op Heaters

Analog HKP

Door Deploy

Survival Bus

Survival HKP

Wide-field Imager for Solar Probe Plus (WISPR)

WISPR Instrument Module

Door Position Sensor

Camera Interface Card

LVDS Interface

RTAX1000 FPGA

Camera Control & Data Interface

ADC

MUX

80 MHz Osc

Voltage Regulators

1.5 Vdc D

±2.5 Vdc D/A

±5 Vdc D/A

+3.3 Vdc

±6.8 Vdc

Detector Interface Board (DIB)

2k x 2k APS

Detector Readout Board (DRB)

Amps

RTAX1000 FPGA

RTAX1000 FPGA

Amps

Detector Readout Board (DRB)

2k x 2k APS

Detector Interface Board (DIB)

Operational Heaters

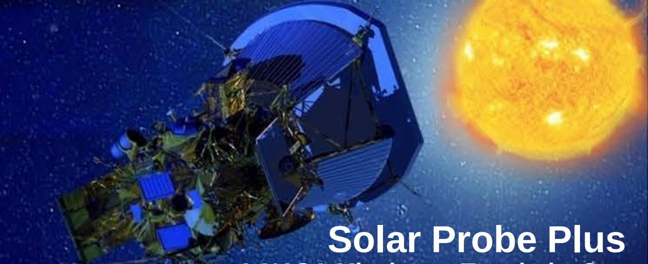
Operational Thermistors/PRTs

Door Deployment Mechansim

Survival Heaters

Survival Thermistors/PRTs

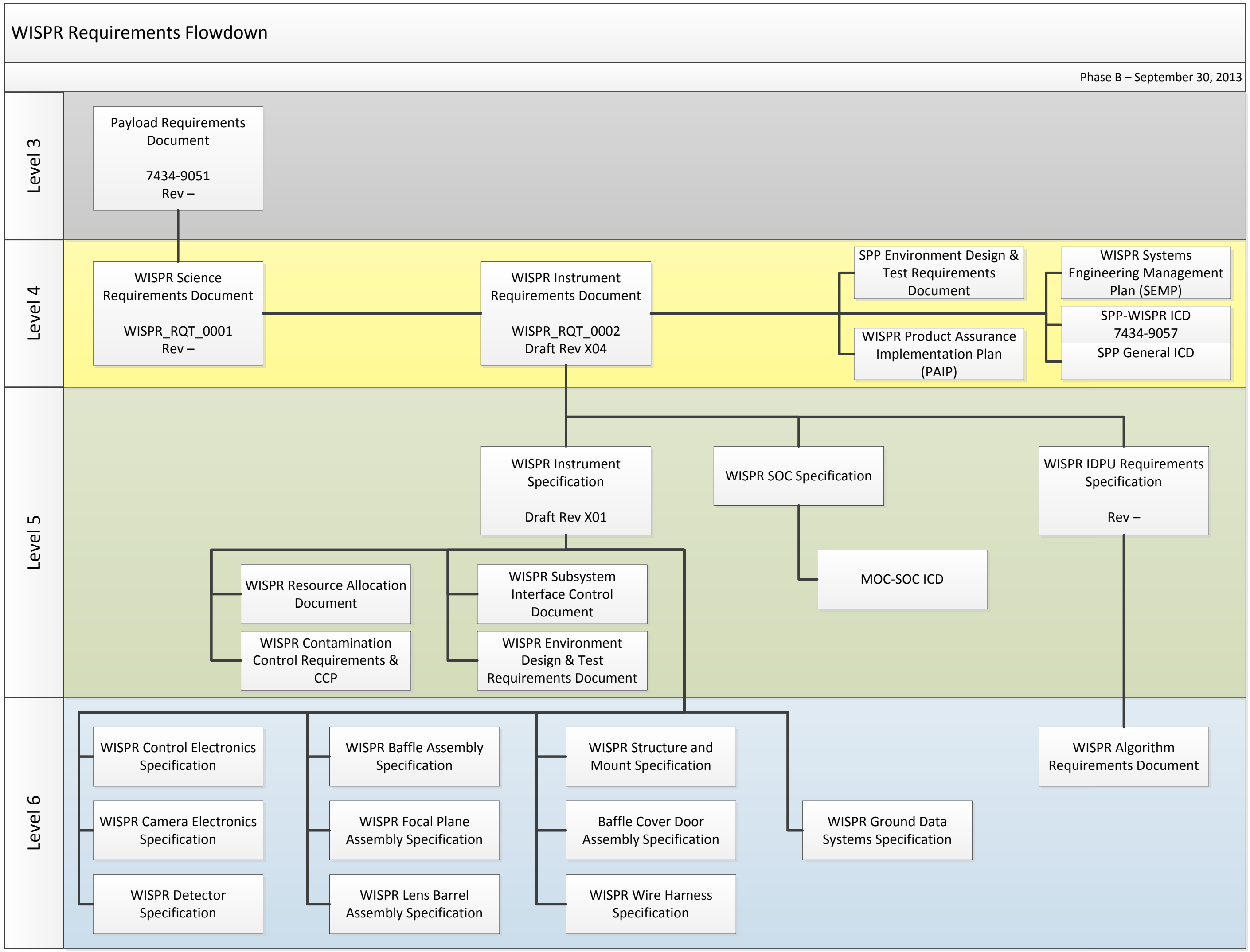
Top-Level Performance Requirements



		Science Measurement Reqt			
Reqt ID	**Reqt Title**	**Baseline**	**Threshold**	**Capability**	**Margin**
MRD-95.1	**Wavelength Range**	Visible broadband	N/C	490-740 nm	Complies
MRD-95.2	**Field of View**	≥ 76° radial x ≥ 20° transverse at 14° elongation to ≥ 44° transverse at 90° elongation	≥ 74.75° radial x ≥ 20° transverse at 15.25° elongation to ≥ 44° transverse at 90° elongation	Tel 1: 48^{o} dia. 40^{o}x40^{o} readout Tel 2: 70^{o} dia. 58^{o}x58^{o} readout	Complies
MRD-95.3	**Inner FOV Boundary**	≤ 14°	≤ 15.25	≤ 13°	Complies
MRD-95.4	**Spatial Resolution**	≤ 6.4 arcmin	≤ 7.5 arcmin	Tel 1: 2.2 arcmin Tel 2: 4.0 arcmin	Complies
MRD-95.5	**Photometric Accuracy (Pixel SNR)**	≥ 20	≥ 8	Sum up to 128 images	Complies
MRD-95.6	**Cadence**	≤ 16.5 min	≤ 22.5 min	FF: 2-7 min	Complies

N/C= No Change

Document Tree



WISPR Requirements Flowdown

Phase B – September 30, 2013

Level 3

Payload Requirements Document
7434-9051
Rev –

Level 4

WISPR Science Requirements Document
WISPR_RQT_0001
Rev –

WISPR Instrument Requirements Document
WISPR_RQT_0002
Draft Rev X04

SPP Environment Design & Test Requirements Document

WISPR Product Assurance Implementation Plan (PAIP)

WISPR Systems Engineering Management Plan (SEMP)

SPP-WISPR ICD
7434-9057

SPP General ICD

Level 5

WISPR Instrument Specification
Draft Rev X01

WISPR SOC Specification

WISPR IDPU Requirements Specification
Rev –

WISPR Resource Allocation Document

WISPR Contamination Control Requirements & CCP

WISPR Subsystem Interface Control Document

WISPR Environment Design & Test Requirements Document

MOC-SOC ICD

Level 6

WISPR Control Electronics Specification

WISPR Camera Electronics Specification

WISPR Detector Specification

WISPR Baffle Assembly Specification

WISPR Focal Plane Assembly Specification

WISPR Lens Barrel Assembly Specification

WISPR Structure and Mount Specification

Baffle Cover Door Assembly Specification

WISPR Wire Harness Specification

WISPR Ground Data Systems Specification

WISPR Algorithm Requirements Document

Electronics Top-Level Requirements

- **Startup and Shutdown of the IDPU and WISPR Instrument Module**
- **Mission Execution (Observation Scheduling)**
- **Telemetry Generation and Prioritization**
- **Autonomous Camera Control**
- **Image Processing Functionality**
- **Provide Data Buffer Storage for Flow Control to Spacecraft**
- **Camera Electronics and Spacecraft Interface**
- **Ground Isolation**
- **Control of exposure, gain and readout of APS detector in up to 3 readout regions**
- **Commanded voltage levels to mitigate radiation damage**
- **Low camera system noise (<2 DN)**
- **Detector Calibration Modes (LED lamps, Gain, CTE, Lag, etc)**
- **Minimize Mass/Power Resources**

Thermal Top-Level Requirements

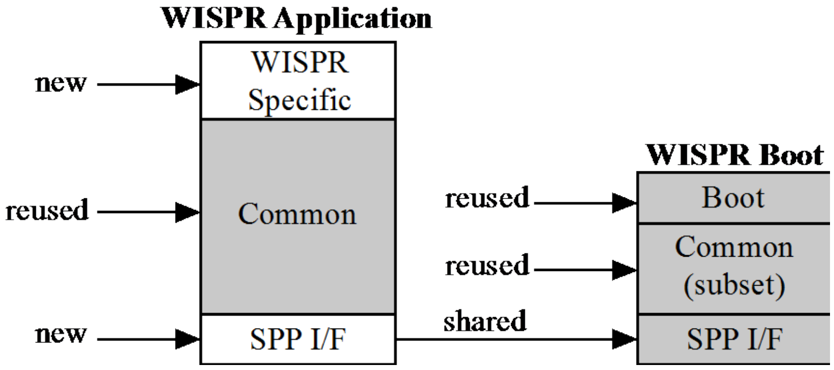
- Provide thermal zones to maintain the instrument temperatures during operations and survival
- Keep temperatures of the optical systems above their minimum temperature in both operating mode and survival mode
- Provide radiators to passively cool the detectors
- Thermally Isolate the detectors from the camera electronics
- Provide a heater to warm up the one-shot door mechanism to its release temperature
- Provide heaters to enable “room-temperature” annealing of the detectors
- Provide stability in temperature of camera electronics during observations
- Minimize Power Resources

Mechanical Driving Requirements

- **Maintain position of front baffle relative to TPS**
- **Maintain baffles in precise co-alignment over large temperature range relative to optical systems**
- **Maintain Pointing of the Optical Systems**
- **Maintain Detectors at the Focal Plane of the Optical System**
- **Provide Passive Cooling of the Detectors**
- **Shield Optical Systems from Stray Light Reflections from Spacecraft**
- **Structural Loads and minimum frequency in accordance with SPP Environmental Design Document**
- **Baffle Cover to protect baffles during ground operations and launch**
- **Materials, Surface Finishes and Vent/Purge in accordance with WISPR Contamination Control Plan**
- **Minimize Mass**

WISPR Software Architecture and Top Level Requirements

- Top Level Requirements
    - Accept and implement observation schedules and configurations
    - Perform image collection and processing as specified in schedule
    - Generate Science, HK telemetry
    - Provide operational heater control
    - Perform Health & Safety Checks
- WISPR application software
    - WISPR-specific software
    - Common software (reused)
    - SPP spacecraft interface software
- WISPR boot software
    - Boot software (reused)
    - Common software (reused)
    - SPP spacecraft interface software (shared with application)



Internal Interface Definition

WISPR Subsystem	Subsystem Organization	Mechanical Interface Control Drawings (MICDs)										Electrical ICDs		
		Mounting Interface	Envelope (w/ Keepout Zone)	Connector Location	Heater/Thermistor Location	Blanket Location	Radiator Location	Wire Harness, Purge Line Routing	Vent, Purge Port, Witness Plate Locations	Calibration LED Locations	Alignment Flat/Cube Location	Connector, Pin, Bond Pad Definitions	Power Interface (Voltage, Current Limits)	Data Interfacce
IT Detector Interface Board (DIB)	NRL Code 8200 Electronics	X	X									X	X	X
IT Detector Readout Board (DRB)		X	X	X								X		
OT Detector Interface Board (DIB)		X	X									X	X	X
OT Detector Readout Board (DRB)		X	X	X								X		
Camera Interface Electronics (CIE)		X	X	X	X	X		X				X		
IT Detector Package (including DIB)	SRI	X	X									X	X	X
OT Detector Package (including DIB)		X	X									X	X	X
IT Lens Barrel Assembly	Optics Vendor	X	X	X	X	X		X	X		X			
OT Lens Barrel Assembly		X	X	X	X	X		X	X		X			
Door Components (ERM, Hinges, Switches, Stops)	NRL Code 8200 Mechanisms	X	X	X	X									
Instrument Data Processing Unit (IDPU)	APL											X		
IT Focal Plane Assembly	ATK			X	X	X	X	X	X	X		X		
OT Focal Plane Assembly				X	X	X	X	X	X	X		X		
WISPR Instrument Module (WIM)				X	X	X		X	X	X	X	X		

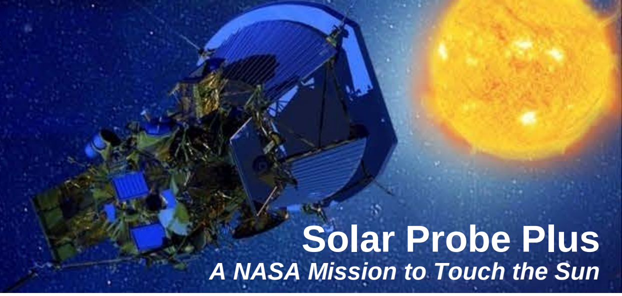
WISPR Resources: Mass, Power, Telemetry

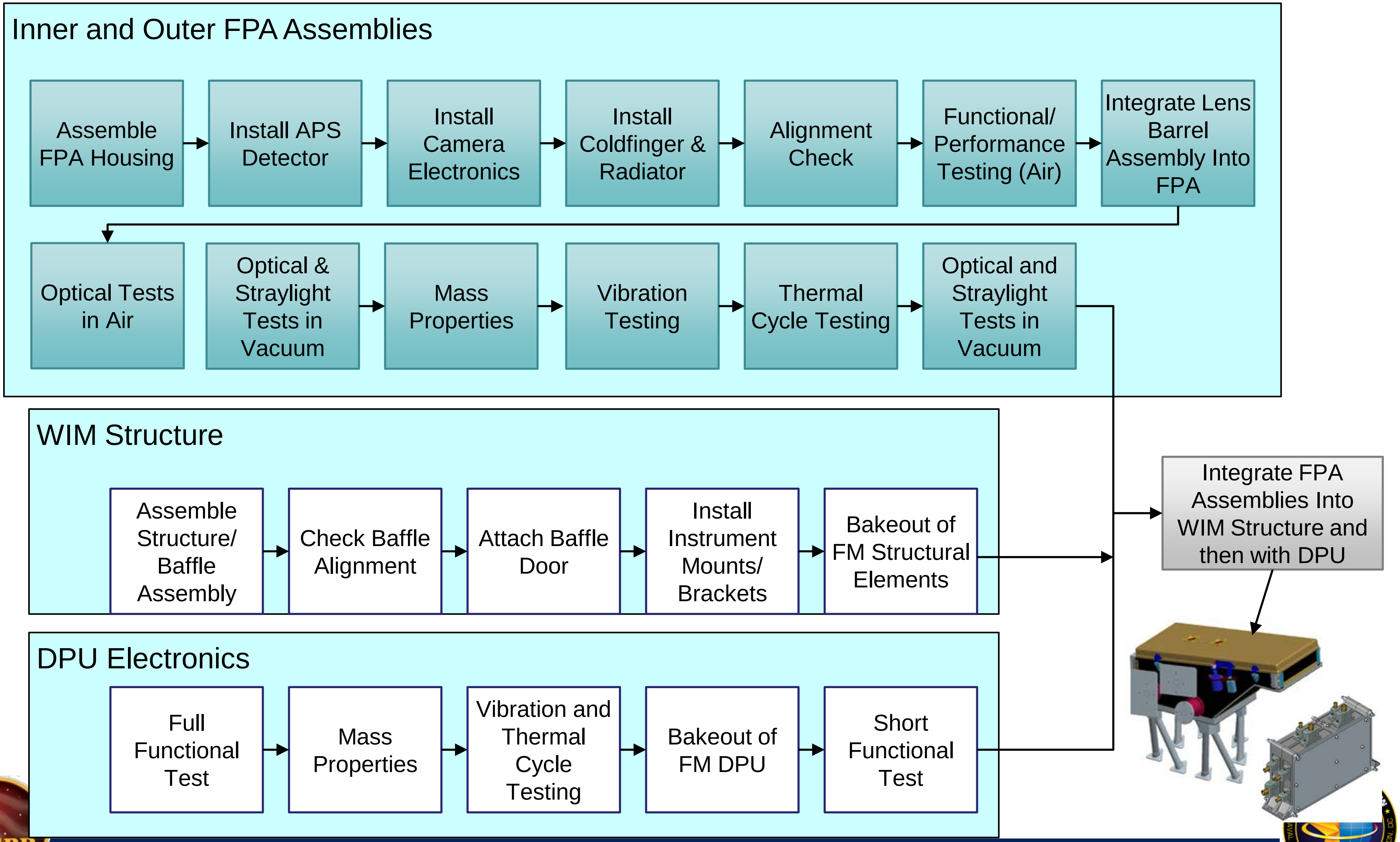
	WIM CBE	WIM Cont.	DPU CBE	DPU Cont.	Harness	Harn. Cont.	Total	Margin
Mass (kg)	10.842	1.646	1.074	0.166	0.547	0.082	14.357	20%

WISPR Power	WIM CBE	WIM Cont.	DPU CBE	DPU Cont.	Total	Margin
Instrument Power (W)	4.59	0.68	7.12	1.07	13.46	15%
Operational Heaters (W)	4.69	0.7	na	na	5.39	15%
Survival Heaters (W)	6.21	na	na	na	6.21	15%

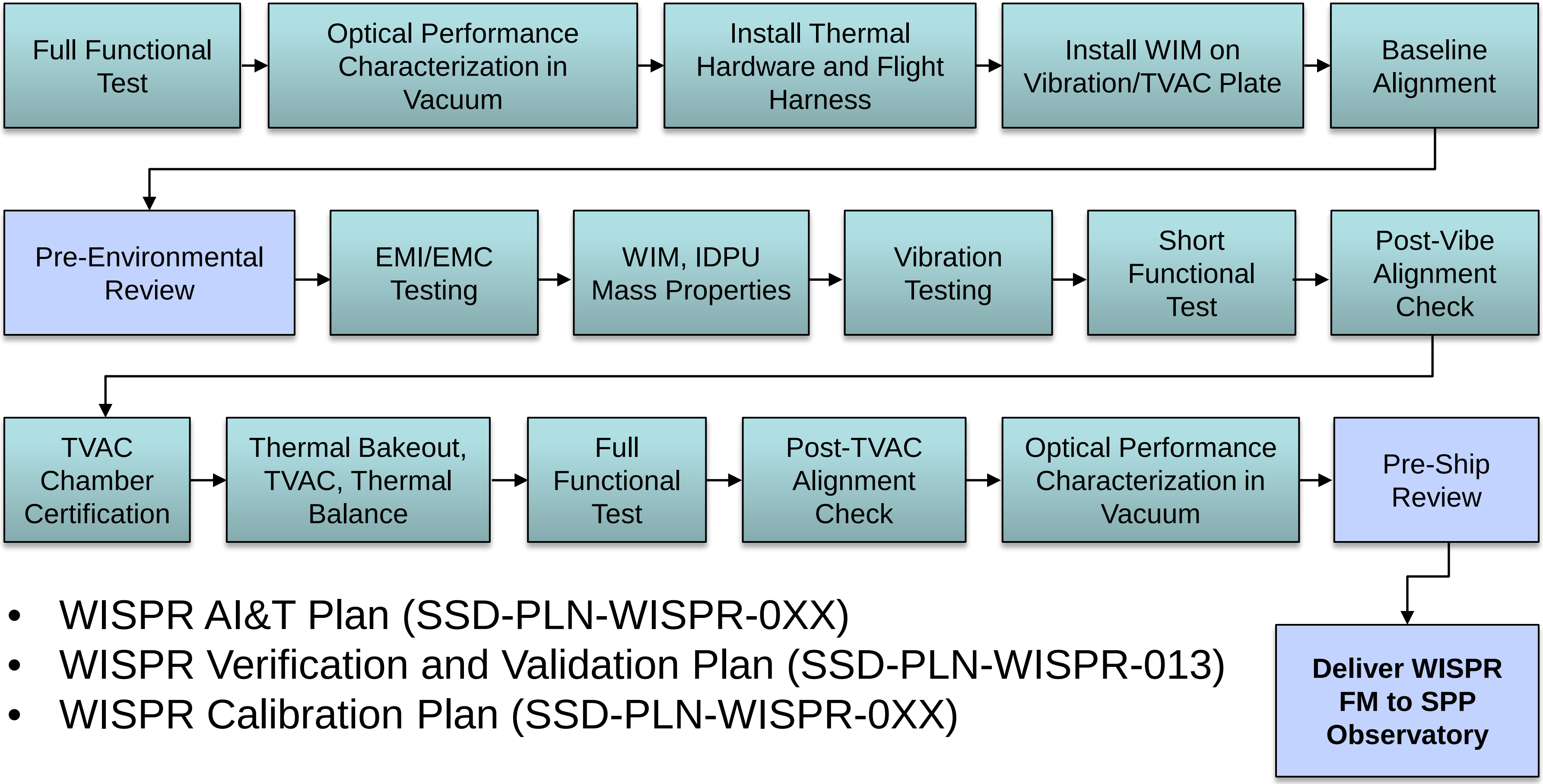
	Full Frame	Sub Frame	HK	Packet OH	Total
Data Volume (Gb/orbit)	14.26	7.18	0.25	1.28	22.97

FM Assembly and Integration Flow





Instrument Level Test Flow



Full Functional Test → Optical Performance Characterization in Vacuum → Install Thermal Hardware and Flight Harness → Install WIM on Vibration/TVAC Plate → Baseline Alignment

Pre-Environmental Review → EMI/EMC Testing → WIM, IDPU Mass Properties → Vibration Testing → Short Functional Test → Post-Vibe Alignment Check

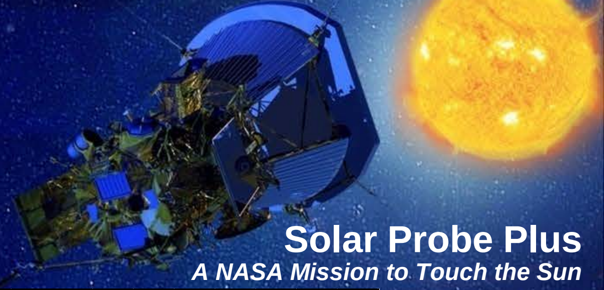
TVAC Chamber Certification → Thermal Bakeout, TVAC, Thermal Balance → Full Functional Test → Post-TVAC Alignment Check → Optical Performance Characterization in Vacuum → Pre-Ship Review

Deliver WISPR FM to SPP Observatory

- WISPR AI&T Plan (SSD-PLN-WISPR-0XX)
- WISPR Verification and Validation Plan (SSD-PLN-WISPR-013)
- WISPR Calibration Plan (SSD-PLN-WISPR-0XX)

Note: Optical performance verification will be performed at temperature during TVAC and in the stray light facility pre- and post-TVAC.

WISPR Instrument Level Environmental Test Matrix



Hardware Model Description	Subsystem Type	Structural/ Mechanical						Thermal Bakeout									EMI/EMC, Magnetics							
		Mass Properties	Static Tests	Shock	Random Vibration	Sine Vibration	Sine Burst	Thermal Bakeout	Thermal Vacuum Cycling	# of Operational Cycles	# of Survival Cycles	Min Thermal Soak Duration	Operational Failure-Free Hrs in Vacuum	Minimum # of Electronics Burn-In Hrs	# of Deployments in Vacuum	Thermal Balance	Conducted Emissions	Radiated Emissions	Conducted Susceptibility	Radiated Susceptibility	Primary Power	Electrostatic	Magnetics	Radiation
Solar Probe Observatory	O	X		PT	PT	PT	PT	X	QT	6	1	24 hr	192	108	1	X	X	X	X	X	X	X	X	
WISPR Science Payload FM	SP	X						X	QT	6	1	12 hr	160	60	1	X	X	X	X	X	X	X	X	
WISPR Instrument Module (WIM) FM	MD	X			PT	PT		X																
WISPR Instrument Module (WIM) EM	MD	X			PT	PT		X	QT	2	1	12 hr			1	X								
Camera Electronics FM (CIE, DRB, and APS)	U							X	QT	6	1	6 hr	70	30										
Camera Electronics EM (CIE, DRB, and APS)	U																							
IDPU FM	U	X			PT			X	QT	6	1	6 hr	70	30			X	X	X	X	X		X	
IDPU EM	U	X															X	X	X	X	X			
Camera Interfacce Electronics (CIE) FM	U	X																						
Camera Interfacce Electronics (CIE) FM	U	X																						
WIM Structure w/ Bipod Mounts FM	U	X	X					X																
WIM Structure FM	U	X																						
WIM Structure DM	U	X						X																
WIM Inner Telescope FM	U	X			PT			X																
WIM Outer Telescope FM	U	X			PT			X																

Responsible Institution
APL
NRL Code 7680
NRL Code 8200
SRI/Sarnoff

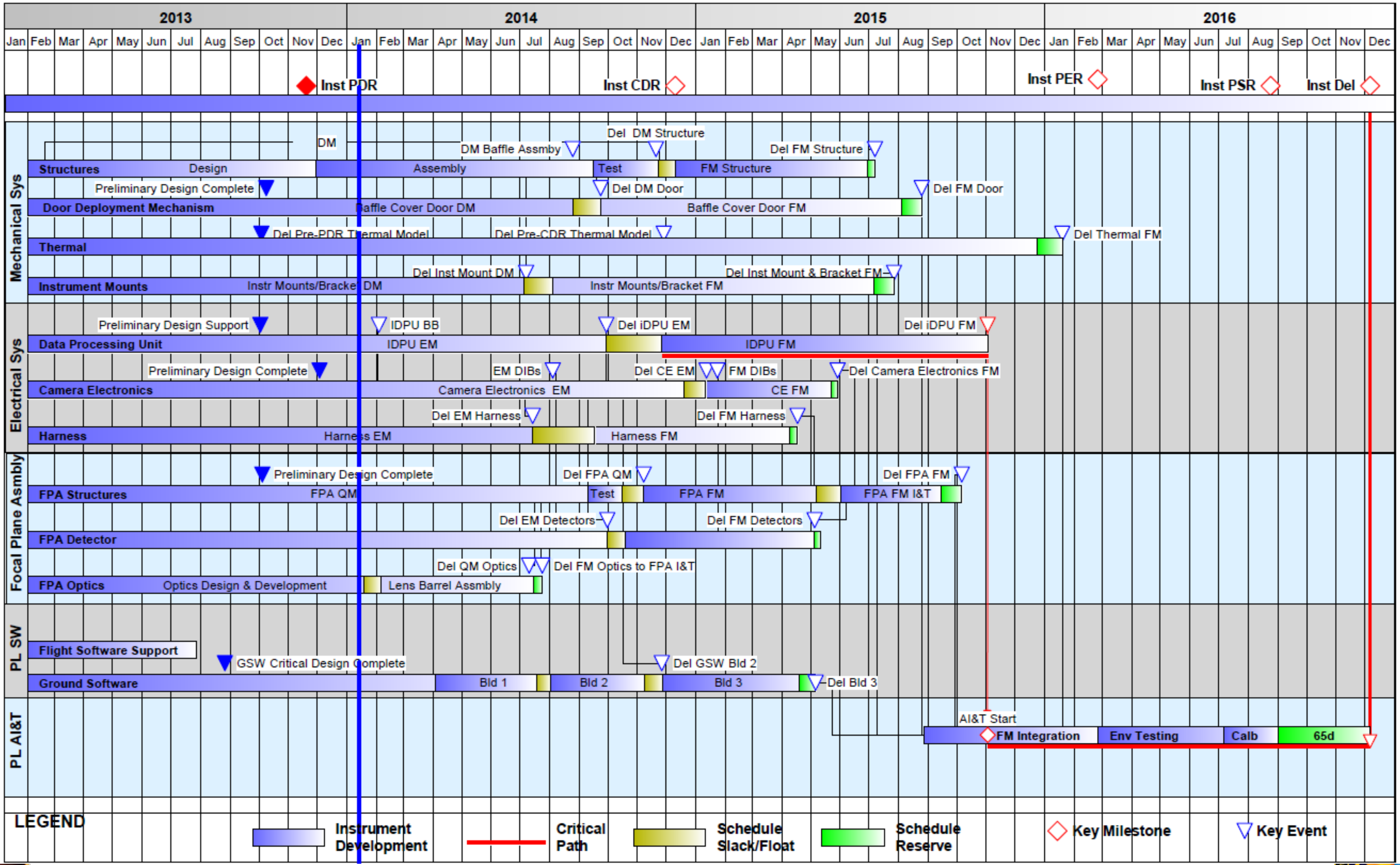
Subsystem Type	
O	Observatory
SP	Science Payload
MD	Module
U	Unit
A	Assembly
SA	Subassembly

Test Level/Duration	
Qualification Test	QT
Protoflight Test	PT
Acceptance Test	AT

WISPR I&T Requirements

- Cleanliness requirements
  - Will be assembled in Class 100 facility at NRL
  - Designed to be tested in 10K facilities
  - Door may only be opened in Class 100 facility
- WISPR alignment to TPS
  - Optical measurements of alignment cubes using TBD procedure
  - Alignment Tolerance of F1 baffle to TPS: +/- 2.45 cm Z; +/- 1.3 cm X
- Purge requirements and plans for maintaining purge
  - The labyrinth seal will be enclosed in a skirt enabling a lower purge rate
  - Continuous purge of the WIM – the details and specifications are under negotiation with the SPP project
- Expected number of operating hours on instrument at delivery to the spacecraft to be >300 hours, with last 100 consecutive hours failure free

WISPR Top-Level Schedule

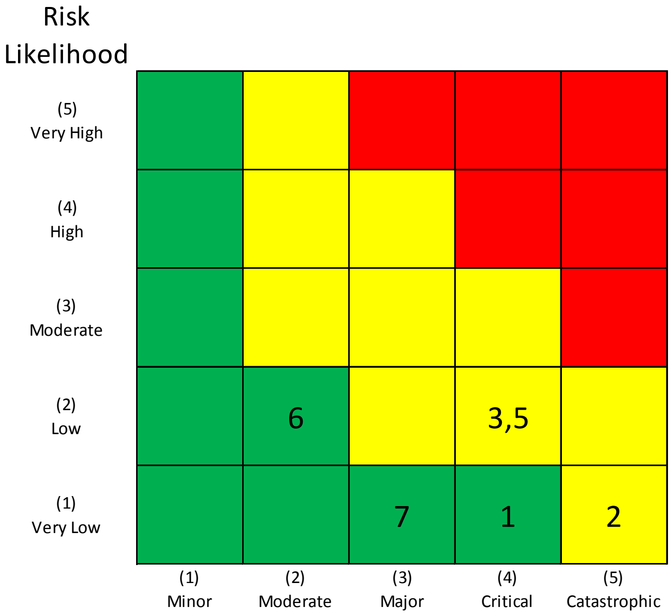


Project Risk Summary

Priority	Risk ID	Risk	Risk Type	Impact	Likelihood	Exposure	Risk Action	Exposure Category
1	3	IF analysis/ test results for WISPR straylight rejection exceed the current predictions, THEN WISPR images with required L1 photometric accuracy cannot be captured at the required cadence for baseline science.	ST	4	2	7	Mitigate	▶
2	5	If SPP spacecraft I&T and launch site processing activities do not satisfy the WISPR particulate /molecular surface cleanliness requirements, THEN WISPR images with the required L1 photometric accuracy cannot be captured at the required cadence for baseline science.	ST	4	2	7	Mitigate	▶
3	2	IF SPP spacecraft cannot satisfy the heat shield to F1 baffle alignment tolerance, THEN the WISPR inner FOV for the L1 threshold radial scene coverage requirement will not be satisfied.	ST	5	1	4.5	Mitigate	▼
4	1	IF the objective lens is damaged in the coronal dust environment over the SPP mission lifetime, THEN WISPR images with the required photometric accuracy or spatial resolution at EOL cannot be captured for baseline science.	ST	4	1	3.5	Mitigate	▶
5	6	If the application of the Aeroglaze 307 on the baffles does not pass reflectivity and survivability test after exposure to launch and on-orbit environment, the proposed backup coating may not satisfy the straylight rejection requirements.	ST	2	2	3	Mitigate	▶
6	7	If the SPP observatory ACS does not satisfy the WISPR pointing jitter or windowed pointing stability requirement, the WISPR image spatial resolution reqt will not be satisfied.	ST	3	1	2.5	Research	▶

Risk Exposure Change in Last Quarter
N New Risk ▶ No Change ▲ Increased ▼ Decreased

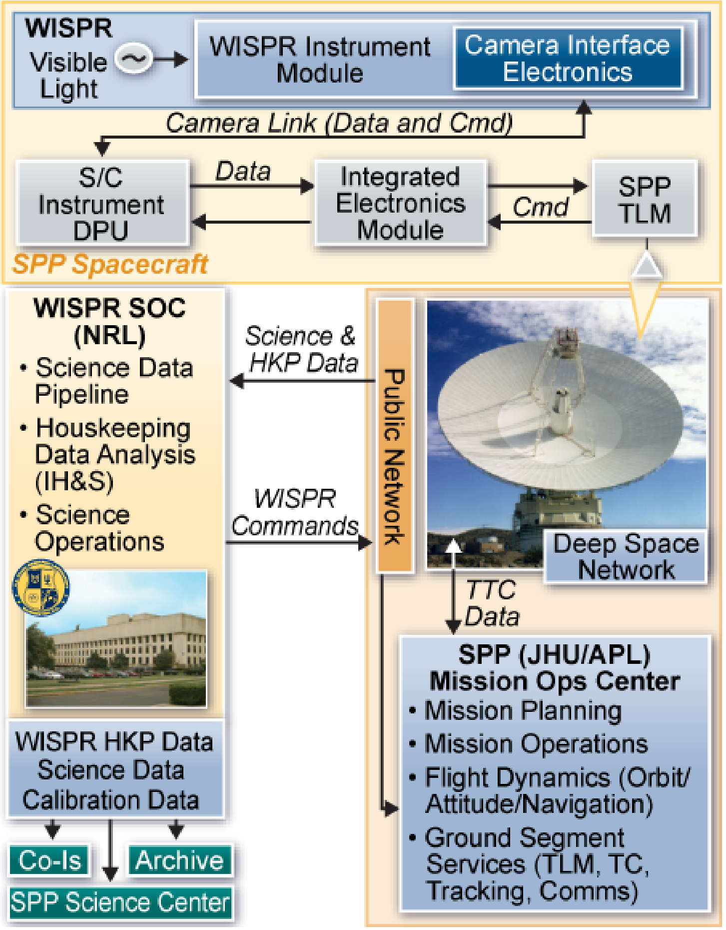
ST= Science/Technical
SB= Schedule/Budget



Risk Likelihood

(5) Very High	🟩	🟨	🟥	🟥	🟥
(4) High	🟩	🟨	🟨	🟥	🟥
(3) Moderate	🟩	🟨	🟨	🟨	🟥
(2) Low	🟩	🟩 6	🟨	🟨 3,5	🟨
(1) Very Low	🟩	🟩	🟩 7	🟩 1	🟨 2
	(1) Minor	(2) Moderate	(3) Major	(4) Critical	(5) Catastrophic

WISPR Concept of Operations



WISPR
Visible Light

WISPR Instrument Module
Camera Interface Electronics

Camera Link (Data and Cmd)

S/C Instrument DPU
Data
Integrated Electronics Module
Cmd
SPP TLM

SPP Spacecraft

WISPR SOC (NRL)
- Science Data Pipeline
- Housekeeping Data Analysis (IH&S)
- Science Operations

Science & HKP Data
WISPR Commands

Public Network

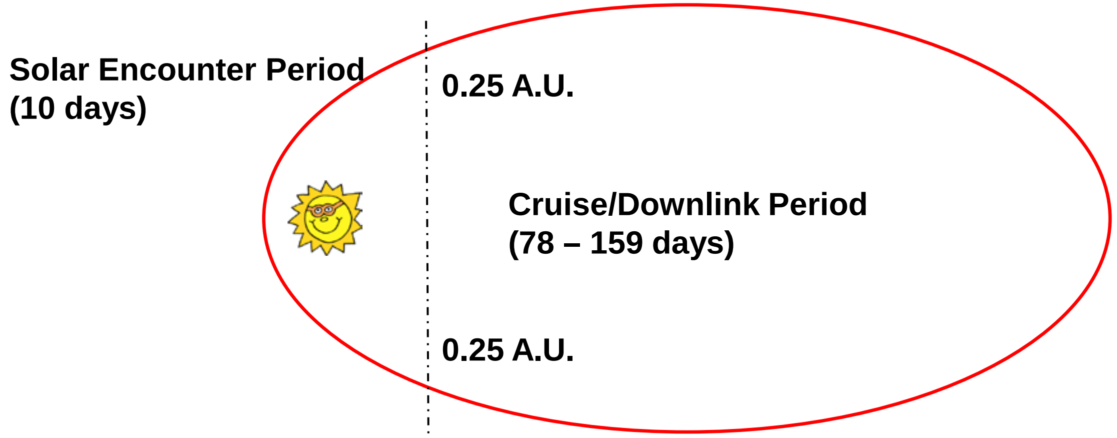
Deep Space Network

TTC Data

SPP (JHU/APL) Mission Ops Center
- Mission Planning
- Mission Operations
- Flight Dynamics (Orbit/ Attitude/Navigation)
- Ground Segment Services (TLM, TC, Tracking, Comms)

WISPR HKP Data
Science Data
Calibration Data

Co-Is
Archive
SPP Science Center



Solar Encounter Period (10 days)

0.25 A.U.

Cruise/Downlink Period (78 – 159 days)

0.25 A.U.

- **Decoupled instrument and spacecraft operations.**
- **Synoptic and tailored science observations for 10 days per orbit using pre-planned schedules uploaded in advance of each solar encounter.**
- **On-orbit checkout and calibrations during cruise prior to each solar encounter.**

SOC Data Flow - Operations

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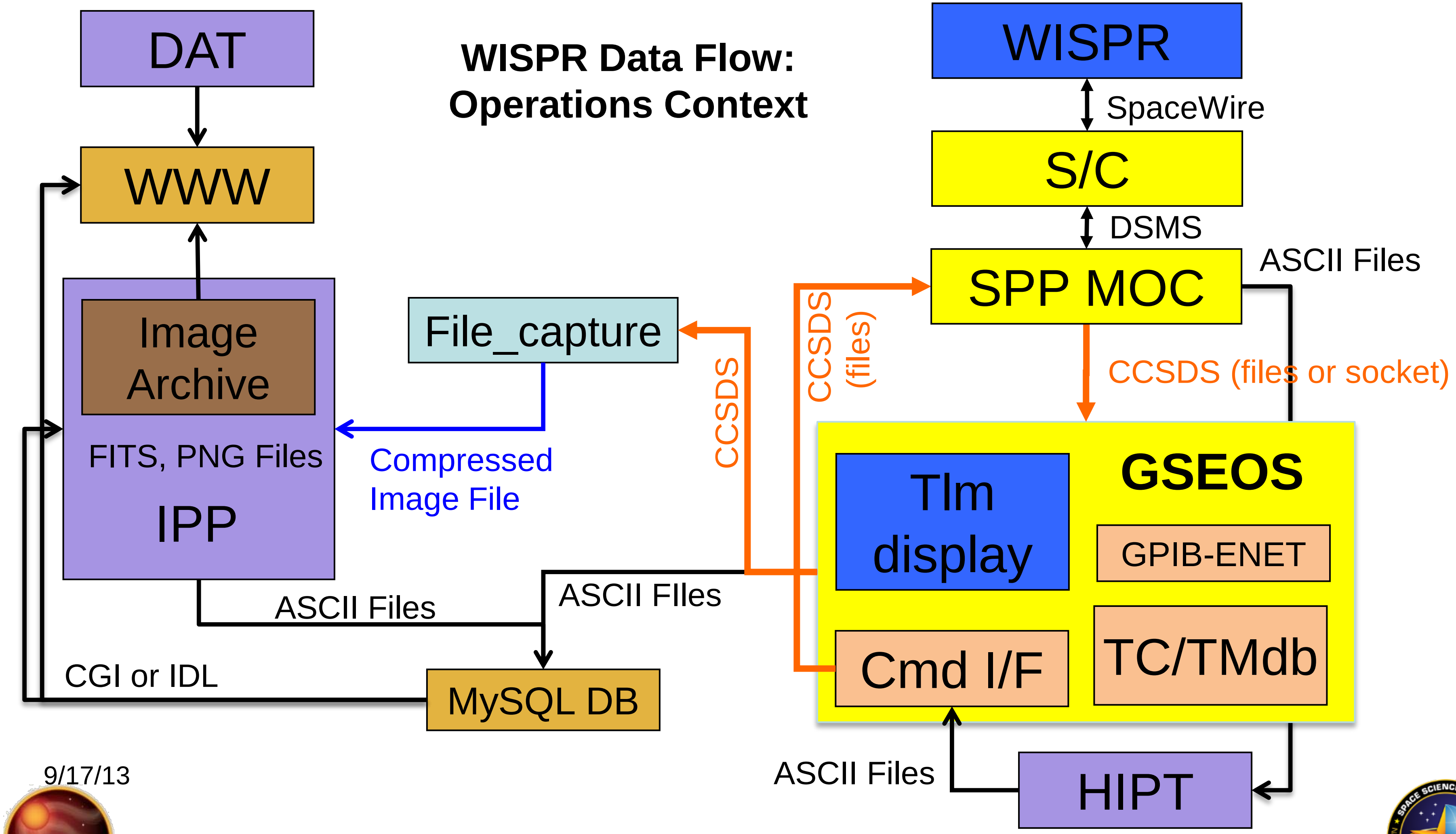

9/17/13

WISPR Data Products

Documented in 7434-9101 Project Data Management Plan

Data Level	Product Title	Contents	Format	Latency	Frequency
L1	Level-1 quick-look	uncalibrated image data	FITS	minutes	track-dependent
L1	Level-1 final	uncalibrated image data	FITS	hours	daily
L3	Browse images (quick-look and final)	uncalibrated binned images with background removed, and compressed	PNG, JPG	minutes or hours	daily
L3	Browse movies	browse images	MPG	hours	daily
L3	Jmaps	time-elongation plots, uncalibrated	PNG	hours	per orbit
L3	syncronic or carrington maps	heliospheric brightness at selected elongation angles	PNG	hours	per orbit
L2	Level-2	calibrated L1, generated by user	FITS	depends on user	as needed
L4	CME masses	image data	FITS	years?	annually?

Review Action Summary

Review	# A/I	# Open	# Closed	# Concurred
I-PDR	13	13		
Electronics Peer	18	0	18	18
Optics Peer	6	0	6	6
Ground Peer	0	0	0	NA
Structure	4	0	4	4
Detector	0	0	0	NA
Flight Software	0	0	0	NA

Summary

- **The WISPR instrument is well defined.**
- **The internal and external interfaces are defined in ICDs that are in release**

- **WISPR is ready to proceed to Phase C**

Solar Probe Plus

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WISPR Backup Slides

APL
The Johns Hopkins University
APPLIED PHYSICS LABORATORY

Solar Probe Plus

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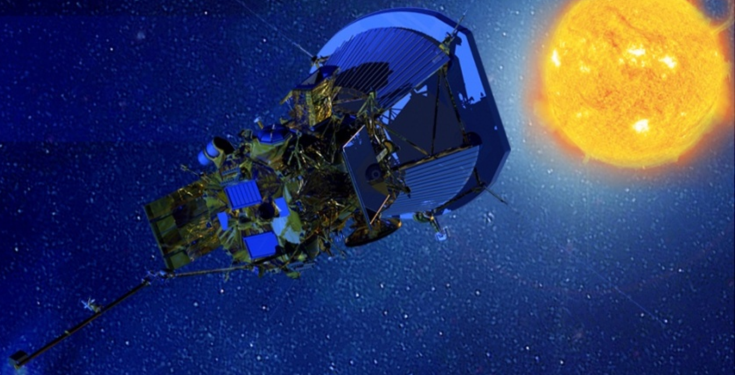

Spacecraft

MK Lockwood
Spacecraft System Engineer
Deputy MSE

mk.lockwood@jhuapl.edu

13 – 16 January 2014

APL
The Johns Hopkins University
APPLIED PHYSICS LABORATORY

Day 2, 3 Agenda
Spacecraft PDR Agenda

Day 2 – January 14, 2014

Time	Topic	Presenter	Time
8:45 AM	Welcome/Logistics	Driesman	15
9:00 AM	17-WISPR	Howard	45
9:45 AM	18-Spacecraft Overview	Lockwood	60
10:45 AM	Break		15
11:00 AM	19-Mechanical Configuration	Cole	30
11:30 AM	20-TPS	Mehoke/Hartk	30
12:00 PM	Lunch		60
1:00 PM	21-Thermal	Abel	30
1:30 PM	22-Solar Array Cooling System	Ercol	30
2:00 PM	23-Power System	Roufberg	30
2:30 PM	24-Solar Array	Gaddy	30
3:00 PM	25-SA Wing Angle Control	Baisden	20
3:20 PM	Break		10
3:30 PM	26-Guidance & Control	Vaughan	45
4:15 PM	27-Propulsion	Bushman	30
4:45 PM	End of Day 2		

Day 3 – January 15, 2014

Time	Topic	Presenter	Time
8:45 AM	Welcome/Logistics	Driesman	15
9:00 AM	28-Electrical System Overview	Conde	30
9:30 AM	29-Avionics	Ottman	30
10:00 AM	30-PDU	Sawada	30
10:30 AM	Break		15
10:45 AM	31-Communication	Copeland	30
11:15 AM	32-Flight Software	Krupiarz	30
11:45 AM	33-Data System Overview	Mick	30
12:15 PM	Lunch		60
1:15 PM	34-Fault Management	Kubota	45
2:00 PM	35-Solar Array Safing	Marsh	30
2:30 PM	36-Reliability	Smith	20
2:50 PM	37-Ground System Hardware	Mitnick	20
3:10 PM	Break		10
3:20 PM	38-Ground System Software	Melin	20
3:40 PM	39-Mission Operations	Pinkine	30
4:10 PM	40-Navigation	Goodson (JPL)	30
4:40 PM	41-Science Planning/SOCs	Kusterer	20
5:00 PM	End of Day 3		

Spacecraft Organization

Solar Probe Plus

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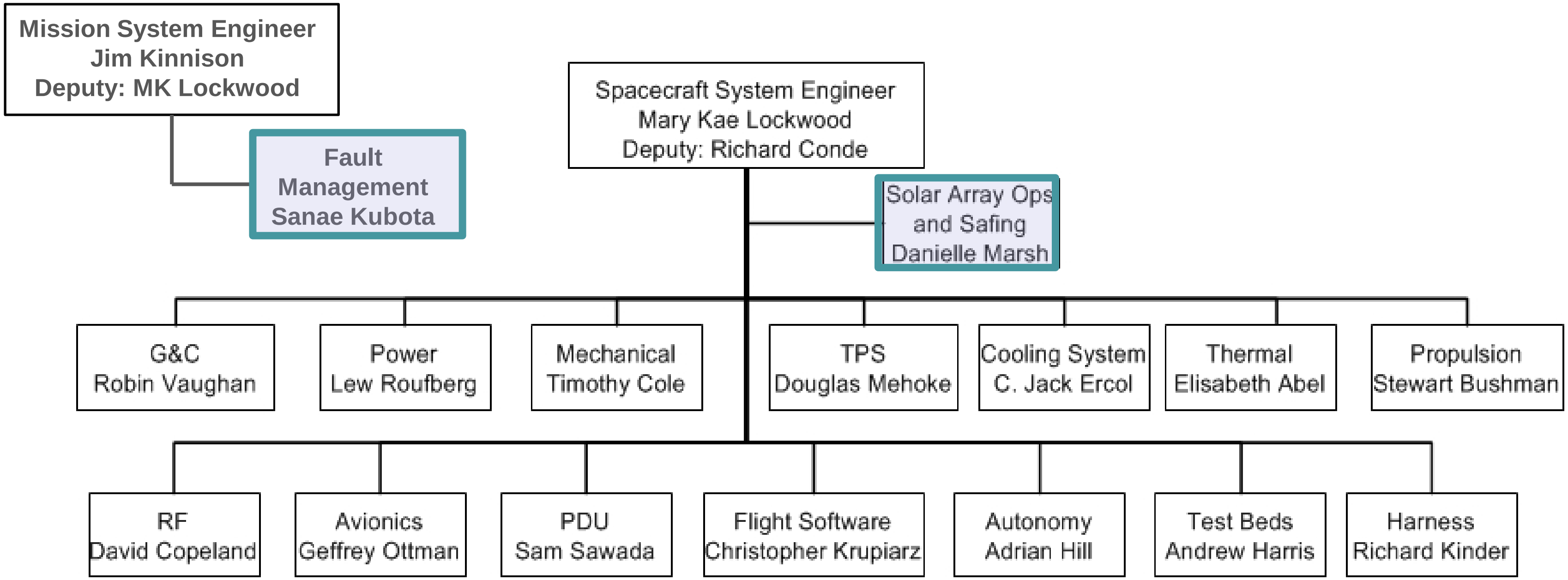


Mission System Engineer
Jim Kinnison
Deputy: MK Lockwood

Fault Management
Sanae Kubota

Spacecraft System Engineer
Mary Kae Lockwood
Deputy: Richard Conde

Solar Array Ops and Safing
Danielle Marsh

G&C
Robin Vaughan

Power
Lew Roufberg

Mechanical
Timothy Cole

TPS
Douglas Mehoke

Cooling System
C. Jack Ercol

Thermal
Elisabeth Abel

Propulsion
Stewart Bushman

RF
David Copeland

Avionics
Geffrey Ottman

PDU
Sam Sawada

Flight Software
Christopher Krupiarz

Autonomy
Adrian Hill

Test Beds
Andrew Harris

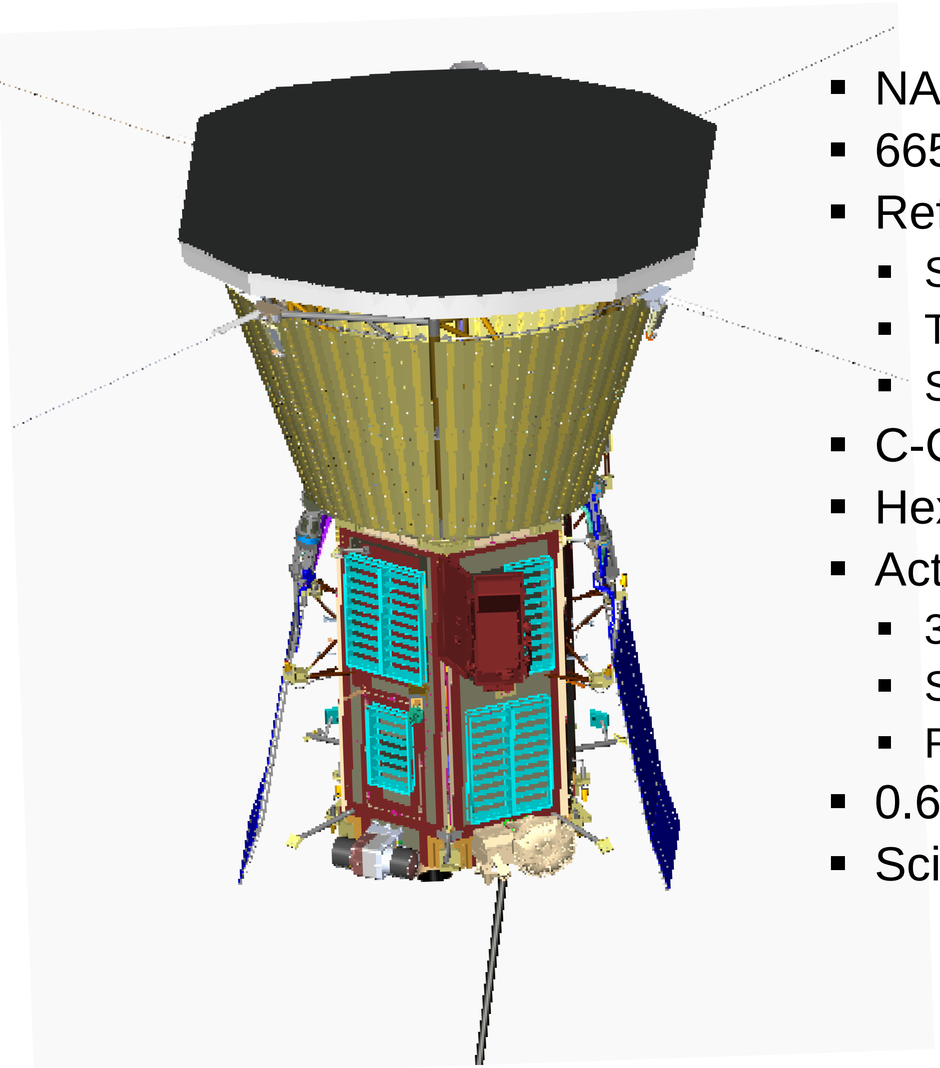
Harness
Richard Kinder

- Close coordination between Spacecraft and Fault Management – SPP Fault Management is an integral part of Spacecraft requirements and Spacecraft design.
- Solar Array Operations and Safing Lead added to address high coupling of Solar Array, Electrical Power System, Cooling System, G&C, Mechanical, Fault Management.

Outline

- Spacecraft Overview
- Key Changes since SRR/MDR
- Requirements Status, Driving Reqs
- Trades
- Spacecraft Pointing Orientations
- Sensors Protecting SPP
- Modes and Power Configuration Availability
- Power
- Cooling System Sizing and Margin
- Solar Array and Cooling System Primary Radiator Sizing
- Mass
- Margin Summary
- Mass and Power Liens/Opportunities
- Backup Launch
- Technology Development Summary
- Verification
- Phase C Plans

Spacecraft Overview

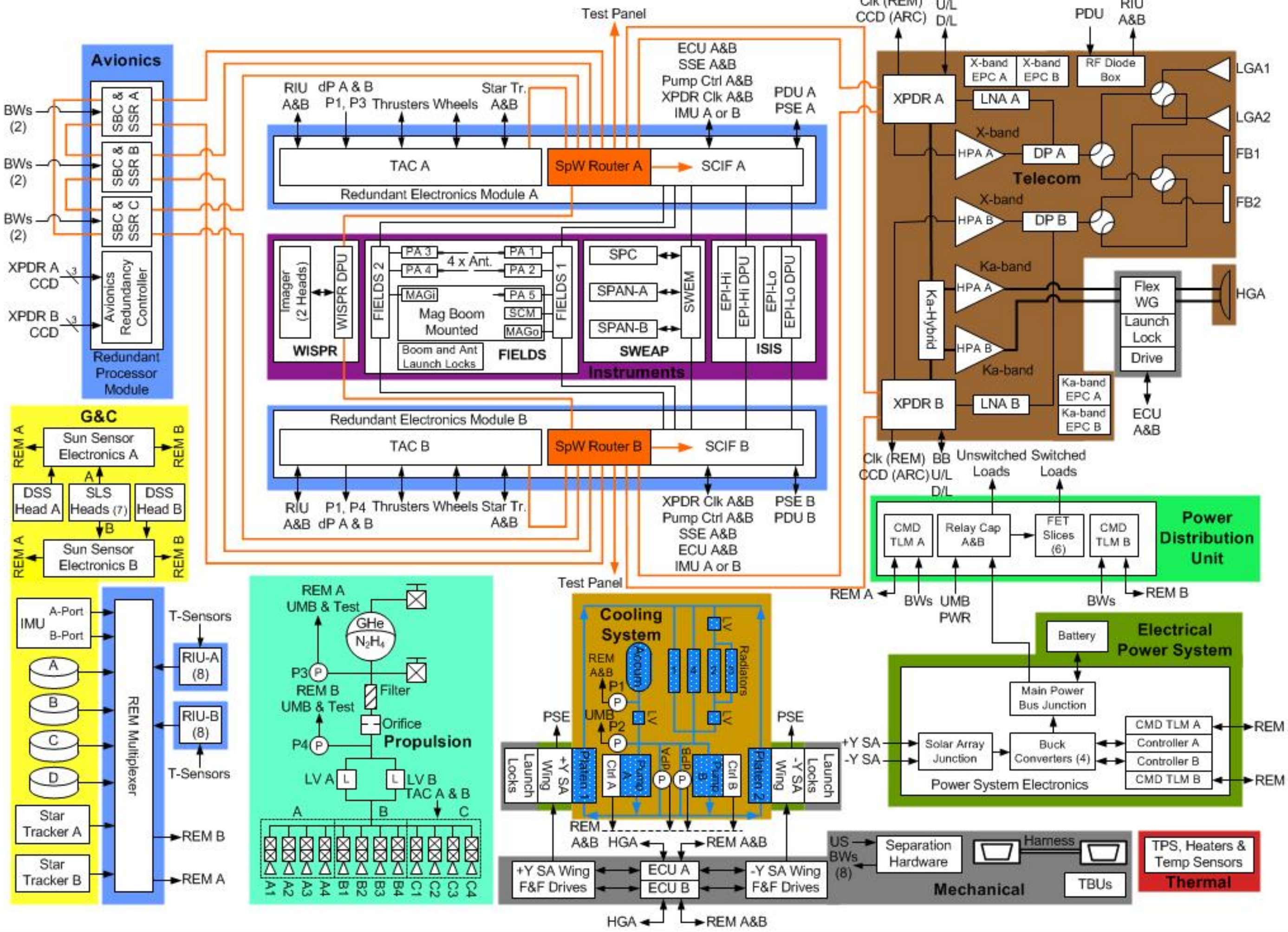


- NASA selected instrument suites
- 665kg max launch wet mass
- Reference Dimensions:
    - S/C height: 3m (TBR)
    - TPS max diameter:2.3m (TBR)
    - S/C bus diameter: 1m (TBR)
- C-C Thermal protection system
- Hexagonal prism s/c bus configuration
- Actively cooled solar array
    - 384W (TBR) electrical power at encounter
    - Solar array total area: 1.54m^2 (TBR)
    - Radiator area under TPS: 4.4m^2 (TBR)
- 0.6m HGA, 34W TWTA Ka-band science DL
- Science downlink rate: 163kb/s (TBR) at 1AU

Block Diagram

Solar Probe Plus Spacecraft Block Diagram

Revision 10-21-2013



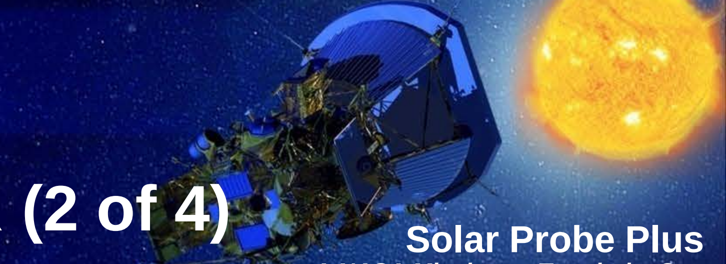
PDR Baseline

Key Changes Compared to SRR/MDR (1 of 4)

SRR/MDR Reference Vehicle	PDR Baseline	Comment
Launch Mass 610kg	Launch Mass 665kg	Launch vehicle enhancements, 9.86 Rs perihelion.
WISPR single telescope	WISPR two telescope	Mitigates stray light from FIELDS V1-V4
Mag boom length: 2.7m	Magnetometer boom length: 3.5m	FIELDS science accommodation
FIELDS V1-V4 antennas	FIELDS V5 added to Mag boom	FIELDS science accommodation
Single Fault Tolerance assessment for science meas not yet complete	Fault tolerance assessment complete. FIELDS divided into FIELDS 1 and 2.	Enables 7 of 9 measurements with single fault, meets Level 1 reqs.
~2 days/instrument suite commissioning placeholder	FIELDS on during SWEAP commissioning; ISIS commissioning increased to 5 days; WISPR commissioning shifted to after SWEAP for thermal, after cooling system activation for fault tolerance	Instrument commissioning sequence and durations updated for instrument accommodation
S/C pointing orientations for inst commissioning not yet defined	SWEAP transient slew added	All other s/c pointing orientations needed for instrument commissioning are within Nominal S/C Pointing Orientations

PDR Baseline

Key Changes Compared to SRR/MDR (2 of 4)

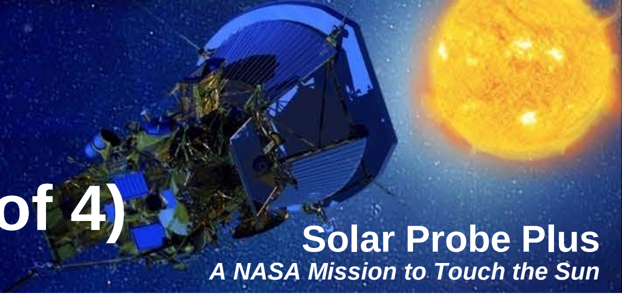


SRR/MDR Reference Vehicle	PDR Baseline	Comment
Initial Fault Management Concept defined	Fault Management approach preliminary design complete- L3 and L4 reqs defined, FMEAs developed, local fault correction approach defined, Safing approach defined, SA Ops and Safing Lead added, successful FM PDR completed	Fault Management highly integrated with Spacecraft Requirements and Spacecraft Design
1 Hz telemetry collection	5 Hz telemetry collection	Reduced time for detection of time critical faults
4 redundant Solar Limb Sensor Heads	7 redundant Solar Limb Sensor Heads; 2 standard digital sun sensors	Enables protection of SPP (within umbra for solar distance <0.7AU and within pointing constraints for solar distance ≥0.7AU) in fault condition or potential star tracker outage
Catbed heaters for 4 thrusters powered during perihelion	Catbed heaters for 8 thrusters powered during perihelion	Enables SPP pointing to be maintained within umbra during momentum dump for fault condition of one thruster out

PDR Baseline

Key Changes Compared to SRR/MDR (3 of 4)

SRR/MDR Reference Vehicle	PDR Baseline	Comment
TPS interface to TSA – low density foam, single pie pan	TPS interface to TSA – added high density foam insert, double pie pan	Enables TPS to accommodate launch environment
TPS C-C to Carbon Foam bondline thickness 0.015”, applied to C-C only	Bondline thickness 0.040”, applied to C-C and foam; C-C flatness at foam interface improved	Increased integrity of bond, enables TPS to accommodate structural loads
2 step approach for cp-cg alignment	1 step for cp-cg alignment	TPS planform shape defined 6 months after I&T start
Composite facesheet structure	Aluminum facesheet structure	Reduced engineering dev and risk
Large cell battery	Small cell battery	Reduced mass, power; eliminated cell balancing electronics
Cooling system solar array, radiator 1, radiator 4 activated serially.	Cooling system solar array, radiator 1, radiator 4 activated simultaneously.	Simplified cooling system activation sequence, simplified valving.
Accumulator pressure 300psi, mounted above top deck	Accumulator pressure 400psi, mounted under top deck.	Reduced accum size and mass, eliminates need for accum heaters
4m2 cooling system primary radiators	4.4m2 cooling system primary radiators; 3.6” taller TSA	Increased Cooling System capacity from 6000W to 6480W. Assessing ability to return to 4m2 for cost.

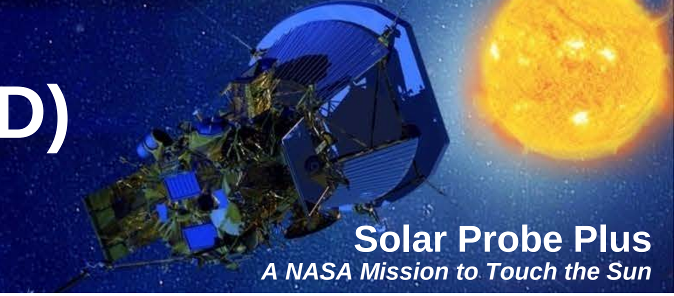


PDR Baseline

Key Changes Compared to SRR/MDR (4 of 4)

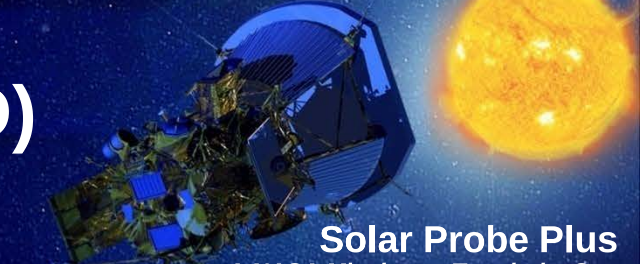
SRR/MDR Reference Vehicle	PDR Baseline	Comment
Semi-standard solar cell stack baseline, High Thermal Conductance Cell Stack alternate	High Thermal Conductance Cell Stack baseline (HTCCS)	HTCCS reduces cell stack temp at high irradiance, and eliminates need for separate MMOD layer.
Solar array 0.65m (25.59”) wide, 9° SSA to PSA	Solar array 0.69m (27.17”) wide, 7.4° SSA to PSA	Assessing ability to return to 0.65m (25.59”) width to reduce NRE platen cost
Solar array autonomous power control – meets power load with minimum thermal load to cooling system	Added: solar array autonomous temperature control – maintains cooling system at or above minimum temperature	Ensures cooling system freeze protection; supports solar array safing timeline
2 SSRs	3 SSRs, one/single board computer	Reduces resources and complexity; maintains redundant data storage
HGA on +y anti-ram panel, Mag boom on –y anti-ram panel	HGA on -y anti-ram panel, Mag boom on +y anti-ram panel	Alleviates mag boom blockage of star tracker FOV.
200 communication slews (from Umbra to Aphelion to Umbra S/C Pointing Orientation)	100 communication slews	S/C maintains Aphelion pointing orientation during selected consecutive slew downlink days

Spacecraft Reqs Document (SCRD) Development (1 of 2)



- SCRD released in PLM, 7434-9048
- Integrated into DOORS, linked to Level 2 mission reqs
- SCRD Reviews completed:
  - FM PDR, including solar array safing
  - SCRD Peer Review completed,
    - 3 actions and 5 recommendations received
    - Actions and recommendations addressed, SCRD updated
- SCRD developed and refined through numerous working meetings
  - Systems, Fault Management, G&C, SA Ops and Safing, Requirements & Verification
- Level 3 spacecraft reqs decomposed to level needed to minimize coupling across Level 4 subsystem reqs
  - Addresses coupling between subsystems inherent to SPP due to solar environment
  - ex. cooling system, solar array, electrical power system, G&C, fault management
- Coordinated with Environmental Design and Test Requirements Document for completeness and elimination of requirements duplication
  - EDTRD released in PLM

Spacecraft Reqs Document (SCRD) Development (2 of 2)



- Level 3 SCRD includes:
  - Fault Management Requirements
    - FM significant driver for SPP spacecraft definition, overlapping requirements
  - Solar Array Operations and Safing
  - Ground System Requirements
    - Specific SCRD reqs flowed to GSYS (“parent” to Mission Ops)
    - Supports later Mission Ops constraints definition
  - Timekeeping Requirements
  - Allocation to MECH, THRM, GC, SACS, EPS, RF, AVI, PDU, TBSW, AUT, TPS, PROP, FSW, HRN
- Spacecraft subsystem Level 4 requirements
  - All are in DOORS and linked to Level 3
  - 12 of 14 in PLM
  - Reviewed as part of subsystem PDRs, or in separate susbystem reqs peer review
    - Autonomy Requirements Review on track for January 28, 2014.
  - Detailed scrub for completeness of L4s to L3s (and reverse) performed for most L4s
    - For remaining, initial scrub complete with detailed planned in first quarter 2014.

Driving Requirements (1 of 4)

Requirement	Description	SCRD Req #	Comply	Chart Reference
Launch Mass	665kg max launch wet mass	5	Y	Chart 40
Operating Life	Lifetime in orbit of 7 years	2	Y	Subsystems
Solar Distance	Operate over solar distance of 9.86Rs to 1.02AU	46	Y	TPS, Solar Array, Cooling System, Dust
Single Fault Tol	No single point failures except those on single point failure list	288 and children	Y	Mission Systems Engineering Overview
Critical Events	Ground contact during critical events	8		Mission Systems Engineering Overview
Inst Accomm	Meet instrument accommodation requirements	55, 56, 57, 58 and children	Y	All
Inst Calib, Commissioning	Meet instrument commissioning and calibration reqs	222, 188, 190, 186, 187, 574	Y	Chart 7, 65, 76
Inst Duty Cycle	Power to operate insts at 100% duty cycle for solar distances ≤0.25 AU	97	Y	Chart 32, 66, 77
Inst Pointing	Meet instrument pointing req's, including WISPR pointing accuracy 6arcmin	160, 161, 162, 163, 164, 165, 166, 167, 168, 169	Y	G&C

Driving Requirements (2 of 4)

Requirement	Description	SCRD Req #	Comply	Chart Reference
Umbra and S/C Pointing Constraints	Maintain s/c within TPS umbra <=0.7AU and within pointing orientation constraints >0.7AU.	34, 489, 175, 177, 23, 24 and children	Y	G&C
3-Axis Stabilized	3-Axis stabilized	148	Y	G&C
Cp-Cg	Achieve cp-cg alignment within 1” with TPS edge shift of no greater than 55mm (2.2“) (TBR) relative to Nominal TPS as measured prior to launch.	44 and children	Currently exceed by ~0.2”	Current cg is >1.6” from z axis. Working cg and will reassess req if necessary.
Trajectory Correction Maneuvers	Support trajectory correction maneuvers	69, 65, 64 and children	Y	MD, G&C Mission Design has requested ≥0.3AU. S/C reviewing.
Communication: Nav, Hskpg, Aliveness	Provide comm for 3 tracks per week to meet navigation, housekeeping DL, and indication of aliveness reqs.	218, 233, 234	Y	Communication
Data downlink	Downlink ave of 127 Gbits (TBR) of data per orbit, during 1st and/or 2nd orbit following solar encounter during which data was collected.	236, 232 and children	Y	Data Systems

Driving Requirements (3 of 4)

Requirement	Description	SCRD Req #	Comply	Chart Reference
Power	Provide power for Power Configurations	90, 91, 95, 96	Y	Chart 32, 76, 77, 78
Cool Solar Arrays 9.86Rs	maintain platen temperatures ≤150C with solar irradiance ≤25 suns (TBR) and 6480W (TBR) cooling system load.	88	Y	Chart 35, Cooling System
Cooling System Constraints	Maintain cooling system within thermal constraints	137, 74, 72 and children	Y	Cooling System
Autonomous Wing Angle Control and SA Safing	Provide autonomous wing angle control; Provide autonomous solar array safing	116, 117	Y	Solar Array Wing Angle Control; Solar Array Safing
Fault Protection	Provide on-board auton system to detect, respond to time-critical faults	289 and children	Y	Fault Management, Solar Array Safing
Safing	Provide autonomous safing and recovery to operational	315, 318 and children	Y	Fault Management Solar Array Safing

Driving Requirements (4 of 4)

Solar Probe Plus

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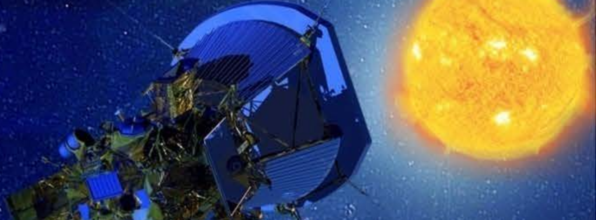
Requirement	Description	SCRD Req #	Comply	Chart Reference
EDTRD	Comply with Environmental Design & Test Reqs Doc	354	Y	Thermal, Mechanical, G&C
EMECP	Comply with Electromagnetic Environment Control Plan	353	Y	EMC
Contamination	Comply with Contamination Control Plan	355	Y	Contamination



Trade Status and Phase B Level 1 Trades Closed

- 33 Level 1-3 Phase B spacecraft trades closed
- 8 Level 2-3 Phase C spacecraft trades

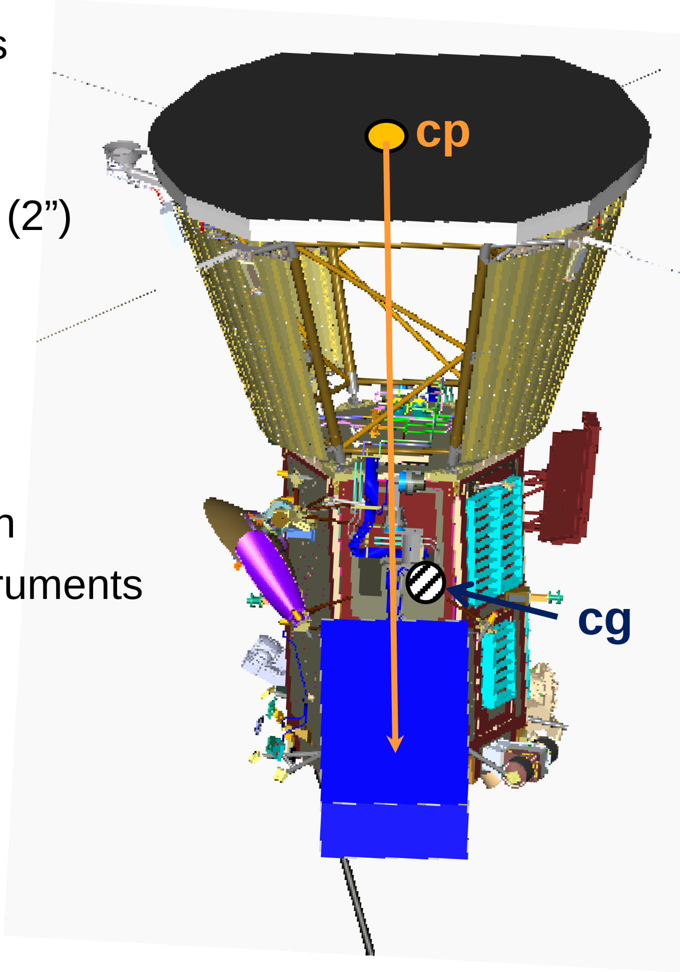
Trade Closed	**Level**	**Result**
TPS cp-cg	1	Late TPS shift eliminated; fabrication TPS shift remains, enables ~1" cp-cg adjustment.
Cooling System Dust Mitigation	1	Radiator tube/fin flat side to space, radiator tube MMOD layer added; solar cell ceramic interposer serves as MMOD on platen; blanket standoff defined.

Center of Pressure – Center of Gravity (cp-cg) Alignment

- Solar torque and propellant req'd to keep s/c behind umbra is proportional to cp-cg offset and solar pressure + re-radiation.

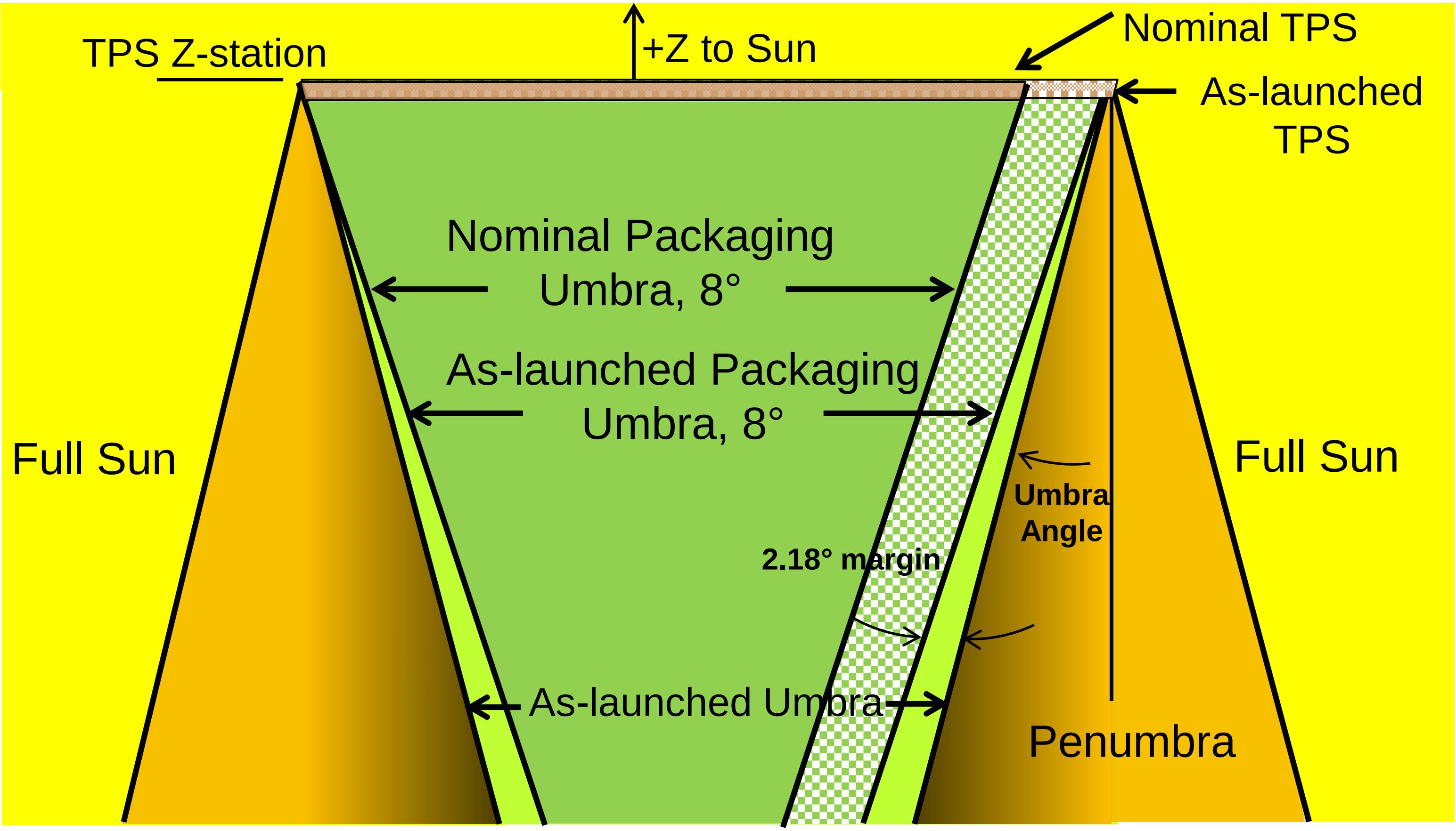
- cp-cg offset from s/c Z with Nominal TPS req'd to be ≤51mm (2")
- TPS planform shape defined 6 months after start of I&T
  - Define: As-Launched TPS shape*
  - Allows up to 28mm **(**1.1") cp shift
  - Enables ≤ 25mm (1") cp-cg offset in flight
- Instruments shift with TPS edge to maximize FOV toward sun
- Solar limb sensors shift with TPS edge to protect shifted instruments

- Current cp-cg offset = 54.6mm (2.15")
- After TPS cp shift, cp-cg offset ~30mm (1.2"),
  - Currently above requirement.
  - Continue to work in Phase C.



*Nominal TPS umbra always contained within As-Launched TPS umbra

As-launched Packaging Umbra

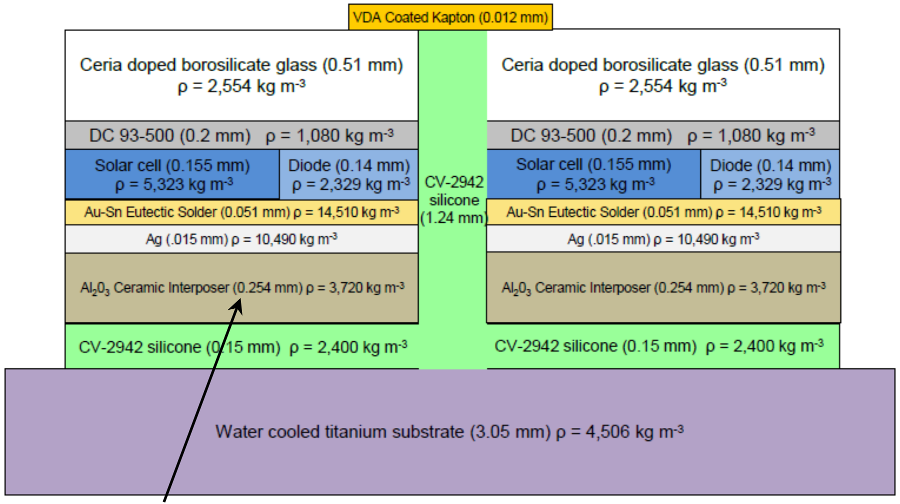


NOTE: As-Launched TPS size increase can be in any X-Y direction for Center of Pressure to Center of Gravity alignment. +X is current expected direction.

Cooling System Dust Mitigation

- Observatory Probability of No-Failure (PNF) >95%
  - See “Dust Study” Day 1 PDR charts
- Cooling system is focus area for dust (MMOD*) protection
  - Solar Array and Cooling System Primary Radiators (CSPRs) geometry and through-thickness layers defined to meet target PNF

Solar Array Cell Stack on Cooling System Platen



VDA Coated Kapton (0.012 mm)

Ceria doped borosilicate glass (0.51 mm) ρ = 2,554 kg m-3

DC 93-500 (0.2 mm) ρ = 1,080 kg m-3

Solar cell (0.155 mm) ρ = 5,323 kg m-3

Diode (0.14 mm) ρ = 2,329 kg m-3

Au-Sn Eutectic Solder (0.051 mm) ρ = 14,510 kg m-3

Ag (.015 mm) ρ = 10,490 kg m-3

Al_2O_3 Ceramic Interposer (0.254 mm) ρ = 3,720 kg m-3

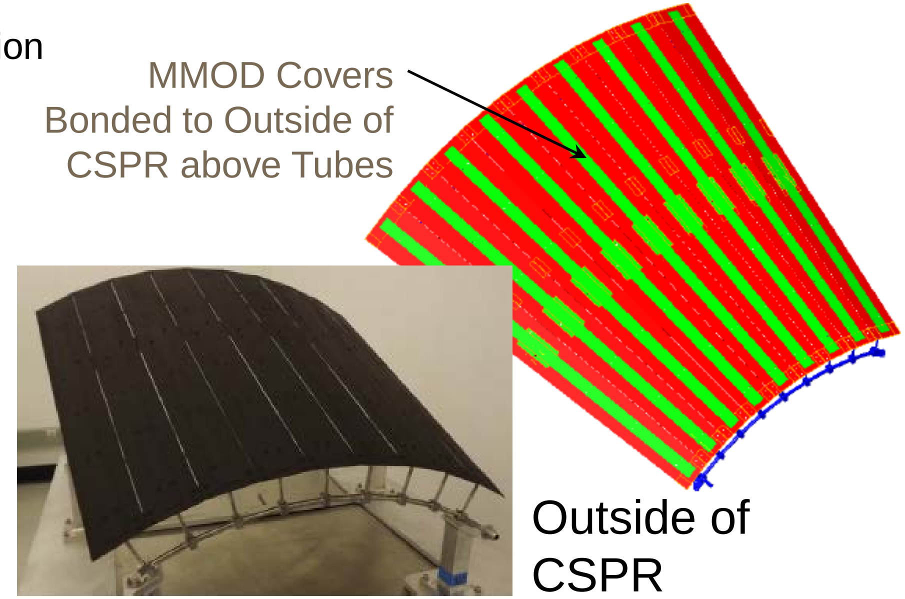
CV-2942 silicone (0.15 mm) ρ = 2,400 kg m-3

CV-2942 silicone (1.24 mm)

Water cooled titanium substrate (3.05 mm) ρ = 4,506 kg m-3

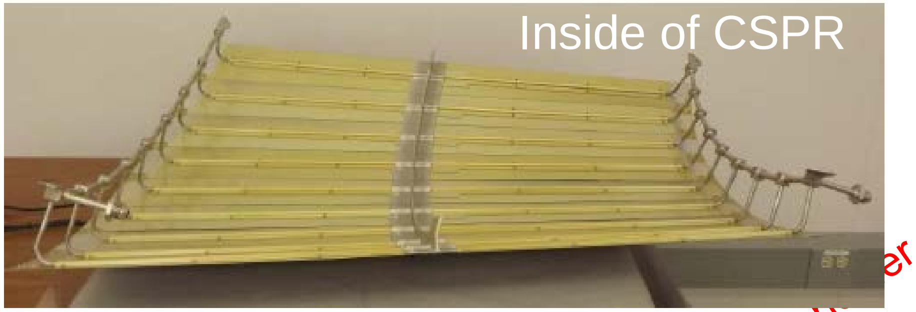
Ceramic carrier and adhesive layers in cell stack provide MMOD protection; in primary SA section every other channel is blocked, reducing flow area.

Cooling System Primary Radiator



MMOD Covers Bonded to Outside of CSPR above Tubes

Outside of CSPR



Inside of CSPR

Tubes bonded on inside of CSPR fins

*MMOD=Micro Meteroid and Orbital Debris

Phase B Trades Closed Level 2 (1 of 2)

Trade Closed	Level	Result
Battery Configuration	2	Selected small cell battery - reduces mass, power; eliminates need for cell balancing electronics
Facesheet/Doubler Trade	2	Selected Aluminum facesheets with Aluminimum honeycomb core - reduces risk, mass neutral
Cell Laydown Approach	2	Ceramic insulator laydown approach - reduces temperature gradient through cell stack, eliminates need for additional MMOD
Solar array charge mitigation	2	VDA Kapton tape for electrostatic cleanliness in one direction on primary; shine thru mitigation on secondary not req'd, higher voltage in small area did not affect science
Magnetometer boom length and configuration	2	Two Segment 3.5m Overtravel Hinge - high herritage, minimize risk of umbra violation
Detection and Mitigation of Time Critical Faults	2	Approach defined - see FM PDR

Phase B Trades Closed Level 2 (2 of 2)

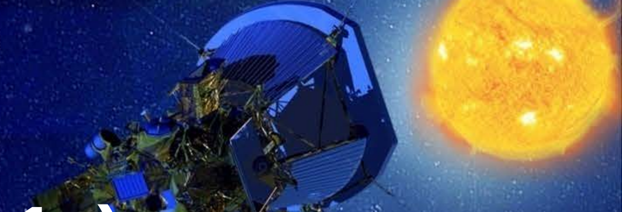
Trade Closed	**Level**	**Result**
Radiator Manufacturing Approach	2	Phosphoric acid bond preparation with tube/fin bond configuration selected
Accumulator Pressure	2	Increased to 400 psi - reduces accumulator size
Fixed vs. Variable Speed Pump	2	Two speed pump - reduces power at aphelion
X-Band TWTA RF Power	2	11W RF power, with 33W electrical power meets X-band reqs; enables competitive selection.
Ka-Band Optimization	2	Stepped data rate over a pass selected to reduce DSN contact time.
DSN tracking schedule	2	Ephemeris reqs can be met, including with comm outages due to small SEP and TPS blockage; Small slew added (within umbra) during comm contacts prior to Venus 4 to provide contact for navigation.
Comm outage vs mitigation	2	
Propulsion Pressurant	2	Helium - lower mass, acceptable to science

- Additional Level 2 trades presented by R Conde in Electrical Systems briefing
- Level 3 trades included in backup charts

Phase C Trades

Trade	**Level**
TPS Edge close-out	2
Cooling system valve redundancy, sensors for fault detection	2
Spare processor maintenance approach: evaluation of Prime commanding of spares and Spare-maintenance-autonomy on spare processors	2
FIELDS antenna deployment options	2
Avionics processor UT699 vs. UT699E	3
SLS cant angle and radial placement (initial definition complete to enable design reqs definition)	3
Flex waveguide vs. rotary joint	3
SLS sun presence vs. angle prediction	3

Definition and Naming Convention Nominal and Mission Default Spacecraft Pointing Orientations (2.1a)

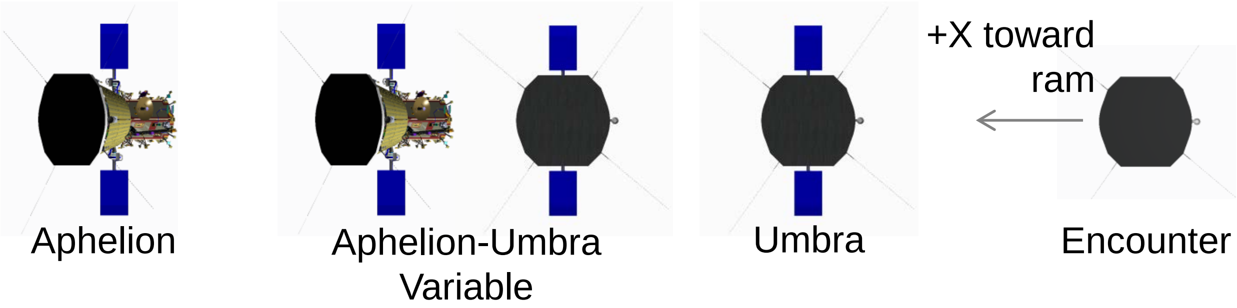


Solar Probe Plus
A NASA Mission to Touch the Sun

Name	S/C – Sun Line Location	Rotation about s/c – sun line
Aphelion	In S/C –X +Z Quadrant, +/-4° from XZ Plane, 45° +/-5° from +Z Axis	Any[1]
Aphelion-Umbra Variable	In S/C –X +Z Quadrant, +/-4° from XZ Plane, 0° to 45° +/-5° from +Z Axis	Any[1]
Umbra	Along S/C +Z Axis	Any[1]
Encounter	Along S/C +Z Axis	+X toward ram

[1] As needed for G&C momentum management or RF Comm; If in Comm orientation, append name with "-Communication", ex. Aphelion-Communication, Aphelion-Umbra Variable-Communication, Umbra-Communication.

View from Sun:



Nominal and Mission Default Spacecraft Pointing Orientations vs Solar Distance (2.1b)

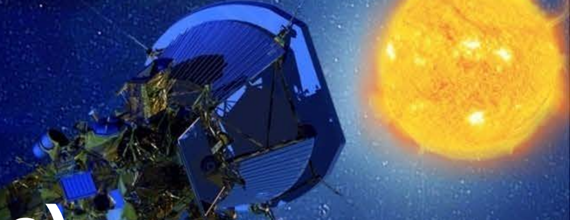
Solar Distance	Nominal	Mission Default
9.86Rs to 0.25AU	Encounter	Encounter[1]
0.25AU to 0.7AU	Umbra	Umbra
0.7AU to 0.76AU (Except Venus eclipse)	Aphelion-Umbra Variable (Aphelion for Venus eclipse)	Umbra[2] (Aphelion for Venus eclipse)
Venus eclipse	Aphelion	Aphelion
0.76AU to 0.82AU	Aphelion-Umbra Variable	Umbra[2]
0.82AU to 1.02AU	Aphelion	Aphelion[3]

[1] Target attitude; may not meet +X toward ram in G&C modes other than full 3D attitude.

[2] Spacecraft Pointing Orientation change from Nominal to Mission Default requires at a minimum operational Digital Sun Sensors, Reaction Wheels, ephemeris, and time, and improves with operational Gyros.

[3] Aphelion is the Mission Default Orientation for the solar distances specified, including from Special Event Spacecraft Pointing Orientations, EXCEPT for Special Event Spacecraft Orientation Activate 1 & 4. In the event of a fault while the spacecraft is in Activate 1 & 4, the spacecraft remains in the Activate 1 & 4 Spacecraft Pointing Orientation.

Definition and Naming Convention
Special Events
Spacecraft Pointing Orientations (2.1c)

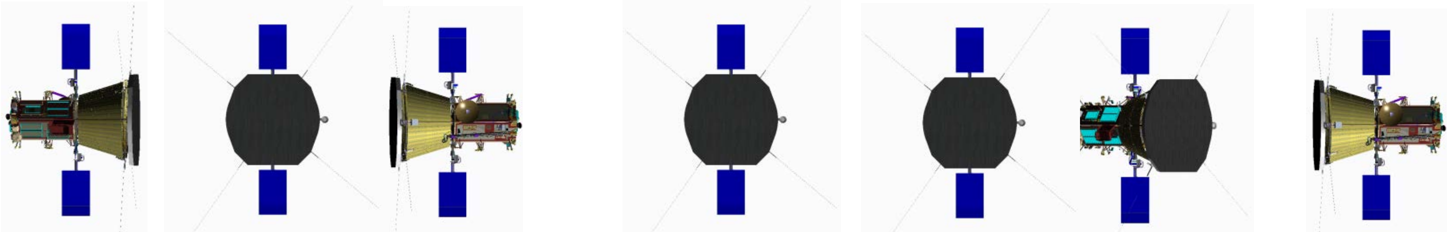


Name	S/C – Sun Line Location	Rotation about s/c – sun line
Activate 1 and 4	Along S/C +X Axis +/-5° (TBR)	Any[1]
Launch Correction	No sun on +X s/c panels, enable primary solar array cell-side normal to Sun. (Specific orientation is unknown until post-launch; Burn direction: any.)	Any[2]
Early Cruise TCMs	Along S/C +Z axis	Any[2]
SWEAP Transient Slew	See SWEAP Transient Slew text	Any[1]
Activate 2 and 3	Along S/C –X Axis +/-5°	Any[1]

[1] As needed for RF Communication

[2] As needed for deltaV direction

View from Sun:



Activate 1 & 4

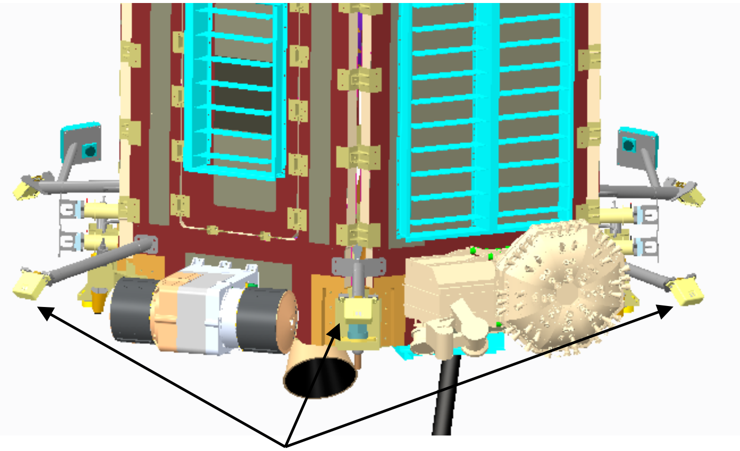
Launch Correc (Bounding Orientations)

Early Cruise TCMs

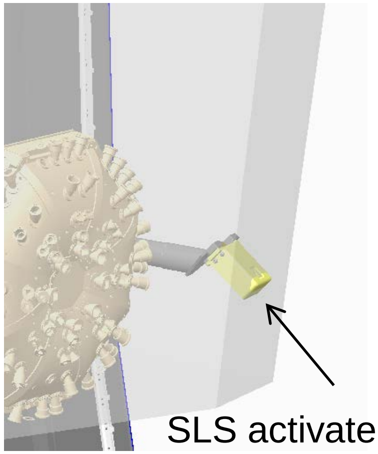
SWEAP Transient Slew

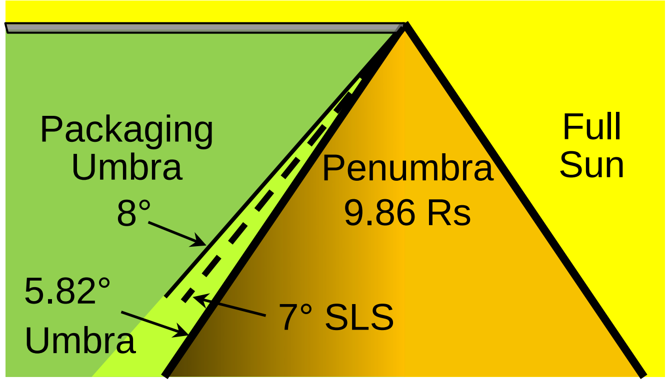
Activate 2 & 3

Solar Limb Sensors, Digital Sun Sensors Protecting SPP S/C



3 Solar Limb Sensors Ram Side





Packaging Umbra 8°

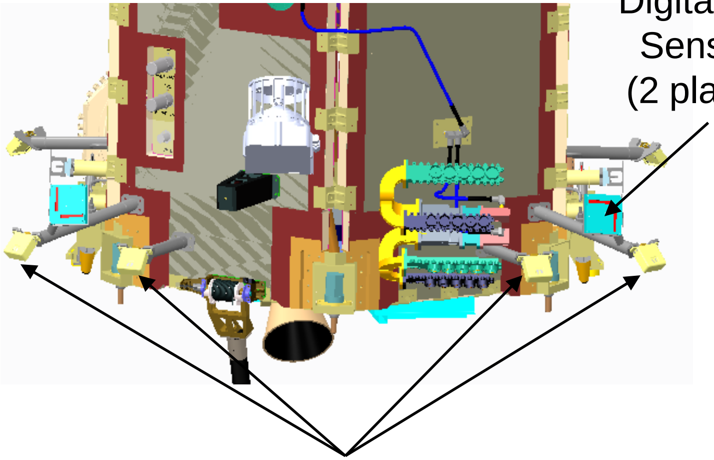
Penumbra 9.86 Rs

Full Sun

5.82° Umbra

7° SLS

SLS activated by breaking umbra in s/c sun off-point >1.18° at 9.86Rs; SLS operates in penumbra



Digital Sun Sensors (2 places)

4 Solar Limb Sensors Anti-Ram Side

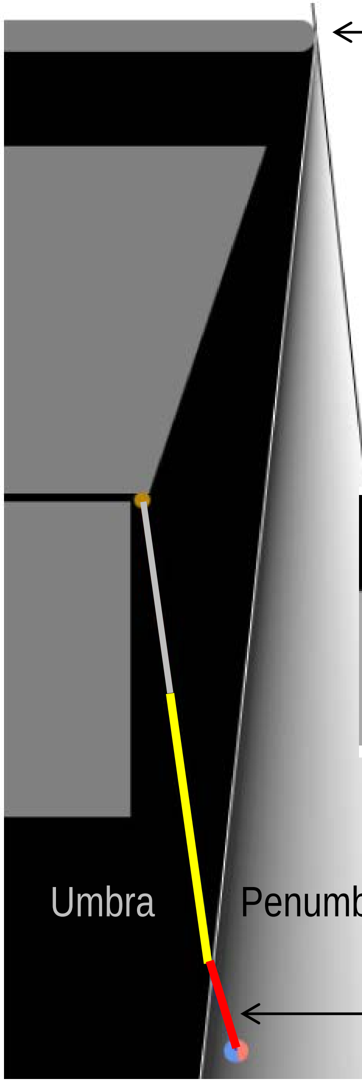
Solar Limb Sensors: primarily <0.7AU

- Provide warning of nearing umbra violation
- Nominally do not see sun
- Become illuminated prior to any s/c component or instrument
- Demonstrated TRL 6 in SPP Phase B

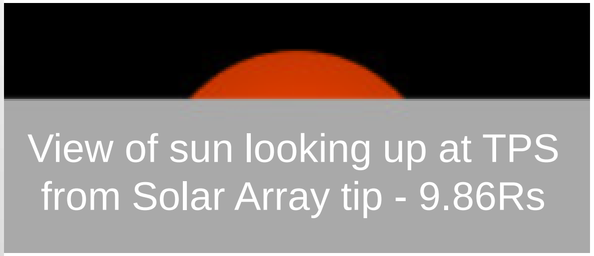
Digital Sun Sensors: s/c slew orientations ≥ 0.7AU

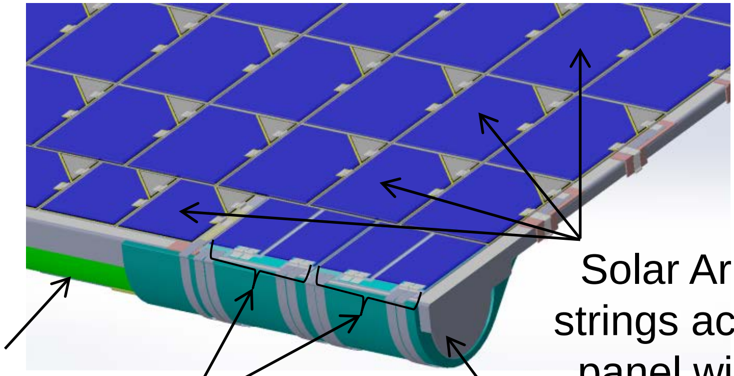
- Protect against Aphelion Thermal Violation
- Direct measurement of sun-relative s/c pointing in slew s/c pointing orientations
- Traditional sun sensors

SA Sensor Cells, Temp Sensors Protecting SPP Solar Array



- High sensitivity of irradiance, power, cooling system load to SA wing angle
  - Electrical: 12.5 W/ 0.1° /wing
  - Thermal: 131.5 W/ 0.1° /wing (2% cooling system capacity)
- Autonomous wing angle control ensures power load is met while maintaining solar array and cooling system within thermal constraints
- SA sensor cells and temp sensors on back of platen enable protection of solar array and cooling system from thermal violation





Power Configuration Availability with Fault Management Modes, G&C Modes

- Spacecraft flight configuration defined by
  - Fault Management Modes: Operational Level 1-3, Safe Mode
  - G&C Mode: Full (full rate & full attitude control), Full/Partial Rate, Full/Partial Attitude Control
  - Spacecraft Pointing Orientations
  - Solar Array Wing Angle Control Mode
  - Power Configurations, PCs: Loads
- Mapping of Power Configurations to FM Modes, G&C Modes:

		Activate SA, 1&4	Cruise or Recharge	Venus Eclipse	Science	Side B Health	Instrument Checkout	Activate 2&3	Science Downlink	LC Catbed	TCMs	Safe
Power Configurations→		PC2	PC3, PC6, PC7, PC15, PC16, PC30	PC29	PC22a, PC22b, PC23, PC24a, PC24b	PC28a, PC28b	PC9, PC10, PC8, PC11, PC13, PC14	PC12	PC17, PC18, PC19a, PC19b, PC20, PC35, PC21	PC4	PC5, PC31, PC32, PC33a, PC34a, PC33b, PC34b	PC25, PC27
FM Mode ↓	G&C Mode ↓											
Operational L3	Full	X	X	X	X	X	X	X	X	X	X	
Operational L2	Any	X	X	X	X, degraded pointing if not Full G&C	X						
Operational L1	Any	X	and PC26	X								
Safe Mode	Any	X										X

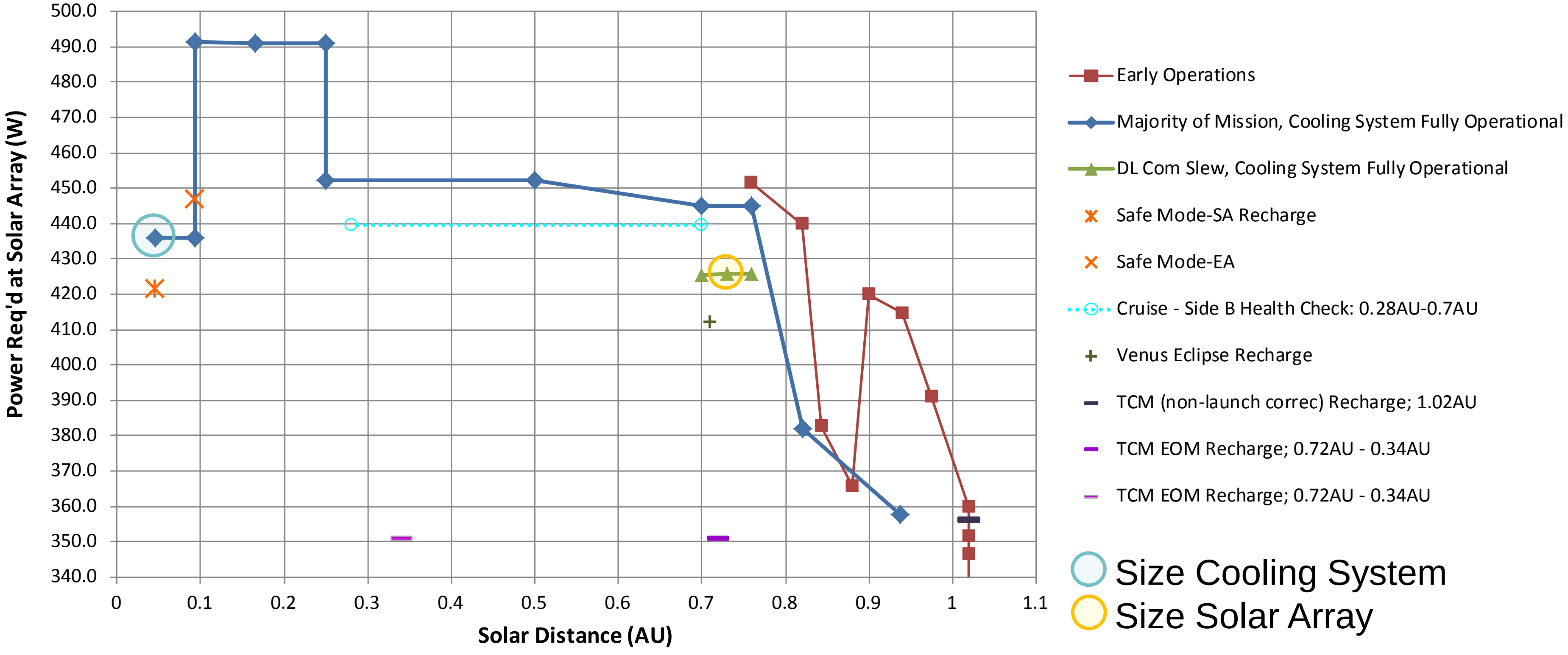
Backup charts include additional information for each FM Mode

Power Required
SCRD 7434-9048

Power Configuration #	PC3	PC23	PC24b	PC20	PC35	PC21
Power Configuration Name	Recharge Post Rad 1&4 and SA Activation	Science: 35.7Rs to 20Rs with 4hr X-band	Science: 20Rs to 9.86Rs	Downlink - 0.76AU (slew)	Downlink - 0.73AU (slew)	Downlink - 0.7AU (slew)
Solar Distance	1.02	0.093	0.0459	0.76	0.73	0.7
Spacecraft Orientation	Aphelion	Encounter	Encounter	Aphelion-Umbra Variable-Comm	Aphelion-Umbra Variable-Comm	Aphelion-Umbra Variable-Comm
Solar Array Control	Sun normal	Auton	Auton	Sun normal	Sun normal	Sun normal
Cooling System Status	Partial	Full	Full	Full	Full	Full
Time in Mission	Early Ops	Last	Last	Last	Last	Last
Cell Temp** (C) (TBR)	43	calc, 65C min	calc, 65C min; 165***	95	100	110
NTE Load (W) (TBR)	310.8	431.7	383.9	375.1	375.1	375.0
Power req'd at SA @SA Bus (W) (TBR)	351.6	491.3	435.9	425.6	425.6	425.5
Battery Target SOC /Full SOC (TBR)	1.00	0.65	0.65	1.00	1.00	1.00
Duration (hrs)						
Driver	SA	Cooling, BatMicro, Power Limit	Cooling, BatMicro	SA	SA	SA

- SPP Power Configurations (PCs) defined (35 PCs)
- Power required for each PC is included in Spacecraft Requirements Document (SCRD)
- Subset of SCRD table shown here

Power Required - Graphical



Baseline Power Summary Driving Power Configurations

Power Configuration Number	PC3	PC35	PC24
Component↓ /Power Configuration→	Recharge Post Rad 1&4 and SA Activation Total (W)	Downlink - 0.73AU (slew) Total (W)	Science: 20Rs to 9.86Rs Total (W)
Instruments CBE Power:	0.0	0.0	66.3
Telecommunications Total:	11.0	95.5	11.0
Guidance and Control Total:	60.8	57.9	77.4
Mechanical Total:	7.3	4.4	7.1
Power Total:	11.3	11.3	11.3
Thermal - SACS Total:	33.0	33.0	41.0
Thermal - SACS Activ Only Total:	0.0	0.0	0.0
Thermal - S/C, non-SACS Total:	23.3	13.9	12.9
Thermal - Instrument Total:	21.5	22.4	0.0
Avionics Total:	27.2	27.2	32.3
Power Distribution Total:	9.5	9.5	9.5
Propulsion (non-Therm) Total:	0.0	0.0	18.5
Propulsion Thermal (non-Tank) Total:	14.1	14.1	8.5
Spacecraft Totals			
Power CBE w/o Harness Loss	219.1	289.3	295.9
Harness Loss	3.7	4.8	4.9
Power CBE	222.7	294.1	300.8
Battery Charge	25	0	0.5
S/C - Sun Distance (AU)	1.02	0.73	0.0459
Spacecraft Pointing Orientation	Aphelion	Aphelion-Umbra Variable-Comm	Encounter
Cooling System Status	Partial	Full	Full
Available Load Power from SA (W)	342.6	379.9	420.5
Req'd Margin	25%	25%	25%
Fault Load (W)	7.4	7.4	7.4
Load with 25% Total Margin	310.8	375.1	383.9
Power Reserves	87.5	78.4	111.8
Actual Margin	39.27%	**26.65%**	**37.17%**

- Excerpt from Spacecraft Systems Engineering Power Loads Budget (see backup for complete set of Power Configurations)
- Recharge post-launch (PC3) is no-longer the driving configuration for solar array sizing.
- Downlink – 0.73AU (slew) (PC35) is solar array sizing driver
- Science (PC24) remains the driving configuration for cooling system capacity required.

Power CBE Changes since SRR/MDR 9.86Rs Science

Science 9.86Rs (PC-24b) power increased 18.6W (from 365.3W to 383.9W)

Decrease /No Change	▪ Cooling System power decreased	19.0 W
	▪ Power System power decreased	7.7 W
	▪ Power Distribution power	no change
	▪ RF power	no change

Increase	▪ Instruments power increased	16.7 W
	▪ WISPR increased 3.9W	
	▪ SWEAP increased 4.9W	
	▪ ISIS increased 0.3W	
	▪ FIELDS increased 7.6W	
	▪ Thermal power increased	8.9 W
	▪ Added power allocation for fault	7.4 W
	▪ Avionics power increased	5.7 W
	▪ Propulsion power increased	5.4 W
	▪ Harness loss power increased	4.4 W
	▪ G&C power increased	0.6 W

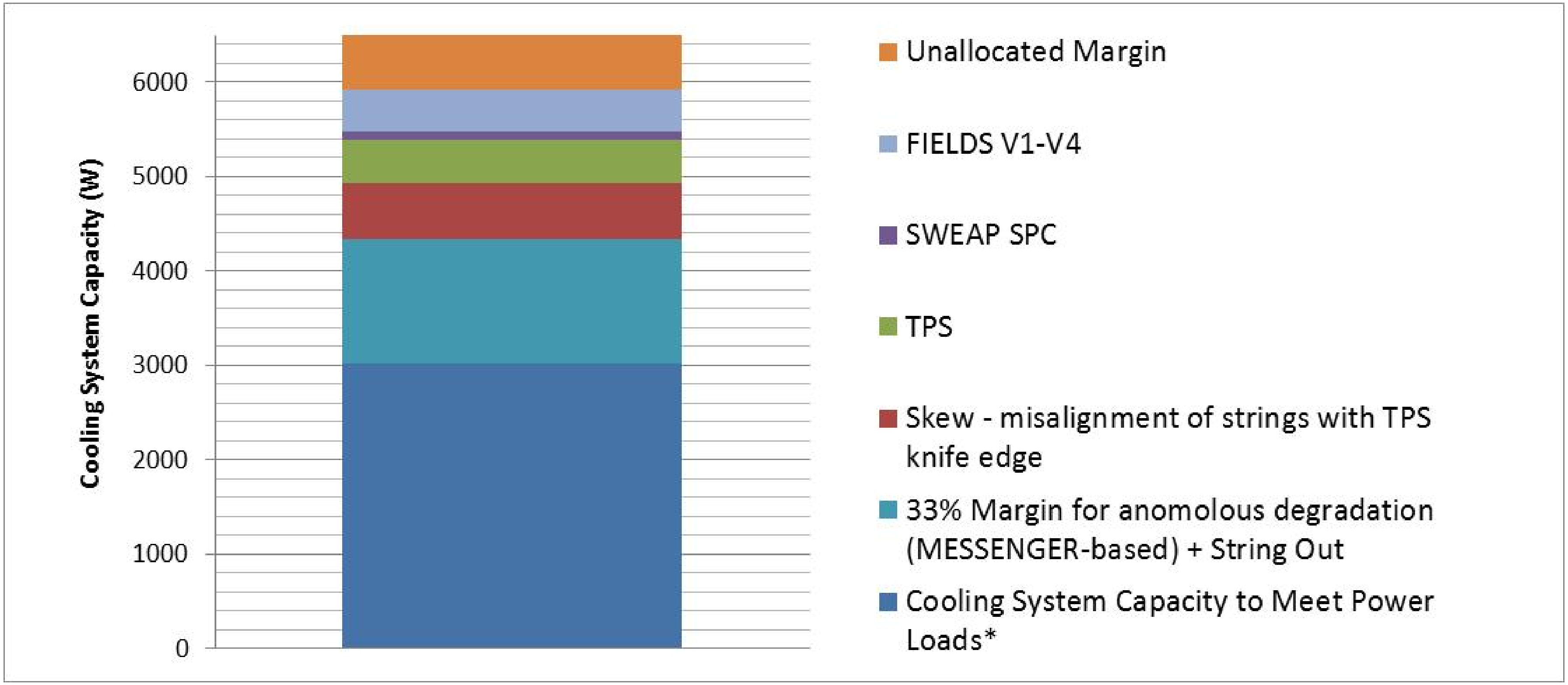
Power CBE Changes since SRR/MDR Downlink Slew

Downlink Slew (PC35) power decreased 24.8W (from 399.9 W to 375.1 W)

Decrease /No Change	Cooling system power decreased	27.0 W
	Power system power decreased	7.7 W
	RF power	no change
	Power Distribution power	no change

Increase	Thermal power increased	13.9 W
	Instrument survival heaters increased	11.7 W
	WISPR increased 2.8 W	
	SWEAP decreased 1.7 W	
	FIELDS increased 6.1 W	
	ISIS increased 1.1 W	
	Added power allocation for fault	7.4 W
	Avionics power increased	5.0 W
	Harness loss power increased	4.3 W
	Propulsion power decreased	0.9 W
	G&C power increased	0.5 W

Cooling System Margin – 9.86Rs



*383.9W Power Load includes 28.4% margin on CBE electrical power loads.

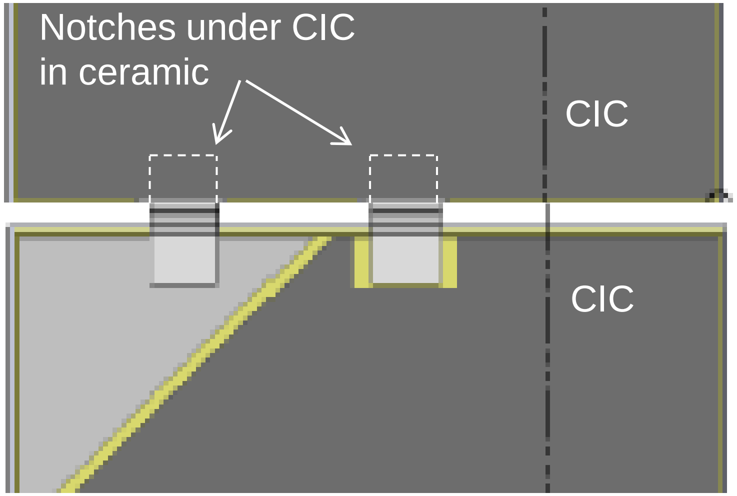
Margin available to power loads is 37.2% if 6480W cooling capacity is utilized.

Flight Solar Array Width Decision (1 of 2)

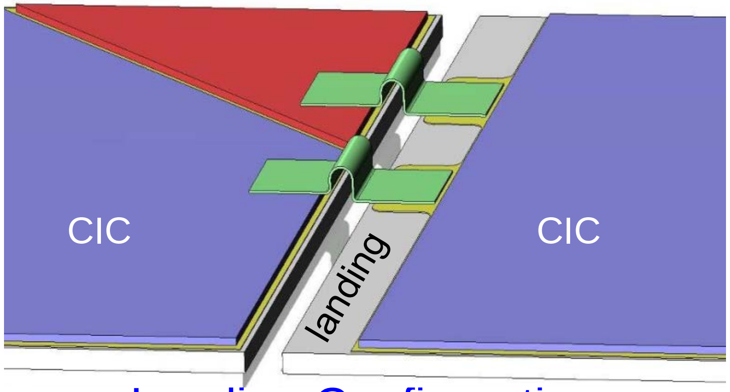
- Current project cost assumes flight Solar Array will be fabricated at the width defined for SRR/MDR and built in Phase B for TRL 6 demonstration
  - Reduced design and tooling cost of flight platens
  - Project Risk #75, 78 added to acknowledge that the flight platen and solar array width may need to be greater than MDR width
- Width change is approach used to adjust SA area; length is maintained.
  - MDR and Phase B as-built width: 0.65m
  - PDR CAD model and MEL width: 0.69m (Power Calcs: 0.65m)
- Decision date for flight Solar Array width: April 2014
  - Provides 2 month development of flight platen ICD between APL, HS and Emcore
  - Meets Solar Array I&T delivery schedule

Flight Solar Array Width Decision (2 of 2)

- Input needed for decision
  - Confirm/update flight load NTEs, assess remaining uncertainty
  - Confirm SA performance
  - Downselect notch vs. landing configuration
    - Notch configuration necessary for reduced SA width
    - Completion of cell crack evaluation for notch configuration
  - Refine anomalous SA degradation estimate; affects EOM Downlink Slew; Assessment of anomalous SA degradation for 2019 Backup
- Impact of decision if change to smaller wing (0.65m)
  - Mass margin: 1.9kg decrease in CBE
  - Power margin: smaller wing already assumed
  - Risk- low medium- to be assessed based on above input
  - Meets cost assumptions



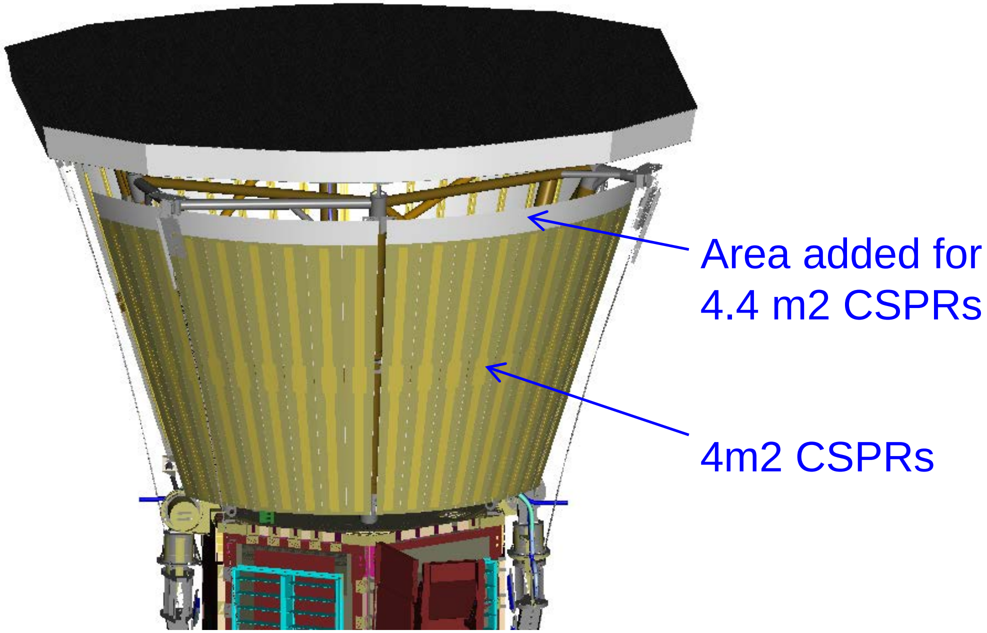
Notch Configuration



Landing Configuration

Cooling System Primary Radiator Size Decision (1 of 2)

- Current project cost assumes flight Cooling System Primary Radiators (CSPRs) will be fabricated at the same size defined for MDR and fabricated in Phase B for TRL 6 demonstration
  - Reduced design and tooling cost of flight CSPRs
  - Project Risk #76 added to acknowledge that the flight CSPR size may need to be greater than the SRR/MDR size
- CSPR size is primary driver for cooling system capacity
  - SRR/MDR and Phase B fabricated size: 4m2
  - PDR CAD model and MEL width: 4.4m2 (Power calcs assume 4.4m2*)
- Decision date: end of February 2014
  - Provides 1 month update on TSA/cooling system radiator ICD and TSA design
  - Meets TPS/TSA Qualification and TSA/Cooling System flight delivery to I&T



*TRL 6 test results indicate 4m2 system has higher performance than predicted

Cooling System Radiator Size Decision (2 of 2)

- Input needed for decision
  - Confirm TRL 6 cooling system perihelion performance and SA temperature EOM DL Slew
  - Confirm off-nominal fault case performance
  - Confirm skew budget adequate
  - Update thermal load from TPS and instruments (possible reduction due to increased distance between top of CSPR and TPS)
  - Confirm/update flight load NTEs, assess remaining uncertainty
  - Confirm SA performance
  - Refine anomalous SA degradation- EOM Perihelion Science, EOM DL Slew
  - Assess 2019 launch anomalous degradation
- Impact of decision
  - Mass margin: 1.8kg decrease in CBE
  - Cooling system capacity margin: expect minimal change from current assumptions
    - 4m2 system performance exceeds predictions
  - Power margin: expect minimal change based on above
  - Risk – low – to be assessed based on above input

MEL Summary

	CBE Total (kg)	NTE (kg)
Instruments Total:	51.55	60.71
Accommodation Hardware Total:	5.76	6.25
Telecommunications Total:	26.15	28.22
Guidance and Control Total:	27.94	30.08
Power Total:	55.07	60.93
Cooling System Total:	72.91	80.65
Thermal Protection System Total:	106.00	118.71
Thermal Total:	17.58	19.82
Avionics & Power Distribution Total:	25.84	27.70
Propulsion Total:	21.28	22.19
Mechanical Total:	58.26	64.08
Harness Total:	25.50	30.55
Spacecraft Dry Mass	493.82	549.89
Propellant Total:		63.78
Spacecraft Wet Mass		613.67
Launch Mass		665.0
Allocated Margin	55.39	11.4%
Unallocated Margin	51.33	**9.3%**
Total Mass Margin + Contingency		**21.75%**

Launch Wet Mass increased 55 kg from MDR to PDR

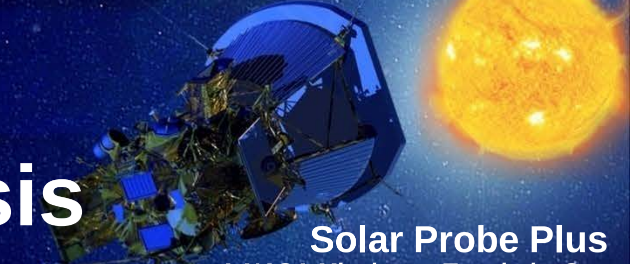
NTEs defined, provided to instruments (included in ICDs) and subsystems (included in Level 4 reqs)

MDR Mass Margin: 24.6%
PDR Mass Margin: 21.8%

Changes to Mass CBEs
PDR vs. SRR/MDR

Decrease/ No Change	Power system mass decrease	4.00 kg
	TPS/TSA blankets mass decreased	2.23 kg
	Avionics mass decrease	1.39 kg
	Thermal mass decrease	0.72 kg
	Propulsion mass decrease	0.52 kg
	RF mass:	no change
Increase	TPS mass increase	14.73 kg
	Instrument mass increase	11.62 kg
	▪ WISPR mass increase 5.64kg	
	▪ SWEAP mass increase 2.17kg	
	▪ ISIS increase 1.23kg	
	▪ FIELDS mass increase 2.58kg	
	Solar array assembly mass increase	6.37 kg
	Cooling system mass increase	8.41 kg
	G&C mass increase	4.64 kg
	TSA mass increase	4.59 kg
	Harness mass increase	4.10 kg
	Propellant mass increase	3.88 kg
	Mechanical mass increase	3.56 kg
	Magnetometer mass increase	2.26 kg
	Power Distribution mass increase	0.83 kg

As-Built Component Mass Basis

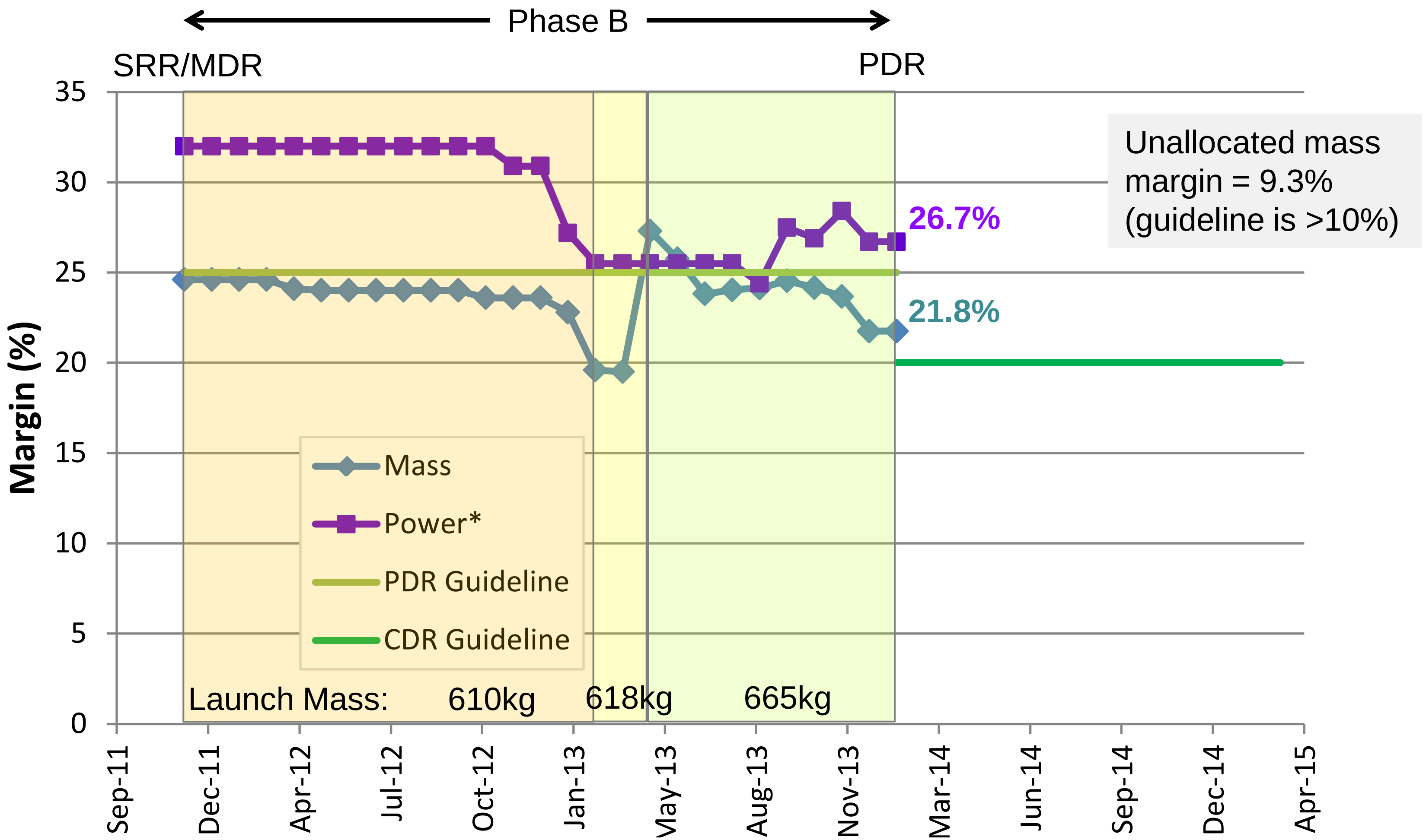


Component with As-Built Mass Basis	Mass (kg)	Comment
TPS	75.9	Built in Phase B
TSA	24.4	Built in Phase B
Cooling System Primary Radiators	19.4	Built in Phase B
Solar Array Platens	23.5	Built in Phase B
Solar Array Cells/Add on Mass	9.6	Built in Phase B
Cooling System Pump	3.8	Built in Phase B
Cooling System Pump Electronics	4.3	Built in Phase B
Solar Limb Sensor Heads	0.7	Built in Phase B
Power Distribution Unit	14.1	RBSP
Battery Cells	6.6	COTS
Propellant Tank	6.4	COTS
Thrusters	4.3	COTS
Total	193.3	

39% of Observatory dry mass based on as-built mass

The mass for many of the higher mass-risk components is based on as-built Phase B mass

Mass, Power Margin History



Unallocated mass margin = 9.3% (guideline is >10%)

* Reporting min margin for driving power configs: Perihelion Science, Downlink, Recharge Post Launch

Margin Summary

Item	Margin	QMS Margin for Green @PDR
Mass	21.8%	25%
Power	26.7%	25%
Cooling System Capacity	33% for anomalous SA degradation, plus TBD %	N/A
Uplink	6dB	6dB
Downlink	2dB science, 3dB emerg	3dB
Data Rate	29%	20%
DL Contact Loss (DL time possible above margined DL req'd)	99%	N/A
deltaV	8%	N/A
Tank Capacity (above Margined Prop)	5%	N/A
CPU	41%	50%
Non Volatile Memory	48%	50%
RAM	50%	45%
On-board Data Throughput	126%	50%

Margin Summary

Item	Margin	QMS Margin for Green @PDR
PDU Services	11 switched or pulsed	N/A
Post-Processed Time Accuracy	43%	N/A
Realtime G&C Time Accuracy	111%	N/A
Worst Case Oscillator Fault Time Accuracy	117%	N/A
Packaging within Umbra	2.18°	N/A
Wing to Safe Angle: Safe Solar Array – Overtemp	51% (37 sec)	N/A
Wing return to Nominal from Safe Overtemp	72% (376 sec)	N/A
Wing return to Nominal from Safe Undertemp	25% (60 sec)	N/A
Pump Switch in Worst Case Pump Failure	31% (4.5 sec)	N/A

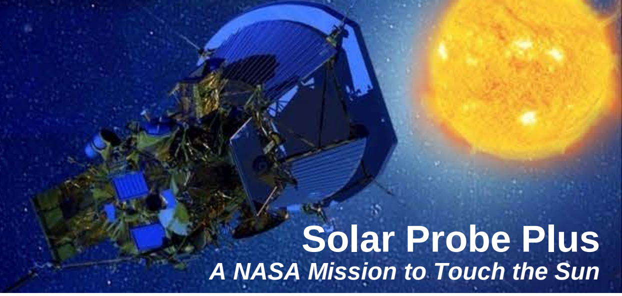
Liens/Opportunities

- **Mass Liens**
  - deltaV propellant- uncertainty in stage performance
  - 2019 propellant increase < 5kg
  - DSS ram side
  - HGA Rotary Joint
  - Harness
  - ACS propellant if cp-cg >1”
- **Mass Opportunities**
  - IMU shielding
  - Cooling system radiator size reduced from 4.4m2 to 4m2
  - Solar array platen width reduced from 0.69m to 0.65m
  - Delta IVH

- **Power Liens**
  - Wheel power
- **Power Opportunities**
  - Solar Array drive internal heaters

- Normal updates in subsystem and instrument mass/power

Spacecraft Accommodation of 2019 Backup Launch (1 of 2)



- Propellant increase < 5kg
  - deltaV propellant increase ≤4kg to accommodate increase in Venus flybys from 7 to 8 (based on rough conservative scaling of non-launch correction deltaV propellant)
  - ACS increase < 1 kg (rough conservative scaling 14% increase)
- Max distance from Sun following cooling system activation increases from 0.94AU to 1.0AU
  - Additional Spacecraft Pointing Orientation: Super Aphelion
    - Solar Distance between 1AU and 0.94AU
    - After full cooling system activation; first 2 orbits
    - Spacecraft-sun line in –XZ quadrant 55 degrees +/- 5 degrees from Z-axis
- Launch parking orbit duration increases 16min; total launch duration 1 hour (TBR); accommodated in power configuration, but with reduced margin.

- No change to: s/c launch mass, min perihelion, data downlink capability, comm outages
- Min solar distance for first 2 (additional 2) orbits increases from 35.7Rs to 43.9 and 42.2 Rs

Spacecraft Accommodation of 2019 Backup Launch (2 of 2)

- Launch delay ~ 9 months: July 31, 2018 to May 2019
- Orbits increase from 24 to 26 (8.3%)
- Mission duration increases from 7 to 8 years (14%)
- Impacts of above:
  - Solar Array degradation: potential 5% increase in anomalous degradation
  - Cooling system pump life requirement increases 14%: will be included in Phase C pump life test
  - TPS a/e end of life: within margin
  - Battery life requirement increases: all within margin
  - Radiation environment: ~5krad increase in total dose in some components - within margin
    - Worst case part has >80% margin for 2018 and 2019
  - Solar Array flap cycles: flap actuator, harness/flex hoses, flap potentiometer
    - Full range flap cycles, due to solar distance variation for 2 add’l orbits: increase 8.3% – within margin
    - Flap cycles due to dither cycles increase 8.3% - within margin
  - S/C thermal cycles due to S/C comm slews unchanged– maintain 100 cycles max by reducing slews from Aphelion to Umbra S/C Pointing Orientation for science downlink in consecutive days.
    - Solar array thermal cycles, solar array feather cycles, instrument thermal cycles, etc
  - Solar array feather cycles, slight increase due to 2 add’l orbits (Super Aphelion to Umbra >0.82AU)
  - HGA gimbal cycles increase 8.3% due to 2 additional orbits – within margin
  - SSR EOL capacity: within margin of 2018 EOL capacity

- Spacecraft can accommodate 2019 Backup Launch

TRL 6 Summary
Solar Array, SLS, Flex Waveguide

	Prototype	Tested in Relevant Environ	Status	TRL
Solar Array	Full Size Secondary Solar Array	High Irradiance, High Temp Irradiance: Perihelion	Complete; will repeat with FSS2	6
	Full Size Secondary Solar Array	Non-Nominal High Irradiance: Perihelion Fault Conditions	Complete; will repeat with FSS2	
	Full Size Secondary; Multi String Coupon- revised solder process	Thermal Cycles – TVAC: Survival Cold to Hot	Complete; will repeat with FSS2	
	Multiple Cell Coupons	UV	Complete	
	Multiple String Coupons	Electrostatic Cleanliness	Complete	
Solar Limb Sensors	SLS Head and Electronics	Elec Perf – Irradiance Gradient	Complete	6
	SLS Head and Electronics	Thermal/Elec Perf – High Intensity, High Temp Irradiance Gradient	Complete	
	SLS Head and Electronics	Thermal Cycles – TVAC	Complete	
Flex Waveguide	Full Size Flexible Waveguide	Life Test – Flex Cycles	Complete; will test at Temp	6

Cooling System and TPS Completed TRL 6

	Prototype	Tested in Relevant Environment	Status	TRL
Cooling System	Half Cooling System: 2 Radiators, 1 Platen, 1 Pump, 1 Accummulator	Thermal Performance – TVAC: Perihlion, Aphelion, Activation, Venus Eclipse, Transients, Pump Stop/Start	Complete	6
	Full Size Platen	Platen Structural Vibration: Launch	Complete	
	Full Size Radiator	Radiator Structural Vibration: Launch; Thermal Cycles: Survival Cold-Hot	Complete	
	Flight-like Pump/Controller	Pump Perf, Back EMF Control, Power – TVAC: Perihelion, Aphelion, Activation, Venus, Transients, Pump Stop/Start	Complete	
Thermal Protection System	Flight Thickness TPS: 22”x22”	Thermal and Thermomechanical Performance – JSC Hot Wall: Perihelion	Complete; will test thermal cycle	6
	TPS/TSA/CSPR/Blanket/ Top Deck Simulator	TPS to Spacecraft and Cooling System Heat Flow – TVAC: Perihelion	Complete	
	Large Area Coating Samples	Coating Optical Properties – BRDF, UV, Radiation: BOL, EOL; Adhesion	Complete	
	Full Size TPS integrated to Flight-like TSA	Structural Performance – Acoustics, Vibration, Static Load: Launch	Complete	

System Level Verification

Solar Probe Plus

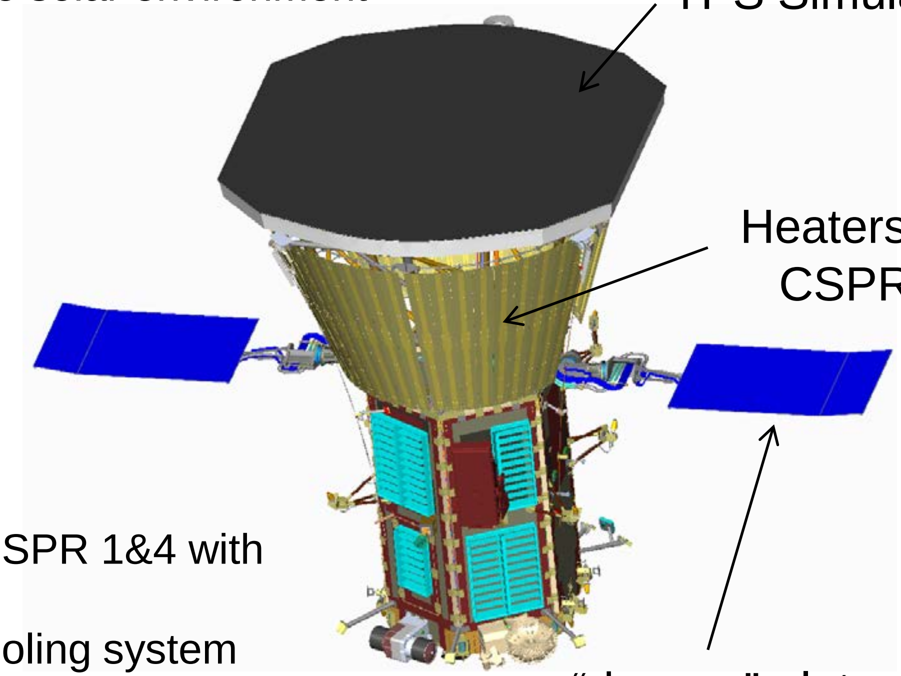
A NASA Mission to Touch the Sun

- Verification Planning Matrix will identify verification approach for each spacecraft requirement
  - Comprehensive Performance Test
  - Special Tests
  - Fault Protection Tests
  - Mission Simulations
- Key system level tests defined in EDTRD 7434-9039, Section 4 and Section 7
  - Thermal
    - Propulsion Thermal Balance - Section 4
    - Integrated Thermal System Balance – Section 4 (integrated Cooling System*, TPS**, TSA, TSA mounted Instruments**, and spacecraft top deck [EDTRD_0073].

      * cooling system platens are simulator platens; ** TPS and TSA-mounted Instruments are simulators.
    - Observatory Thermal Balance – Section 7
    - Observatory Thermal Cycling – Section 7
  - Structural
    - Primary Structure Strength– Section 7
    - Spacecraft Mass Properties: 6 mos. after start of I&T to define TPS cp and planform – SCRD
    - Observatory Sine Sweep Vibration– Section 7
    - Observatory Acoustics– Section 7
    - Observatory Shock– Section 7
    - Observatory Vibration– Section 7
    - Observatory Mass Properties– Section 7
    - Observatory Leakage– Section 7

Observatory TVAC Thermal Balance

- Configuration
  - Cooling system operational
    - Platen, CSPR heaters simulate solar environment
  - Solar Array Simulator (electrical)
  - TPS simulator
  - SA actuator bypass
- Power Configurations: Driving Cases
- Cooling System Thermal Cases
  - Perihelion, aphelion, slew, etc
- CPT
- Mission Sims
- Special tests
  - Autonomous Activation of SA and CSPR 1&4 with Ground Monitor
  - Wing angle control with flight-like cooling system response using “dummy platen” and SAS
    - Ex. transition between Temp Control and Power Control (bypass SA actuator)
  - Pump speed change, pump switch
- Fault Protection Tests



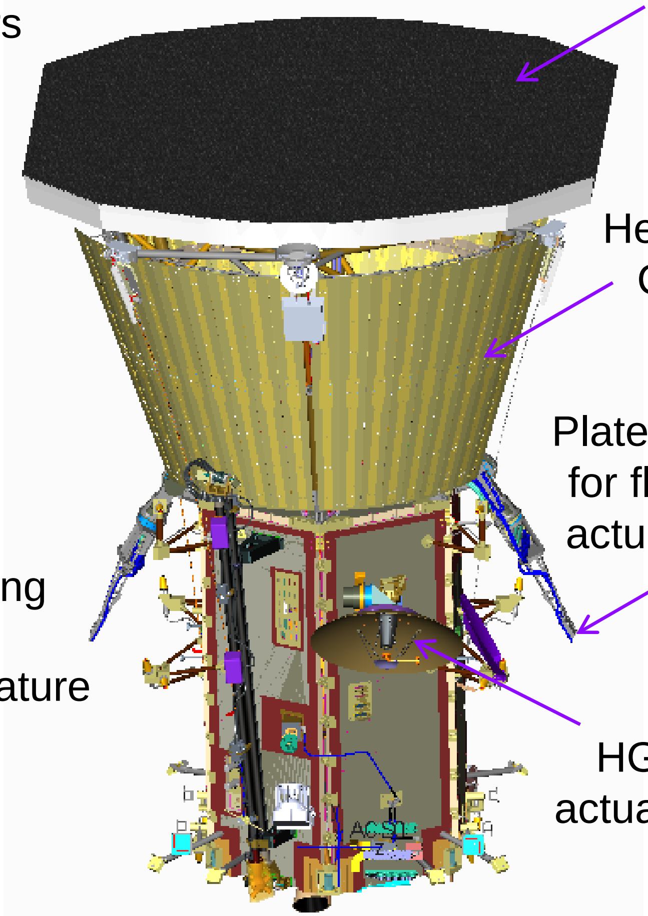
TPS Simulator

Heaters on CSPRs

“dummy” platens with heaters and flight-like temperature sensors

Observatory TVAC Thermal Cycle

- Configuration
  - Platens removed- bypass at platen inlet/outlet, water circulated, temp controlled with CSPR heaters
  - Solar Array Simulator (electrical)
  - TPS simulator
  - Gimbals driven by ECU
- Power Configurations: Driving Cases
- Cooling System Thermal Cases
  - Near-Perihelion, aphelion, slew, etc
- CPT
- Mission Sims
- Special Tests
  - SA Deploy, SA range of motion through cooling system activation, etc.
  - Wing angle control – Power Control, Temperature Control, Momentum dump, TCM
  - HGA actuation
- Fault Management Tests
  - Solar Array Safing



Verification in Solar Environment (1 of 3)

System, subsystem, and component testing, modeling and simulation are utilized together to provide end-to-end verification of SPP performance piecewise in flight-like environment

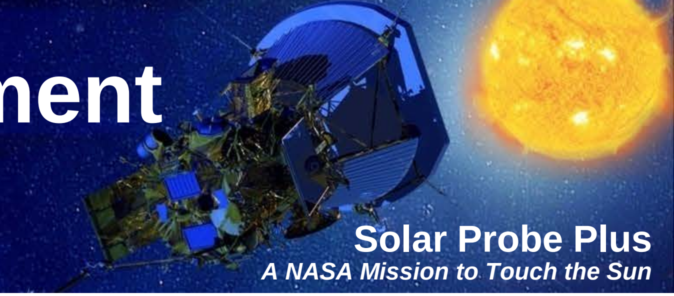
- TPS, Cooling System, Spacecraft Bus, SLS and G&C performance in solar environment:

	TPS Coating	TPS	TPS/TSA, Inst /Cooling /S/C Heat Flow	Solar Limb Sensors
BRDF, EOL Perf Tests	X			
JSC Hot Wall		X		
XT-30 Simulator, Motion Tests				X
Integrated Thermal	TPS Simulator		X	
Observatory Thermal Balance	TPS Simulator		X	
Observatory Thermal Cycle	TPS Simulator		X	
Integrated Thermal Model	X			
G&C Simulation Models	Solar Pressure, Re-Radiation Pressure, Umbra/Penumbra Truth Model		Cooling System Momentum Loop Model	Truth Model

Verification includes, in addition:

- Standard G&C testing and simulation
- Alignment of TPS, solar array, SLS, all G&C components, and instruments
- Testing of coupons and components for EOL performance, etc.

🟩	Verifies Performance
🟦	Provides flight-like interface to hardware being verified
🟪	Model or Simulation content used in analysis verifications



Verification in Solar Environment (2 of 3)

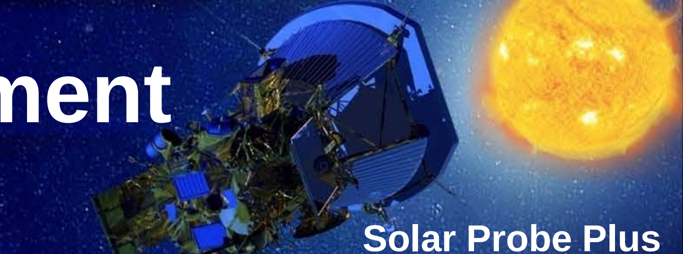
- Test verification of solar array, cooling system, solar array ECU, gimbals, electrical power system, avionics, G&C, autonomy interactions and end-to-end performance:

	Solar Array (Cell Stack, Elec Comp)	Solar Cell Sensors	Solar Array Temp Sensors	Platen	Cooling System, CSPR Temp Sensors	PSE, Avionics, Wing Angle Control/ G&C FSW, Autonomy	ECU	Flex Line /Harness	Gimbals
Solar Array Heliostat	X	X	X	X	Cooling Cart				
Integrated Thermal TVAC			Dummy	Dummy	X			(flex line only; stationary)	
Observ Thermal Balance	Solar Array Simulator		Dummy	Dummy	X	X	command	(stationary)	
Observ Thermal Cycle	Solar Array Simulator				CSPR heat input	X	X	X	X
EPS Testbed	SAS		Truth Model			X	Truth Model		

🟩 Verifies Performance 🟦 Provides flight-like interface to hardware being verified

- Verification includes, in addition, testing of coupons and components for EOL performance, off-nominal survival performance, etc.

Verification in Solar Environment (3 of 3)



Analysis supports verification of solar array, cooling system, solar array ECU, gimbals, electrical power system, avionics, G&C, autonomy interactions and end-to-end performance:

	Irradiance	Add'l Heat Input to CSPR (ex. TPS)	SA Electrical Perf	Solar Cell Sensors, SA Temp Sensors	Cooling Sys Perf	S/C and SA Jitter	Spacecraft Attitude, Control	Wing Angle Control	Fault Inputs
SA Elec Performance Modeling	X	X	X	SA Cell Sensor Elec	SA Temp Model				
Cooling Sys Modeling	SA Heat Flux Profile as input	X	Elec Load as input	Platen Temp at Sensors	X				
Wing Angle Control Simulation	X	X	X	X	SA Temp Model	SA Model	X	X	X
G&C Simulation	X	X		X	SA Temp Model	X	X	X	X

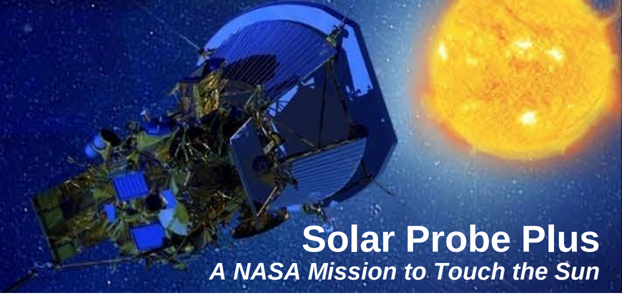
▨ Model or Simulation content used in analysis verification

Phase C

- Complete testing on second Solar Array Full Size Secondary (FSS2) with improved solder process
- Define TPS Qualification Plan
- Resolve TBDs and TBRs for Level 3 and Level 4 requirements
- Complete assessment of Level 3 to Level 4 requirements for completeness of both
- Develop initial verification matrix and test definitions
- Continue instrument accommodation
- Refine fault management and solar array safing
- Complete Phase C trades
- Decision on solar array width
- Decision on cooling system radiator size
- Glint analysis on SLS, DSS and star trackers
- Other standard CDR preparation work

BACKUP

MEL, NTEs
Instruments, Totals



	Qty	CBE Each (kg)	CBE Total (kg)	NTE (kg)	Remain Contin (%)
Instruments Total:			51.55	60.71	
FIELDS MEP (w/ Mag electronics)	1	7.75	7.75	9.300	20.0%
FIELDS E-Field Sensors, Brackets	1	5.87	5.87	6.622	12.8%
FIELDS Search Coil Magnetometer	1	1.06	1.06	1.215	14.9%
FIELDS FGMs (w/o Mag elec in MEP)	1	1.83	1.83	2.032	10.9%
SWEAP SPC	1	2.92	2.92	3.546	21.4%
SWEAP SPC Power Supply	1	1.19	1.19	1.428	20.0%
SWEAP SPAN A+	1	4.97	4.97	6.029	21.2%
SWEAP SPAN B	1	2.26	2.26	2.723	20.3%
SWEAP Brackets for SPAN A+&B	1	0.61	0.61	0.732	20.0%
SWEAP SWEM	1	1.62	1.62	1.949	20.0%
SWEAP Interunit Cabling	1	1.12	1.12	1.351	20.8%
WISPR Instrument Module w/ bracket	1	10.84	10.84	12.544	15.7%
WISPR DPU, LVPS	1	1.07	1.07	1.229	15.4%
WISPR-DPU Harness	1	0.55	0.55	0.629	15.0%
ISIS (EPI-Hi, EPI-Lo)	1	7.88	7.88	9.383	19.1%
Accommodation Hardware Total:			5.76	6.25	
Mag Boom, Launch Locks (no harness	1	5.76	5.76	6.25	8.5%
Spacecraft Dry Mass			493.82	549.89	
Propellant Total:				63.78	
Useable				63.05	
Residual, Lines				0.63	
Pressurant				0.10	
Spacecraft Wet Mass				613.67	
Launch Mass				665.0	
Allocated Margin			55.39	11.4%	
Unallocated Margin			51.33	**9.3%**	
Total Mass Margin + Contingency				**21.75%**	

MEL, NTEs
Telecomm, G&C

	Qty	CBE Each (kg)	CBE Total (kg)	NTE (kg)	Remain Contin (%)
Telecommunications Total:			26.15	28.22	
High Gain Antenna Dish, Dish Mount Brkt	1	2.41	2.41	2.62	8.5%
HGA Actuator EH25	1	1.98	1.98	2.15	8.5%
HGA Launch Lock	1	0.50	0.50	0.54	8.5%
HGA Flex Waveguide	2	0.02	0.05	0.05	8.5%
HGA Assembly Mounting Bracket	1	0.81	0.81	0.91	12.8%
HGA Plume Shield	1	0.44	0.44	0.50	12.8%
Fanbeam Antenna Assembly	2	0.65	1.30	1.36	4.3%
LGA Assembly	2	0.37	0.74	0.83	12.8%
11W X-band TWT	2	0.96	1.92	2.00	4.2%
34W Ka-band TWT	2	0.86	1.72	1.79	4.3%
X-band TWTA EPC	2	1.26	2.52	2.63	4.3%
Ka-band TWTA EPC	2	1.26	2.52	2.63	4.3%
X-band EPC-TWT Cable***	2	0.44	0.88	0.95	8.5%
Ka-band EPC-TWT Cable***	2	0.44	0.88	0.95	8.5%
RF Switch Plate	1	0.34	0.34	0.38	12.8%
RF Diode Unit	1	0.32	0.32	0.36	12.8%
Coaxial Switch	4	0.07	0.28	0.30	4.3%
Low Noise Amplifiers (external)	2	0.01	0.02	0.02	8.5%
X-band Diplexer	2	0.15	0.30	0.33	8.5%
Ka-band 90 deg Hybrid	1	0.15	0.15	0.16	8.5%
Flex Waveguide	1	0.10	0.10	0.11	8.5%
Rigid Thin Wall Waveguide, WR34	1	0.12	0.12	0.13	8.5%
Rigid Thin Wall Waveguide, WR28	1	0.03	0.03	0.03	8.5%
0.29" dia. Coax	1	1.12	1.12	1.22	8.5%
Ka band Coax	1	0.09	0.09	0.10	8.5%
Semi-rigid	1	0.17	0.17	0.18	8.5%
Semi-rigid 0.25	1	0.42	0.42	0.46	8.5%
Radio	2	2.01	4.02	4.53	12.8%
Guidance and Control Total:			27.94	30.08	
Inertial Measurement Unit	1	7.8	7.80	8.13	4.3%
Star Tracker	2	2.5	5.00	5.43	8.5%
Reaction Wheels	4	3.20	12.80	13.89	8.5%
Reaction Wheel Metglass Shields	4	0.03	0.12	0.13	8.5%
Solar Limb Sensor Electronics Box	1	1.00	1.00	1.13	12.8%
Solar Limb Sensor Detector Heads	7	0.10	0.70	0.79	12.8%
Digital Sun Sensors	2	0.26	0.52	0.59	12.8%

MEL, NTEs
Power, Cooling System


Solar Probe Plus
A NASA Mission to Touch the Sun

	Qty	CBE Each (kg)	CBE Total (kg)	NTE (kg)	Remain Contin (%)
Power Total:			55.07	60.93	
Solar Array w/o Substrate (platen) =			33.57	36.68	9.3%
CICs, diodes, adhesive, wiring, etc.	2	4.78	9.55	10.63	11.3%
SA Flap & Feather Actuators	4	1.98	7.91	8.58	8.5%
ECU Solar Array and HGA	1	5.95	5.95	6.46	8.5%
SA Boom Assembly	2	2.55	5.10	5.53	8.5%
SA Cooling Line Management	2	1.53	3.05	3.31	8.5%
SA Restraint and Release	2	1.00	2.00	2.17	8.5%
Power Electronics =			21.50	24.25	
PSE	1	10.00	10.00	11.28	12.8%
Battery - 25Amp-hr, baseplate	1	11.50	11.50	12.97	12.8%
Cooling System Total:			72.91	80.65	
Solar Array Substrate (platen)	2	11.73	23.46	25.81	10.0%
Radiators(CSPR), Paint (4.4m2 total)	4	4.84	19.36	21.30	10.0%
Pumps and Check Valve Assy	1	3.81	3.81	4.19	10.0%
Pump Electronics	1	4.33	4.33	4.76	10.0%
Accumulator	1	5.51	5.51	6.06	10.0%
Accumulator Brackets	1	0.81	0.81	0.91	12.8%
Isolation Valves	3	1.02	3.06	3.45	12.8%
Harness, Motor Controller	4	0.24	0.96	1.08	12.8%
Differential Pressure Sensors	2	0.18	0.36	0.41	12.8%
Pressure Sensors	2	0.18	0.36	0.41	12.8%
Fill and Drain	2	0.11	0.22	0.25	12.8%
Fluid Lines	1	3.07	3.07	3.46	12.8%
Flexible Cooling Lines	8	0.29	2.32	2.62	12.8%
Mounting Hardware	1	0.36	0.36	0.41	12.8%
Fluid	1	4.92	4.92	5.55	12.8%

MEL, NTEs
TPS, Thermal

	Qty	CBE Each (kg)	CBE Total (kg)	NTE (kg)	Remain Contin (%)
Thermal Protection System Total:			106.00	118.71	
TPS =			75.93	85.18	
Carbon Foam Core - Machined	1	23.56	23.56	26.57	12.8%
Carbon Foam Insert (130 ppi)	1	2.31	2.31	2.60	12.8%
Facesheet, Top (C-C)	1	6.96	6.96	7.85	12.8%
Facesheet, Bottom (C-C)	1	9.71	9.71	10.95	12.8%
Panel, Foam Core Support (C-C)	1	3.86	3.86	4.36	12.8%
Cp/Cg shift	1	1.66	1.66	1.87	12.8%
Mounting Plate (3D CC)	1	1.63	1.63	1.84	12.8%
Mounting Plate Support Sleeve	1	0.53	0.53	0.58	8.5%
Support Sleeve Washer	1	0.06	0.06	0.06	8.5%
Support Sleeve Nut	1	0.26	0.26	0.29	8.5%
C-C Bolts	1	0.17	0.17	0.19	8.5%
Coating, Optical	1	1.34	1.34	1.46	8.5%
Coating, Barrier	1	3.33	3.33	3.62	8.5%
Coating, Bottom	1	2.39	2.39	2.60	8.5%
Adhesive, Carbon Foam Bonding	1	1.53	1.53	1.73	12.8%
Adhesive, Top Facesheet/Core Bonding	1	7.01	7.01	7.91	12.8%
Adhesive, Btm Facesheet/Core Bonding	1	6.77	6.77	7.64	12.8%
Edge Closeout, Felt	1	1.89	1.89	2.05	8.5%
Edge Closeout, Bonding	1	0.11	0.11	0.13	12.8%
Fasteners (All Attachment)	1	0.83	0.83	0.90	8.5%
TSA =			24.39	27.37	
TSA structure	1	20.91	20.91	23.59	12.8%
TSA / TPS I/F fittings	1	1.50	1.50	1.63	8.5%
TSA / SC I/F fittings	1	1.12	1.12	1.22	8.5%
Radiator brackets	1	0.86	0.86	0.93	8.5%
Blankets =			5.67	6.16	
Radiator panel MLI	1	2.39	2.39	2.60	8.5%
Radiator tube MLI	1	0.23	0.23	0.25	8.5%
Barrier MLI	1	0.71	0.71	0.77	8.5%
TSA MLI	1	2.34	2.34	2.54	8.5%
Thermal Total:		8.19	17.58	19.82	
MLI-bus,top deck cool lines	1	6.07	6.07	6.84	12.8%
MLI - SA back, SA boom	2	0.88	1.75	1.97	12.8%
MLI - Mag boom	1	0.37	0.37	0.42	12.8%
Radiators	1	0.26	0.26	0.29	12.8%
7 Blade Louver (Battery)	1	0.58	0.58	0.65	12.8%
10 Blade Lvrs (IMU,MEP; TWTs; RWs)	3	0.89	2.67	3.01	12.8%
20 Blade Lvrs (PSE; Ka EPCs, DPU)	2	1.29	2.58	2.91	12.8%
Ka TWTA, PSE Doublers	1	0.89	0.89	1.00	12.8%
Heater/Thermistor Harness	1	1.00	1.00	1.13	12.8%
Gaskets	1	1.41	1.41	1.59	12.8%

MEL, NTEs Avionics, Propulsion

	Qty	CBE Each (kg)	CBE Total (kg)	NTE (kg)	Remain Contin (%)
Avionics & Power Distribution Total:			25.84	27.70	
Redundant Processor Module	1	5.26	5.26	5.79	10.0%
Redundant Electronics Module	1	5.36	5.36	5.90	10.0%
Remote Interface Units	16	0.07	1.09	1.18	8.5%
Power Distribution Unit	1	14.13	14.13	14.84	5.0%
Propulsion Total:			21.28	22.19	
Hydrazine Tank	1	6.36	6.36	6.63	4.3%
4N (1 lbf) Thruster (MR-111C)	12	0.36	4.32	4.51	4.3%
Latch Valve	2	0.34	0.68	0.71	4.3%
Filter	1	0.16	0.16	0.17	4.3%
Service Valves	2	0.21	0.42	0.43	4.2%
Pressure Transducers	2	0.23	0.46	0.48	4.3%
Tubing/Fasteners/Clamps	1	3.94	3.94	4.11	4.3%
Thermal Hardware	1	1.51	1.51	1.57	4.2%
Cabling (Wire, Harness, Supports)	1	3.40	3.40	3.54	4.3%
Orifice	1	0.03	0.03	0.03	4.3%

MEL, NTEs
Mechanical, Harness

	Qty	CBE Each (kg)	CBE Total (kg)	NTE (kg)	Remain Contin (%)
Mechanical Total:			58.26	64.08	
Primary Structure=			49.76	54.74	
Panel 7 (top deck)	1	6.35	6.35	6.99	10.0%
Panel 5 (anti-ram)	1	4.38	4.38	4.82	10.0%
Panel 4 (fixed, -y)	1	4.96	4.96	5.46	10.0%
Panel 3 (ram)	1	5.61	5.61	6.17	10.0%
Panel 2 (ram)	1	5.39	5.39	5.93	10.0%
Panel 1 (fixed, +y)	1	5.18	5.18	5.70	10.0%
Panel 0 (anti-ram)	1	4.55	4.55	5.01	10.0%
Panel, Battery, Removable	1	0.95	0.95	1.05	10.0%
Panel 6 (bottom deck)	1	7.91	7.91	8.70	10.0%
Tank Supports	3	0.73	2.20	2.42	10.0%
Paint, Interior Panel Surface	1	1.00	1.00	1.10	10.0%
Fasteners	1	1.28	1.28	1.41	10.0%
Secondary Structure=			8.50	9.35	
Fan Beam Ant Brkt	2	0.21	0.42	0.46	10.0%
Low Gain Ant Brkt	2	0.23	0.46	0.50	10.0%
Thruster, Fill & Drain Brackets	1	2.00	2.00	2.20	10.0%
Star Tracker Brkt	2	0.37	0.75	0.82	10.0%
Reaction Wheel Brackets	2	0.83	1.66	1.82	10.0%
SLS, DSS Brackets	1	1.26	1.26	1.38	10.0%
Purge Components	1	0.39	0.39	0.43	10.0%
Arming Plug, Test Connector Plates	1	0.24	0.24	0.27	10.0%
Umbilical Bracket	1	0.07	0.07	0.07	10.0%
Separation Nut Bolt Retractor	6	0.21	1.26	1.39	10.0%
Harness Total:			25.50	30.55	
Main Harness	1	24.00	24.00	28.92	20.5%
Plugs	1	1.00	1.00	1.09	8.5%
Grounding Straps	1	0.50	0.50	0.54	8.5%

Power Required – Early Operations

	Early Operations													
Power Configuration #	PC1	PC2	PC3	PC4	PC5	PC6	PC7	PC9	PC10	PC12	PC8	PC11	PC13	PC14
Power Configuration Name	Launch	Warm-up and Activate Rad 1&4 and Solar Array	Recharge Post Rad 1&4 and SA Activation	Catbed Warm Up for Launch Error Correction	Launch Error Correction	Recharge Post LC	Early Cruise	FIELDS CO, Fanb Playback	SWEAP CO, with FIELDS on, Fanb Playback	Warm-up and Activate Rad 2&3	ISIS CO, Fanb Playback	WISPR CO, Fanb Playback	All Inst CO, Fanb Playback	HGA Commissioning
Solar Distance	1.02	1.02	1.02	1.02	1.02	1.02	1.02	0.975	0.94	0.9	0.88	0.843	0.82	0.76
Spacecraft Orientation		Activate 1 and 4	Aphelion	Aphelion	Launch Correction	Aphelion	Aphelion	Aphelion-Comm	Aphelion-Comm, SWEAP Transient	Activate 2 and 3	Aphelion-Comm	Aphelion-Comm	Umbra-Comm	Umbra-Comm
Solar Array Control	Stowed	5deg from Sun normal	Sun normal	Sun normal	5deg from Sun normal	Sun normal	Sun normal	Sun normal	Sun normal	5deg from Sun normal	Sun normal	Sun normal	Sun normal	Sun normal
Cooling System Status	Dry	Dry	Partial	Partial	Partial	Partial	Partial	Partial	Partial	Partial	Full	Full	Full	Full
Time in Mission	Early Ops	Early Ops	Early Ops	Early Ops	Early Ops	Early Ops	Early Ops	Early Ops	Early Ops	Early Ops	Early Ops	Early Ops	Early Ops	Early Ops
Cell Temp** (C) (TBR)		122	43	43	43	43	43	49	56	63	60.7	60.7	calc	calc
NTE Load (W) (TBR)	170.6	417.2	310.8	344.5	401.8	306.2	317.8	345.0	365.6	370.1	323.1	337.7	387.3	397.3
Power req'd at SA @SA Bus (W) (TBR)		as available	351.6	as available	as available	346.3	359.7	391.0	414.7	419.9	365.8	382.5	439.8	451.4
Battery Target SOC /Full SOC (TBR)			1.00			1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Duration (hrs)	1.00	1.00		1.00	2.00									
Driver	Battery	Battery	SA	Battery	Battery	no	no	no	no	no	no	no	no	no

*For "Time in Mission" designated by "Early Ops", the time in mission shall be calculated using the first time the solar distance occurs following launch.
For "Last", the time in mission shall be calculated using the last time the solar distance occurs in the mission.

**Estimated cell temperature is provided for dry and partial cooling system cases, and slew cases; other temperatures are assumed to be calculate using Gayle's thermal analysis for appropriate SA wing angle control approach, and appropriate degradation on wing for time in mission.

Power Required – Majority of Mission

	Majority of Mission										
Power Configuration #	PC15	PC16	PC17	PC18	PC19a	PC19b	PC22a	PC22b	PC23	PC24a	PC24b
Power Configuration Name	Cruise/ Aphelion	Cruise/ Umbra	Downlink: 0.76AU	Downlink: 0.7AU	Downlink: 0.25 - 0.5AU	Downlink: 0.25 - 0.5AU	Science: 0.25AU to 35.7Rs	Science: 0.25AU to 35.7Rs	Science: 35.7Rs to 20Rs with 4hr X-band	Science: 20Rs to 9.86Rs	Science: 20Rs to 9.86Rs
Solar Distance	0.9380	0.8200	0.76	0.7	0.5	0.25	0.25	0.166	0.093	0.093	0.0459
Spacecraft Orientation	Aphelion	Umbra	Umbra-Comm	Umbra-Comm	Umbra-Comm	Umbra-Comm	Encounter	Encounter	Encounter	Encounter	Encounter
Solar Array Control	Sun normal	Sun normal	Sun normal	Sun normal	Auton	Auton	Auton	Auton	Auton	Auton	Auton
Cooling System Status	Full	Full	Full	Full	Full	Full	Full	Full	Full	Full	Full
Time in Mission	Last	Last	Last	Last	Last	Last	Last	Last	Last	Last	Last
Cell Temp** (C) (TBR)	56	calc	calc	calc	calc, 65C min	calc, 65C min	calc, 65C min	calc, 65C min	calc, 65C min	calc, 65C min	calc, 65C min; 165***
NTE Load (W) (TBR)	316.2	337.2	391.7	391.7	398.0	398.0	431.4	431.4	431.7	383.9	383.9
Power req'd at SA @SA Bus (W) (TBR)	357.8	382.0	444.8	444.8	452.2	452.2	491.0	491.0	491.3	435.9	435.9
Battery Target SOC /Full SOC (TBR)	1.00	1 (>=0.7AU), 0.65 (<0.7AU)	1.00	1.00	1.00	1.00	0.65	0.65	0.65	0.65	0.65
Duration (hrs)											
Driver	no	no	no	no	no	no	BatMicro, Power Limit	BatMicro, Power Limit	Cooling, BatMicro, Power Limit	BatMicro, Power Limit	Cooling, BatMicro

*For "Time in Mission" designated by "Early Ops", the time in mission shall be calculated using the first time the solar distance occurs following launch.
For "Last", the time in mission shall be calculated using the last time the solar distance occurs in the mission.

**Estimated cell temperature is provided for dry and partial cooling system cases, and slew cases; other temperatures are assumed to be calculate using Gayle's thermal analysis for appropriate SA wing angle control approach, and appropriate degradation on wing for time in mission.

***Power capability is to be determined at calculated temperature and at 165C. 165C is the temperature at which the wings would be safed.
Power required must be met up to the 165C safing temperature. Calculating both temperatures provides an indication of margin.

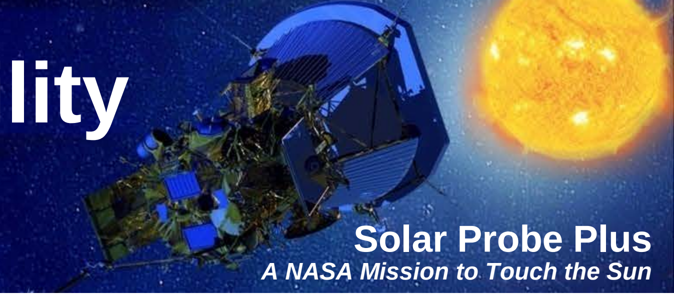
Power Required – Add'l PCs

Power Configuration #	PC20	PC35	PC21	PC25	PC26	PC27	PC28a	PC28b	PC29	PC30	PC31	PC32	PC33a	PC34a	PC33b	PC34b
Power Configuration Name	Downlink - 0.76AU (slew)	Downlink - 0.73AU (slew)	Downlink - 0.7AU (slew)	Safe Mode-Solar Array, <0.5AU	Safe Mode- SA Recharge, <0.5AU	Safe Mode-Earth Acquisition	Cruise - Side B Health Check: 0.28AU-0.7AU	Cruise - Side B Health Check: 0.28AU-0.7AU	Venus Eclipse	Venus Eclipse Recharge	TCM (non-launch correc); 1.02AU	TCM (non-launch correc) Recharge; 1.02AU	TCM EOM; 0.72AU - 0.34AU	TCM EOM Recharge; 0.72AU - 0.34AU	TCM EOM; 0.72AU - 0.34AU	TCM EOM Recharge; 0.72AU - 0.34AU
Solar Distance	0.76	0.73	0.7	0.0459	0.0459	0.093	0.70	0.28	0.71	0.71	1.02	1.02	0.72	0.72	0.34	0.34
Spacecraft Orientation	Aphelion-Umbra Variable-Comm	Aphelion-Umbra Variable-Comm	Aphelion-Umbra Variable-Comm	Umbra	Umbra	Umbra	Umbra-Comm	Umbra-Comm	Aphelion	Aphelion	Umbra	Umbra	Umbra	Umbra	Umbra	Umbra
Solar Array Control	Sun normal	Sun normal	Sun normal	N/A	Auton	Auton	Auton	Auton	Sun normal	Sun normal	Sun normal	Sun normal	Sun normal	Sun normal	Auton	Auton
Cooling System Status	Full	Full	Full	Full	Full	Full	Full	Full	Full	Full	Partial	Partial	Full	Full	Full	Full
Time in Mission	Last	Last	Last	Last	Last	7 years	Last	Last	Last	Last	Last	Last	Last	Last	Last	Last
Cell Temp** (C) (TBR)	95	100	110	N/A	calc, 65C min	calc, 65C min	calc, 65C min	calc, 65C min	108	108	calc	calc	calc	calc	calc, 65C min	calc, 65C min
NTE Load (W) (TBR)	375.1	375.1	375.0	348.9	371.3	393.4	387.2	387.2	328.6	363.2	434.3	314.6	431.0	310.0	431.0	310.0
Power req'd at SA @SA Bus (W) (TBR)	425.6	425.6	425.5	0.0	421.3	446.8	439.7	439.7	0.0	412.0	as avail	355.9	as avail	350.6	as avail	350.6
Battery Target SOC /Full SOC (TBR)	1.00	1.00	1.00	0.65	0.65	1.00 (>=0.7AU), 0.65 (<0.7AU)	0.65	0.65		1.00		1.00		1.00		
Duration (hrs)				0.25					0.18		0.50		0.5		0.5	
Driver	SA	SA	SA	Battery	no	no	no	no	Battery	no	Battery	no	no	no	no	no

*For "Time in Mission" designated by "Early Ops", the time in mission shall be calculated using the first time the solar distance occurs following launch.
For "Last", the time in mission shall be calculated using the last time the solar distance occurs in the mission.

**Estimated cell temperature is provided for dry and partial cooling system cases, and slew cases; other temperatures are assumed to be calculate using Gayle's thermal analysis for appropriate SA wing angle control approach, and appropriate degradation on wing for time in mission.

Power Configuration Availability in Operational Level 3



Operational L3 G&C Mode: Full only	Activate SA, 1&4	Cruise or Recharge	Venus Eclipse	Science	Side B Health	Instrument Checkout	Activate 2&3	Science Downlink	LC Catbed	TCMs
Power Configurations	PC2	PC3, PC6, PC7, PC15, PC16, PC30	PC29	PC22a, PC22b, PC23, PC24a, PC24b	PC28a, PC28b	PC9, PC10, PC8, PC11, PC13, PC14	PC12	PC17, PC18, PC19a, PC19b, PC20, PC35, PC21	PC4	PC5, PC31, PC32, PC33a, PC34a, PC33b, PC34b
Solar Distance	1.02AU	1.02AU - 0.25AU	Venus	9.86RS - 0.25AU; >0.25AU as possible	0.28AU - 0.7AU	1AU - 0.76AU	0.89AU - 0.9AU	0.28AU - 0.76AU	1.02AU	0.5AU(TBR) - 1.02AU
S/C Pointing Orientation: Nominal	Activate 1&4	Varies with PC, solar distance	Aphelion	Encounter (≤0.25AU)	Umbra	Varies with PC, solar distance	Activate 2&3	Varies with PC, solar distance	Aphelion	Varies with PC, solar distance
Solar Array Wing Angle Control	Fixed	Any	Fixed	Power Control, Temp Control	Power Control, Temp Control	Fixed	Fixed	Varies with solar dist	Fixed	Varies with solar dist
Loads		Differ in: - X-band on/off, - Redundant SSE on/off - battery charge		Differ in: - X-band on or off		Differ in: - individual instrument suites on or off				Differ in: - thruster selections
Comments	Critical Sequence						Ground Contact			

- **Fault Management Mode: Level 3**
- **G&C: Full Rate, Full Control**
- **All Power Configurations available**

Power Configuration Availability in Operational Level 2

Operational L2 G&C: Any	Activate SA, 1&4	Cruise or Recharge	Venus Eclipse	Science	Side B Health
Power Configurations	PC2	PC3, PC6, PC7, PC15, PC16, PC30	PC29	PC22a, PC22b, PC23, PC24a, PC24b	PC28a, PC28b
Solar Distance	1.02AU	1.02AU - 0.25AU	Venus	9.86RS - 0.25AU; >0.25AU as possible	0.28AU - 0.7AU
S/C Pointing Orientations: Mission	Activate 1&4	Varies with PC, solar distance	Aphelion	Umbra (≤0.25AU), degraded pointing if not Full G&C	Umbra
Solar Array Wing Angle Control	Fixed	Any	Fixed	Power Control, Temp Control	Power Control, Temp Control
Loads		Differ in: - X-band on/off, - Redundant SSE on/off - battery charge or not		1-4 Instrument Suites On; PC loads differ in: - X-band on or off	

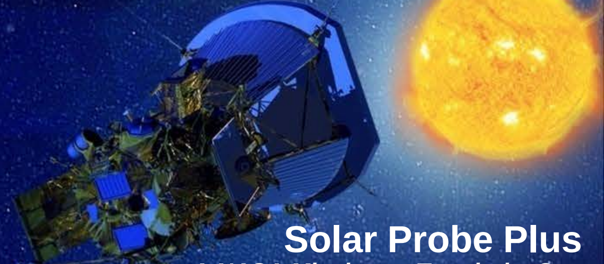
Power Configuration Availability in Operational Level 1

Operational L1 G&C: Any	Activate SA, 1&4	Cruise or Recharge	Venus Eclipse
Power Configurations	PC2	PC3, PC6, PC7, PC15, PC16, PC30, PC26	PC29
Solar Distance	1.02AU	1.02AU - 0.25AU	Venus
S/C Pointing Orientations: Mission	Activate 1&4	Varies with PC, solar distance	Aphelion
Solar Array Wing Angle Control	Fixed	Any	Fixed
Loads		- battery charge < 0.5AU solar distance PCs Loads differ in: - X-band on/off - Redundant SSE on/off	
Comments	Critical Sequence		

Power Configurations in Safe Mode

Safe Mode G&C Mode: Any	Activate SA, 1&4	Safe Mode
Power Configurations	PC2	PC25, PC27
Solar Distance	1.02AU	9.86Rs - 1.02AU
S/C Pointing Orientations: Mission Default	Activate 1&4	Varies with solar distance
Solar Array Wing Angle Control	Fixed	Defined by Safe Mode Type
Comments	Critical Sequence	

Power Loads Budget, NTEs (1 of 4)

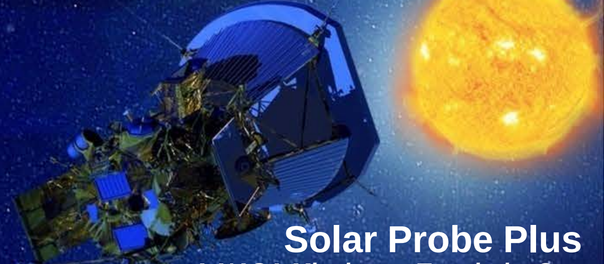


Solar Probe Plus

A NASA Mission to Touch the Sun

Power Configuration Number						PC3			PC24			PC20		
Component↓ /Power Configuration→		CBE Each	CBE Total	NTE	Remain Conting	Recharge Post Rad 1&4 and SA Activation			Science: 20Rs to 9.86Rs			Downlink - 0.76AU (slew)		
	Qty	(W)	(W)	(W)	(%)	Duty Cycle (%)	CBE (W)	CBE +Cont (W)	Duty Cycle (%)	CBE (W)	CBE +Cont (W)	Duty Cycle (%)	CBE (W)	CBE +Cont (W)
Instruments														
Instruments CBE Power:							0.0	0.0		66.3	77.7		0.0	0.0
FIELDS MEP - FIELDS 1 (DCB, RFS, DFB	1	13.72	13.7	16.07	17.1%	0%	0.0	0.0	100%	13.72	16.07	0%	0.0	0.0
FIELDS MEP - FIELDS 2 (TDS, AEB2, MA	1	7.53	7.5	8.85	17.5%	0%	0.0	0.0	100%	7.53	8.85	0%	0.0	0.0
FIELDS E-field Preamps V1-4	1	0.98	1.0	1.13	15.3%	0%	0.0	0.0	100%	0.98	1.13	0%	0.0	0.0
FIELDS E-field Preamp V5	1	0.12	0.1	0.14	16.7%	0%	0.0	0.0	100%	0.12	0.14	0%	0.0	0.0
FIELDS SCM	1	0.30	0.3	0.33	10.0%	0%	0.0	0.0	100%	0.30	0.33	0%	0.0	0.0
FIELDS MAGi	1	0.06	0.1	0.07	16.7%	0%	0.0	0.0	100%	0.06	0.07	0%	0.0	0.0
FIELDS MAGo	1	0.06	0.1	0.07	16.7%	0%	0.0	0.0	100%	0.06	0.07	0%	0.0	0.0
FIELDS MEP Heater Control (SCM, MAGi	1	1.21	1.2	1.38	14.0%	0%	0.0	0.0	100%	1.21	1.38	0%	0.0	0.0
FIELDS E-field Preamp V1-V4 Op Heate	1	0.00	0.0	0.00	0.0%	0%	0.0	0.0	0%	0.00	0.00	0%	0.0	0.0
FIELDS SCM Op Heaters	1	0.30	0.3	0.35	16.7%	0%	0.0	0.0	100%	0.30	0.35	0%	0.0	0.0
FIELDS MAGi Op Heaters	1	1.24	1.2	1.43	15.3%	0%	0.0	0.0	100%	1.24	1.43	0%	0.0	0.0
FIELDS MAGo Op Heaters	1	1.24	1.2	1.43	15.3%	0%	0.0	0.0	100%	1.24	1.43	0%	0.0	0.0
SWEAP SPC	1	3.24	3.2	3.89	20.0%	0%	0.0	0.0	100%	3.24	3.89	0%	0.0	0.0
SWEAP SPAN A+ and B	1	6.68	6.7	8.02	20.0%	0%	0.0	0.0	100%	6.68	8.02	0%	0.0	0.0
SWEAP SWEM	1	4.40	4.4	5.28	20.0%	0%	0.0	0.0	100%	4.40	5.28	0%	0.0	0.0
SWEAP Op Heaters	1	2.80	2.8	3.22	15.0%	0%	0.0	0.0	93%	2.60	2.99	0%	0.0	0.0
WISPR Instrument Module	1	4.59	4.6	5.27	14.9%	0%	0.0	0.0	100%	4.59	5.27	0%	0.0	0.0
WISPR Op Heaters	1	4.69	4.7	5.39	14.9%	0%	0.0	0.0	20%	0.96	1.10	0%	0.0	0.0
WISPR DPU	1	7.1	7.1	8.19	15.0%	0%	0.0	0.0	100%	7.1	8.19	0%	0.0	0.0
ISIS EPI-Hi	1	5.78	5.8	6.76	17.1%	0%	0.0	0.0	100%	5.78	6.76	0%	0.0	0.0
ISIS EPI-Lo	1	4.17	4.2	5.00	20.0%	0%	0.0	0.0	100%	4.17	5.00	0%	0.0	0.0
Subsystems														
Subsystems CBE Power:							219.1			229.6			289.3	
Telecomunications														
Telecommunications Total:							11.0	12.7		11.0	12.7		95.5	101.8
Ka-band TWT	2	80.0	160.0	168.0	5.0%	0%	0.0	0.0	0%	0.0	0.0	50%	80.0	84.0
X-band TWTA	2	33.0	66.0	69.3	5.0%	0%	0.0	0.0	0%	0.0	0.0	0%	0.0	0.0
Radio A rcv only	1	5.5	5.5	6.3	15.0%	100%	5.5	6.3	100%	5.5	6.3	0%	0.0	0.0
Radio B rcv only	1	5.5	5.5	6.3	15.0%	100%	5.5	6.3	100%	5.5	6.3	100%	5.5	6.3
Radio A (rcv+X only)	1	9.5	9.5	10.9	15.0%	0%	0.0	0.0	0%	0.0	0.0	0%	0.0	0.0
Radio A (rcv+Ka only)	1	10.0	10.0	11.5	15.0%	0%	0.0	0.0	0%	0.0	0.0	100%	10.0	11.5

Power Loads Budget, NTEs (2 of 4)

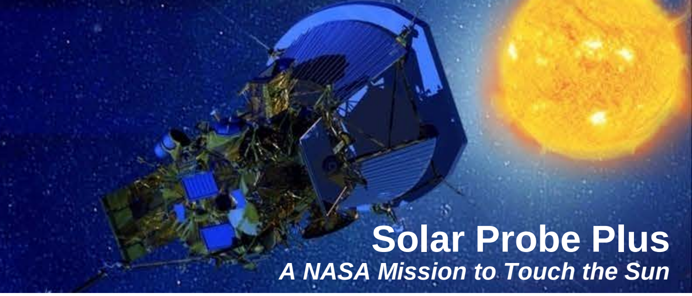


Power Configuration Number						PC3			PC24			PC20		
Component↓ /Power Configuration→		CBE Each	CBE Total	NTE	Remain Conting	Recharge Post Rad 1&4 and SA Activation			Science: 20Rs to 9.86Rs			Downlink - 0.76AU (slew)		
	Qty	(W)	(W)	(W)	(%)	Duty Cycle (%)	CBE (W)	CBE +Cont (W)	Duty Cycle (%)	CBE (W)	CBE +Cont (W)	Duty Cycle (%)	CBE (W)	CBE +Cont (W)
Guidance and Control														
Guidance and Control Total:							60.8	68.9		77.4	88.8		57.9	65.4
IMU (Accels off,Heaters off)	1	27.6	27.6	29.0	5.0%	100%	27.6	29.0	100%	27.6	29.0	100%	27.6	29.0
IMU Accels	1	1.4	1.4	1.5	5.0%	0%	0.0	0.0	0%	0.0	0.0	0%	0.0	0.0
Gyro Heaters	1	0.0	0.0	0.0	0.0%	0%	0.0	0.0	0%	0.0	0.0	0%	0.0	0.0
Star Tracker	2	7.4	14.8	17.8	20.0%	50%	7.4	8.9	81%	12.0	14.4	50%	7.4	8.9
Reaction Wheels	4	11.0	44.0	52.8	20.0%	45%	20.0	24.0	73%	32.0	38.4	45%	20.0	24.0
Solar Limb Sensor (7) and DSS (2)	2	2.9	5.8	7.0	20.0%	100%	5.8	7.0	100%	5.8	7.0	50%	2.9	3.5
Mechanical														
Mechanical Total:							7.3	8.4		7.1	8.1		4.4	5.1
Actuator ECU Solar Array and HGA	1	4.4	4.4	5.1	15.0%	100%	4.4	5.1	100%	4.4	5.1	100%	4.4	5.1
Actuator ECU Solar Array Actuation	4	20.0	80.0	92.0	15.0%	4%	2.9	3.3	3%	2.7	3.1	0%	0.0	0.0
SA Release (3 loc/wing, prim+redun)	6	80.6	483.8	556.4	15.0%	0%	0.0	0.0	0%	0.0	0.0	0%	0.0	0.0
Power														
Power Total:							11.3	13.6		11.3	13.6		11.3	13.6
Power System Electronics	1	11.3	11.3	13.6	20.0%	100%	11.3	13.6	100%	11.3	13.6	100%	11.3	13.6
Thermal Control														
Thermal - SACS Total:							33.0	37.9		41.0	47.1		33.0	37.9
Solar Array Pump, Motor Controller	1	39	39.0	44.9	15.0%	79%	31.0	35.7	100%	39.0	44.9	79%	31.0	35.7
Cooling System Pump deltap	2	1	2.0	2.2	10.0%	100%	2.0	2.2	100%	2.0	2.2	100%	2.0	2.2
Cooling System - System Pressure	2	1	2.0	2.2	10.0%	0%	0.0	0.0	0%	0.0	0.0	0%	0.0	0.0
Thermal - SACS Activ Only Total:							0.0	0.0		0.0	0.0		0.0	0.0
CSPR Manifold Heaters 1&4	4	6	24.0	27.6	15.0%	0%	0.0	0.0	0%	0.0	0.0	0%	0.0	0.0
CSPR Manifold Htrs 2&3, top deck lines	4	7.5	30.0	34.5	15.0%	0%	0.0	0.0	0%	0.0	0.0	0%	0.0	0.0
CSPR Lines Heaters	2	2	4.0	4.6	15.0%	0%	0.0	0.0	0%	0.0	0.0	0%	0.0	0.0
SA Flex Line Heaters	2	4.8	9.6	11.0	15.0%	0%	0.0	0.0	0%	0.0	0.0	0%	0.0	0.0
Thermal - S/C, non-SACS Total:							23.3	27.4		12.9	15.0		13.9	16.1
Battery Heater	1	6.0	6.0	7.2	20.0%	50%	3.0	3.6	45%	2.7	3.2	35%	2.1	2.5
S/A Feather Drive Heater	2	3.3	6.5	7.5	15.0%	94%	6.1	7.0	100%	6.5	7.5	89%	5.8	6.7
S/A Flap Drive Heater	2	1.3	2.5	2.9	15.0%	100%	2.5	2.9	100%	2.5	2.9	100%	2.5	2.9
Star Tracker Heater	2	3.5	7.0	8.1	15.0%	50%	3.5	4.0	0%	0.0	0.0	50%	3.5	4.0
Internal Prop Heaters	1	15.0	15.0	18.0	20.0%	55%	8.2	9.8	8%	1.2	1.4	0%	0.0	0.0

Power Loads Budget, NTEs (3 of 4)

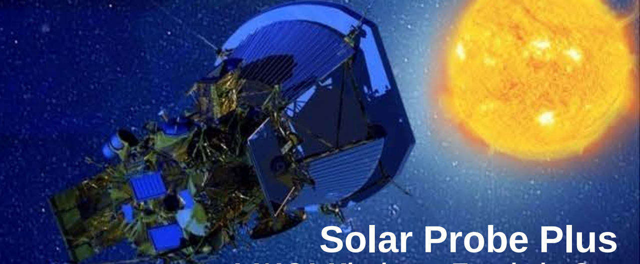
Power Configuration Number						PC3			PC24			PC20		
Component↓ /Power Configuration→		CBE Each	CBE Total	NTE	Remain Conting	Recharge Post Rad 1&4 and SA Activation			Science: 20Rs to 9.86Rs			Downlink - 0.76AU (slew)		
	Qty	(W)	(W)	(W)	(%)	Duty Cycle (%)	CBE (W)	CBE +Cont (W)	Duty Cycle (%)	CBE (W)	CBE +Cont (W)	Duty Cycle (%)	CBE (W)	CBE +Cont (W)
Thermal - Instrument Total:							21.5	24.7		0.0	0.0		22.4	25.8
ISIS EPI Hi Survival Heaters	1	3.6	3.6	4.1	15.0%	100%	3.6	4.1	0%	0.0	0.0	100%	3.6	4.1
ISIS EPI Lo Survival Heaters	1	2.2	2.2	2.5	15.0%	100%	2.2	2.5	0%	0.0	0.0	100%	2.2	2.5
SWEAP SPAN A+ Survival Heaters	1	3.5	3.5	4.0	15.0%	100%	3.5	4.0	0%	0.0	0.0	100%	3.5	4.0
SWEAP SPAN B Survival Heaters	1	3.1	3.1	3.6	15.0%	0%	0.0	0.0	0%	0.0	0.0	0%	0.0	0.0
SWEAP SPC Pre-Amp Survival Heaters	1	3.9	3.9	4.5	15.0%	25%	1.0	1.1	0%	0.0	0.0	0%	0.0	0.0
WISPR Survival Heaters	1	6.2	6.2	7.1	15.0%	76%	4.7	5.4	0%	0.0	0.0	100%	6.2	7.1
FIELDS MEP Heater Control Survival He	1	1.2	1.2	1.4	16.9%	100%	1.2	1.4	0%	0.0	0.0	100%	1.2	1.4
FIELDS E-field Preamp V1-V4 Survival H	1	4.9	4.9	5.6	15.1%	42%	2.1	2.4	0%	0.0	0.0	50%	2.5	2.8
FIELDS SCM Survival Heaters	1	0.6	0.6	0.7	15.0%	100%	0.6	0.7	0%	0.0	0.0	100%	0.6	0.7
FIELDS MAGi Survival Heaters	1	1.3	1.3	1.5	15.4%	100%	1.3	1.5	0%	0.0	0.0	100%	1.3	1.5
FIELDS MAGo Survival Heaters	1	1.3	1.3	1.5	15.4%	100%	1.3	1.5	0%	0.0	0.0	100%	1.3	1.5
FIELDS Deploy Mech (Mag Boom, PWI)	1	0.5	0.5	0.6	15.0%	0%	0.0	0.0	0%	0.0	0.0	0%	0.0	0.0
Avionics														
Avionics Total:							27.2	31.3		32.3	37.1		27.2	31.3
RPM: Prim,HS,ARC (1 SSR/SBC)	1	13.2	13.2	15.2	15.0%	100%	13.2	15.2	100%	13.2	15.2	100%	13.2	15.2
RPM: Prime/HS SpW Ports to REM	2	0.7	1.5	1.7	15.0%	50%	0.7	0.8	50%	0.7	0.8	50%	0.7	0.8
RPM: WS	1	5.0	5.0	5.8	15.0%	0%	0.0	0.0	100%	5.0	5.8	0%	0.0	0.0
REM: SCIF,TAC	2	12.2	24.4	28.1	15.0%	50%	12.2	14.0	50%	12.2	14.0	50%	12.2	14.0
RIU - 8 units each	2	0.56	1.1	1.3	15.0%	100%	1.1	1.3	100%	1.1	1.3	100%	1.1	1.3
Power Distribution														
Power Distribution Total:							9.5	10.5		9.5	10.5		9.5	10.5
Power Distribution Unit	2	9.5	19.0	20.9	10.0%	50%	9.5	10.5	50%	9.5	10.5	50%	9.5	10.5
Propulsion														
Propulsion (non-Therm) Total:							0.0	0.0		18.5	19.5		0.0	0.0
4.4N (1lbf) Thruster Valve (MR-111C)	12	10.79	129.5	135.9	5.0%	0%	0.0	0.0	0%	0.2	0.2	0%	0.0	0.0
4.4N (1lbf) Catbed Heater (MR-111C)	12	2.521	30.2	31.8	5.0%	0%	0.0	0.0	61%	18.3	19.2	0%	0.0	0.0
Latch Valve	2	36.0	72.0	75.6	5.0%	0%	0.0	0.0	0%	0.0	0.0	0%	0.0	0.0
Pressure Transducers	2	0.9	1.8	2.0	10.0%	0%	0.0	0.0	0%	0.0	0.0	0%	0.0	0.0
Propulsion Thermal (non-Tank) Total:							14.1	16.2		8.5	9.8		14.1	16.2
4.4N (1lbf) Valve Heater (MR-111C)	12	0.9	10.8	12.4	15.0%	100%	10.8	12.4	48%	5.2	6.0	100%	10.8	12.4
Line Heater	1	3.3	3.3	3.8	15.0%	100%	3.3	3.8	100%	3.3	3.8	100%	3.3	3.8

Power Loads Budget, NTEs (4 of 4)



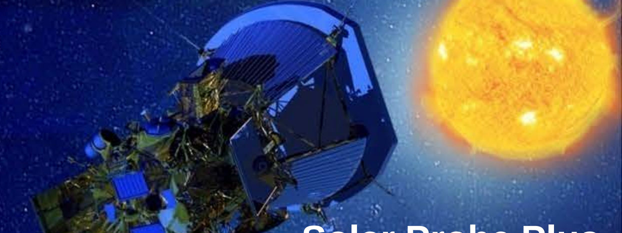
Power Configuration Number	PC3			PC24			PC20		
Component↓ /Power Configuration→	Recharge Post Rad 1&4 and SA Activation			Science: 20Rs to 9.86Rs			Downlink - 0.76AU (slew)		
	Duty Cycle (%)	CBE (W)	CBE +Cont (W)	Duty Cycle (%)	CBE (W)	CBE +Cont (W)	Duty Cycle (%)	CBE (W)	CBE +Cont (W)
Spacecraft Totals									
Power w/o Harness Loss		219.1	241.0		295.9	329.3		289.3	313.1
Harness Loss		3.7	3.7		4.9	4.9		4.8	4.8
Power w/ Harness Loss		222.7	244.6		300.8	334.3		294.1	318.0
Battery Charge		25.0	25.0		0.5	0.5		0.0	0.0
Fault Load (W)		7.4	7.4		7.4	7.4		7.4	7.4
S/C - Sun Distance (AU)		1.02			0.0459			0.76	
Available Load Power from SA (W)		342.6	342.6		420.5	420.5		395.5	395.5
Allocated Margin		21.9	9.8%		33.5	11.1%		23.8	8.1%
Unallocated Margin		65.6	26.8%		78.3	23.4%		70.1	22.1%
Total Margin		87.5	39.27%		111.8	37.17%		93.9	31.94%

Power Loads Budget
Early Operations



Power Configuration Number	PC1	PC2	PC3	PC4	PC5	PC6	PC7	PC9	PC10	PC12	PC8	PC11	PC13	PC14
Component↓ /Power Configuration→	Launch	Warm-up and Activate Rad 1&4	Recharge Post Rad 1&4 and SA Activation	Catbed Warm Up for Launch Error	Launch Error Correction	Recharge Post LC	Early Cruise	FIELDS CO, Fanb Playback	SWEAP CO, with FIELDS on, Fanb	Warm-up and Activate Rad 2&3	ISIS CO, Fanb Playback	WISPR CO, Fanb Playback	All Inst CO, Fanb Playback	HGA Commissioning
26.8	Total (W)	Total (W)	Total (W)	Total (W)	Total (W)	Total (W)	Total (W)	Total (W)	Total (W)	Total (W)	Total (W)	Total (W)	Total (W)	Total (W)
Instruments														
Instruments CBE Power:	0.0	0.0	0.0	0.0	0.0	0.0	0.0	26.8	43.9	0.0	9.9	16.4	70.2	0.0
Subsystems CBE Power:	128.4	322.4	219.1	265.3	310.4	215.4	244.3	238.9	237.9	285.4	238.5	243.5	228.7	306.8
Telecommunications Total:	11.0	48.0	11.0	48.0	48.0	11.0	48.0	48.0	48.0	48.0	48.0	48.0	48.0	95.5
Guidance and Control Total:	0.0	68.2	60.8	57.9	62.2	57.9	57.9	57.9	57.9	60.8	57.9	65.3	68.2	68.2
Mechanical Total:	4.4	21.8	7.3	5.4	4.4	5.4	4.4	4.4	8.4	6.4	4.4	4.4	4.4	4.4
Power Total:	11.3	11.3	11.3	11.3	11.3	11.3	11.3	11.3	11.3	11.3	11.3	11.3	11.3	11.3
Thermal - SACS Total:	0.0	33.0	33.0	33.0	33.0	33.0	33.0	33.0	33.0	33.0	33.0	33.0	33.0	33.0
Thermal - SACS Activ Only Total:	9.6	37.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	34.0	0.0	0.0	0.0	0.0
Thermal - S/C, non-SACS Total:	7.8	9.0	23.3	21.8	22.2	24.2	17.9	17.9	17.9	11.5	17.9	14.4	12.9	14.5
Thermal - Instrument Total:	18.0	17.6	21.5	21.5	29.9	20.8	20.8	15.5	10.5	20.0	15.0	16.1	0.0	29.0
Avionics Total:	27.2	27.2	27.2	27.2	27.2	27.2	27.2	27.2	27.2	27.2	27.2	27.2	27.2	27.2
Power Distribution Total:	9.5	19.0	9.5	9.5	9.5	9.5	9.5	9.5	9.5	19.0	9.5	9.5	9.5	9.5
Propulsion (non-Therm) Total:	21.1	21.1	0.0	21.1	54.0	0.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Propulsion Thermal (non-Tank) Total:	8.5	8.5	14.1	8.5	8.5	14.1	14.1	14.1	14.1	14.1	14.1	14.1	14.1	14.1
Spacecraft Totals														
Power CBE w/o Harness Loss	128.4	322.4	219.1	265.3	310.4	215.4	244.3	265.7	281.8	285.4	248.4	259.9	299.0	306.8
Harness Loss	2.1	5.4	3.7	4.4	5.2	3.6	4.1	4.4	4.7	4.8	4.1	4.3	5.0	5.1
Power CBE	130.6	327.8	222.7	269.7	315.5	219.0	248.4	270.1	286.5	290.2	252.6	264.2	304.0	311.9
Battery Charge	0	0	25	0	0	25.0	0	0	0	0	0	0	0	0
S/C - Sun Distance (AU)	1.02	1.02	1.02	1.02	1.02	1.02	1.02	0.975	0.94	0.9	0.88	0.843	0.82	0.76
Spacecraft Pointing Orientation		Activate 1 and 4	Aphelion	Aphelion	Launch Correction	Aphelion	Aphelion	Aphelion-Comm	Aphelion-Comm, SWEAP Transient	Activate 2 and 3	Aphelion-Comm	Aphelion-Comm	Umbra-Comm	Umbra-Comm
Cooling System Status	Dry	Dry	Partial	Partial	Partial	Partial	Partial	Partial	Partial	Partial	Full	Full	Full	Full
Available Load Power from SA (W)	0.0	275.5	342.6	342.6	342.6	342.6	342.6	352.0	371.2	411.0	419.4	446.2	446.2	446.2
Req'd Margin	25%	25%	25%	25%	25%	25%	25%	25%	25%	25%	25%	25%	25%	25%
Fault Load (W)	7.4	7.4	7.4	7.4	7.4	7.4	7.4	7.4	7.4	7.4	7.4	7.4	7.4	7.4
Load with 25% Total Margin	170.6	417.2	310.8	344.5	401.8	306.2	317.8	345.0	365.6	370.1	323.1	337.7	387.3	397.3
Power Reserves			87.5			91.2	86.9	74.5	77.3	113.5	159.4	174.6	134.8	126.9
Actual Margin			39.27%			41.64%	34.98%	27.58%	26.98%	39.10%	63.11%	66.07%	44.36%	40.67%

Power Loads Budget
Majority of Mission



Power Configuration Number	PC15	PC16	PC17	PC18	PC19	PC20	PC35	PC21	PC22	PC23	PC24
Component↓ /Power Configuration→	Cruise/ Aphelion	Cruise/ Umbra	Downlink: 0.76AU	Downlink: 0.7AU	Downlink: 0.25 - 0.5AU	Downlink - 0.76AU (slew)	Downlink - 0.73AU (slew)	Downlink - 0.7AU (slew)	Science: 0.25AU to 35.7Rs	Science: 35.7Rs to 20Rs with 4hr X-	Science: 20Rs to 9.86Rs
26.8	Total (W)	Total (W)	Total (W)	Total (W)	Total (W)	Total (W)	Total (W)	Total (W)	Total (W)	Total (W)	Total (W)
Instruments											
Instruments CBE Power:	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	66.3	66.3	66.3
Subsystems CBE Power:	243.0	259.5	302.4	302.4	307.4	289.3	289.3	289.2	267.0	267.2	229.6
Telecommunications Total:	48.0	48.0	95.5	95.5	95.5	95.5	95.5	95.5	48.0	48.0	11.0
Guidance and Control Total:	57.9	60.8	60.8	60.8	60.8	57.9	57.9	57.9	80.2	80.2	77.4
Mechanical Total:	4.4	4.4	4.4	4.4	4.4	4.4	4.4	4.4	5.1	5.1	7.1
Power Total:	11.3	11.3	11.3	11.3	11.3	11.3	11.3	11.3	11.3	11.3	11.3
Thermal - SACS Total:	33.0	33.0	33.0	33.0	33.0	33.0	33.0	33.0	41.0	41.0	41.0
Thermal - SACS Activ Only Total:	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Thermal - S/C, non-SACS Total:	15.1	22.7	18.0	18.0	18.0	13.9	13.9	13.8	12.7	12.7	12.9
Thermal - Instrument Total:	22.3	28.4	28.4	28.4	28.4	22.4	22.4	22.4	0.0	0.0	0.0
Avionics Total:	27.2	27.2	27.2	27.2	32.3	27.2	27.2	27.2	32.3	32.3	32.3
Power Distribution Total:	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5
Propulsion (non-Therm) Total:	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	18.3	18.5	18.5
Propulsion Thermal (non-Tank) Total:	14.1	14.1	14.1	14.1	14.1	14.1	14.1	14.1	8.5	8.5	8.5
Spacecraft Totals											
Power CBE w/o Harness Loss	243.0	259.5	302.4	302.4	307.4	289.3	289.3	289.2	333.3	333.5	295.9
Harness Loss	4.1	4.3	5.0	5.0	5.1	4.8	4.8	4.8	5.6	5.6	4.9
Power CBE	247.0	263.9	307.4	307.4	312.5	294.1	294.1	294.1	338.8	339.0	300.8
Battery Charge	0	0	0	0	0	0	0	0	0.5	0.5	0.5
S/C - Sun Distance (AU)	0.938	0.82	0.76	0.7	0.5	0.76	0.73	0.7	0.166	0.0930	0.0459
Spacecraft Pointing Orientation	Aphelion	Umbra	Umbra-Comm	Umbra-Comm	Umbra-Comm	Aphelion-Umbra Variable-Comm	Aphelion-Umbra Variable-Comm	Aphelion-Umbra Variable-Comm	Encounter	Encounter	Encounter
Cooling System Status	Full	Full	Full	Full	Full	Full	Full	Full	Full	Full	Full
Available Load Power from SA (W)	364.3	446.2	405.8	406.7	446.2	395.5	379.9	403.2	446.2	446.2	420.5
Req'd Margin	25%	25%	25%	25%	25%	25%	25%	25%	25%	25%	25%
Fault Load (W)	7.4	7.4	7.4	7.4	7.4	7.4	7.4	7.4	7.4	7.4	7.4
Load with 25% Total Margin	316.2	337.2	391.7	391.7	398.0	375.1	375.1	375.0	431.4	431.7	383.9
Power Reserves	109.9	174.9	91.0	91.9	126.3	93.9	78.4	101.8	99.5	99.2	111.8
Actual Margin	44.47%	66.29%	29.61%	29.89%	40.41%	31.94%	**26.65%**	34.61%	29.35%	**29.27%**	**37.17%**

Power Loads Budget
Additional Power Configurations

Power Configuration Number	PC25	PC26	PC27	PC28	PC29	PC30	PC31	PC32	PC33	PC34
Component↓ /Power Configuration→	Safe Mode-Solar Array, <0.5AU	Safe Mode-SA Recharge, <0.5AU	Safe Mode-Earth Acquisition	Cruise - Side B Health Check:	Venus Eclipse	Venus Eclipse Recharge	TCM (non-launch correc); 1.02AU	TCM (non-launch correc) Recharge	TCM EOM; 0.72AU - 0.34AU	TCM EOM Recharge ; 0.72AU - 0.34AU
26.8	Total (W)	Total (W)	Total (W)	Total (W)	Total (W)	Total (W)	Total (W)	Total (W)	Total (W)	Total (W)
Instruments										
Instruments CBE Power:	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Subsystems CBE Power:	268.7	266.7	303.7	298.5	252.8	260.3	335.9	222.0	333.3	218.4
Telecommunications Total:	11.0	11.0	48.0	48.0	48.0	48.0	48.0	11.0	48.0	11.0
Guidance and Control Total:	80.2	80.2	80.2	60.8	60.8	60.8	62.2	60.8	62.2	60.8
Mechanical Total:	6.4	4.4	4.4	4.4	4.4	4.4	4.4	6.4	4.4	4.4
Power Total:	11.3	11.3	11.3	22.7	11.3	11.3	11.3	11.3	11.3	11.3
Thermal - SACS Total:	41.0	41.0	41.0	35.0	33.0	33.0	33.0	33.0	33.0	33.0
Thermal - SACS Activ Only Total:	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Thermal - S/C, non-SACS Total:	19.6	19.6	19.6	23.1	15.5	23.1	22.3	23.3	22.3	23.7
Thermal - Instrument Total:	29.4	29.4	29.4	29.4	28.8	28.8	31.4	24.4	28.8	22.4
Avionics Total:	32.3	32.3	32.3	40.2	27.2	27.2	27.2	27.2	27.2	27.2
Power Distribution Total:	9.5	9.5	9.5	19.0	9.5	9.5	9.5	9.5	9.5	9.5
Propulsion (non-Therm) Total:	19.4	19.4	19.4	1.8	0.0	0.0	80.8	0.9	80.8	0.9
Propulsion Thermal (non-Tank) Total:	8.5	8.5	8.5	14.1	14.1	14.1	5.7	14.1	5.7	14.1
Spacecraft Totals										
Power CBE w/o Harness Loss	268.7	266.7	303.7	298.5	252.8	260.3	335.9	222.0	333.3	218.4
Harness Loss	4.5	4.5	5.1	5.0	4.2	4.3	5.6	3.7	5.6	3.6
Power CBE	273.2	271.1	308.8	303.5	257.0	264.7	341.5	225.7	338.9	222.1
Battery Charge	0	25	0	0.5	0	25	0	25	0	25
S/C - Sun Distance (AU)	0.0459	0.0459	0.0930	0.28	0.71	0.71	1.02	1.02	0.72	0.72
Spacecraft Pointing Orientation	Umbra	Umbra	Umbra	Umbra-Comm	Aphelion	Aphelion	Umbra	Umbra	Umbra	Umbra
Cooling System Status	Full	Full	Full	Full	Full	Full	Partial	Partial	Full	Full
Available Load Power from SA (W)	0.0	419.6	446.2	406.7	0.0	388.6	340.9	340.9	446.2	446.2
Req'd Margin	25%	25%	25%	25%	25%	25%	25%	25%	25%	25%
Fault Load (W)	7.4	7.4	7.4	7.4	7.4	7.4	7.4	7.4	7.4	7.4
Load with 25% Total Margin	348.9	371.3	393.4	387.2	328.6	363.2	434.3	314.6	431.0	310.0
Power Reserves		116.1	130.0	95.3		91.5		82.8		191.7
Actual Margin		42.81%	42.11%	31.42%		34.57%		36.66%		86.34%

Trade Level Definition

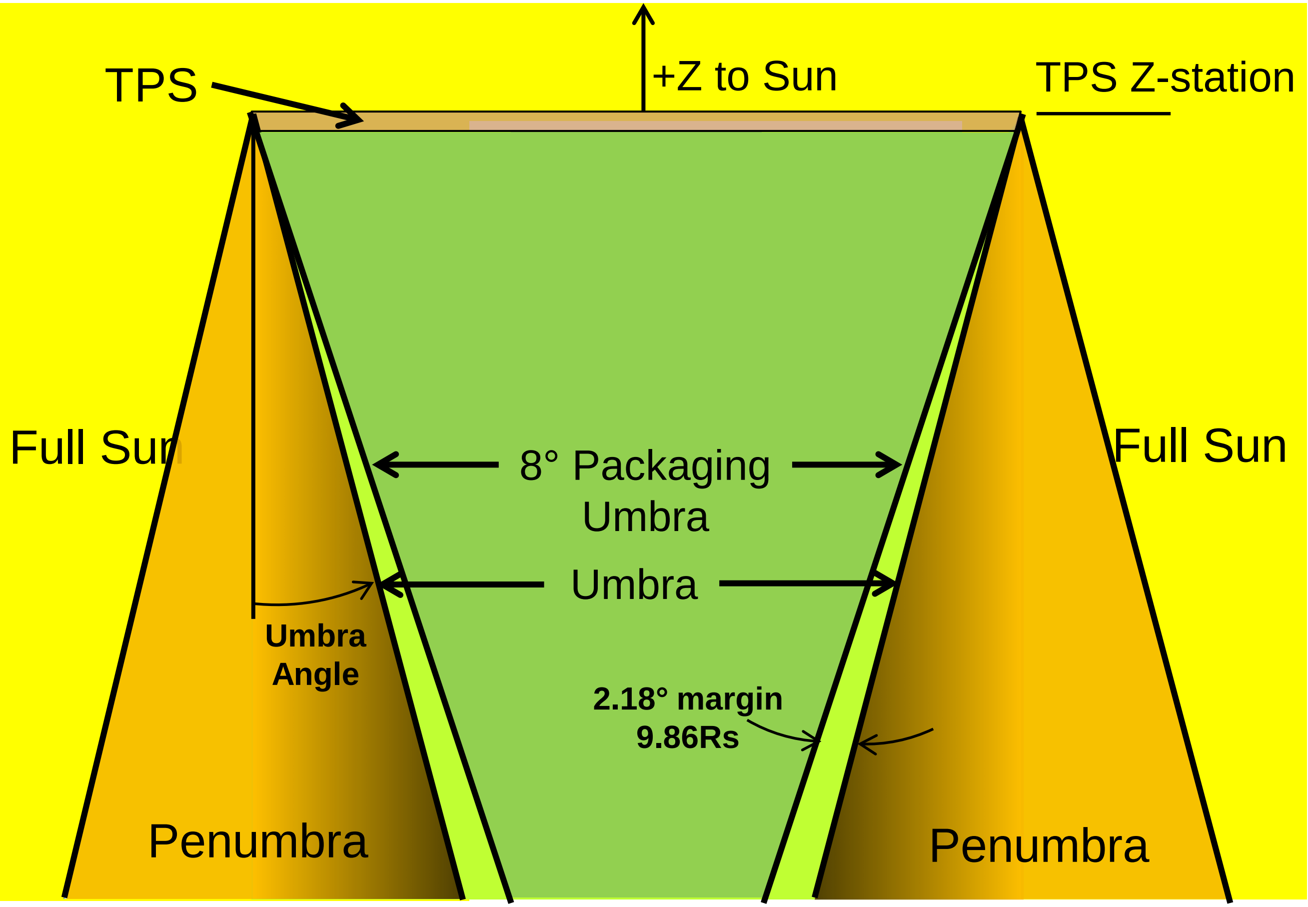
Level	Trade Result Impact	Lead	Approval/ Concurrence
1	Trades that significantly affect cost, schedule, Level 1 requirements or risk. Trades where low-TRL technology is considered	Depends on trade	Project Manager and/or higher
2	Trades that cross element boundaries or that impact overall mission performance and/or margins	MSE or delegate	Project Manager
3	Trades that cross multiple subsystems within a system element	Element SE	MSE
4	Trades within a particular subsystem	Subsystem Engineer	Element SE

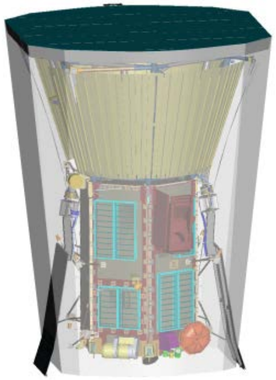
Phase B Trades Closed
Level 3

- Additional Level 3 trades included in R Conde Electrical Systems briefing

Trade Closed	**Level**	**Result**
Approach to provide Hot Spare, new Prime with G&C data	3	Prime provides minimally processed star tracker data to hot spare - minimizes potential for corrupt data to be passed to hot spare, while providing hot spare with initial data with minimal lag
Solar array launch lock configuration	3	Electrically redundant, mechanically non-redundant - reduced complexity
TSA configuration	3	Frequency requirements reduced for TSA based on coupled loads results - reduced mass
Faster than Real Time Simulator Make/Buy	3	FAST selected as software simulator

Umbra, Penumbra

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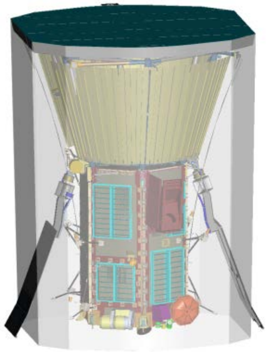
0.25AU

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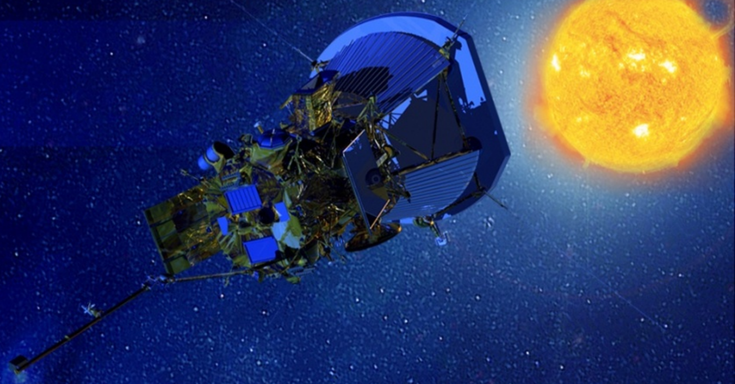

Mechanical Configuration

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Lead Mechanical Engineer

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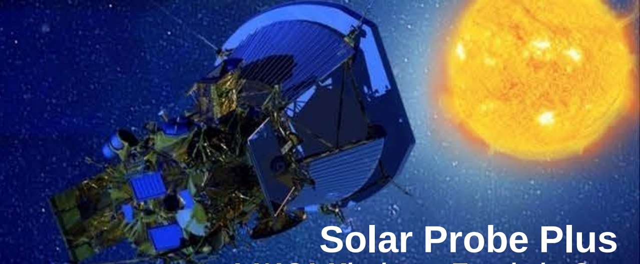
13 – 16 January 2014

The Johns Hopkins University
APPLIED PHYSICS LABORATORY

Driving Requirements (1 of 2)



Requirement	Description	Notes
Structure Mass	Minimize structure mass whenever possible	Allocation split between primary and secondary structure, mag boom, actuators, ECU, solar array boom, etc.
Instrument Accommodations	Provide interfaces and meet FOV and alignment requirements for all instrument suites	Includes FIELDS, SWEAP, ISIS and WISPR
RF Accommodations	Provide interfaces and meet FOV requirements for all RF telecomm components	Includes High Gain Antenna, Onmi Antenna (x2) and Fan Beam (x2)
G&C Accommodations	Provide interfaces for G&C and align such that components are compatible with all other subsystems	Includes Solar Limb Sensors, Digital Sun Sensors, Reaction Wheels, and IMU
Propulsion Accommodations	Provide interfaces for Prop components and align such that components are compatible with all other subsystems	Includes Prop Tank and thrusters
Solar Array Actuators	Provide SA feather/flap actuators with sufficient operational range of motion and torque while meeting mass and volume restrictions	Flap 0°/+88° Feather -85°/+85°
High Gain Antenna Actuator	Provide an HGA Actuator to point the HGA through its specified range of motion	-45°/+45° Range of Motion
ECU	Provide ECU to control the SA and HGA Actuators that meets all spacecraft requirements	Fully-redundant and cross-strapped

Driving Requirements (2 of 2)

Requirement	Description	Notes
Mag Boom	Provide a mag boom that accommodates the MAGi, MAGo, SCM and V5 instruments spaced according to the Mag Boom ICD.	The instrument spacing ensures maximum science return.
Cg Location	Ensure that the Cg of the Observatory is within 1.6” of the centerline of the observatory in the XY plane at launch.	This minimizes the Center-of-Pressure to Center-of-Gravity offset.
Component Packaging	Locate all of the components, except SPC, FIELDS antennas, TPS, solar arrays, and SLS within the nominal packaging umbra.	This ensures solar protection of the spacecraft components.
SA Oscillation	Provide SA flap drives capable of maintaining the solar array platen outer edge translational displacement to ±1.0 mm (± 0.04 inches) in total amplitude and a translational velocity of ±1.0 mm (±0.04 inches) over 0.67s for each wing angle articulation at a drive rate of ≤ 0.1 deg/s, when solar distance ≤ 0.35 AU.	This ensures proper solar loading of the SA platen.

Major Changes Since MDR

- Increased the height of TPS above the separation plane from 2.96m (116.5”) to 3.05m (120.1”)
- Increased the area of the cooling system radiators from 4.0m^2 to 4.4m^2
- Reduced the range of motion of the solar array feather angle from ±90° to ±85°
- Increased the Magnetometer boom length from 2.7m to 3.5m
- Increased the Solar Array width from 0.65m (25.6”) to 0.69m (27.2”)
- Condensed the PSE from 2 boxes to 1 box
- Reconfigured the thrusters to avoid plume impingement and instrument FOVs
- Added 3 Solar Limb Sensors (SLS) and 2 Digital Sun Sensors (DSS)
- Star cameras separated to eliminate obstructions to their FOV
- Selected Aluminum facesheets for the spacecraft structural panels rather than composite
- Added a restraint for each Solar Array Boom
- Solar array stow position fixed at 88° (previously 90°)
- Reaction wheel overall size increased to represent current wheel design
- Bottom deck layout reconfigured to reduce total RF line length
- All exterior panel 5 components were moved to panel 0 and vice versa (panels mirrored)
- Propulsion diode box eliminated, functions absorbed
- Omni antenna pointing changed, now parallel with X-Y plane
- Solar Array Cooling System (SACS) diode box eliminated
- Moved SACS Accumulator tank from the top to the underside of the top deck
- Louvers reconfigured to accommodate updated heat load

Requirements Flow-Down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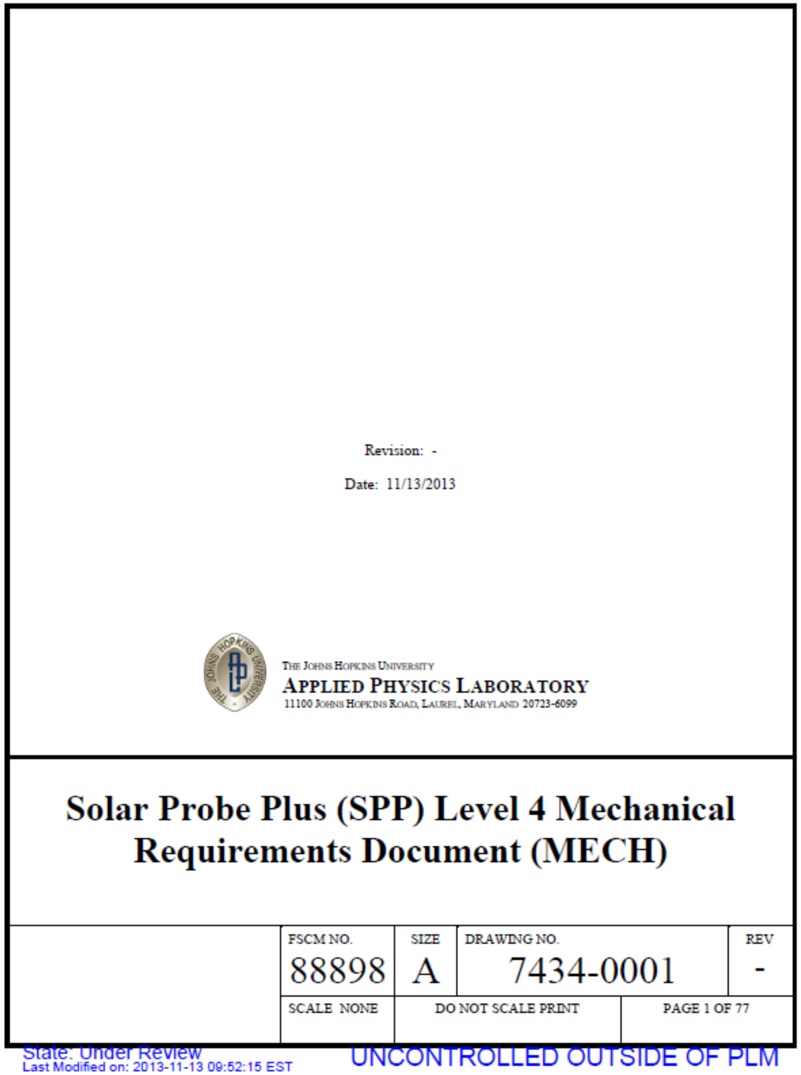
Revision: -

Date: 11/13/2013

The Johns Hopkins University
Applied Physics Laboratory
11100 Johns Hopkins Road, Laurel, Maryland 20723-6099

Solar Probe Plus (SPP) Level 4 Mechanical Requirements Document (MECH)

FSCM NO. 88898	SIZE A	DRAWING NO. 7434-0001	REV -
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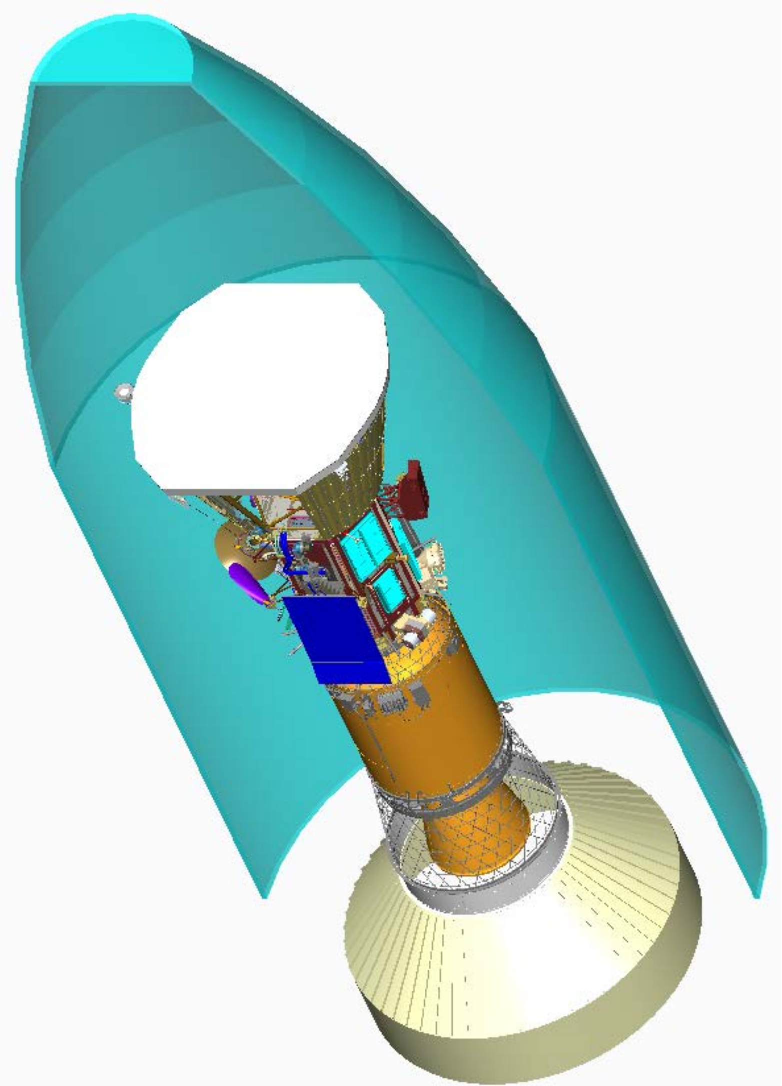
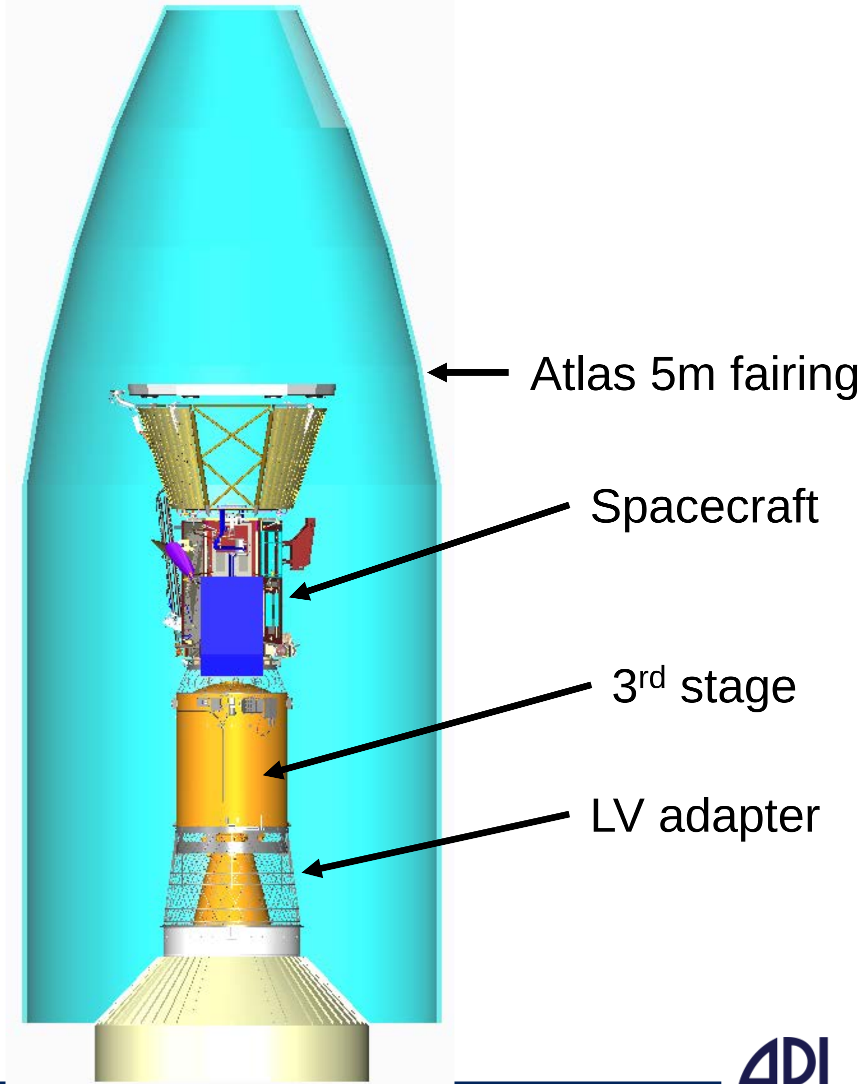
State: Under Review
Last Modified on: 2013-11-13 09:52:15 EST

UNCONTROLLED OUTSIDE OF PLM

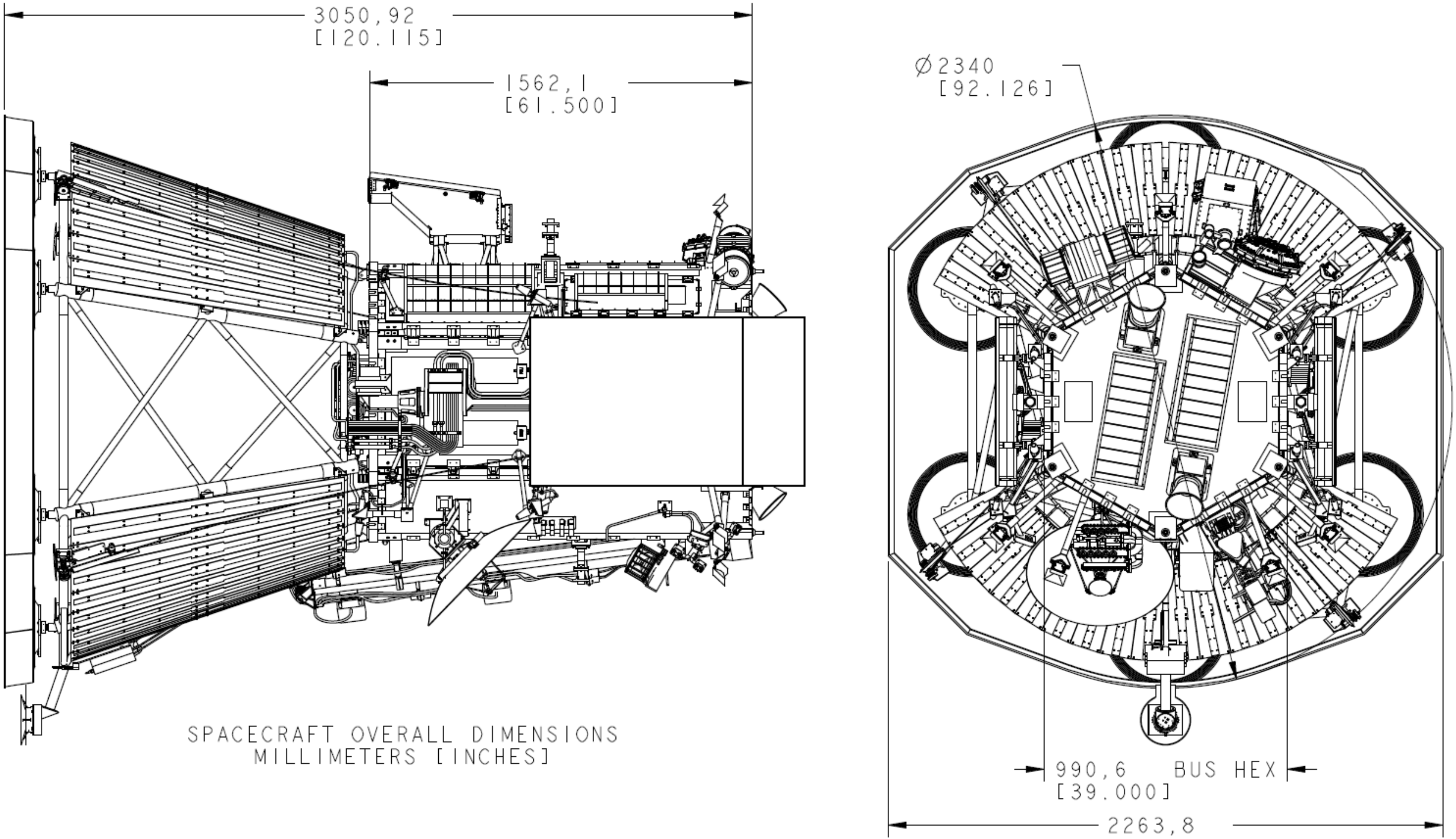
- **Level 4 Mechanical Requirements are captured in DOORS and in the Mechanical Subsystem Requirements Document (7434-0001)**
- **7434-0001 is configured in APL PLM**

Launch Views



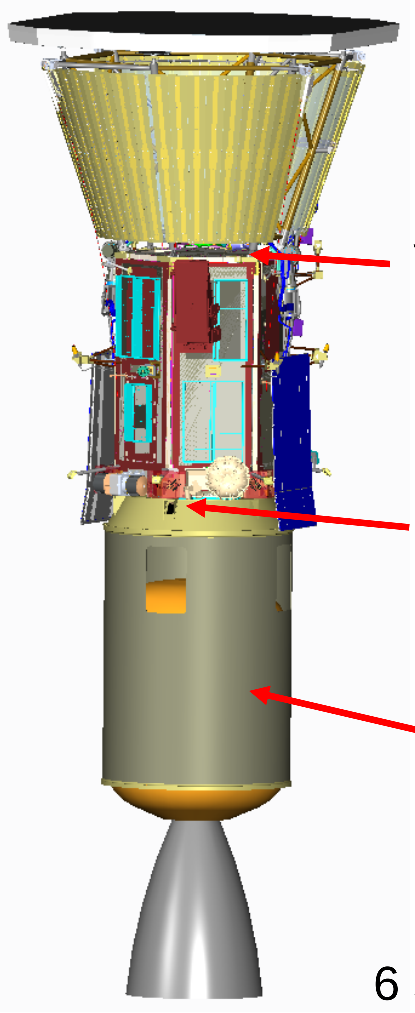


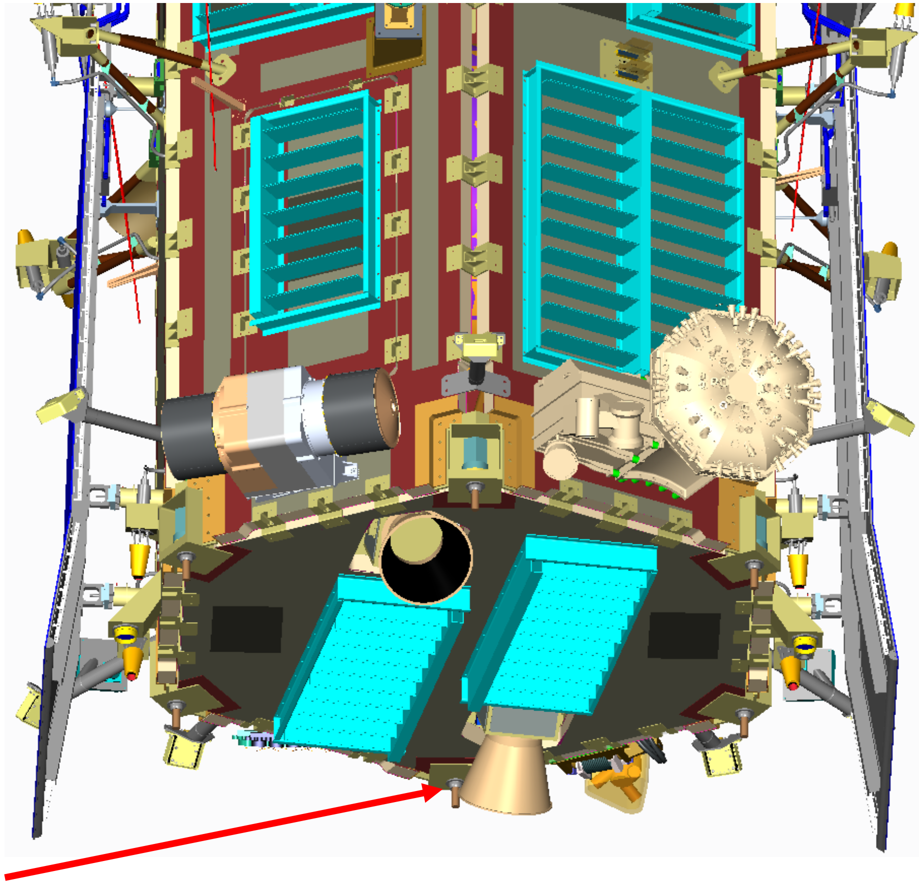
Spacecraft Overall Dimensions



SPACECRAFT OVERALL DIMENSIONS
MILLIMETERS [INCHES]

Primary Interfaces





SC to TSA aligned with 6 fittings

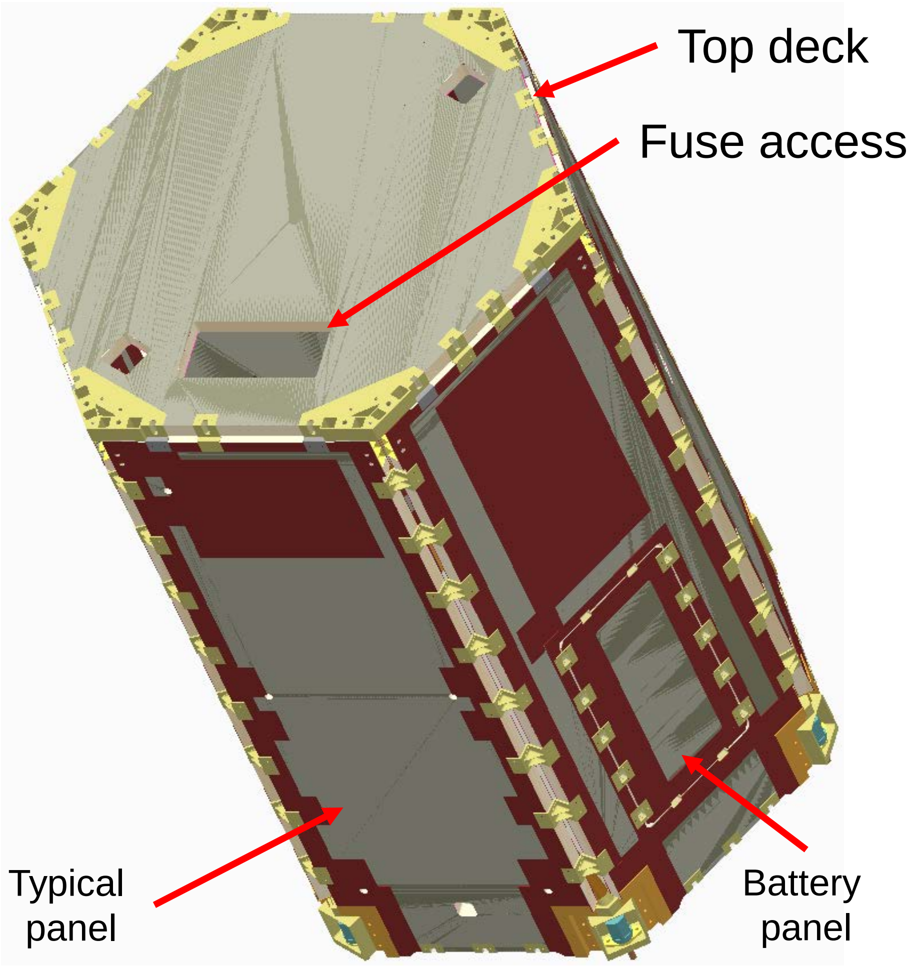
Separation plane

3rd stage

6 bolt extractors for 6 sep nuts on a 42” BC

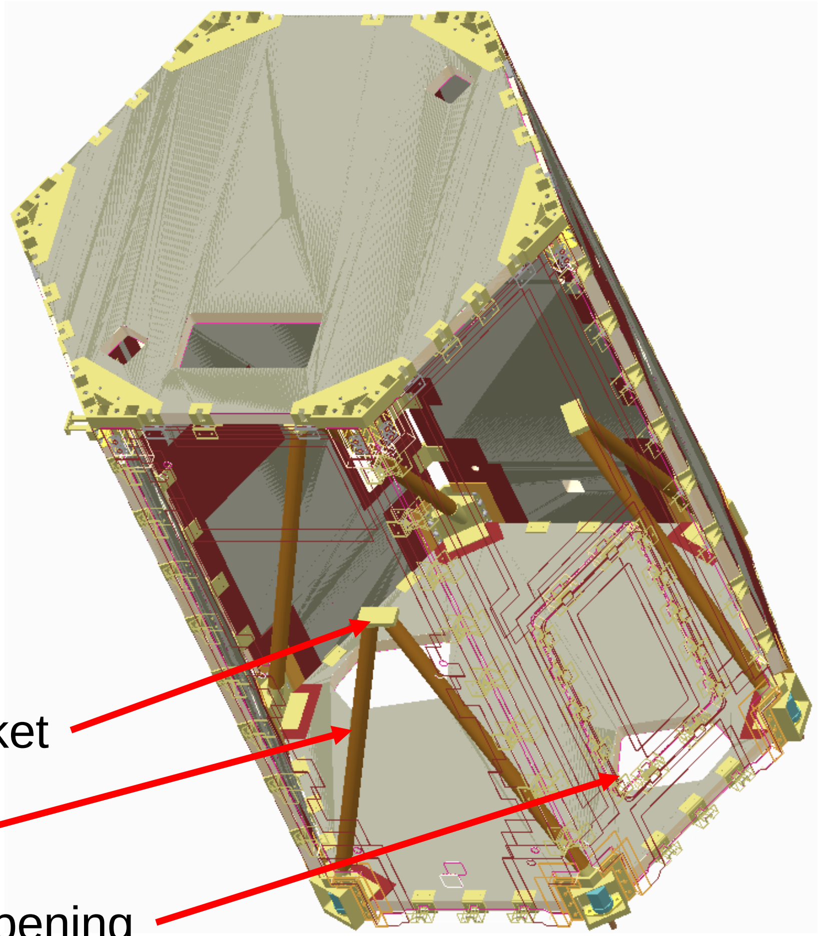
Primary Structure

- Hex structure with top and bottom decks, 31.75mm (1.25") thick
- Aluminum honeycomb panels with aluminum face sheets with internal structural and thermal doublers, 29.6mm (1.166") thick
- Two densities of honeycomb used with the higher density limited to high load locations
- Aluminum and titanium clips used to attach panels and decks together
- Aluminum and titanium edge members in panels in high load areas
- Removable panel for field installation of flight battery
- Hole in top deck to access fuses during I&T and field operations



Primary Structure

- 6 composite struts with titanium end fittings support the propulsion tank and direct the load into the 6 corner fittings of the structure
- Holes in the bottom deck allow star trackers to be recessed.



Tank mounting bracket

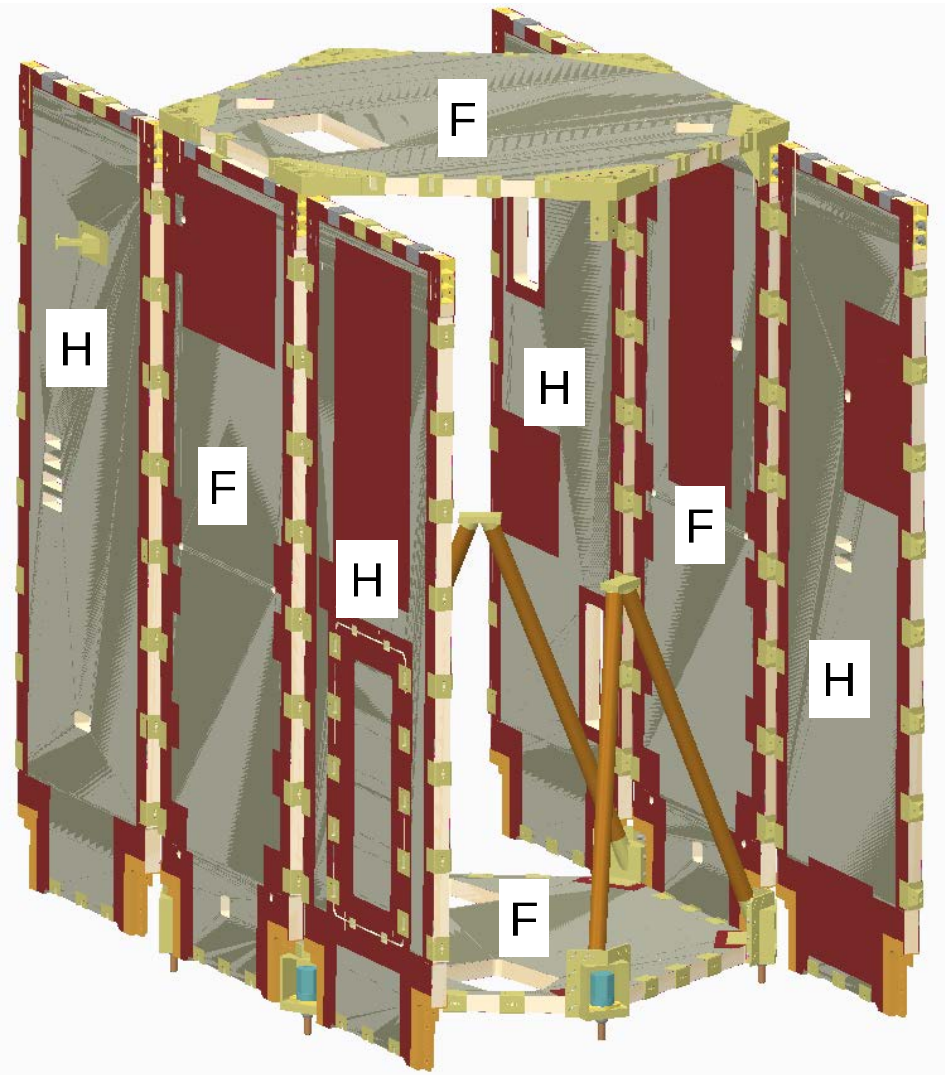
Tank strut

Star camera opening

Bus Integration Concept

- Top and bottom decks and two side panels are always “Fixed”
- Two “Fixed” panels support solar arrays and other “essential” components
- Four “Hinged” panels utilize GSE hinges or other tbd supports to hold panels in open configuration

F – Fixed panel, or top/bottom deck
H – Hinged panel

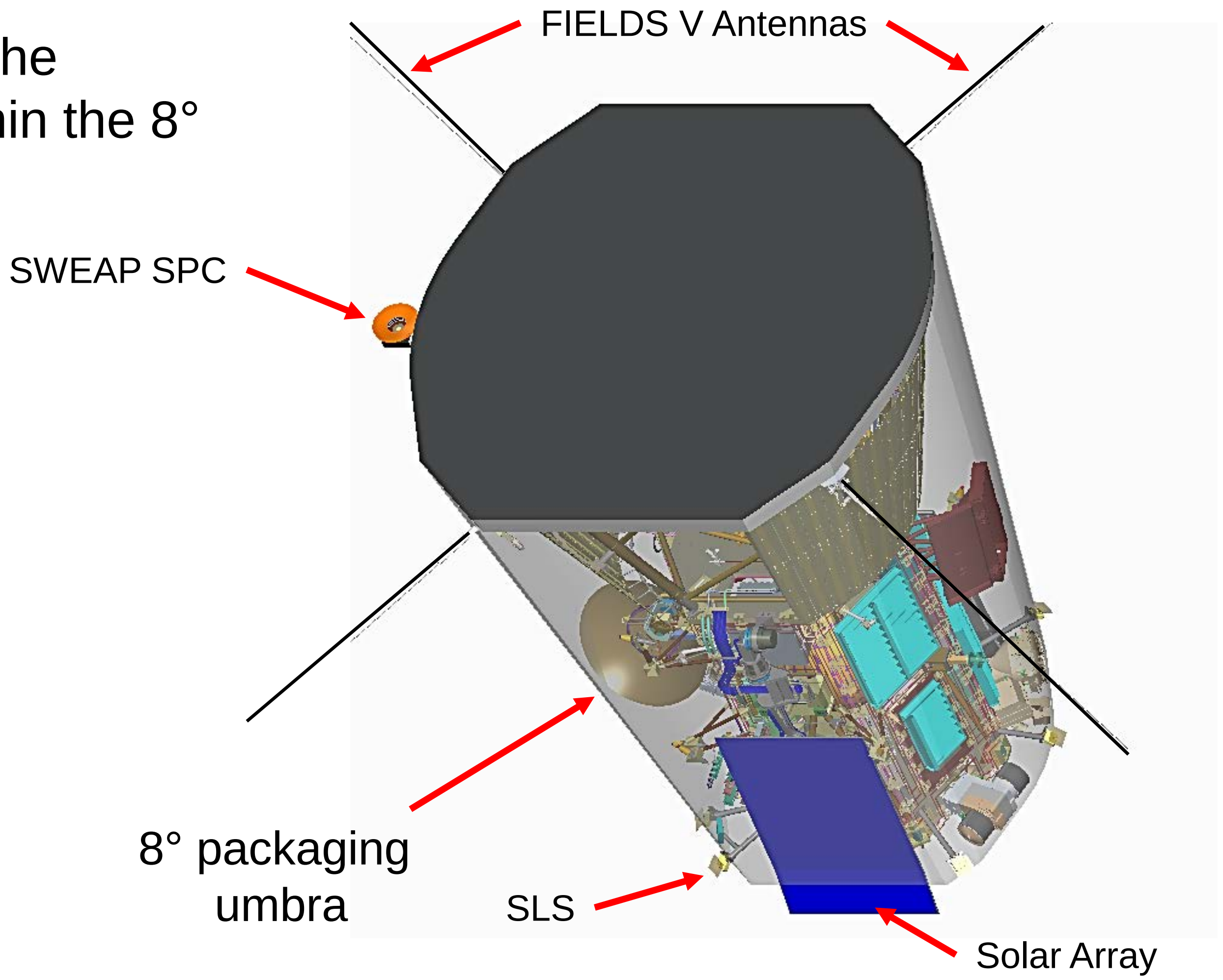


8° packaging umbra

All items packaged on the spacecraft must be within the 8° packaging umbra.

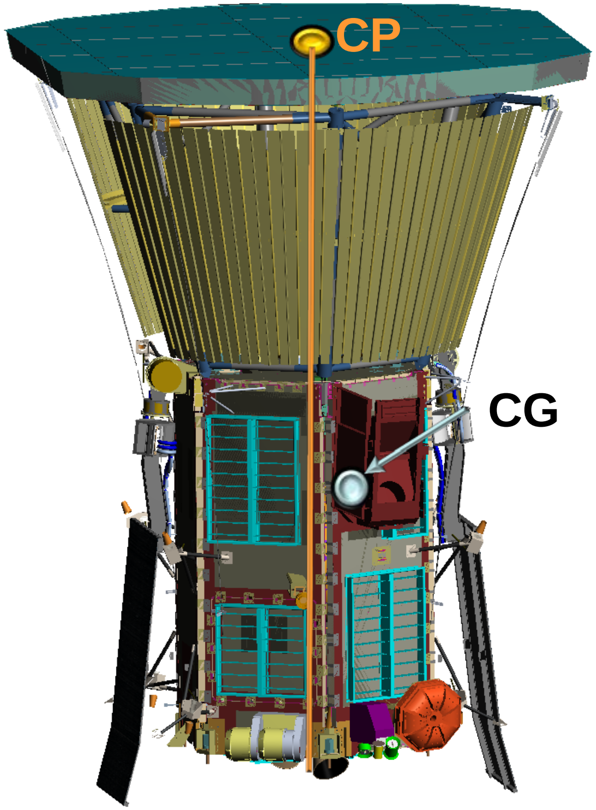
Exceptions are:

- FIELDS PWI antennas
- SWEAP SPC
- Solar limb sensors
- Solar arrays



Center of Pressure – Center of Gravity (CP-CG) Alignment

- Solar torque and propellant is required to keep spacecraft behind umbra is proportional to CP-CG offset and solar pressure + re-radiation.
- Max CP-CG offset from s/c centerline at launch estimated to be 51mm (2”)
    - 41mm (1.6”) CG offset, ~10mm (0.4”) CG offset
- TPS planform shaping 6 months after I&T start allows 28mm (1.1”) CG shift
    - Reduces a 51mm (2”) CP-CG offset to ~25mm (1”) CP-CG offset
    - Resulting TPS shape is defined as the “As-Launched TPS”
- Instruments shift with TPS edge to maximize Field of View (FOV) toward sun
- Solar limb sensors are shifted with TPS edge to protect shifted instruments



CP – CG Offset Requirement

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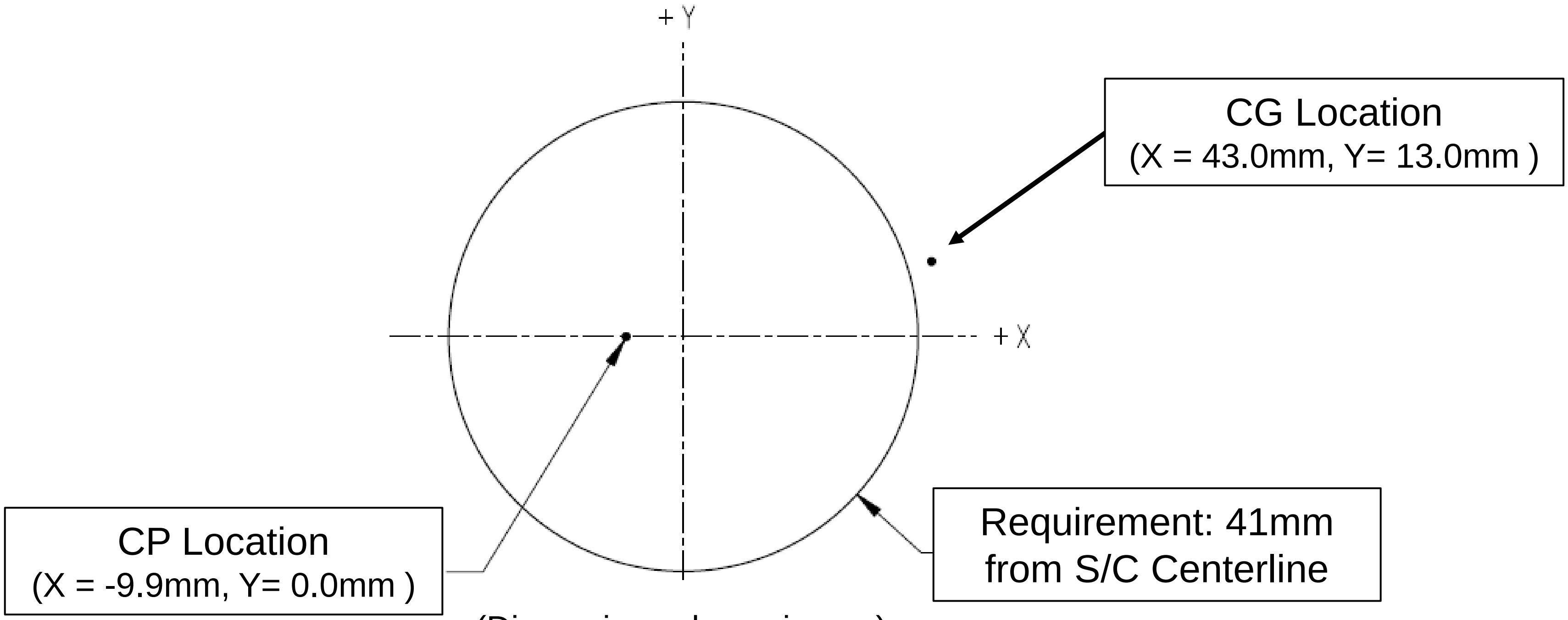
The spacecraft CG shall be within 41mm (1.6”) of the spacecraft centerline.
The spacecraft CP and CG shall be within 6.35mm (0.25”) of each other.

Present CG location: X = 43.0mm (1.693”), Y = 13.0mm (0.512”)
Present CP location: X = -9.9mm (-.390”), Y = 0.0mm



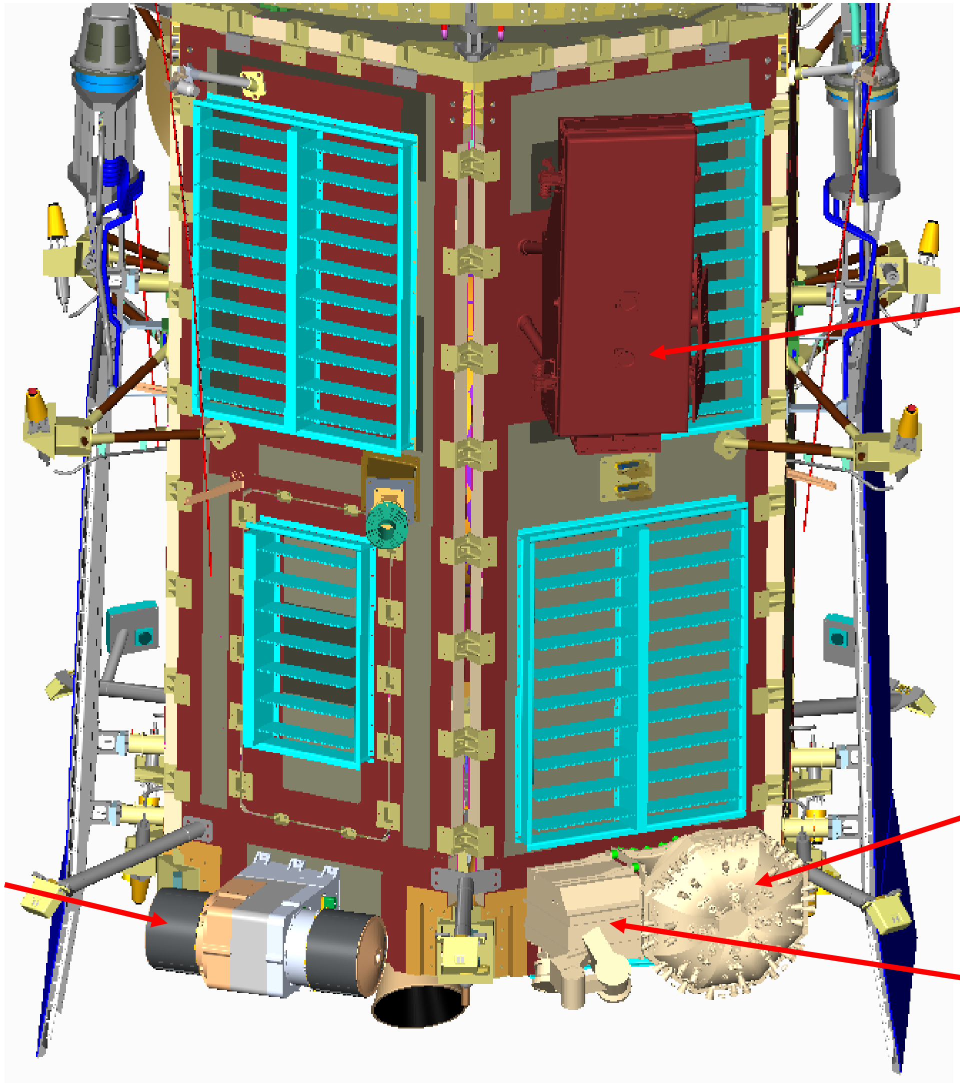
CG Location
(X = 43.0mm, Y= 13.0mm)

Requirement: 41mm
from S/C Centerline

CP Location
(X = -9.9mm, Y= 0.0mm)

(Dimensions shown in mm)

Instrument Accommodations



Ram side

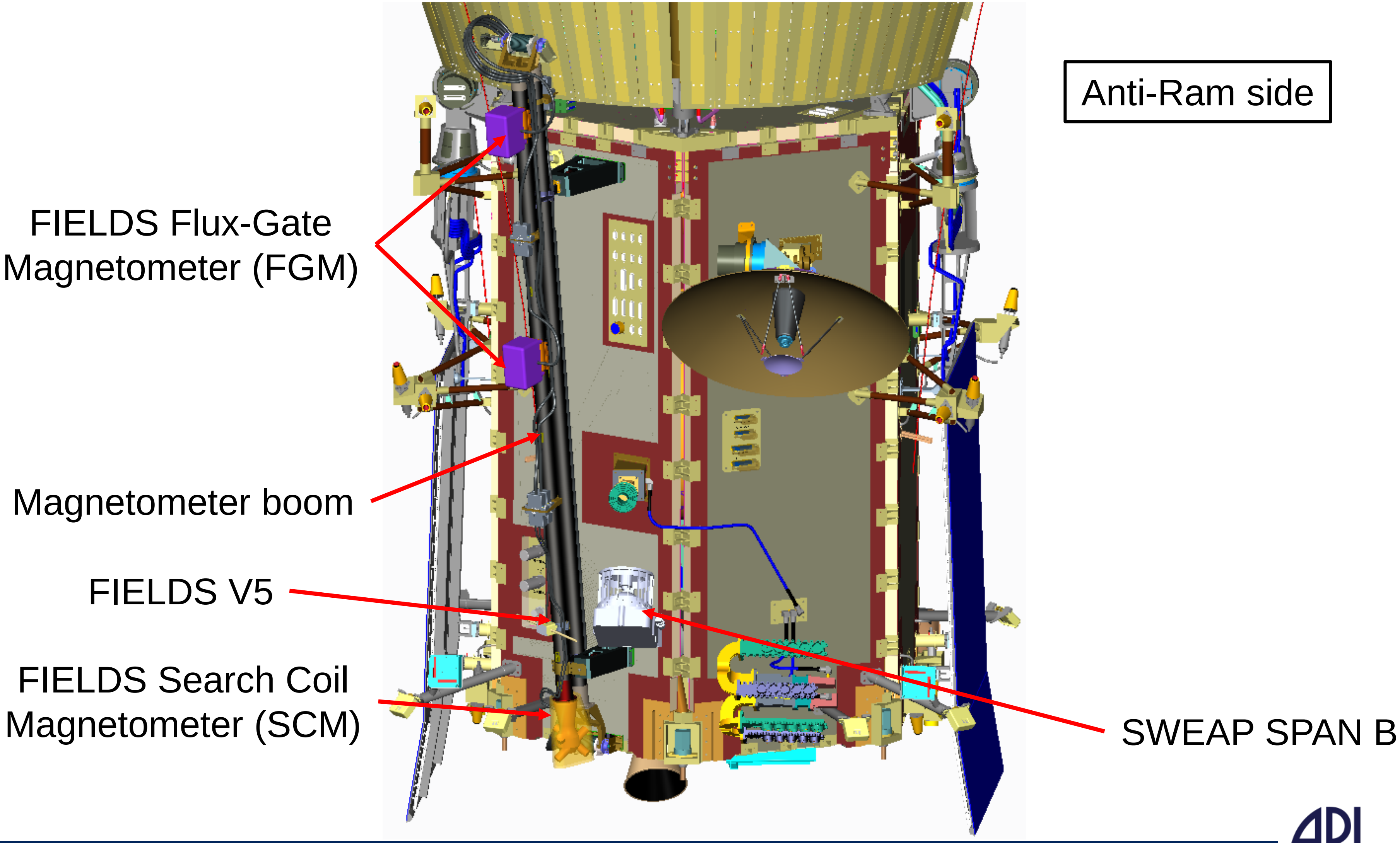
WISPR

ISIS EPI-Lo

SWEAP SPAN A+

ISIS EPI-Hi

Instrument Accommodations



Anti-Ram side

FIELDS Flux-Gate Magnetometer (FGM)

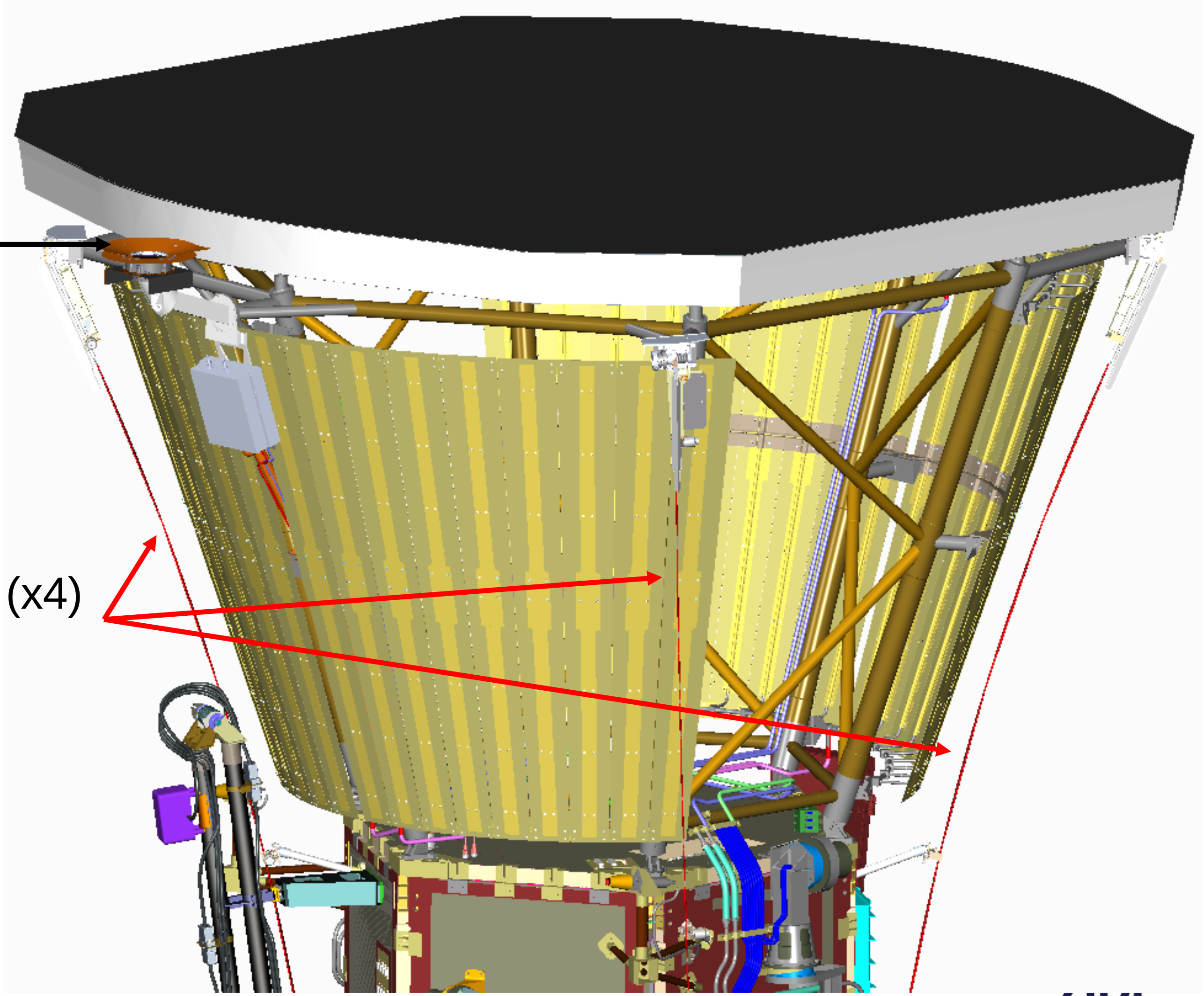
Magnetometer boom

FIELDS V5

FIELDS Search Coil Magnetometer (SCM)

SWEAP SPAN B

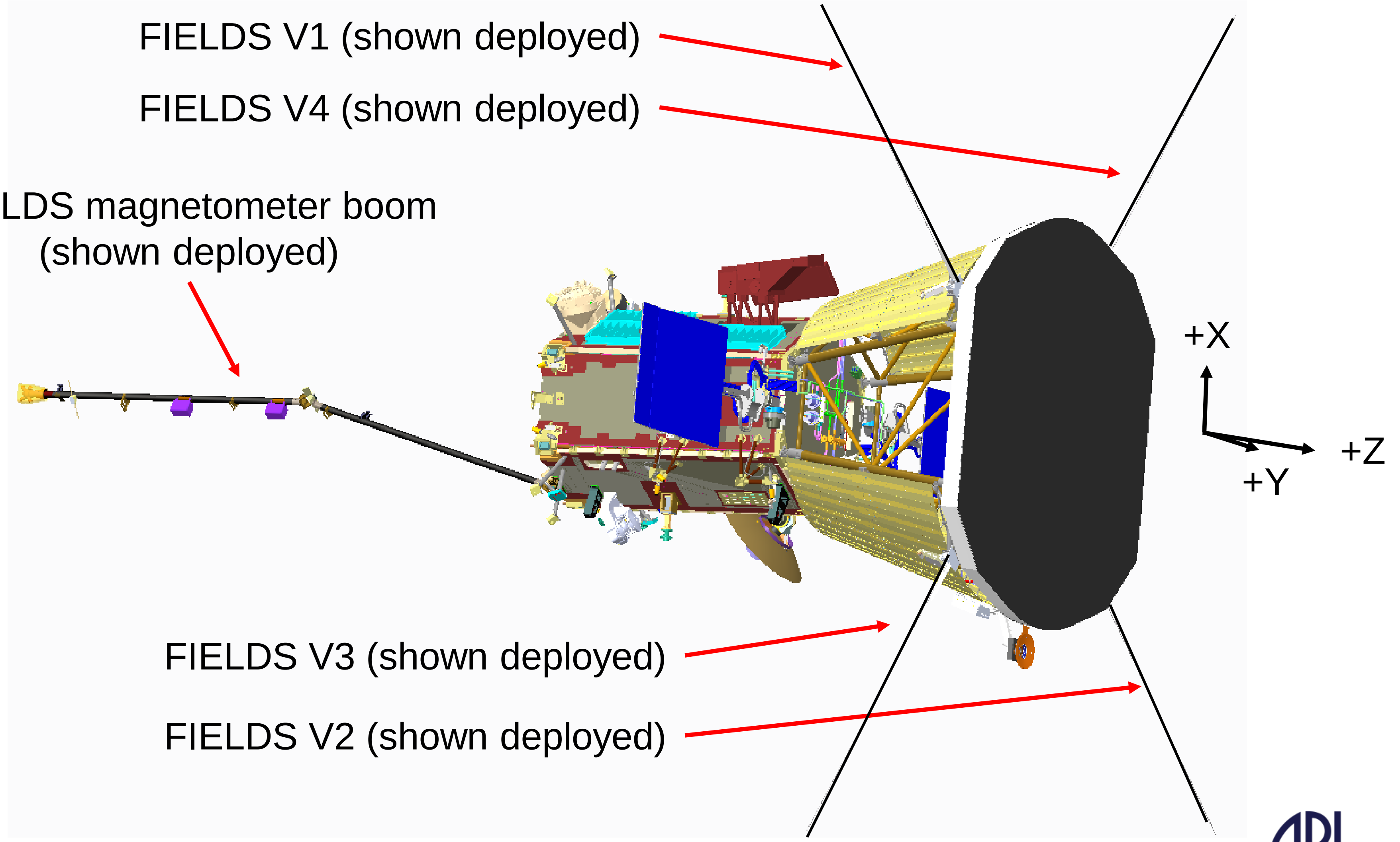
Instrument Accommodations



SWEAP SPC

FIELDS V1-V4 antennas (x4)
(shown stowed)

Instrument Accommodations



FIELDS V1 (shown deployed)

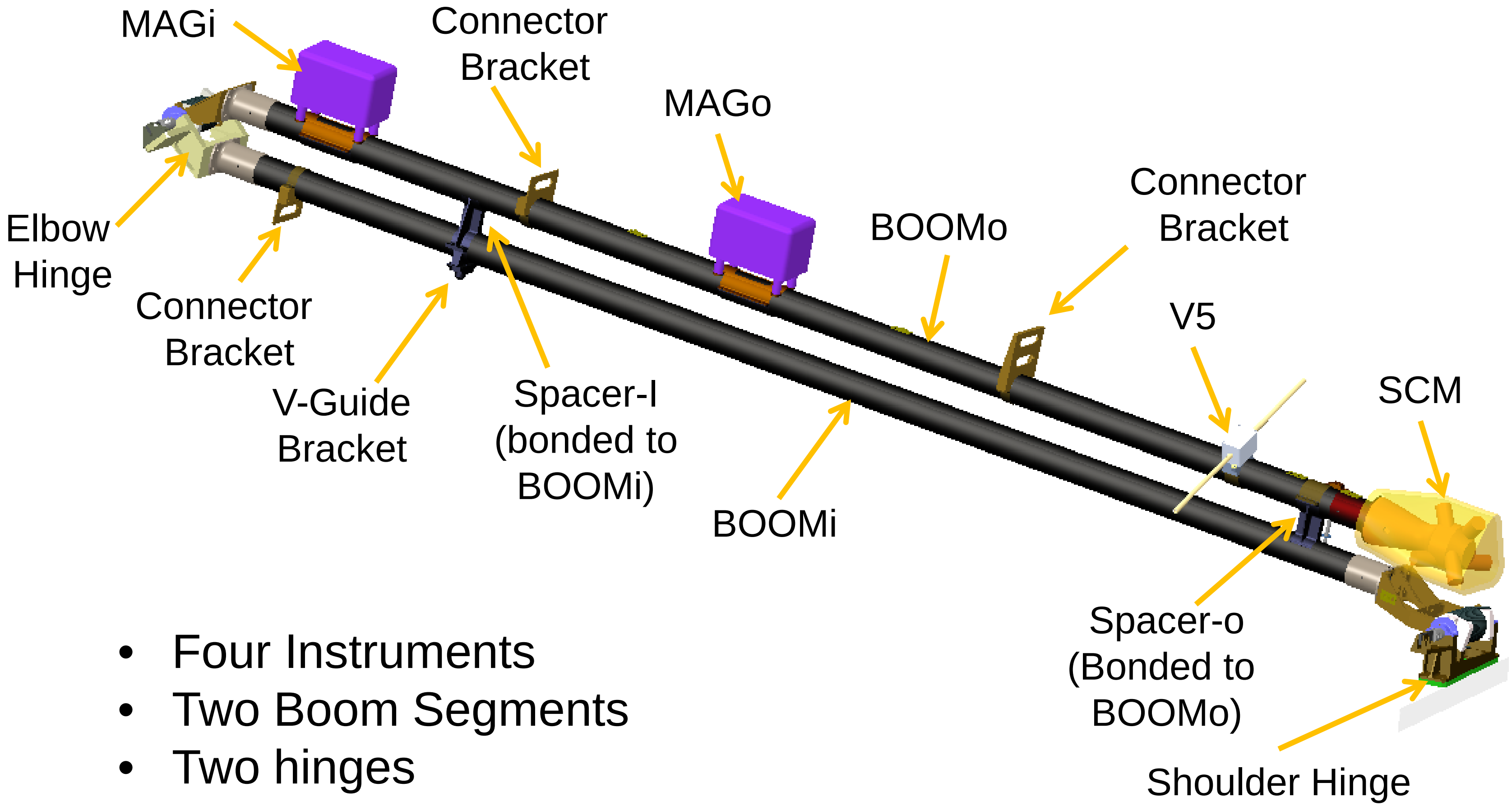
FIELDS V4 (shown deployed)

FIELDS magnetometer boom
(shown deployed)

FIELDS V3 (shown deployed)

FIELDS V2 (shown deployed)

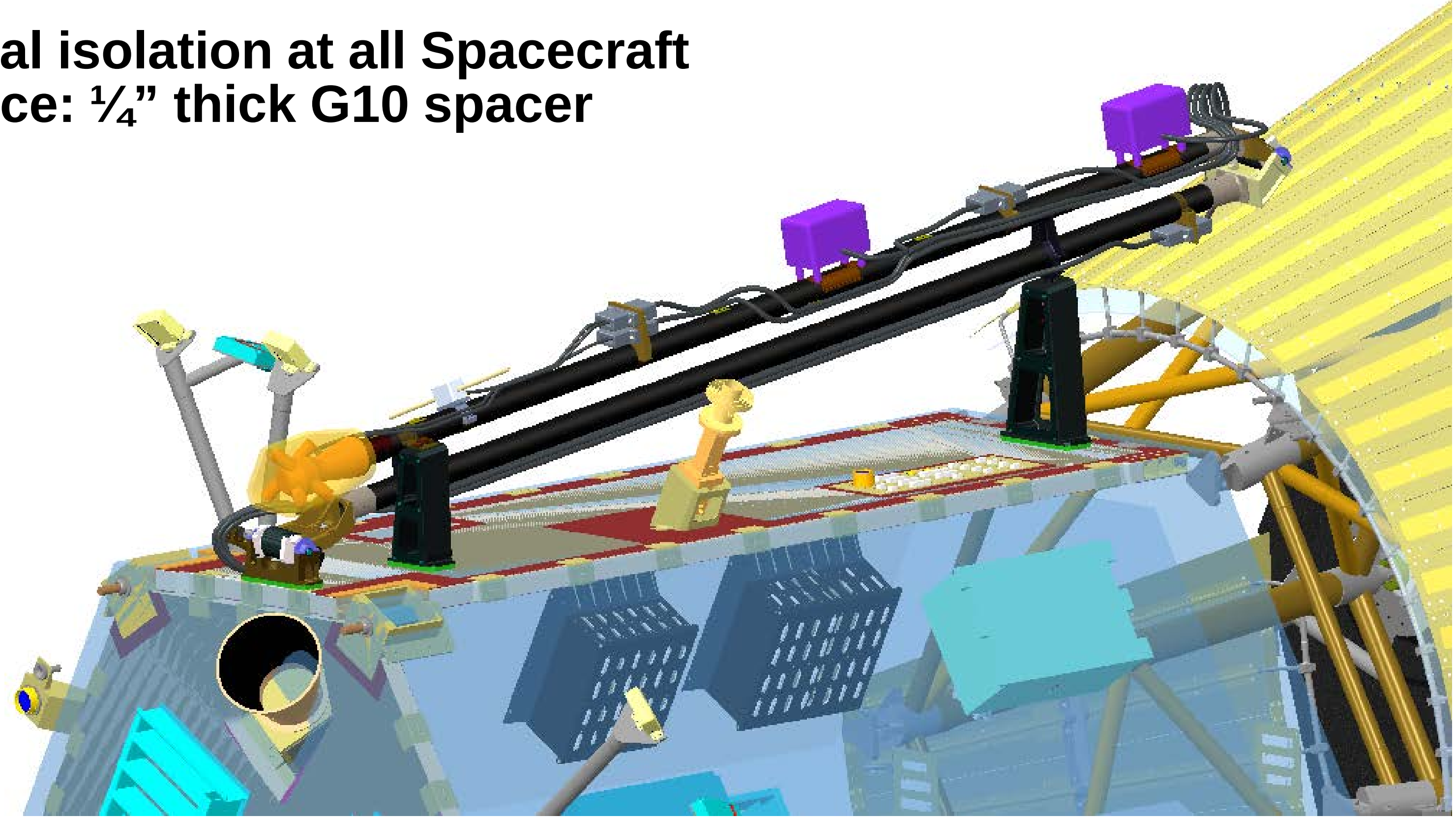
Boom Description



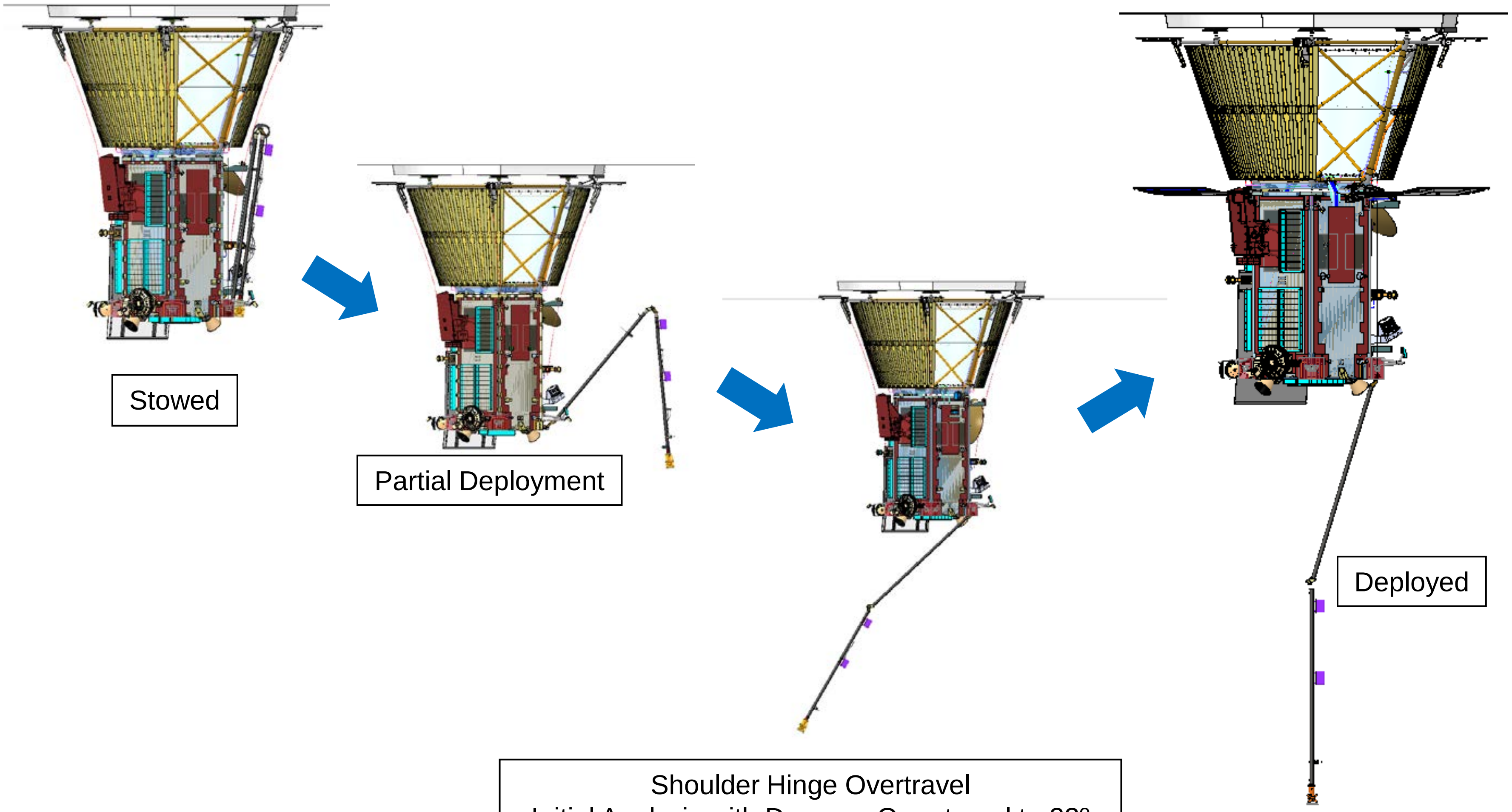
- Four Instruments
- Two Boom Segments
- Two hinges

Interface to Spacecraft

- **One shoulder hinge**
- **Two release assemblies**
- **Thermal isolation at all Spacecraft Interface: ¼” thick G10 spacer**



Boom Deployment



Stowed

Partial Deployment

Deployed

Shoulder Hinge Overtravel
Initial Analysis with Damper: Over-travel to 23º
Hinge Build-in Safety Hard stop at 30º

Trades –
Structural Panel Facesheets

- **MDR structure design used composite facesheets with Al honeycomb core material, however requirements for thermal and electrical conductivity created mass threats**
- **Composite facesheets lose mass efficiency after adding thermal doublers (required for thermal conduction) and copper foil (required for electrical conductivity)**
- **Stiffer AL/SiC only decreases interface moment by 3% relative to AL skin**
- **Other materials considered – ALBeMet, Be, Mg, AL-Li**
- **High strength AL facesheets have been selected due to:**
  - **Balanced strength and stiffness that meets all bus requirements**
  - **Low cost and extensive spaceflight heritage**

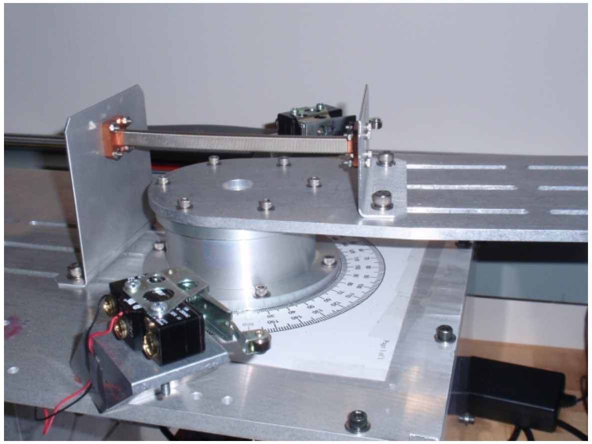
	M46J	AL/SiC-17.5p	AL7075-T7351
E (msi)	12	14	10.3
Density (lbs/in^3)	0.065	0.101	0.101
CTE (ppm/C)	~0	16.7	22.5
Ftu (ksi)	48.5	59	67
Fty (ksi)	n/a	46	55
1st bending mode of SPP [1] (Hz)	14.5	15.0	14.1
SPP/US IF Moment [2] (in-kips)	506	503	511
Total WT (lbs)	30.6	31.1	31.1
- All skins & structure doublers	20.0	31.1	31.1
- Thermal Doubler	7.0	0	0
- Copper foil	3.6	0	0

[1] Based on the model dated April/2012.
[2] Sine base shake and notch US/LV IF moment to not exceed 2.5G lateral acceleration.

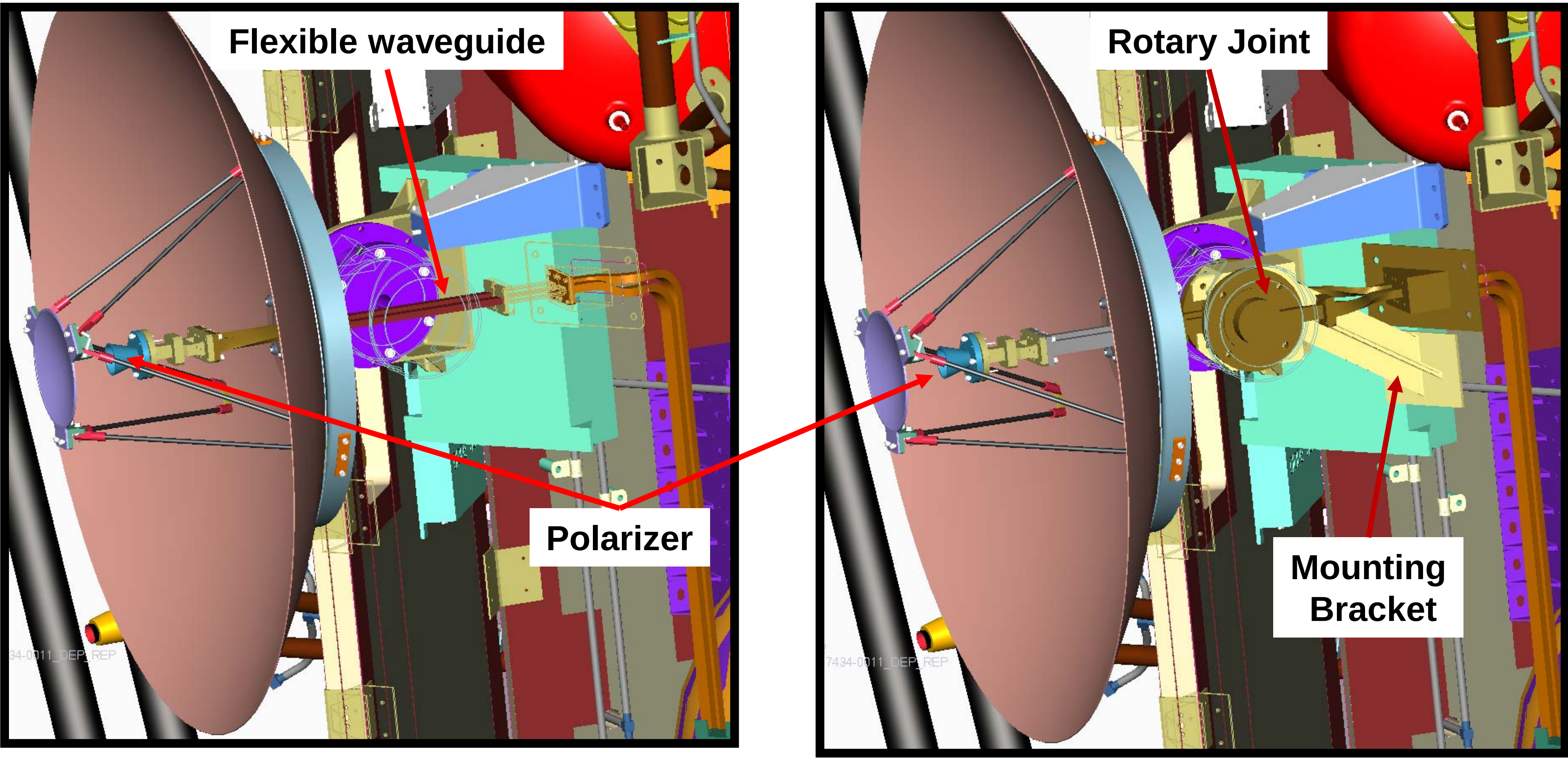
Trades –

TRL - 6 Flexible Waveguide vs. Rotary Joint

- Waveguides subjected to 200 cycles between -50 and +50 deg
- No change in resistance torque after life cycle test
- Visual inspection at 80X showed no new blemishes or degradation of existing blemishes on SN3. No problems noticed on SN1. No changes noticed in RF performance.
- Waveguides subjected to sine survey and random vibration.
- Visual inspection under 10X did not show any issues. No changes in RF performance.
- Waveguides subjected to 200 cycles between -45 deg and +45 deg
- Resistance torque was under .2 in-lb (resolution of transducer)
- Visual inspection under 10X did not show any issues. No changes in RF performance.



Trades –
TRL - 6 Flexible Waveguide vs. Rotary Joint



Flexible waveguide

Rotary Joint

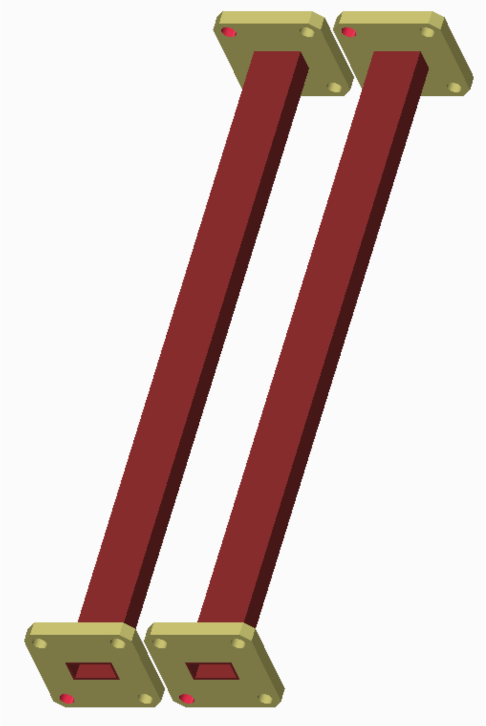
Polarizer

Mounting Bracket

Trades –
TRL - 6 Waveguide vs. Rotary Joint

Flexible Waveguide Option

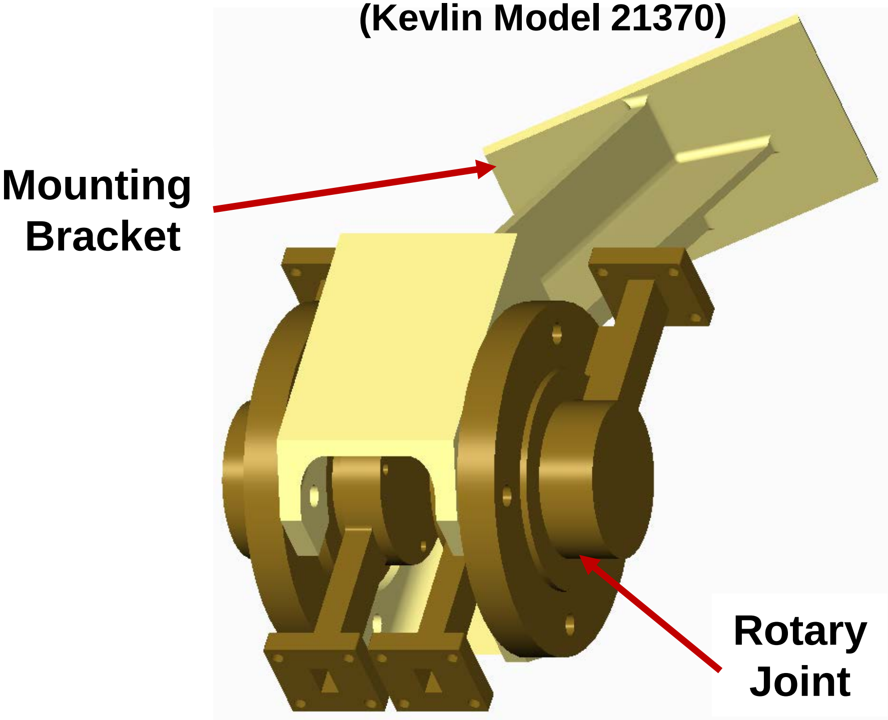
Total System Mass = .08kg



Rotary Joint Option

Total System Mass = 0.85kg

(Kevlin Model 21370)



The flexible waveguide is the baseline due to its mass savings.

The only concern was the failures on MRO, SDO missions and during GPM testing. However, the flexible waveguides that are baseline for SPP use an electro-forming process which produces a more durable waveguide than those waveguides that experienced failures on other missions.

Mass Estimate vs. Allocation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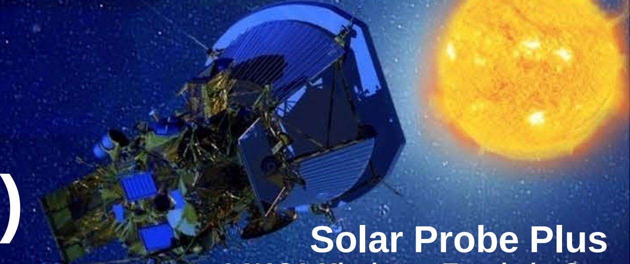
	Qty.	CBE Each (kg)	CBE Total (kg)	NTE (kg)	Notes
Primary Structure			49.76	54.74	Includes all panels, Tank supports, Interior Paint and Fasteners
Secondary Structure			8.50	9.35	Includes Purge Components, Fan Beam Ant Brkt, Low Gain Ant Brkt, Thruster Brackets, Star Tracker Brkt, Reaction Wheel Brkts, SLS Brkts and Sepnut Bolt Extractor
	Structure Total =		58.26	64.09	
Mag Boom	1	5.49	5.49	6.25	Includes mag boom and launch locks but no instruments (FGMi, FGMo, SCM, V5)
SA Actuators	4	2.04	8.16	8.58	Includes feather/flap actuators for both Solar Arrays
ECU (SA \ HGA Actuators)	1	5.95	5.95	6.46	
Solar Array Boom Assembly	2	2.55	5.10	5.53	
Cooling Line Management	2	1.53	3.05	3.31	Includes brackets for supports SACS flex lines and harnesses
SA Restraints and Release Mech			2.00	2.17	Includes frangibolt tie-downs and snubbers
HGA Actuator	1	2.04	2.04	2.15	
	Subsystem Total =		148.31	162.63	

Requirement

Minimum Resonant Frequency (Hz)



Solar Probe Plus

A NASA Mission to Touch the Sun

	TPS + TSA[1]	Observatory[2]	US + Adaptor[3]
Lateral (Requirement) / **Actual**	(18) / **17.9**	(11) / **11.9**	(9) / **TBD**
Axial (Requirement) / **Actual**	(50) / **70**	(40) / **50+**	(35) / **TBD**

[1] Applied to the flexible TPS + TSA subsystem.

[2] Applied to the SPP Observatory including flexible TPS+TSA and BUS.

[3] Applied to the US + Adaptor with rigid Observatory.

SC Optimization Since MDR

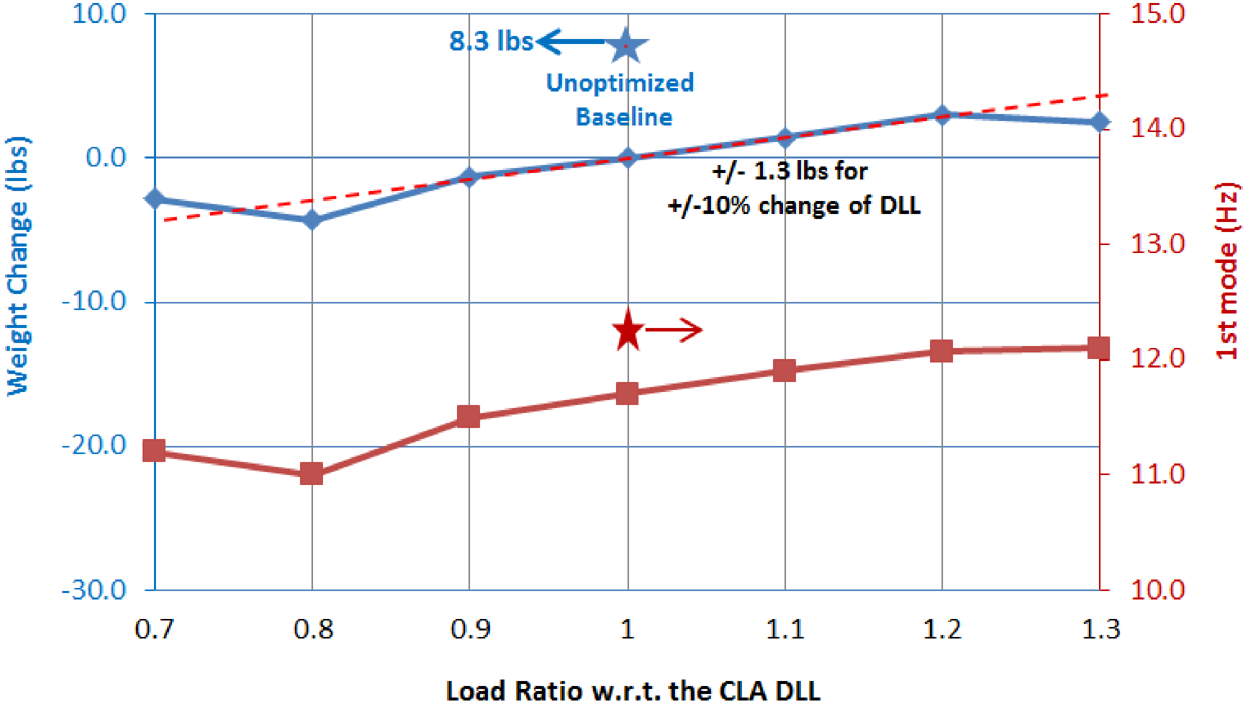
The SPP spacecraft is a balanced stiffness and strength design.

Optimization analysis suggests a 8.3 lbs mass savings (optimized for both strength and stiffness).

Additional mass reduction is insensitive to either load or stiffness.

Structural optimization has been implemented

- **Reduced 24 pairs of panel/panel clips (~ 8 lbs mass savings)**
- **Optimize SA interface and components (~ 5 lbs mass savings)**



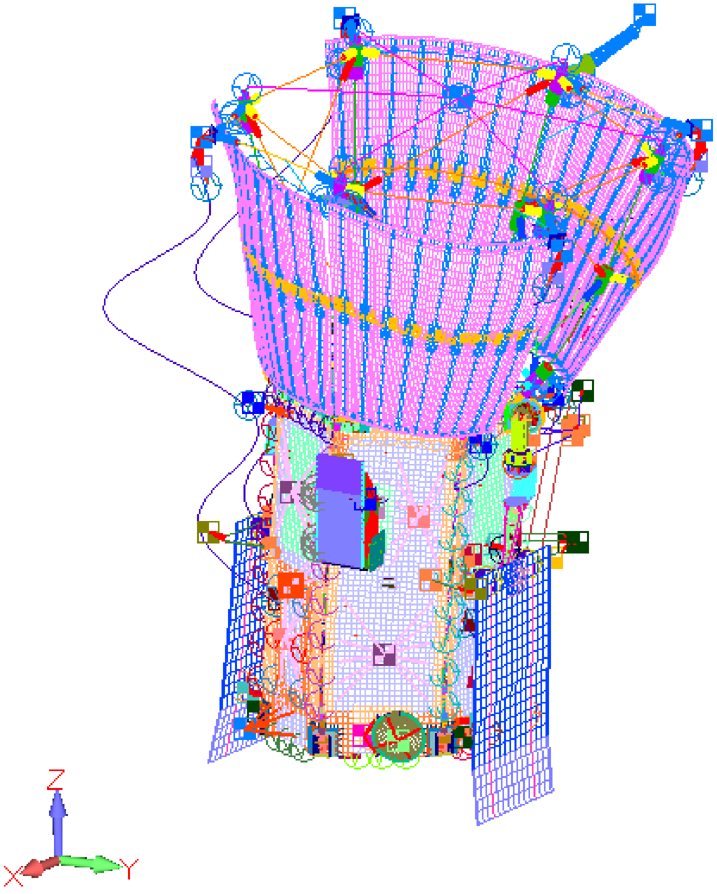
SPP Spacecraft FEM

Spacecraft FEM includes:

- **116,457 Elements**
- **117,252 Nodes**

1st RX bending mode @ 11.9 Hz &
1st RY bending mode @ 12.0 Hz

1st RZ twisting mode @ 17.8 Hz



Output Set: Mode 17, 11.90413 Hz
Animate(1.415): Total Translation

SPP Alignment Status / Future Work

Status

Alignment Peer Review Held 8 Nov 2013

- Action Items and Summary Memo in-work

Requirements are understood and complete in all cases

- Requirements are being decomposed, flowed down, and implemented in reqm't modules
- Recommendations on design accommodations are being made

Plans are being developed for verifying alignment requirements

- More specific planning is being developed
- Alignment Plan framework is in place
- Sub-system measurement and test planning are on-going, with design recommendations being made

Future Work

Alignment PDR Action Item responses, early 2014

Alignment Plan Review, early-2014 Review, mid-2014 Release

Budget refinements

- Adjust budgets and perform tolerance analysis of clearances and mechanical interfaces
- Develop Measurement Plans
- Determine: master cube location, coordinate system mapping, and sub-system-level measurement plans

Unique SPP Alignment Considerations

TPS-TSA Alignment to SC Structure

Rationale: Supports CP-CG and locating Umbra

- Typical GD&T and mechanical tolerancing are implemented, but plans for adjustment are being refined after work with TRL-6 development article

TPS-to-Platen Alignment examined

Rationale: Supports SA Slew Budget for Solar Array Cooling System Capacity

- Requirement decomposition to: Platen, Rotary joints, SC, TPS
- Mechanical errors fed back into solar array cooling system budget

WISPR-to-TPS

Rationale: WISPR Utilizes TPS as its first baffle

- Angular and positional requirements preliminarily established
- Further work on positional requirement to TPS edge

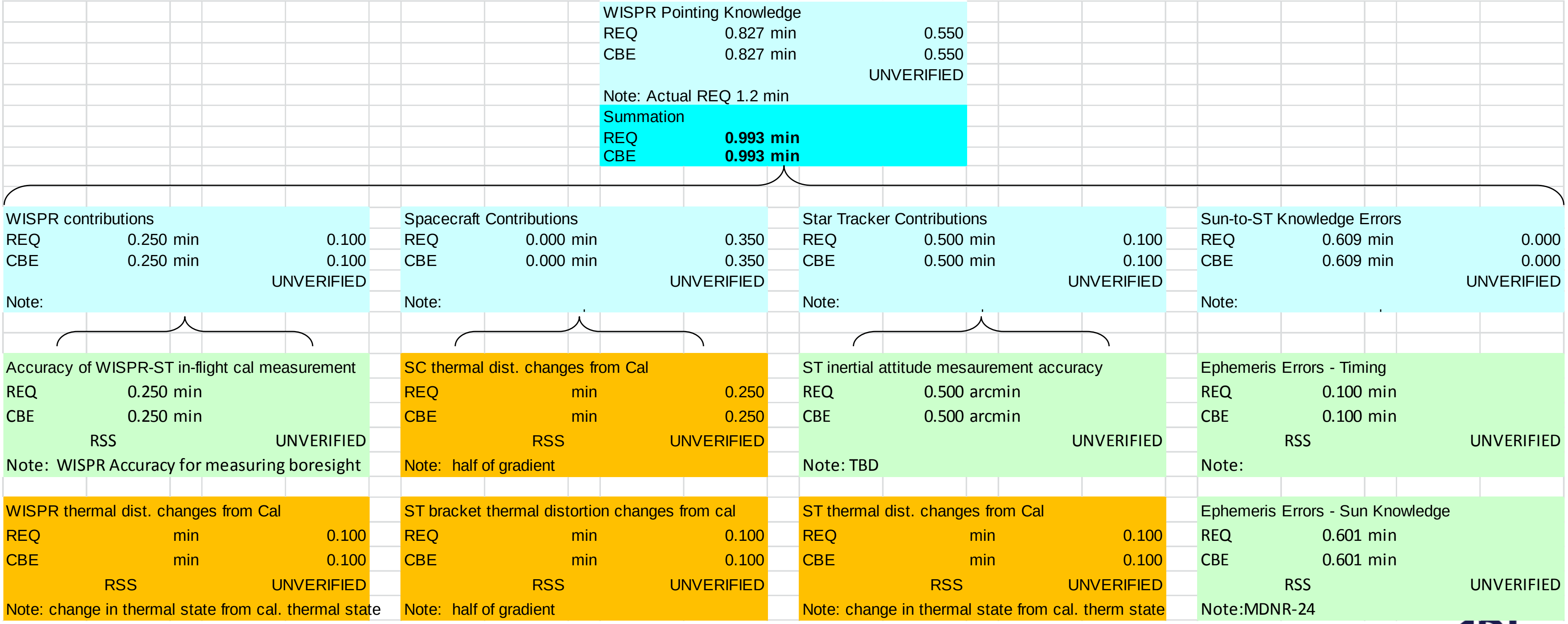
Cp-to-Cg

Rationale: Critical to Observatory stability and propellant use

- Cp-to-Cg requirement examined with an error budget developed (Presented at the Alignments Peer Review)

Sample Alignment Budget: WISPR Z-axis Knowledge to sun line

- **This is a special case for attitude knowledge based on the results of an in-flight calibration between WISPR and the ST frame**
  - **Bypasses the SC body frame**
  - **More accurate because of direct optical-to-optical calibration**



WISPR Pointing Knowledge
REQ 0.827 min 0.550
CBE 0.827 min 0.550
UNVERIFIED
Note: Actual REQ 1.2 min

Summation
REQ **0.993 min**
CBE **0.993 min**

WISPR contributions
REQ 0.250 min 0.100
CBE 0.250 min 0.100
UNVERIFIED
Note:

Spacecraft Contributions
REQ 0.000 min 0.350
CBE 0.000 min 0.350
UNVERIFIED
Note:

Star Tracker Contributions
REQ 0.500 min 0.100
CBE 0.500 min 0.100
UNVERIFIED
Note:

Sun-to-ST Knowledge Errors
REQ 0.609 min 0.000
CBE 0.609 min 0.000
UNVERIFIED
Note:

Accuracy of WISPR-ST in-flight cal measurement
REQ 0.250 min
CBE 0.250 min
RSS UNVERIFIED
Note: WISPR Accuracy for measuring boresight

SC thermal dist. changes from Cal
REQ min 0.250
CBE min 0.250
RSS UNVERIFIED
Note: half of gradient

ST inertial attitude mesaurement accuracy
REQ 0.500 arcmin
CBE 0.500 arcmin
UNVERIFIED
Note: TBD

Ephemeris Errors - Timing
REQ 0.100 min
CBE 0.100 min
RSS UNVERIFIED
Note:

WISPR thermal dist. changes from Cal
REQ min 0.100
CBE min 0.100
RSS UNVERIFIED
Note: change in thermal state from cal. thermal state

ST bracket thermal distortion changes from cal
REQ min 0.100
CBE min 0.100
RSS UNVERIFIED
Note: half of gradient

ST thermal dist. changes from Cal
REQ min 0.100
CBE min 0.100
RSS UNVERIFIED
Note: change in thermal state from cal. therm state

Ephemeris Errors - Sun Knowledge
REQ 0.601 min
CBE 0.601 min
RSS UNVERIFIED
Note:MDNR-24

Mechanical Subsystem PDR

- **The Mechanical Subsystem PDR was held on November 14th at APL**

- **Review Members were:**
    - **Ken Hinkle – GSFC (SRB Chair)**
    - **Jeff Bolognese – GSFC**
    - **David Robinson – GSFC**
    - **Terry Betenbaugh – APL**
    - **Stuart Hill – APL**

- **14 RFAs and 15 Recommendations were written by the review team**

Phase C Plans

- **Work to resolve RFAs and Recommendations from Subsystem PDRs**
- **Continue detailed design of spacecraft structure**
- **Re-test flex joint harnesses at temperature**
- **Complete life testing of Flexible waveguide at temperature**
- **Procure EM Flap Actuator and Dev unit ECU and perform characterization tests**
- **Assess gaps in the assembled spacecraft structure for DDD issues, EMI and adequate structure Venting**
- **Fabricate EM Magnetometer Boom**
- **Assist RF Telecom team with HGA procurement and paint selection**
- **Complete GSE design**
- **Update component Sine, Random and DLL**
- **Generate Craig-Bampton model for phase C CLA**
- **Process CLA results**

Conclusion

- All Mechanical requirements have been identified
- The flow down of requirements is complete
- The requirements are traceable to mission requirements
- All significant interfaces (Upper Stage, TPS/TSA and instruments) have been identified
- The Master Equipment List (MEL) is consistent with the component designs, CAD models, and requirements
- Any new technology (HGA - Flexible waveguide) has developed to TRL-6
- Project Risks are understood and have been credibly assessed
- Technical trade studies are mostly complete to sufficient detail, plans exist for their closure and impacts are understood
- Preliminary analysis of the subsystem has been completed and summarized, highlighting performance and design margin challenges
- Appropriate modeling and analytical results are available and have been considered in the design
- Manufacturability has been adequately included in the design

The Mechanical Subsystem is ready for Phase C

Backup Material

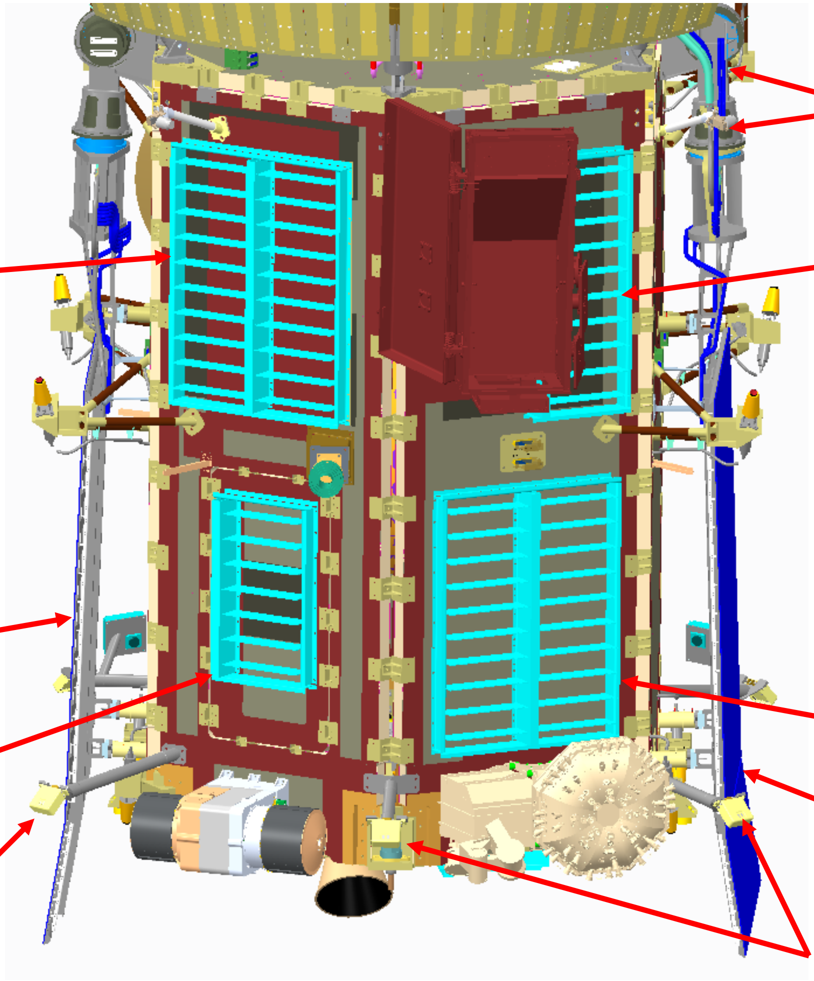
Requirement – Design Limit Load (DLL)

	TPS + TSA[1]
Case #1- L/O	
Axial (G)	+/- 4.8
Case #2- L/O	
Lateral (G)	+/- 13.5
Case #3 - TECO	
Axial (G)[4]	+16

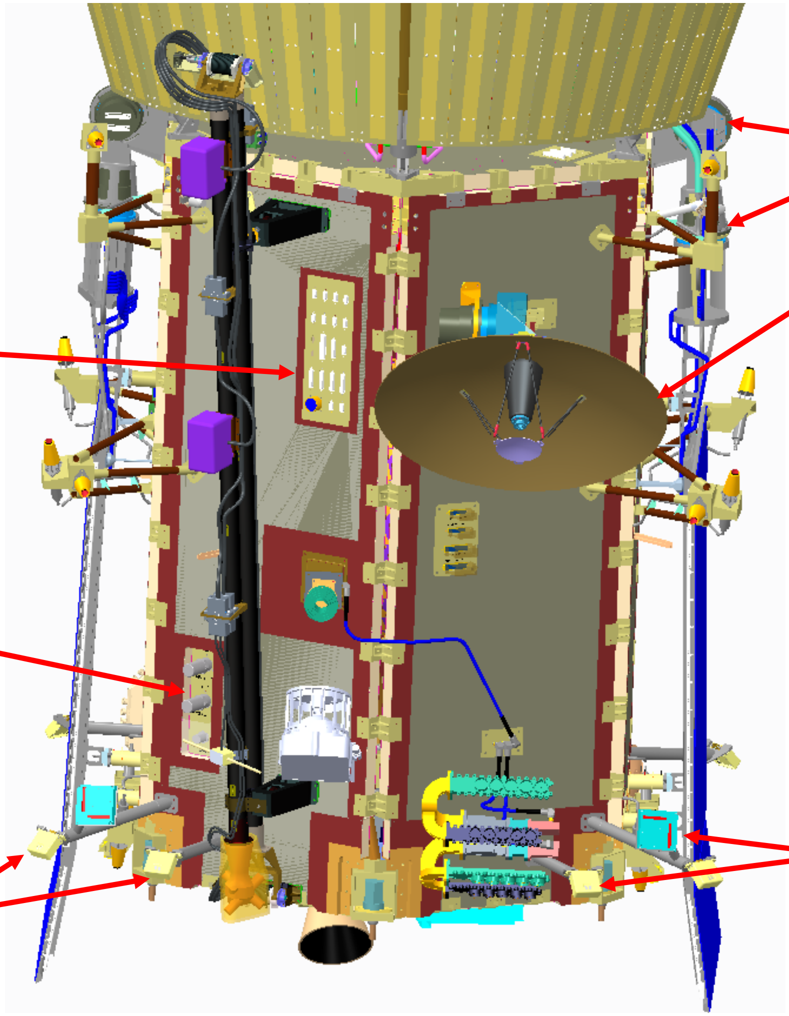
	BUS[2]	US + Adaptor [3]
Case #1- L/O		
Axial (G)	+7.25 / -3.0	+7.25 / -1.63
Lateral (G)	+/- 3.9	+/- 1.85
Axial rotation (rd/s/s)	+/- 22.4	+/- 18.8
Lateral rotation (rd/s/s)	+/- 28	+/- 13
Case #2 - TECO		
Axial (G)[4]	+16	+16

1. Loads to be applied to the CG of TPS + TSA
2. Loads to be applied to the CG of the SPP Observatory (BUS+TSA+TPS).
3. Loads to be applied to the CG of the SPP payload stack up (Adaptor + US + SPP Observatory).
4. In axial direction, positive is in compression.
5. Derived from KSC/CLA for Atlas V-551 with DUF=1.5, SUF=1.0 and MUF=1.10 for axial compression & 1.25 for other components.
6. TECO load updated per OSC “mc_axial_accel_profiles.jpg” on Oct-04-2013
7. **Stress Analyses show positive margin with GEVS factors of safety applied.**

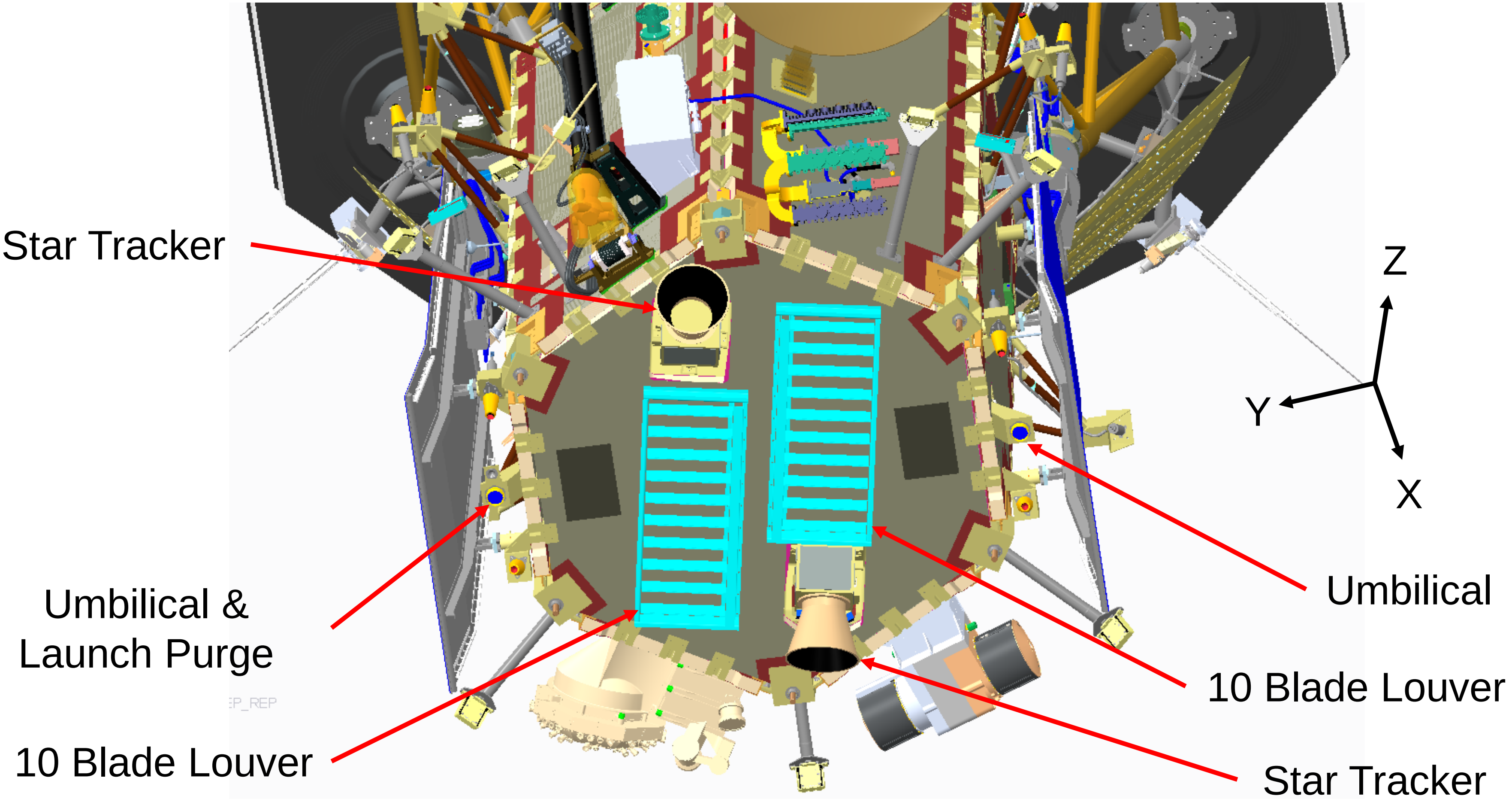
Component Accommodations Ram Side



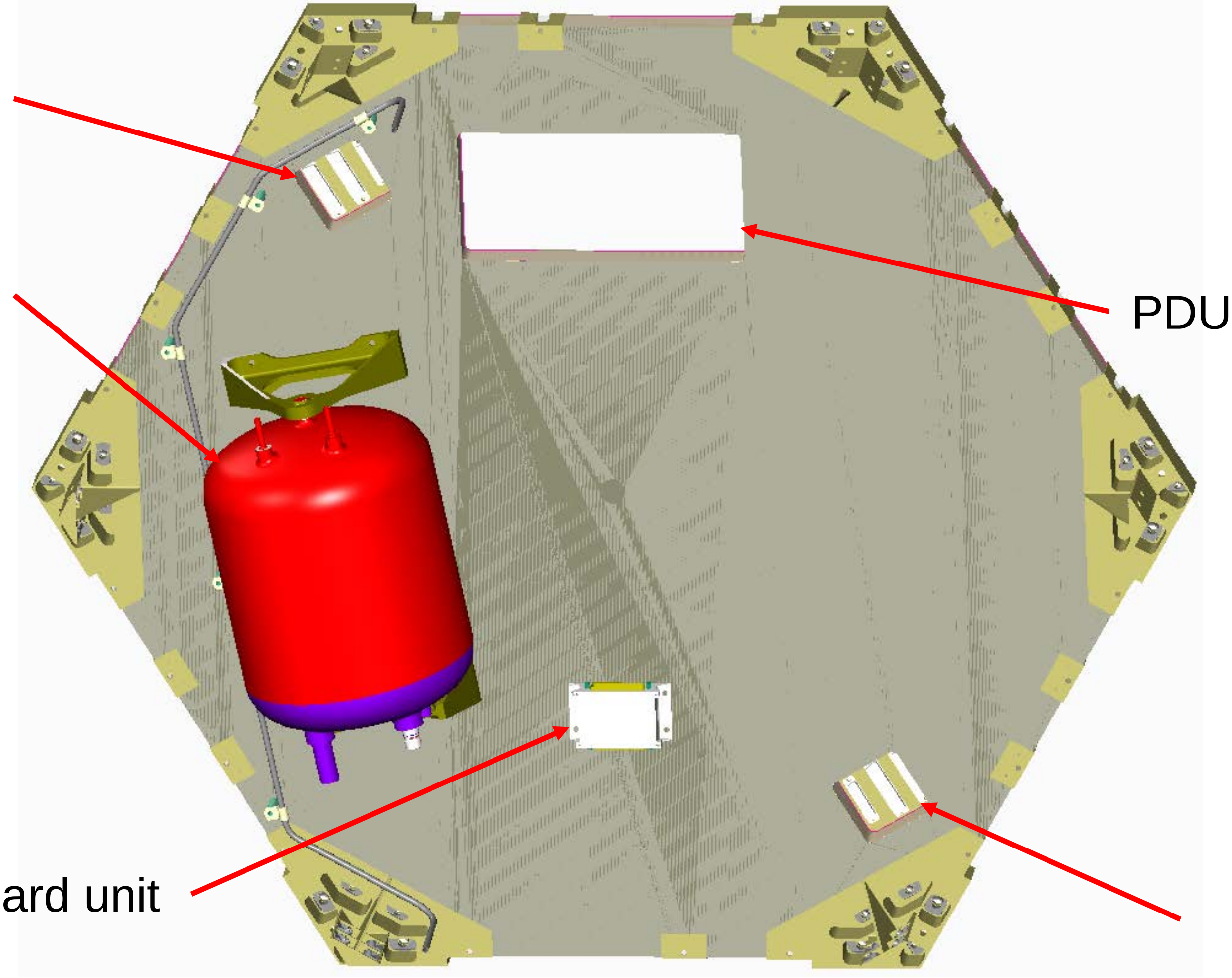
Component Accommodations
Anti-Ram side



Component Accommodations Bottom Deck - Outside



Component Accommodations Top Deck - Inside



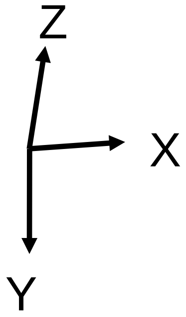
Solar array bulkhead

Accumulator tank

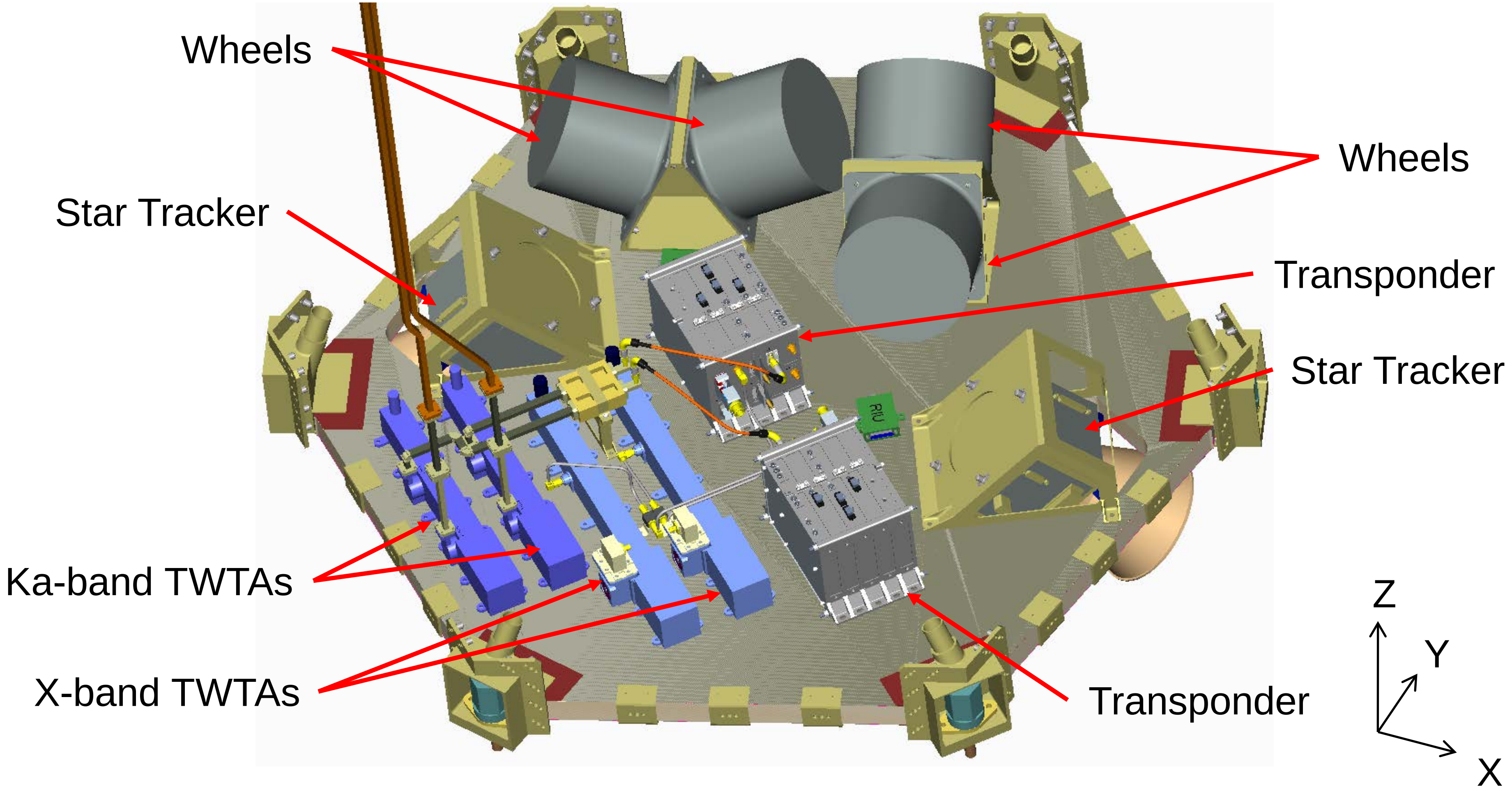
PDU Fuse Access

Terminal board unit

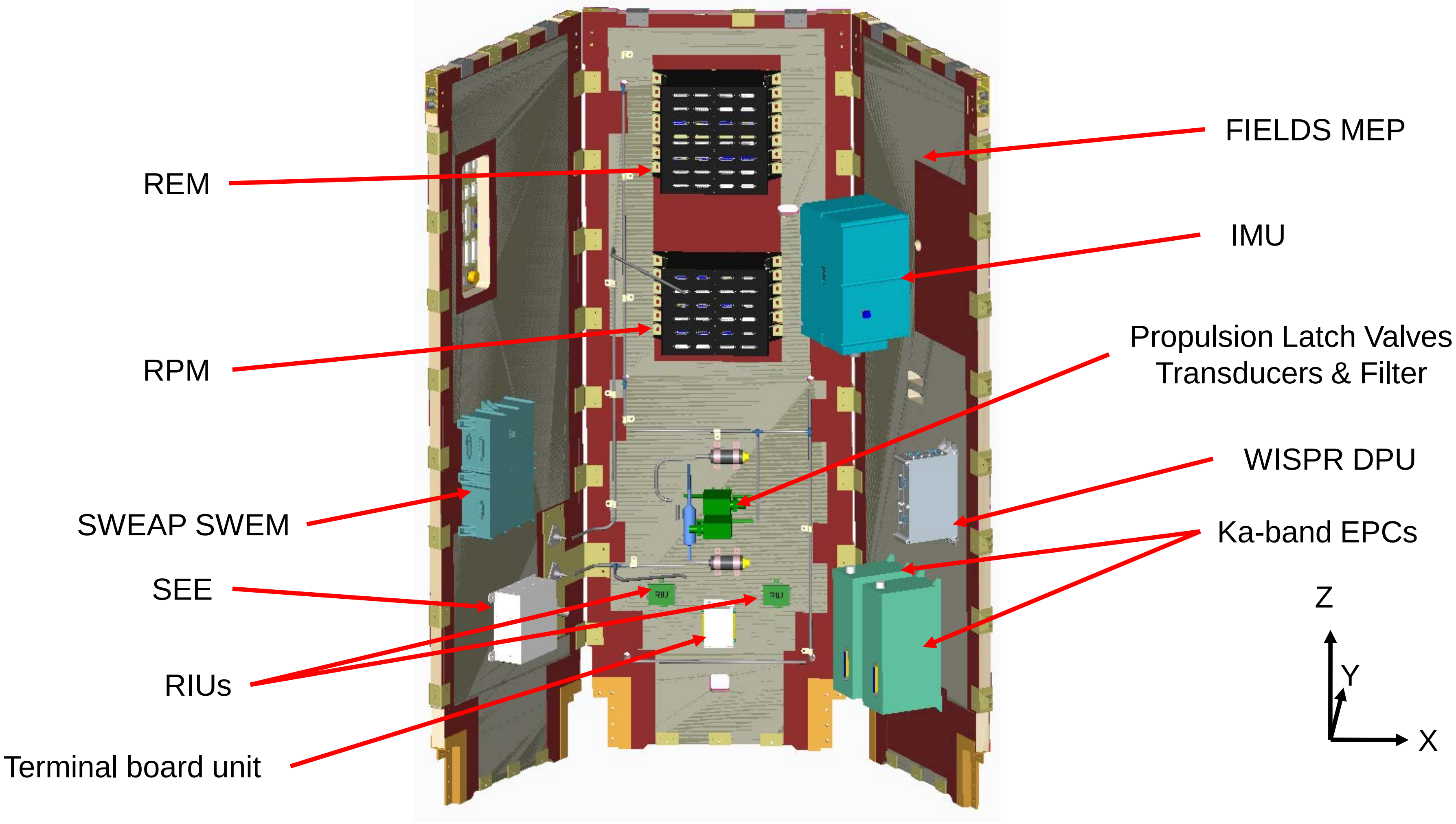
Solar array bulkhead



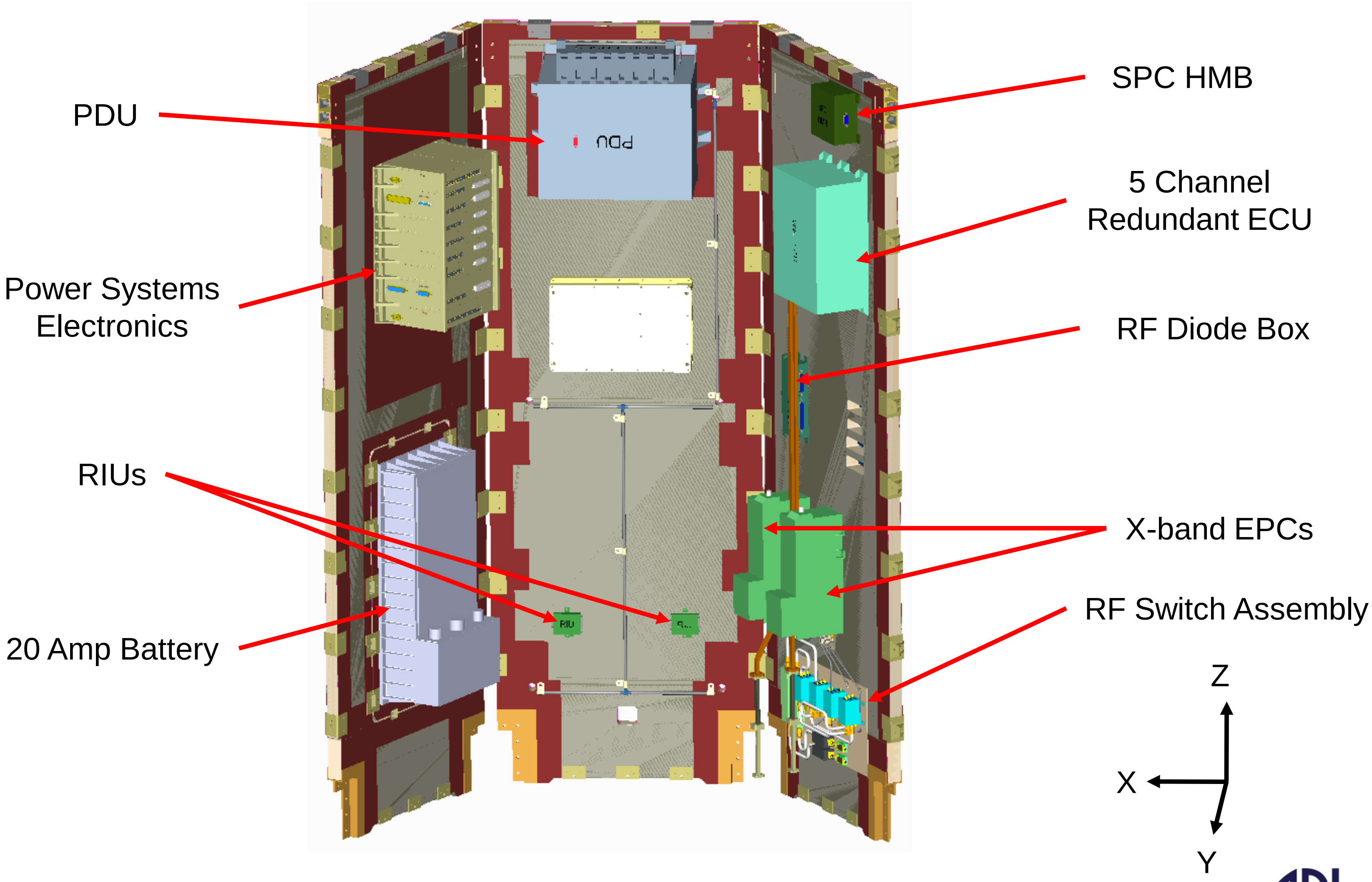
Component Accommodations Bottom Deck - Inside



Component Accommodations
+Y Inside



Component Accommodations -Y Inside



PDU

Power Systems Electronics

RIUs

20 Amp Battery

SPC HMB

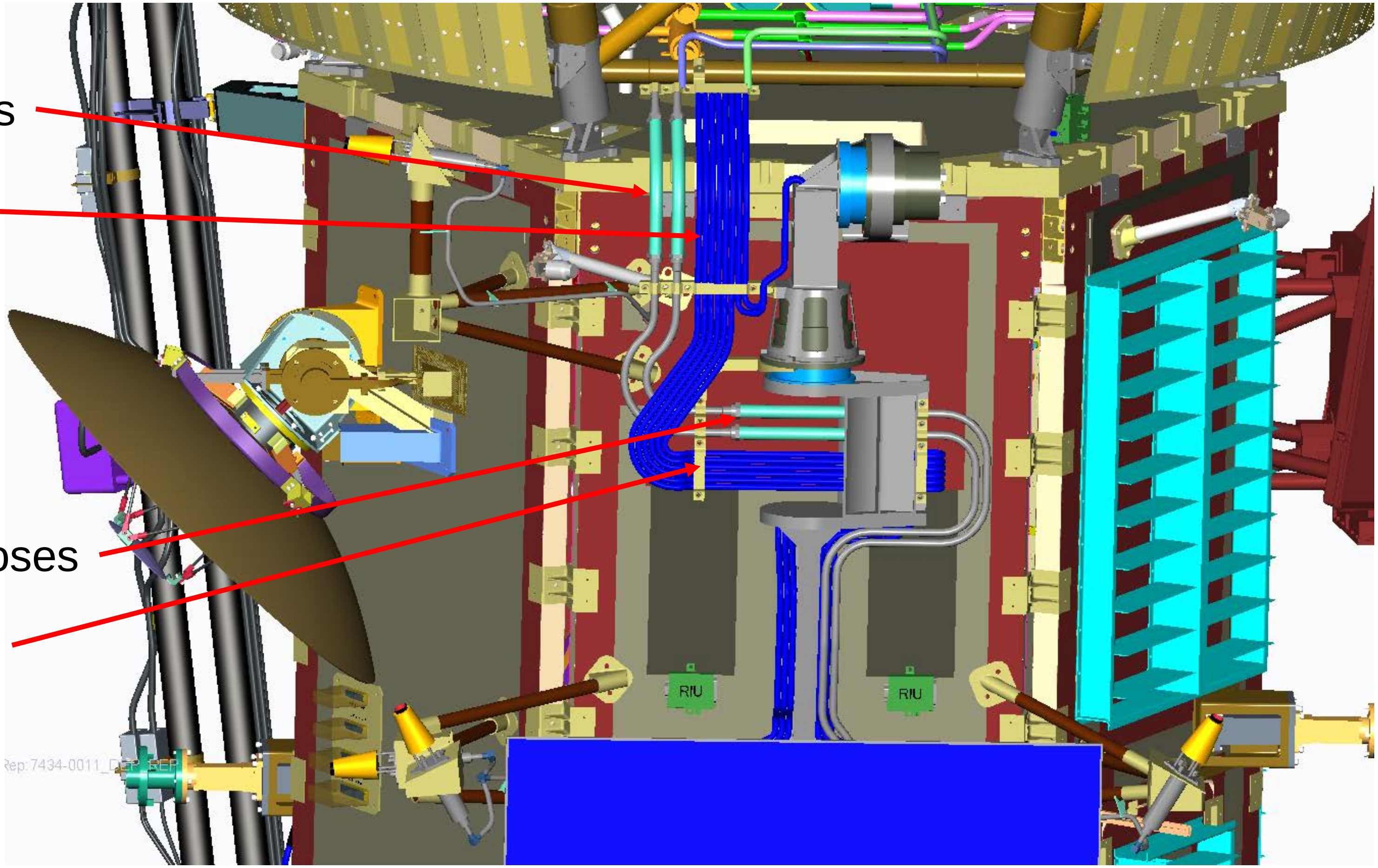
5 Channel Redundant ECU

RF Diode Box

X-band EPCs

RF Switch Assembly

Solar Arrays



Flap cooling hoses

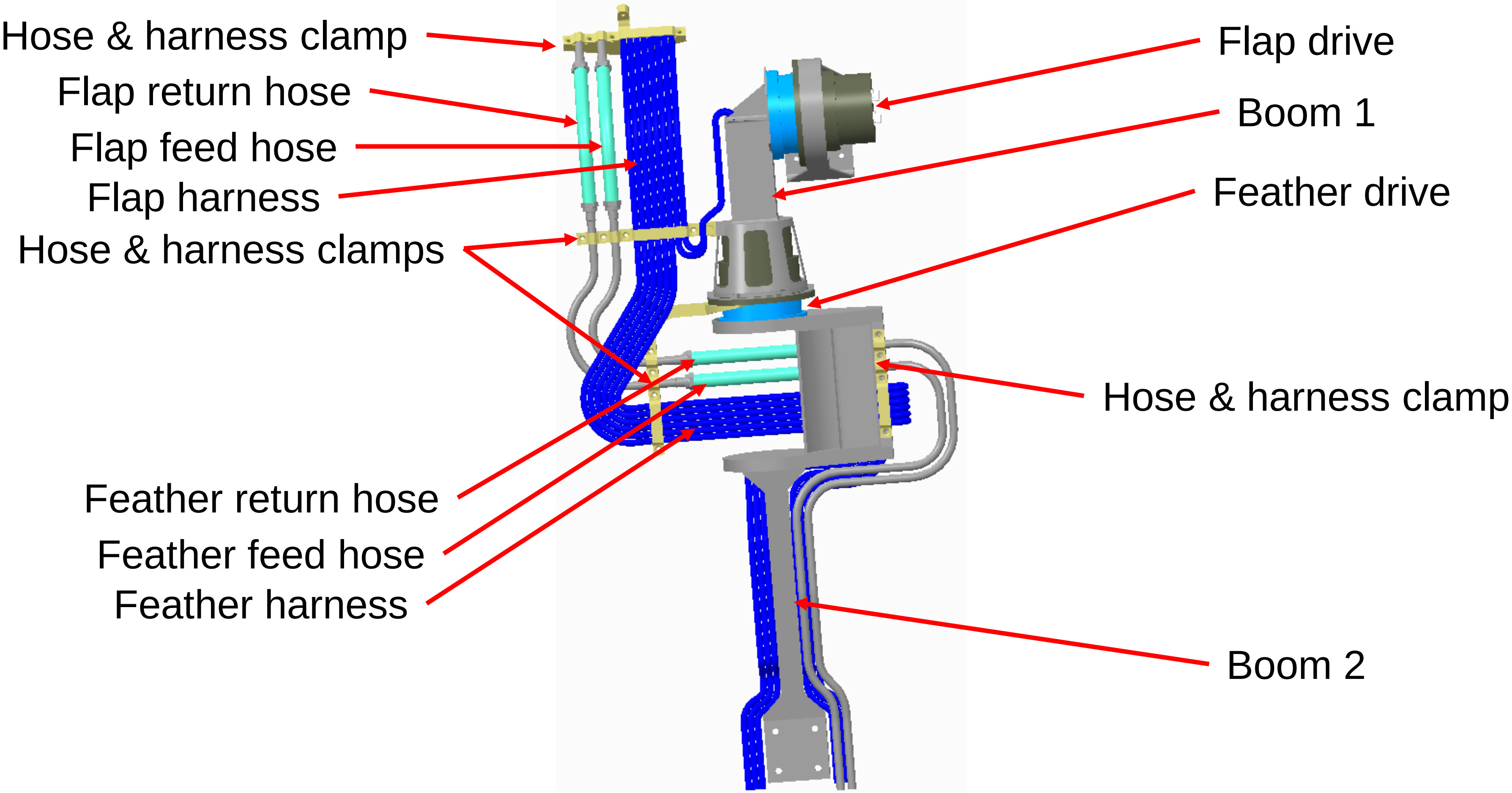
Flap harness

Feather cooling hoses

Feather harness

Flexible cooling lines and gimbal harness accommodations

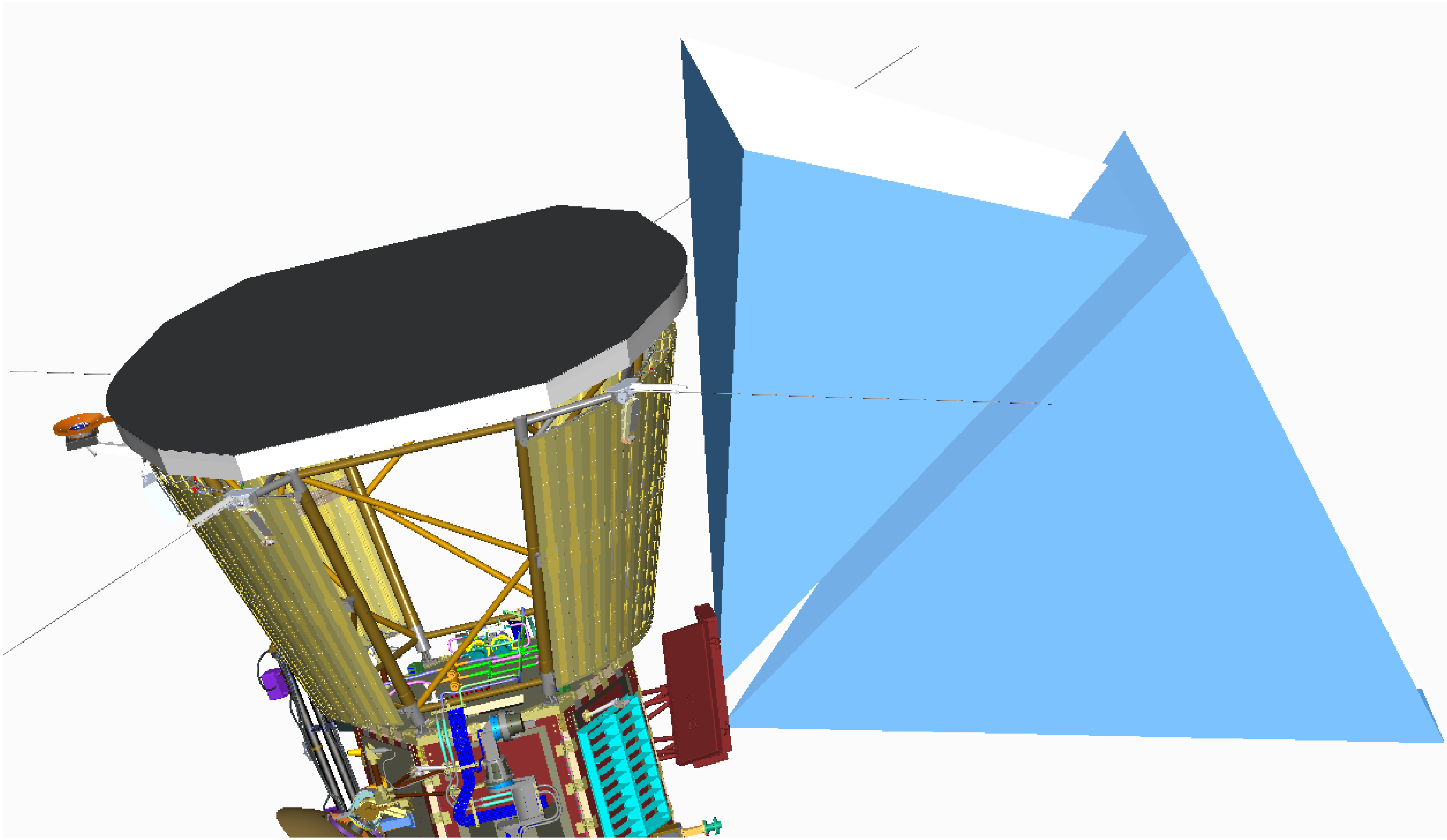
Solar Arrays



Gimbal details

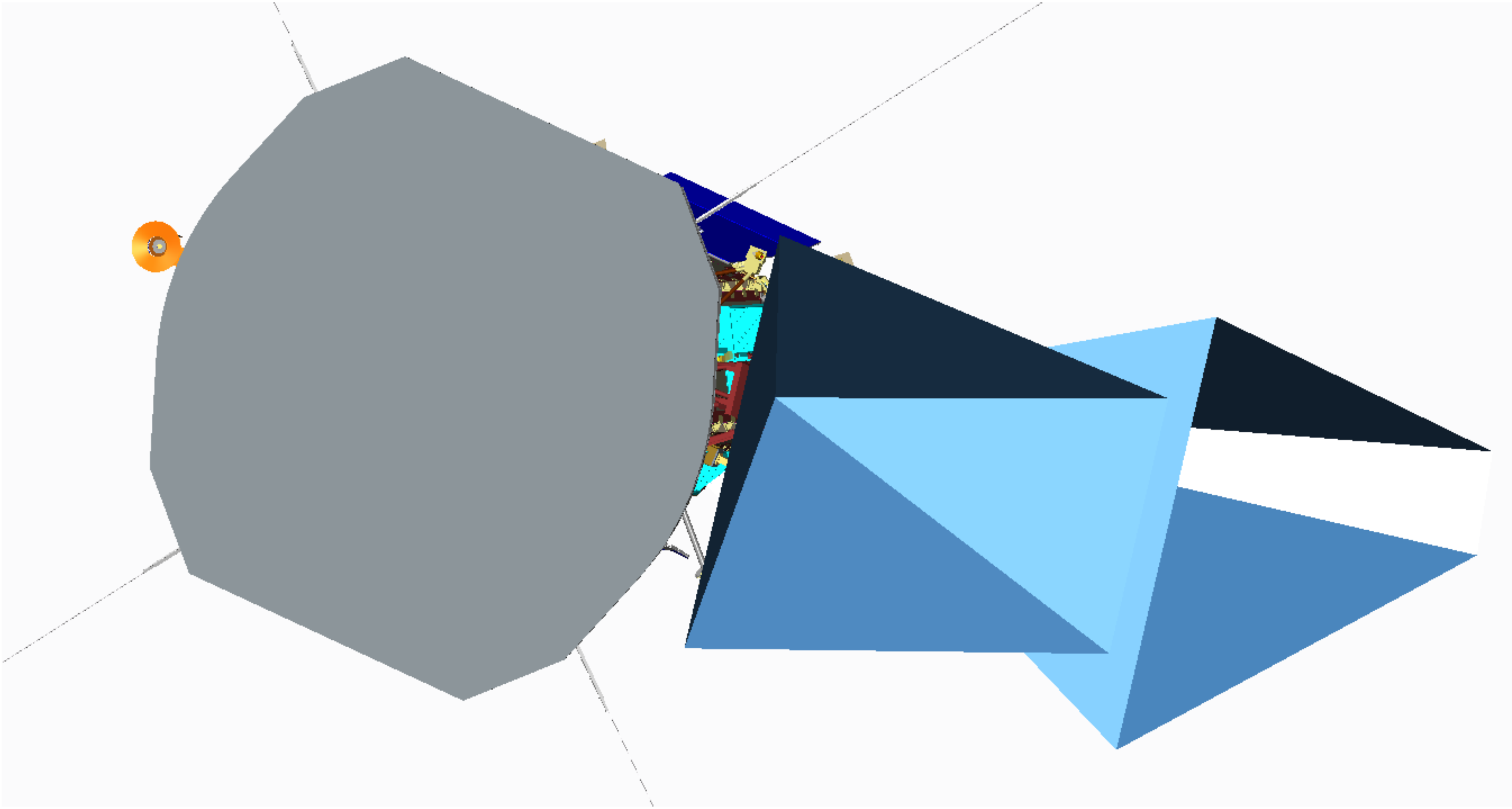
Instrument Accommodations

WISPR FOV



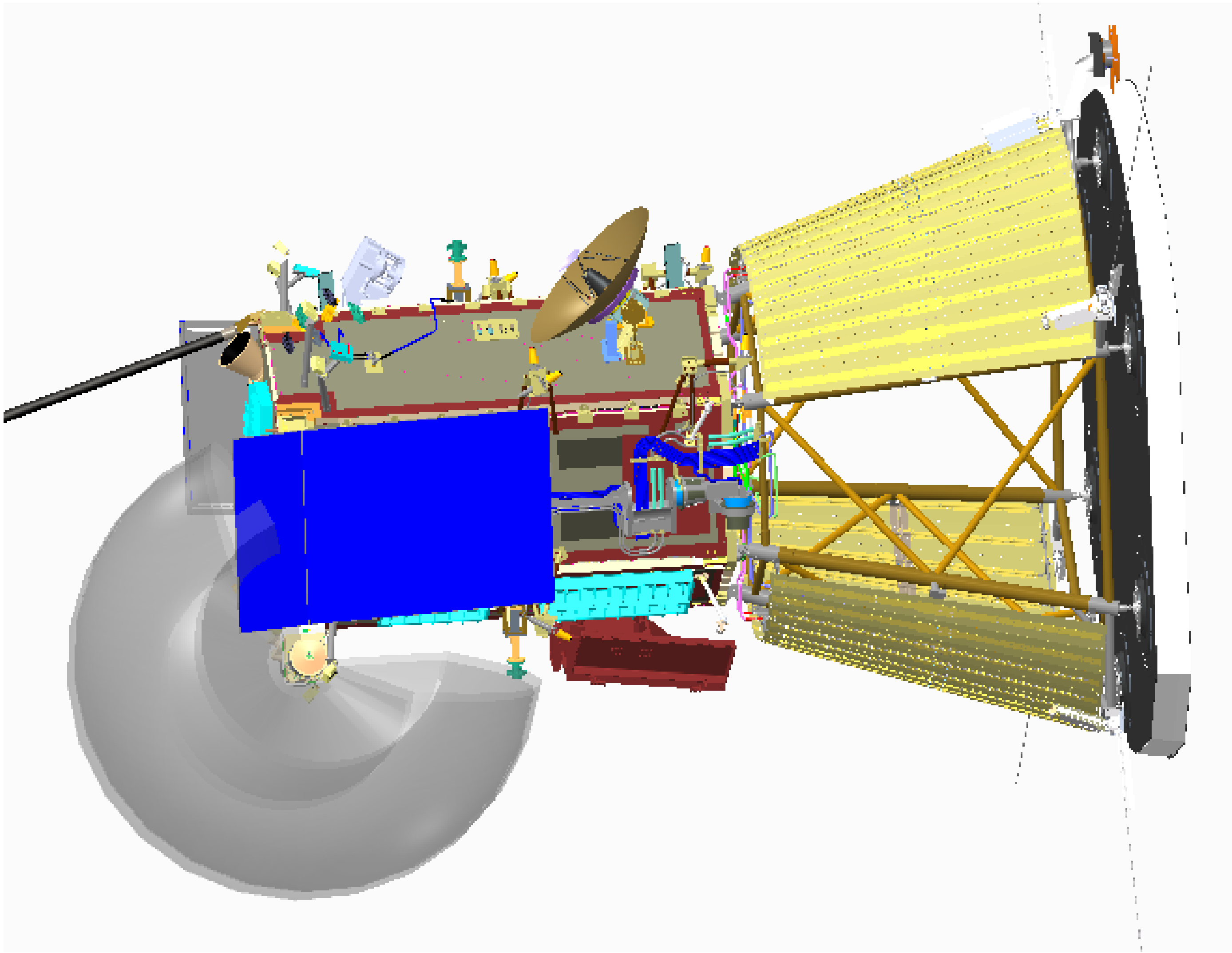
Instrument Accommodations

WISPR FOV



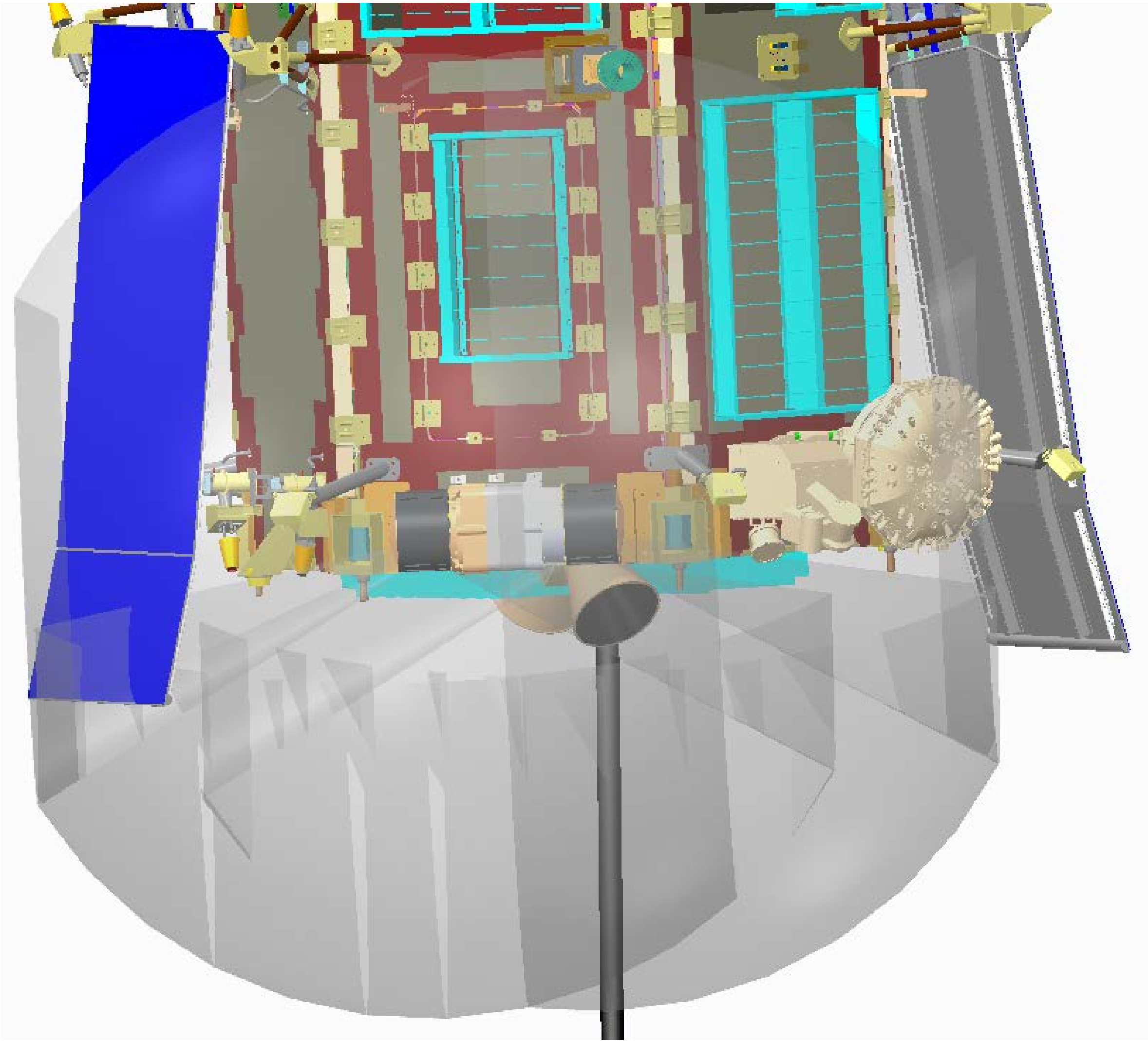
Instrument Accommodations

SWEAP SPAN A+ FOV



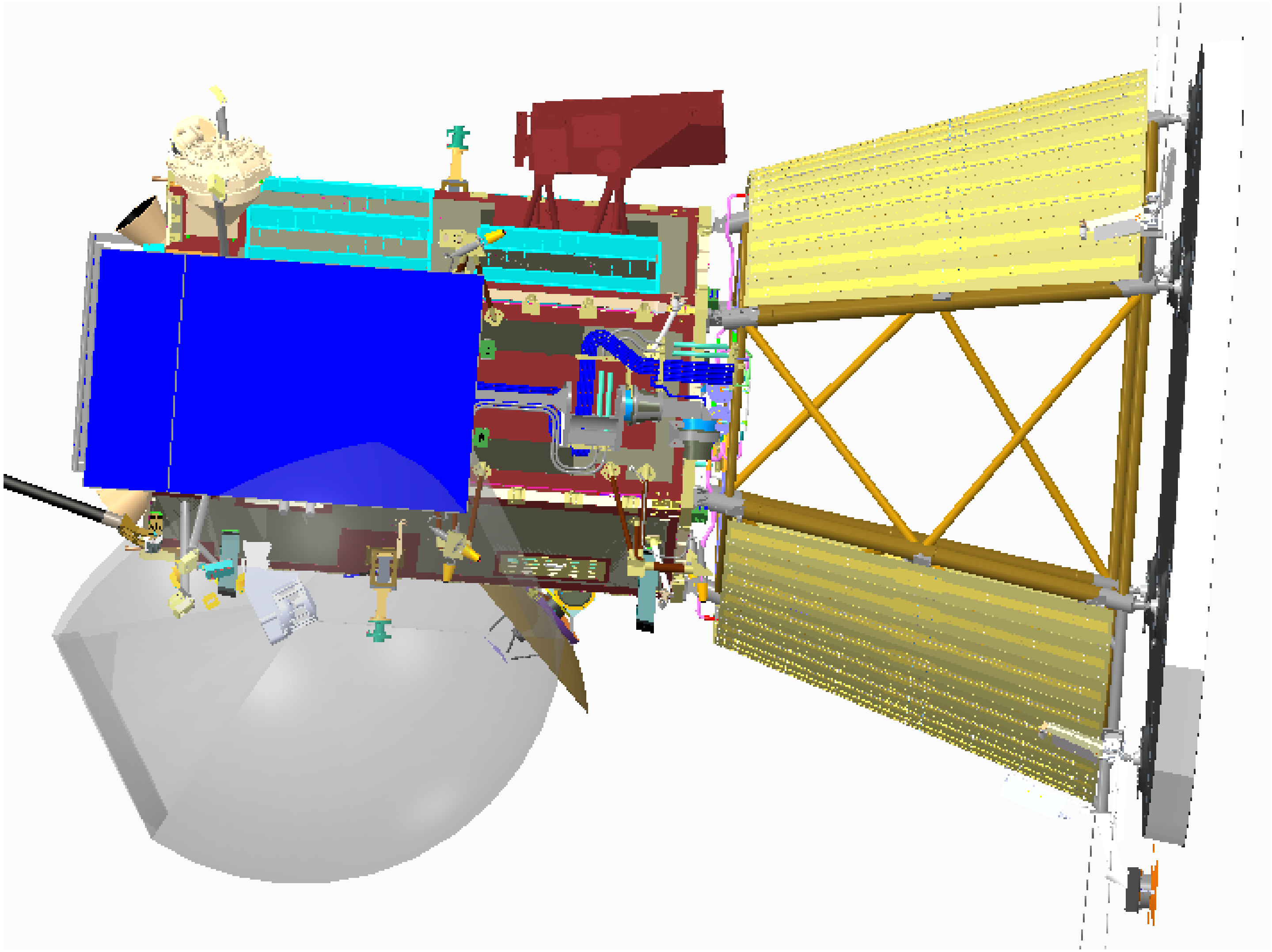
Instrument Accommodations

SWEAP SPAN-A+ FOV



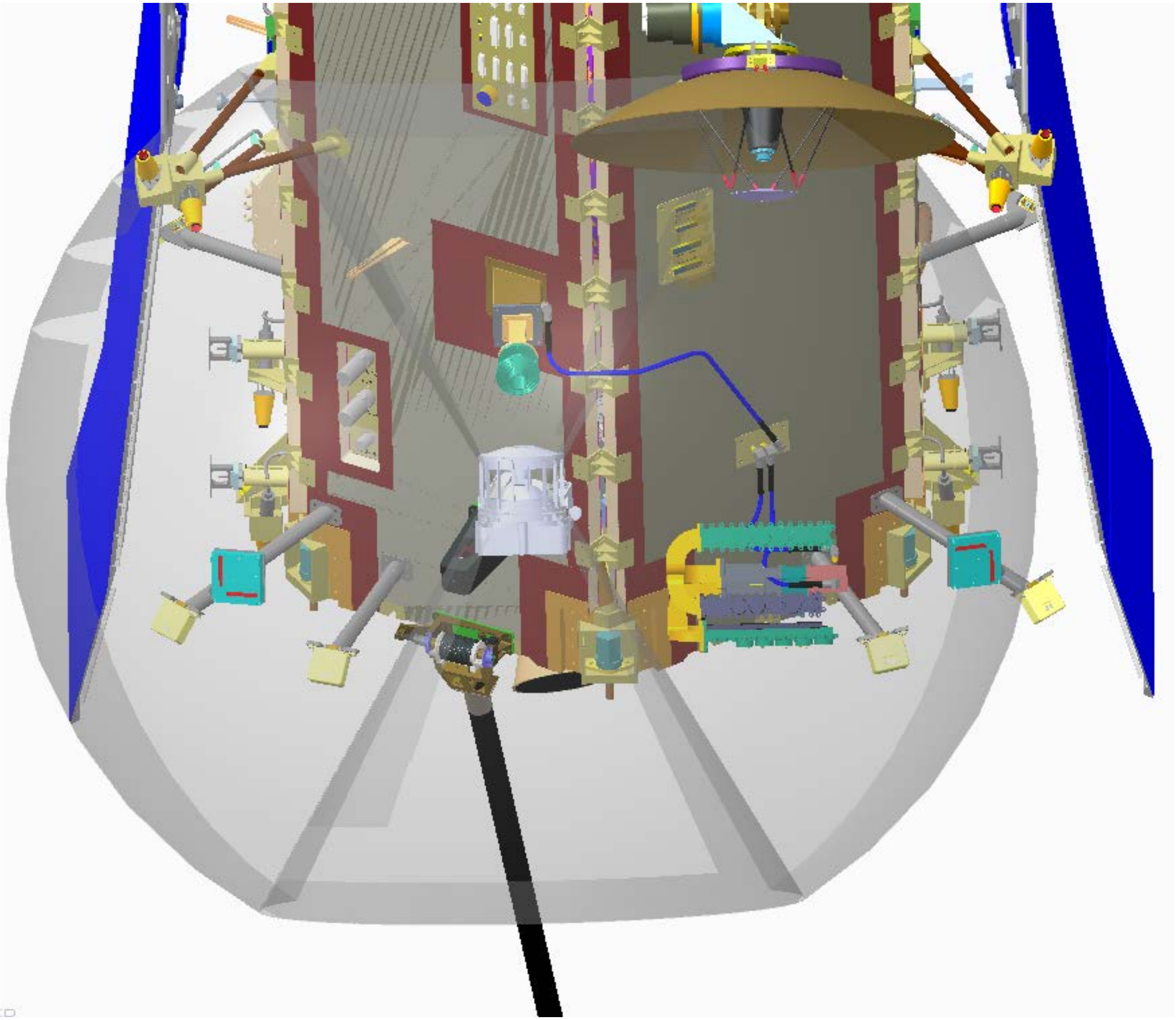
Instrument Accommodations

SWEAP SPAN-B FOV



Instrument Accommodations

SWEAP SPAN-B FOV

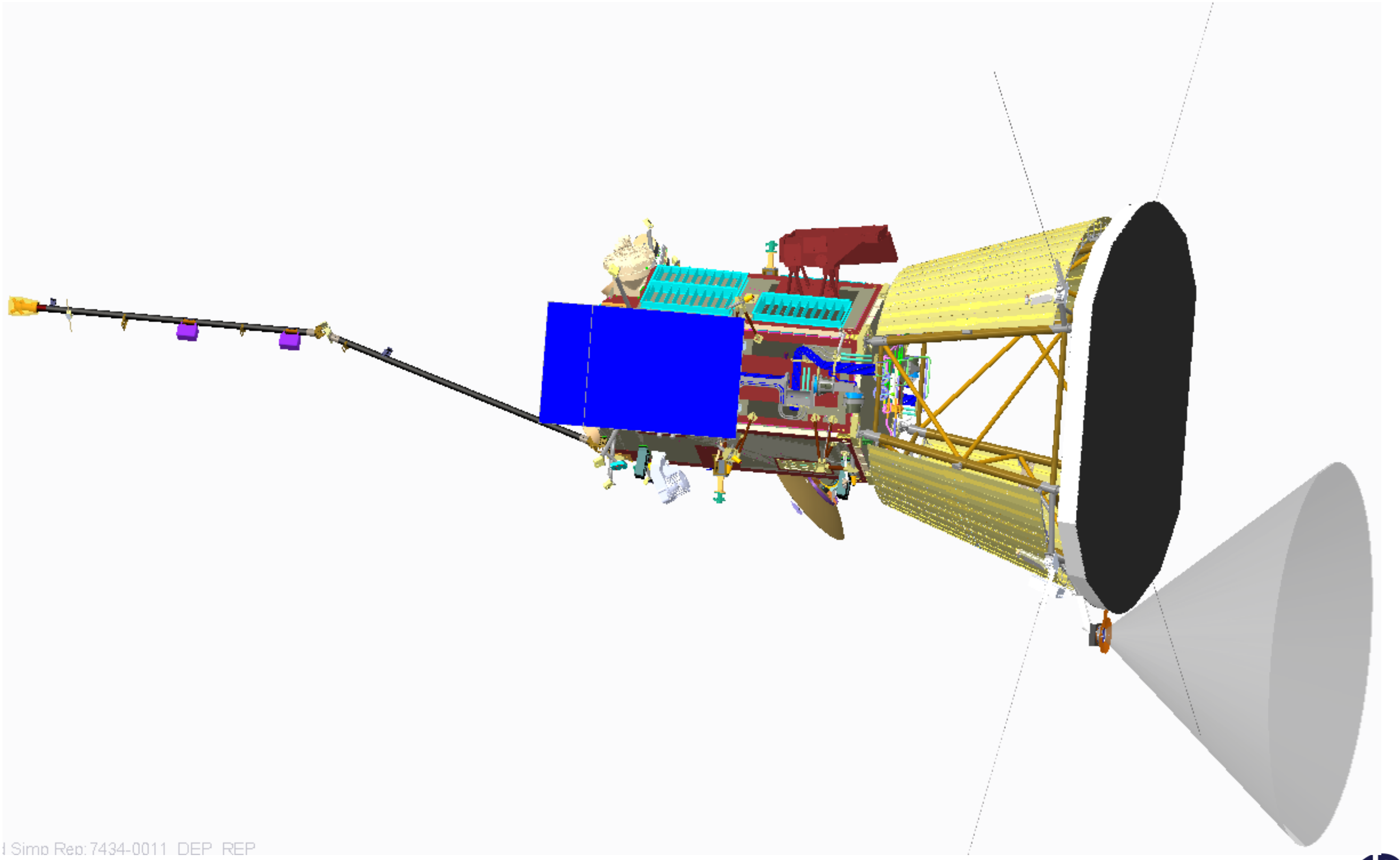


Instrument Accommodations

SWEAP SPC FOV

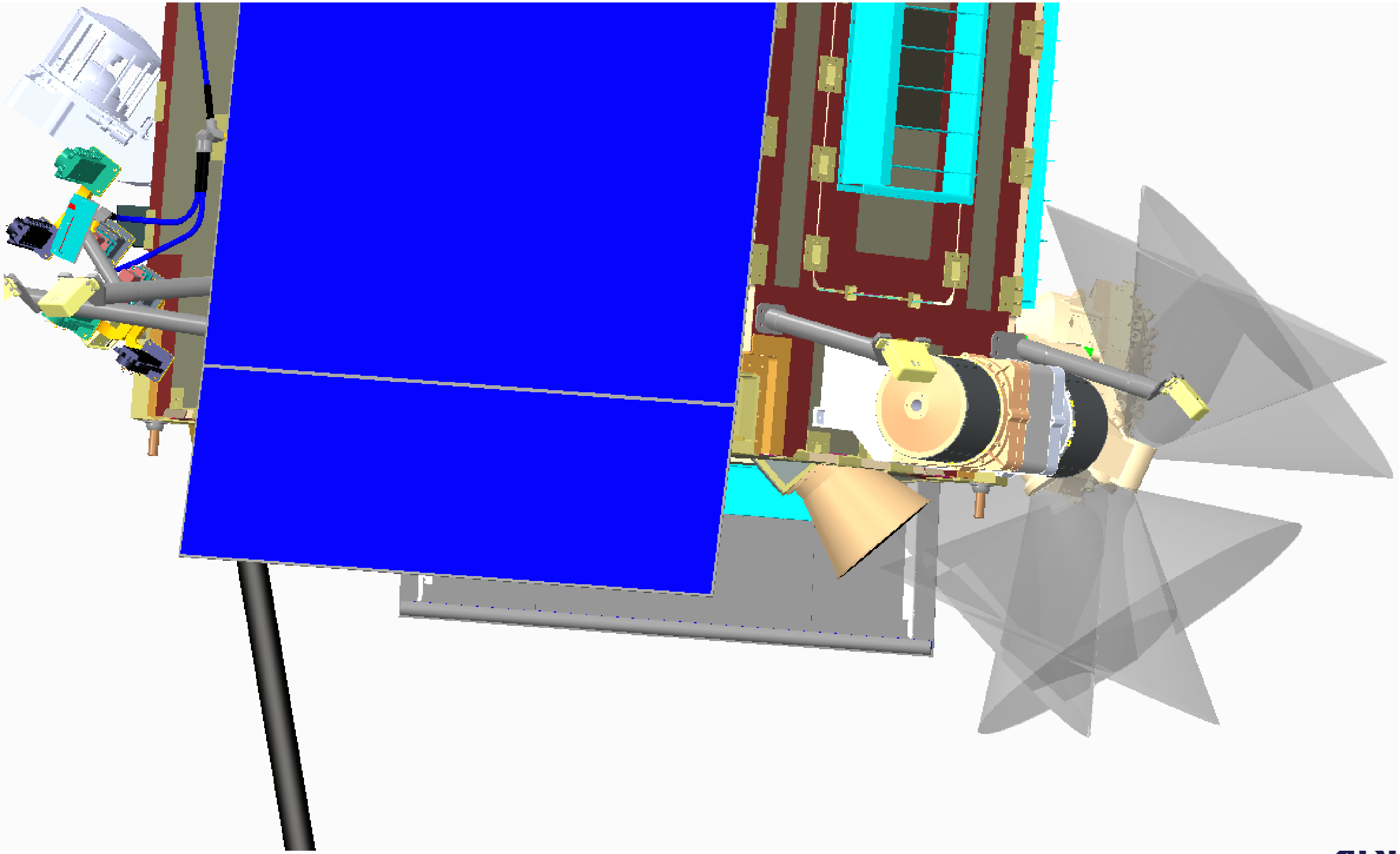
Solar Probe Plus

A NASA Mission to Touch the Sun



Instrument Accommodations

ISIS EPI-Hi FOV



Instrument Accommodations

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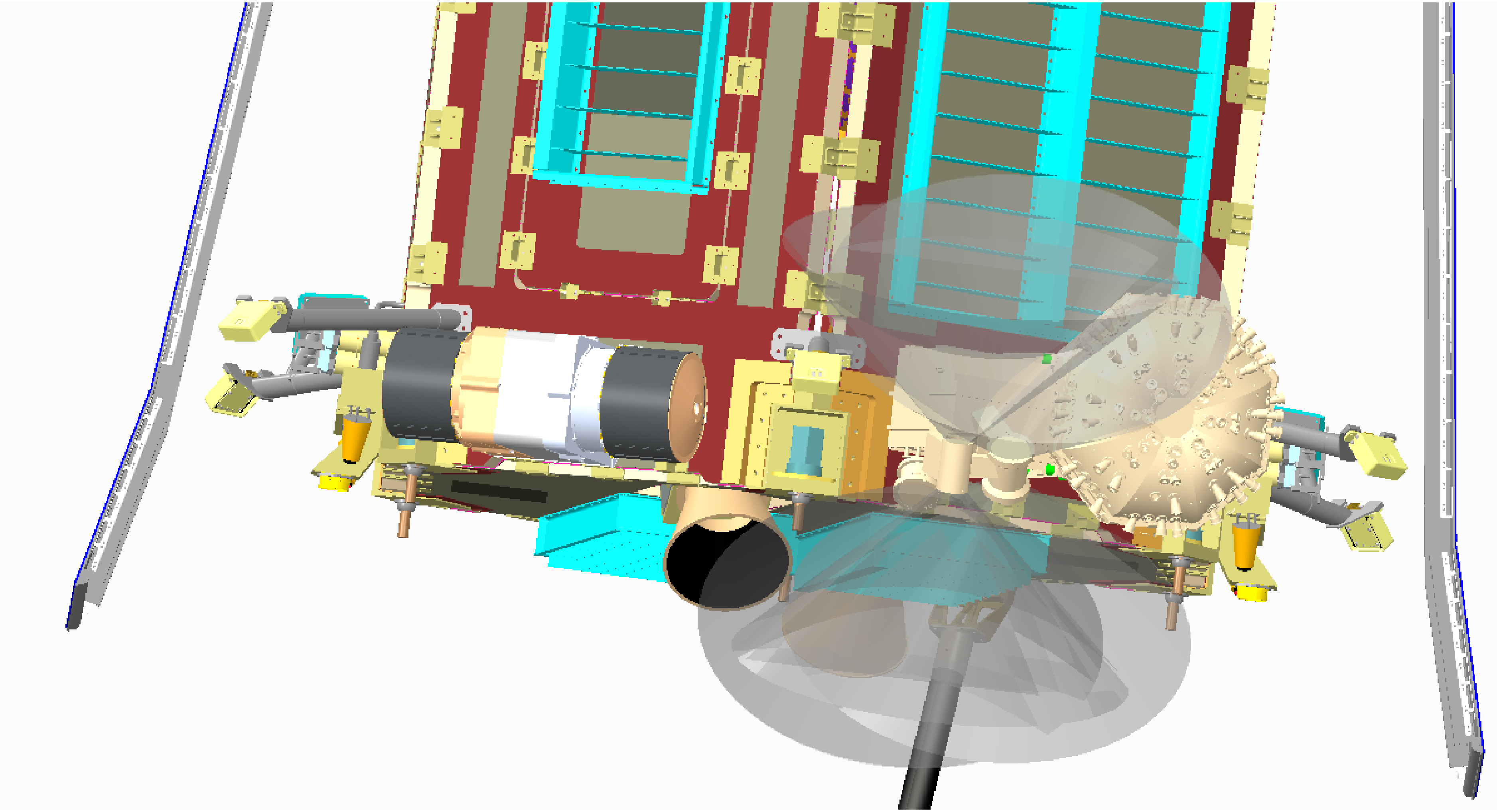
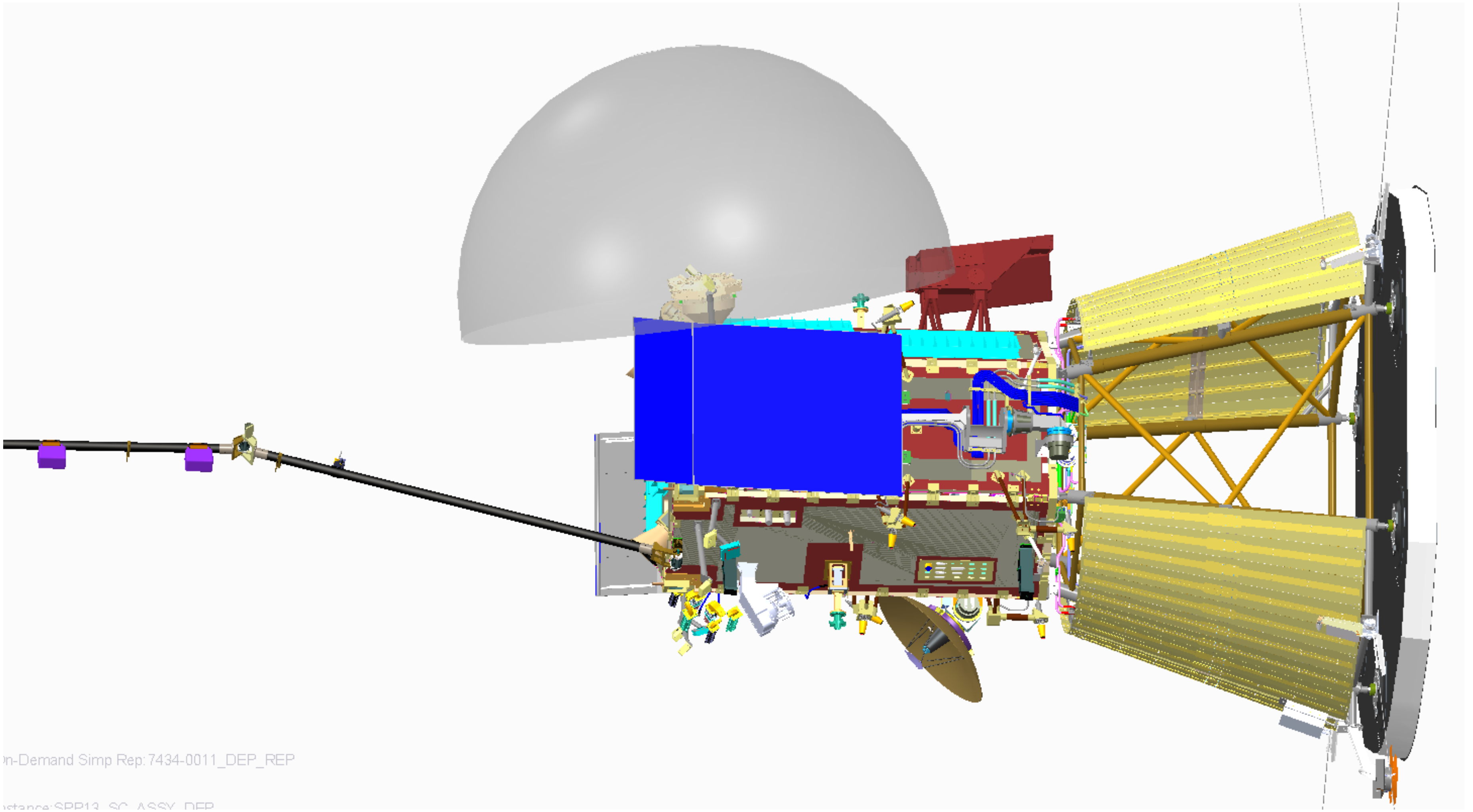


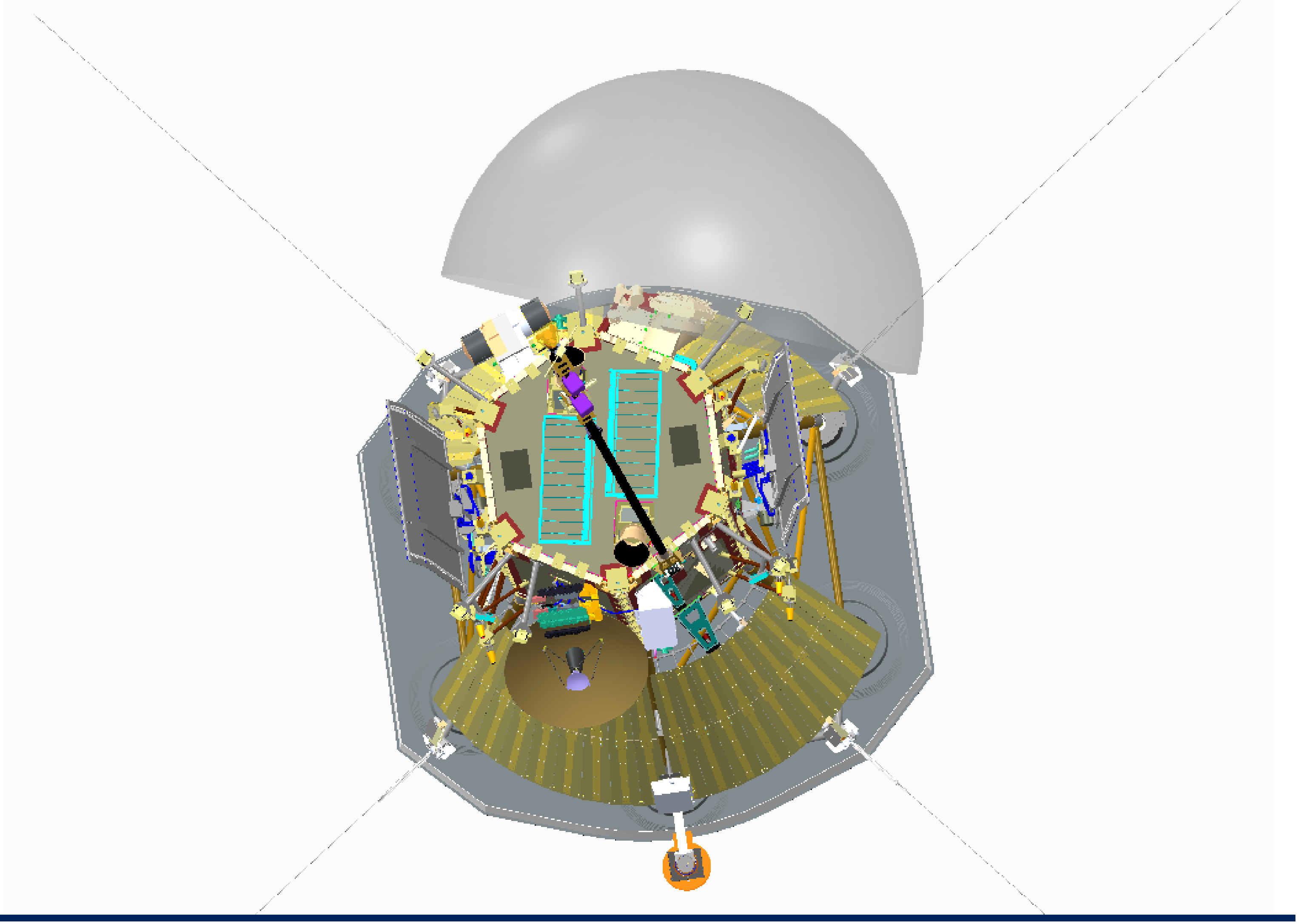
Instrument Accommodations

ISIS EPI-Lo FOV

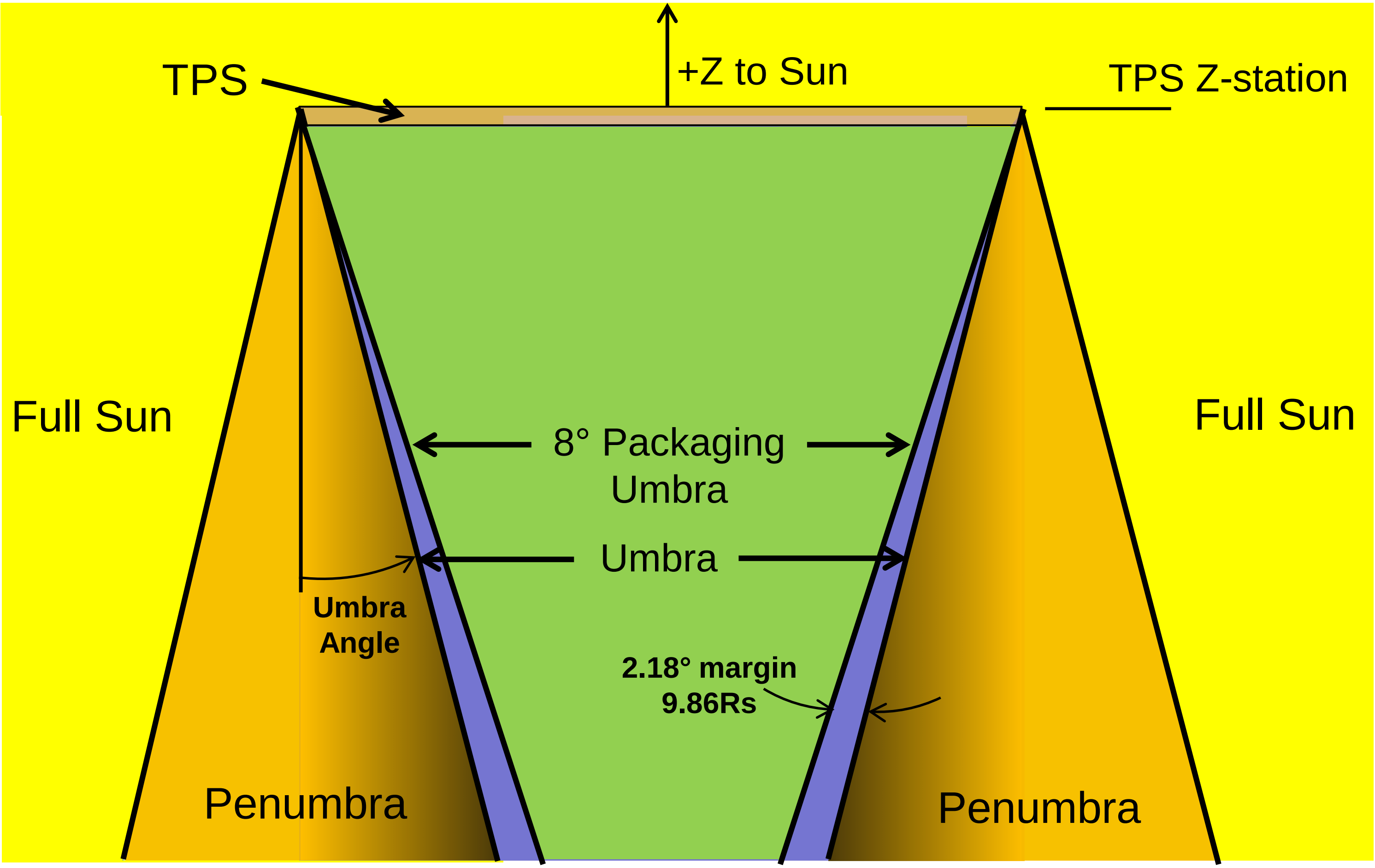


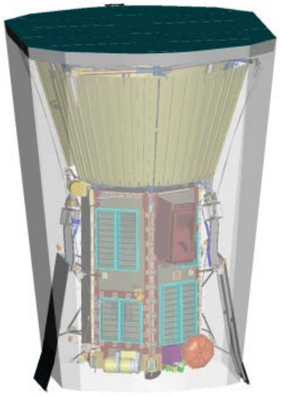
Instrument Accommodations

ISIS EPI-Lo FOV

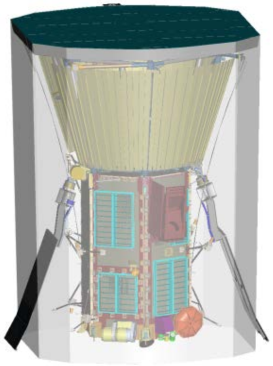


Umbra, penumbra





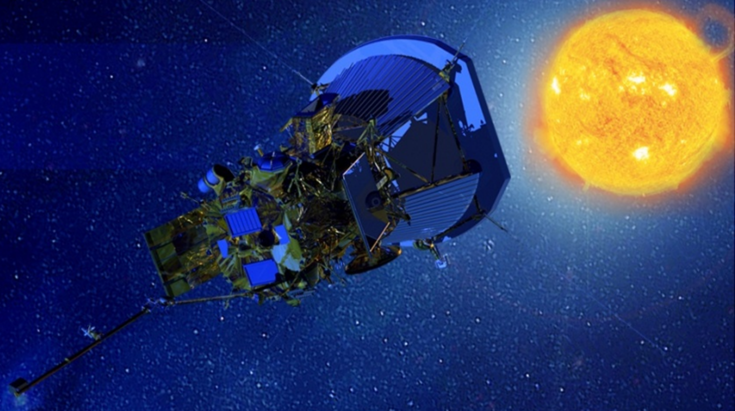
9.86Rs



0.25AU

Solar Probe Plus

A NASA Mission to Touch the Sun



Thermal Protection System

Douglas Mehoke/Ted Hartka

douglas.mehoke@jhuapl.edu

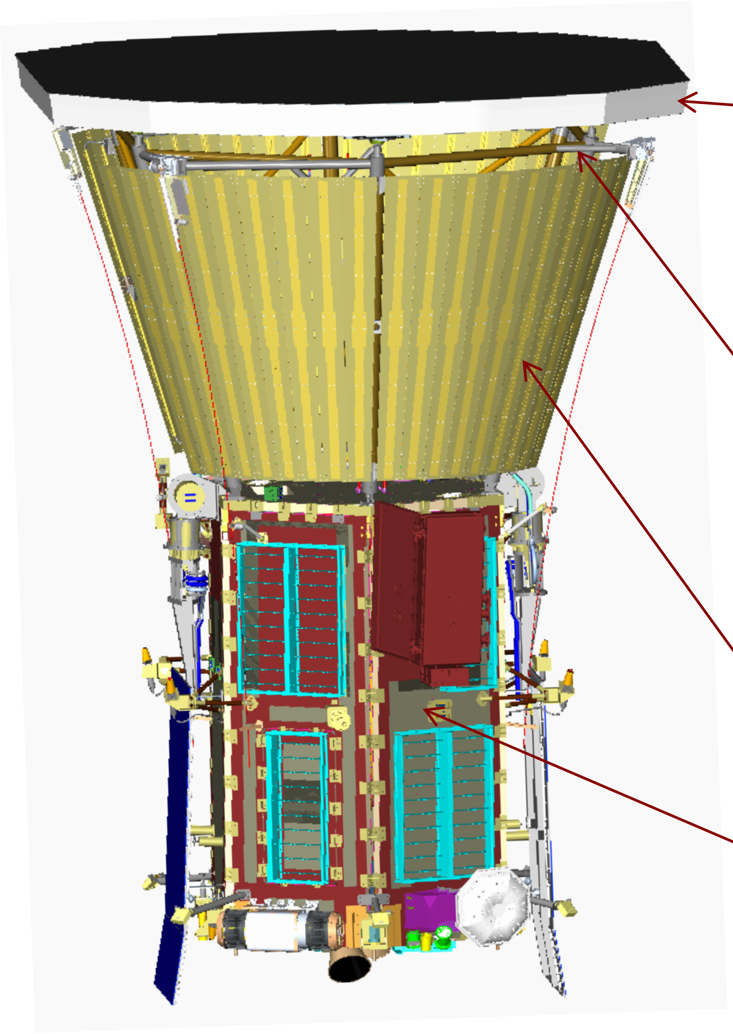
13 – 16 January 2014

APL
The Johns Hopkins University
APPLIED PHYSICS LABORATORY

Overview

- TPS / TSA Orientation and PDR Status
- Requirements flow down and driving subsystem requirements
- Configuration
- Documentation
- System requirement changes and trades
- Phase A Actions and PDR Peer Review
- TRL-6 Demonstration
    - Thermal Prototype
        - TPS/TSA Thermal Balance Test
        - JSC Test
    - Mechanical Prototype
        - TSA Static Load Test
        - TPS/TSA Acoustics Test
        - TPS/TSA Vibration Test
        - TPS/TSA Static Load Test

TPS / TSA Orientation



TPS (Thermal Protection System)

- **C-C facesheets / Carbon foam sandwich construction**
- **Technology developmental item**

TSA (Truss Structure Assembly)

- **Welded Titanium truss**
- **Interfaces to S/C, TPS, CSPR, SPC, and FIELDS antennas**
- **Not a technology developmental item**

Cooling System Radiators

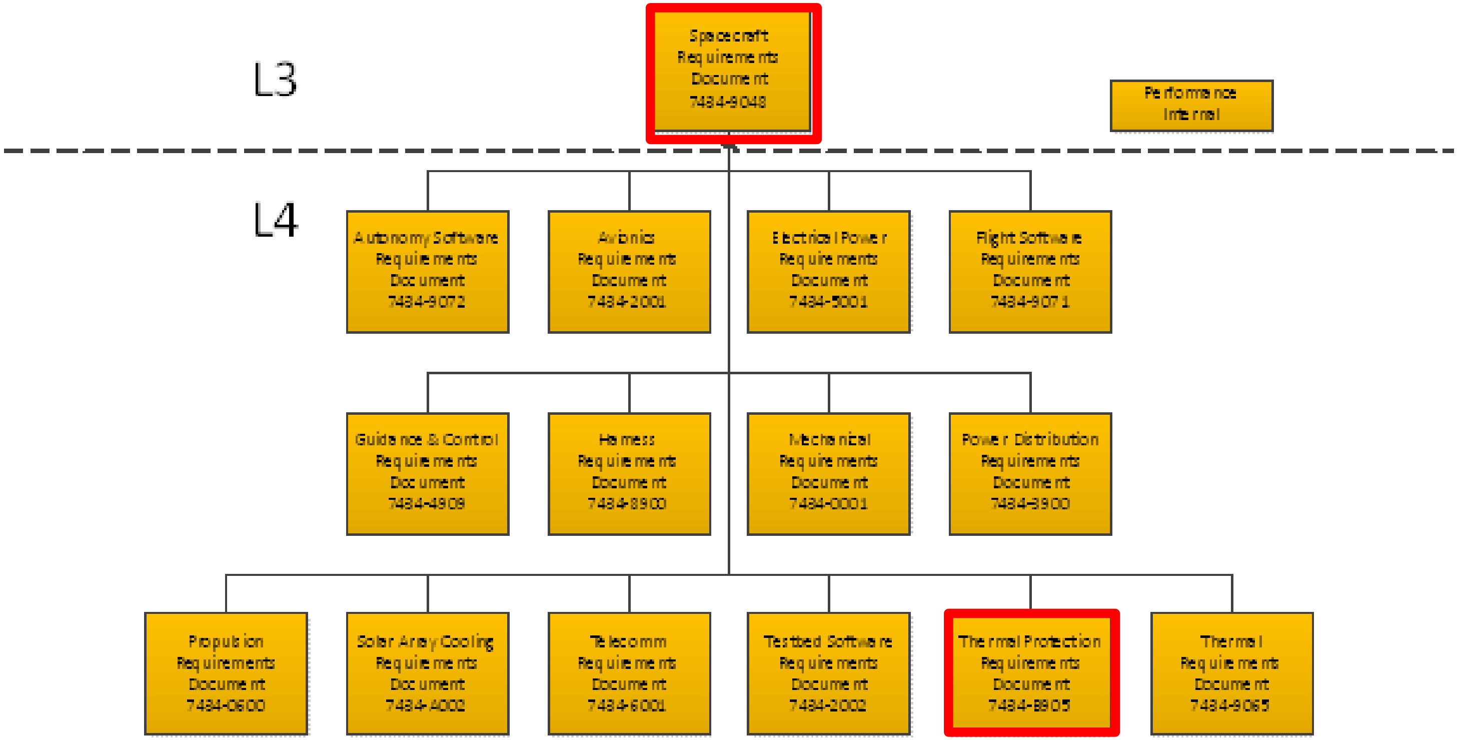
S/C Bus

TPS PDR Status

- The TPS requirements and interfaces have are defined, and the design has been verified by analysis, analog testing, and full-scale testing
- Phase B risks have been mitigated
- Subsystem and system level analyses have been completed and results presented at PDR and peer reviews
- Manufacturing drawings, process plans, and test specifications have been generated for all planned operations and tests
- The technology has been demonstrated by prototype testing at full-scale (Mechanical Unit) and sub-scale (Thermal Unit) testing

Requirements Flow Down

- **TPS level 4 requirements are flown down from S/C and mission requirements**
- **7434-B905, TPS Requirement Document (in DOORS)**
- **All fabrication drawings, work orders, and test specifications are in place**

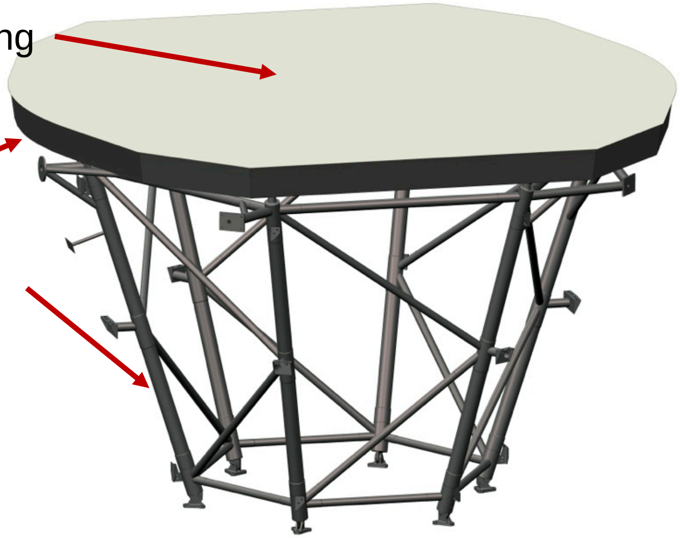


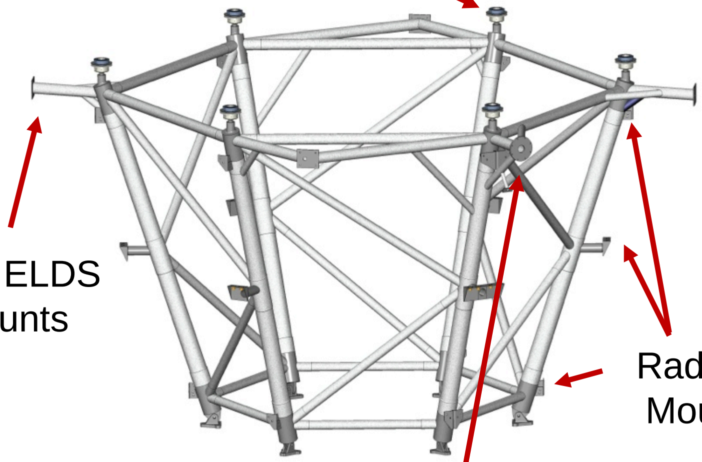
Driving Subsystem Requirements

- Thermal
    - S/C heat Flow:
        - TPS/TSA < 10 (TBR) W radiation and conduction hot case
        - TPS/TSA < -10 (TBR) W conduction cold case
    - CSPR heat flow: < 200 (TBR) W radiation and conduction hot case
- Structural
    - TPS/TSA: Survive launch and on orbit environments
- Mechanical
    - Mass: TPS < 85.18 kg (NTE), TSA < 33.53 (NTE)
    - TPS Plan shape: nominal packaging umbra that shields the S/C bus
    - TPS knife edge: provide shadow line for solar panels
    - TPS Cp: provide capability for Cp adjustment
    - TSA: provide mounting location for SPC and FIELDS antennas
    - 1st light baffle for WISPR and Solar Limb Sensor

Configuration Overview

- **TPS**
  - **Coating:**
    - **Alumina, MgO, BN coating mixture; W barrier layer**
  - **6 ply C-C facesheets, additional plys in mounting regions**
  - **4.5” carbon foam core**
- **TSA**
  - **Welded, thin wall, Ti tubes**



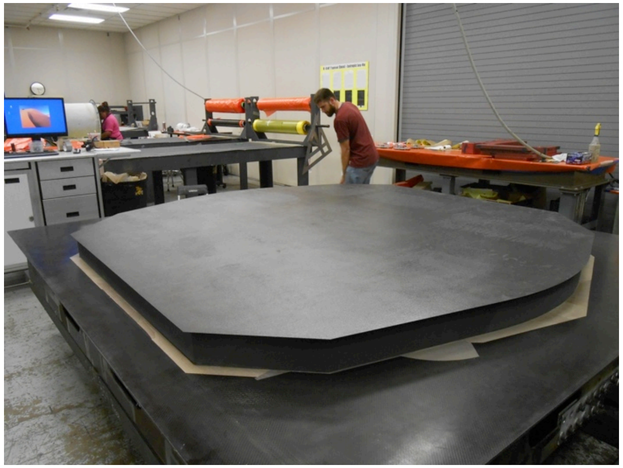


TPS Assembly

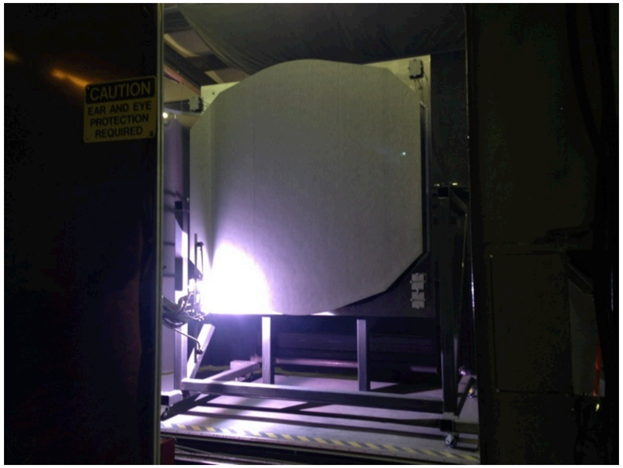
Bottom facesheet

Foam core

Top facesheet



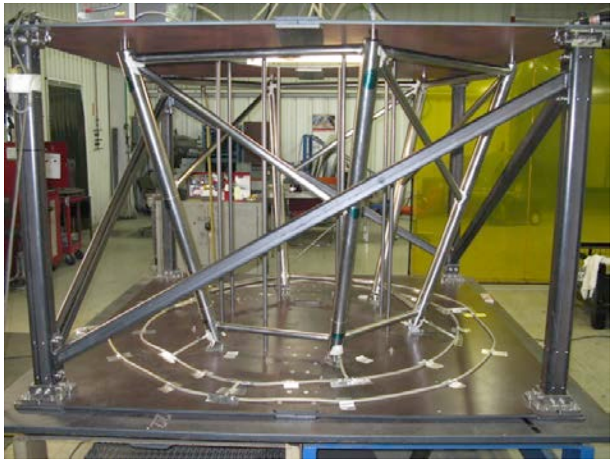
Complete Assembly

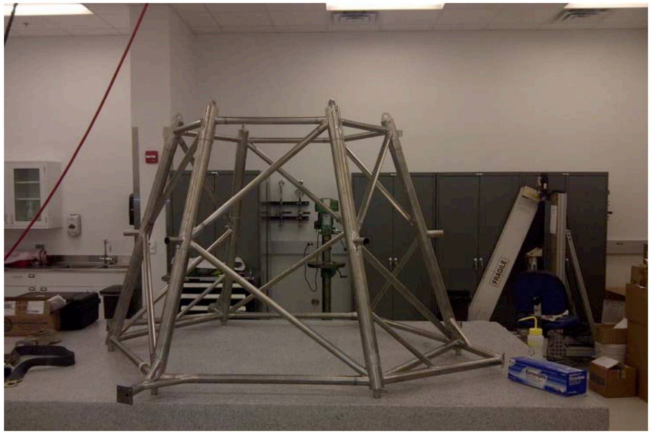


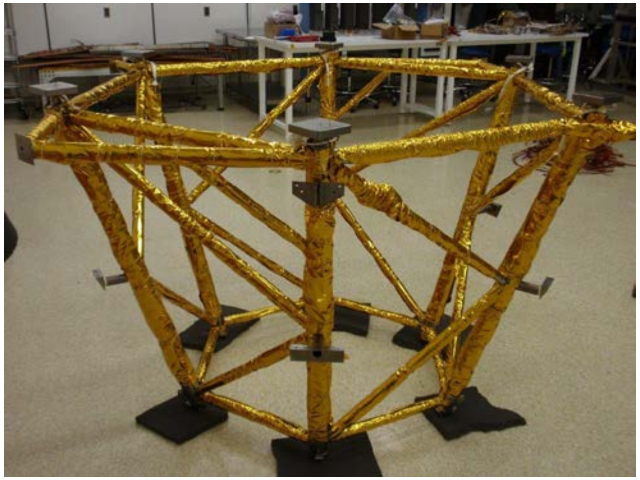
Plasma Spraying

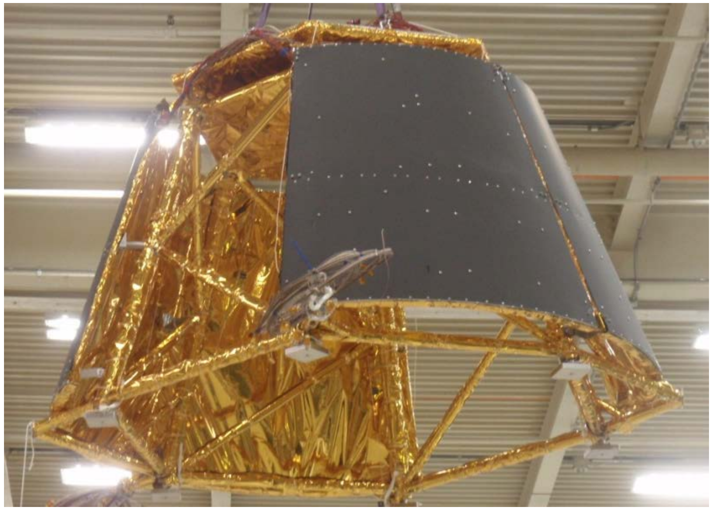
Final Assembly at APL

TSA Assembly


TSA in Welding Fixture


TSA at APL


TSA with MLI Blankets


TSA with radiator sim panels

Requirement Documents and Specifications

Requirement Documents

7434-9062	Thermal Protection Requirements Document (In DOORS)
7434-9095-14	SPP Truss Structure Assembly (TSA) PAIP Matrix
7434-9095-09	SPP Thermal Protection System (TPS) Product Assurance Implementation Plan (PAIP)

Configuration Documents

7434-B911	Qualification Unit Mechanical Prototype Fabrication Statement of Work

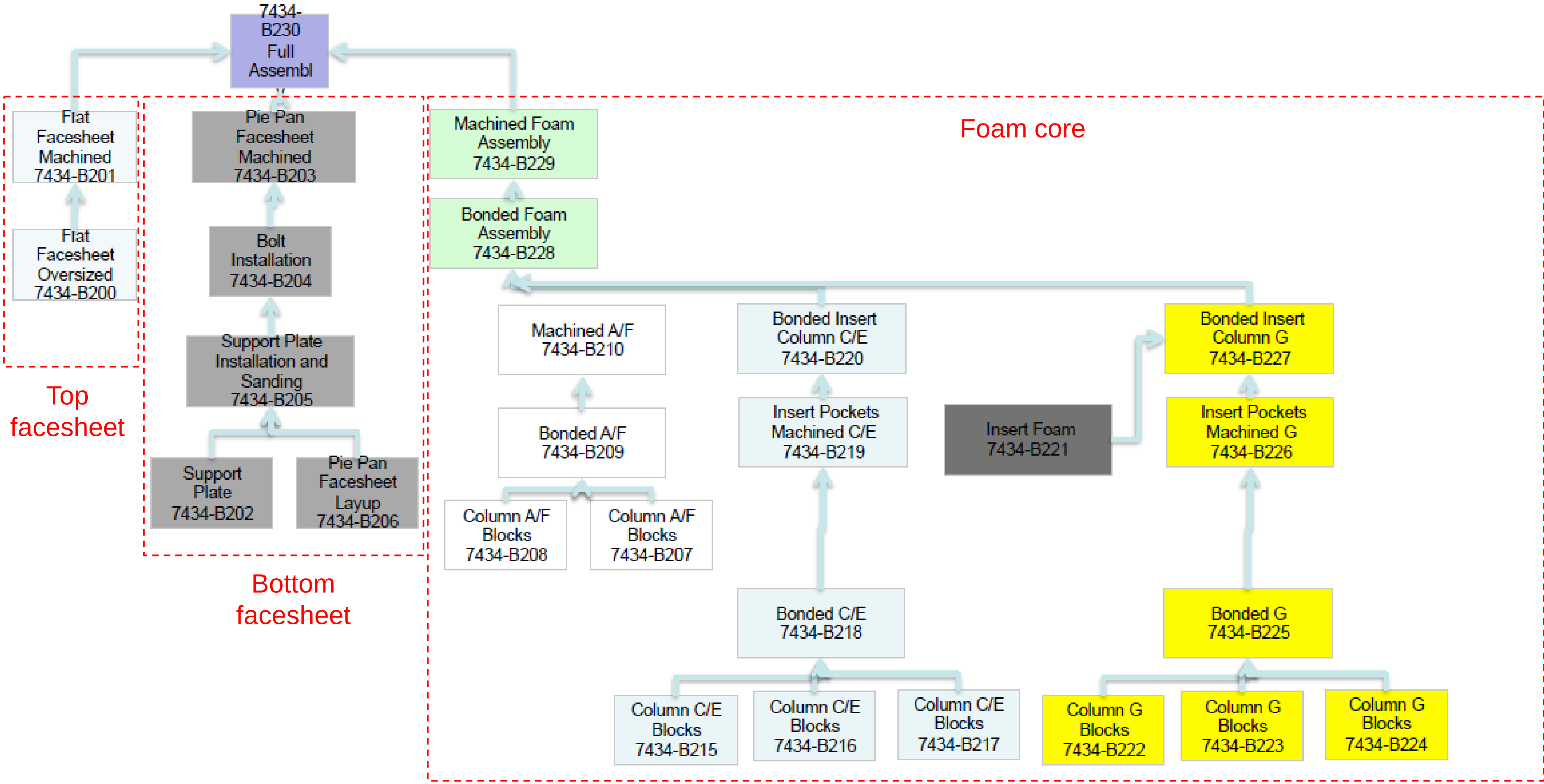
Testing Documents

7434-B903	GSFC Mechanical Operations Procedure, TRL-6 Thermal Balance Test
7434-B904	GSFC Thermal Balance Test Plan
7434-B907	TSA TRL 6 Static Load Test Plan
7434-B920	GSFC Mechanical Operations Procedure Solar Probe Plus, TRL-6 Acoustic Test
7434-B908	TPS TRL 6 Acoustic Test Plan
7434-B909	TPS TRL 6 Vibration Test Plan

Coating Documents

7434-B912	SPP Thermal Protection System (TPS) Plasma Spray Coating SOW
7434-B917	Procedure for Applications of Plasma Spray Coatings to SPP Thermal Protection System
7434-B910	SOW for Radiation Exposure Studies for the Optically White Coatings of the SPP TPS

TPS Drawing Tree



Requirement Changes and Trades

Key requirement changes

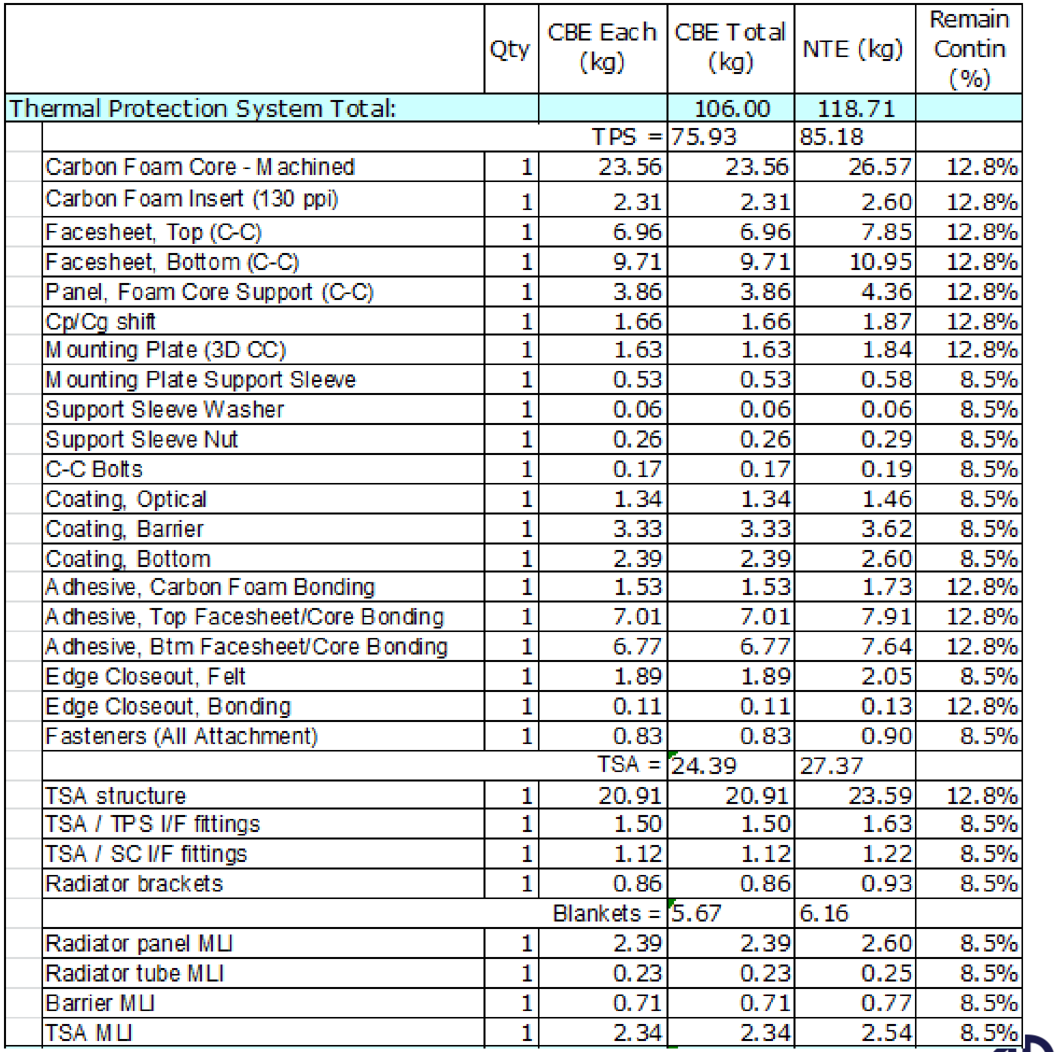
- Change in perihelion from 9.5 Rs to 9.86 Rs
- Elimination of late stage Cp adjustment
- Radiator size increase from 4 m^2 to 4.4 m^2
- Reduction in TPS/TSA frequency design requirement from 21 Hz to 18 Hz

TPS / TSA Trades

- TPS Configuration Trades
  - Option A (baseline – presented here)
  - Option A'
  - Option B
- TSA fabrication approach
- Design Trades
  - Flatness of Top of TPS Assembly
  - Edge Closeout
- Manufacturing Trades
  - Tooling
  - Flatness/Sanding Plies
  - Bondline
  - Insert Foam

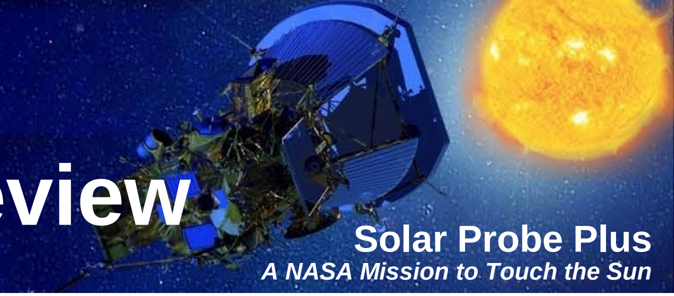
Mass

- **Subsystem CBE masses reflect the as-built measurements of the TRL-6 Mechanical Prototype adjusted for the slightly larger PDR configuration**



	Qty	CBE Each (kg)	CBE Total (kg)	NTE (kg)	Remain Contin (%)
Thermal Protection System Total:			106.00	118.71	
		TPS =	75.93	85.18	
Carbon Foam Core - Machined	1	23.56	23.56	26.57	12.8%
Carbon Foam Insert (130 ppi)	1	2.31	2.31	2.60	12.8%
Facesheet, Top (C-C)	1	6.96	6.96	7.85	12.8%
Facesheet, Bottom (C-C)	1	9.71	9.71	10.95	12.8%
Panel, Foam Core Support (C-C)	1	3.86	3.86	4.36	12.8%
Cp/Cg shift	1	1.66	1.66	1.87	12.8%
Mounting Plate (3D CC)	1	1.63	1.63	1.84	12.8%
Mounting Plate Support Sleeve	1	0.53	0.53	0.58	8.5%
Support Sleeve Washer	1	0.06	0.06	0.06	8.5%
Support Sleeve Nut	1	0.26	0.26	0.29	8.5%
C-C Bolts	1	0.17	0.17	0.19	8.5%
Coating, Optical	1	1.34	1.34	1.46	8.5%
Coating, Barrier	1	3.33	3.33	3.62	8.5%
Coating, Bottom	1	2.39	2.39	2.60	8.5%
Adhesive, Carbon Foam Bonding	1	1.53	1.53	1.73	12.8%
Adhesive, Top Facesheet/Core Bonding	1	7.01	7.01	7.91	12.8%
Adhesive, Btm Facesheet/Core Bonding	1	6.77	6.77	7.64	12.8%
Edge Closeout, Felt	1	1.89	1.89	2.05	8.5%
Edge Closeout, Bonding	1	0.11	0.11	0.13	12.8%
Fasteners (All Attachment)	1	0.83	0.83	0.90	8.5%
		TSA =	24.39	27.37	
TSA structure	1	20.91	20.91	23.59	12.8%
TSA / TPS I/F fittings	1	1.50	1.50	1.63	8.5%
TSA / SC I/F fittings	1	1.12	1.12	1.22	8.5%
Radiator brackets	1	0.86	0.86	0.93	8.5%
		Blankets =	5.67	6.16	
Radiator panel MLI	1	2.39	2.39	2.60	8.5%
Radiator tube MLI	1	0.23	0.23	0.25	8.5%
Barrier MLI	1	0.71	0.71	0.77	8.5%
TSA MLI	1	2.34	2.34	2.54	8.5%

Phase A Actions and Peer Review



- **Phase A actions - All 18 Phase A actions have been formally closed**
- **Phase B Peer Review held Nov 20-21 2013**
  - **Review Committee**

Stuart Hill	APL	Co-chair
Terry Betenbaugh	APL	Co-chair
Mike Marley	APL	Co-chair
Marcel Bluth	ATK	
David Robinson	NASA GSFC	
David Steinfeld	NASA GSFC	SRB
Ted Michalek	ESS	
Kaushik Iyer	APL	
Ken Hinkle	NASA GSFC	SRB
Keith Bowman	AFRL	SRB
Craig Ohlhorst	NASA LaRC	

  - **33 actions, 1 concern, and 14 recommendations generated**
  - **Review Conclusions:**
    - **The team made significant progress since the MDR and has demonstrated that TRL-6 objectives were met**
    - **The review was successful and was well received by the Review Board**

TPS Plan Forward (1 of 2)

- **The Phase C efforts will be aimed at showing that these results can be repeated as we move from the Qual through to the Flight Units**
  - **Repeat the full size and sectional TPS prototypes already built and tested**
  - **Due to the non-standard nature of the materials involved, we will be reporting periodically to the peer review board with analytical and test results**
- **Fabrication: All fabrication steps have been completed on the TRL-6 unit**
  - **Include lessons learned from TRL-6 build to improve the processes**
- **Thermal:**
  - **TPS thermal insulation: JSC testing has shown the thermal performance is repeatable to within about 5%**
    - **Additional test data will be taken that will improve the confidence in the thermal performance**
  - **S/C and CSPR heat flow: Initial test correlation results have been completed that show heat flows are in the acceptable range**
    - **Recommendations for updating the requirement values will be made after the completion of the detailed correlation results**

TPS Plan Forward (2 of 2)

- **Structural: The large variability of material properties limit the ability of the structural analysis to predict the various failure modes of the TPS**
  - **Launch load performance has been verified by full-size structural testing at room temperature**
    - **A Qualification / Acceptance testing approach is planned**
    - **TRL-6, Qual, Spare, and Flight units will be tested to show repeatability**
  - **Thermal load performance will be verified by comparing the structural model results with the thermal-gradient, bulk temperature, and thermal cycling data from full-sized and analog testing**
    - **Flight-like thermal gradient testing, at and beyond the expected flight environments, with displacement measurement (LVDTs) will happen at least five times on different analog units to show repeatability and margin**
    - **Bulk temperature testing will happen on analog test articles above and below the flight temperatures to validate CTE differences between the C-C laminates and carbon foam**

TRL – 6 TPS Demonstration Plan

TPS Technology Demonstration Plan

▪ **Thermal**	
• **TB test: TSA with TPS, radiator, S/C simulators**	
- **Thermal Balance test**	**Complete**
• **JSC test: 22” x 22” Sandwich Panel**	
- **Pathfinder test**	**Complete**
- **Repeat of Pathfinder test**	**In process**
▪ **Mechanical** **Full Size Prototype**	
• **Acoustic test**	**Complete**
• **Vib test**	**Complete**
• **3rd stage static load test**	**Complete**
▪ **Fabrication and Assembly**	
• **Drawings for all TPS and TSA hardware**	**Released**
• **Process plans for all TPS assembly operations**	**Complete**

TPS/TSA Thermal Balance Test

TPS/TSA Thermal Balance Test Goals

- Verify predicted heat flows between TPS and TPS-mounted instruments to the cooling system radiators and S/C bus

Timeline

- May to Aug 2013 - Completed

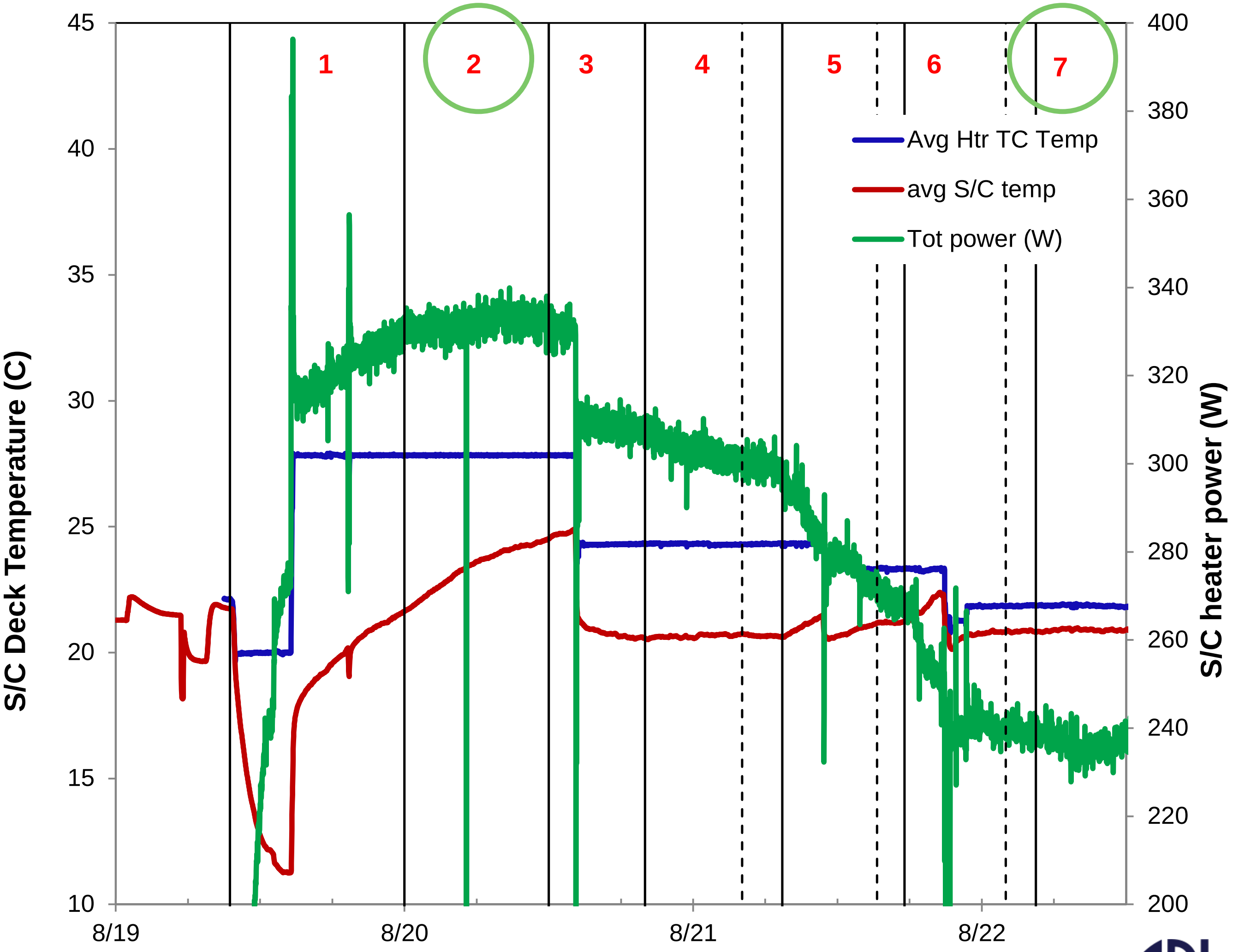
Facility

- Chamber 238 at GSFC

TB test article in Chamber 238

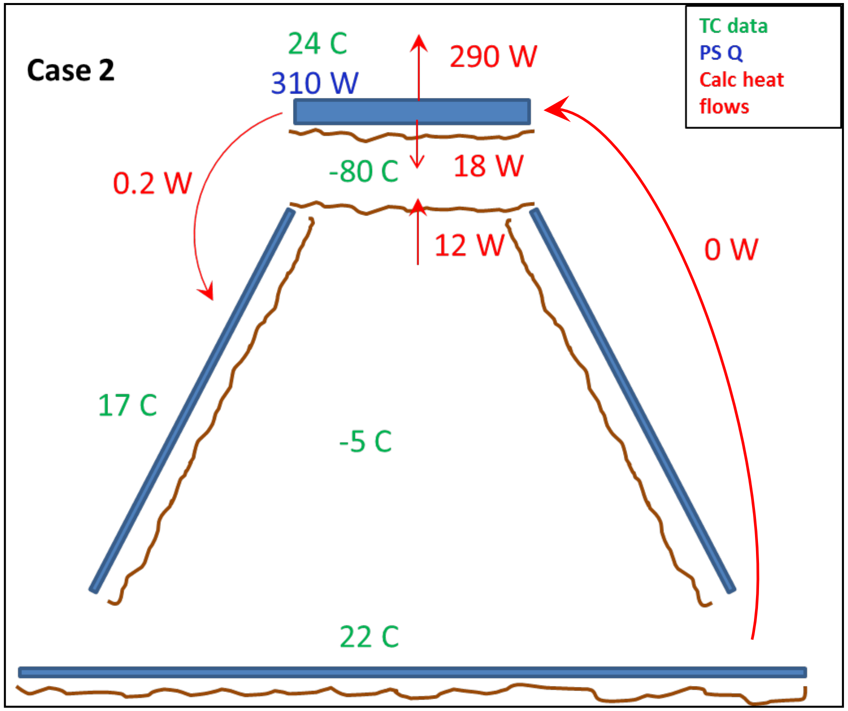
TPS/TSA Thermal Balance Test Data

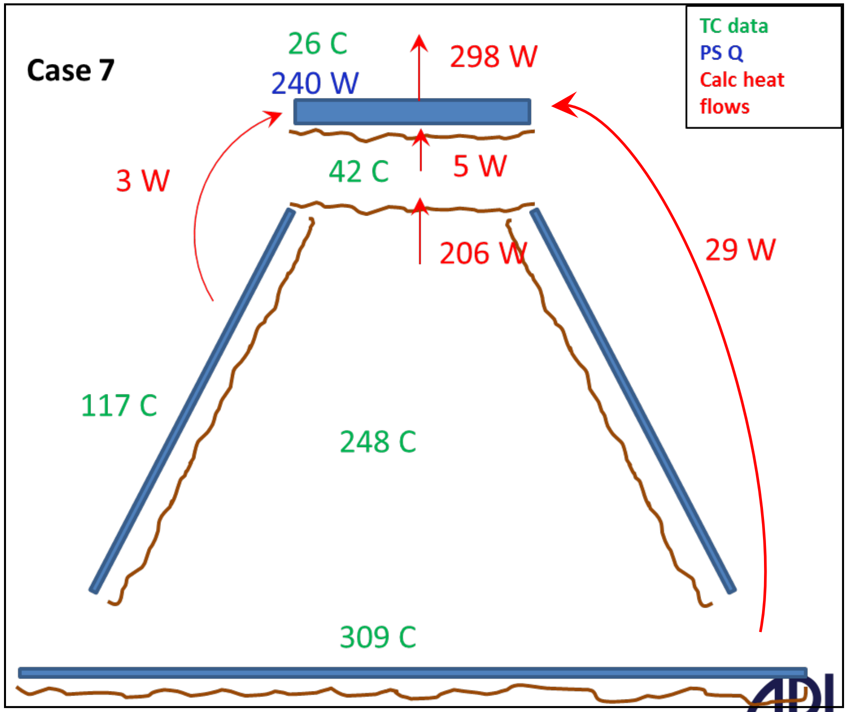
- **The graph shows the S/C thermocouples, S/C heater thermocouples, and heater power over the 1st seven balance cases with the 20 S/C**
- **Detailed test analyses are in progress**
- **Initial balance results for Cases 2 and 7 are shown in the following charts**



TPS/TSA Thermal Balance Test
Heat Flow to and from Spacecraft

- **Heat flow to and from the S/C is acceptable and correlates with the model results**
  - **Heat flow from the S/C is ~20 W, about 5 is conducted via the TSA**
  - **Heat to the S/C in the hot case is about 10 W**

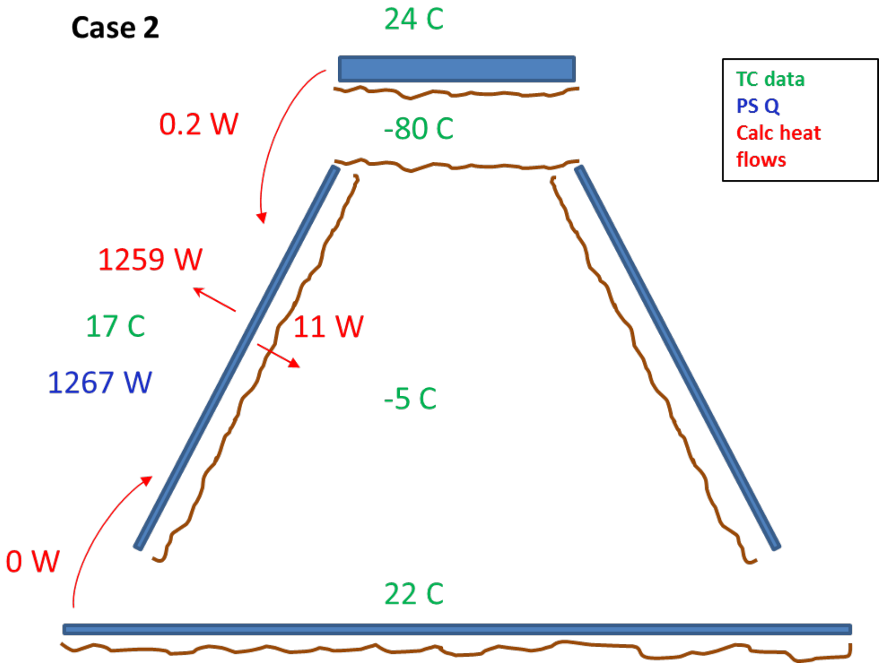


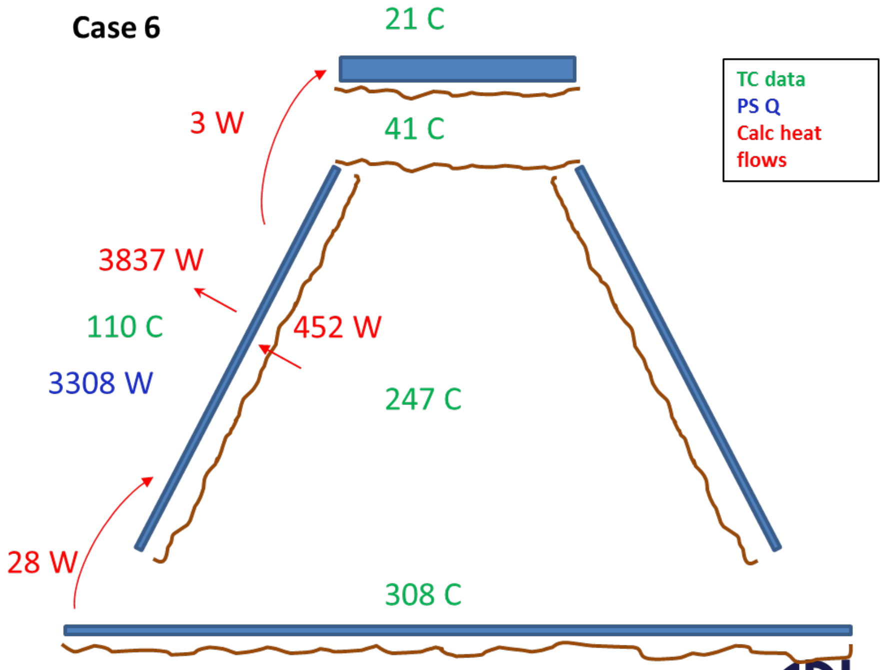


TPS/TSA Thermal Balance Test

Heat Flow to and from Cooling System

- **Heat flow to and from the cooling system radiators is acceptable and correlates with the model results**
  - **Heat to the radiators is dominated by the MLI leakage**

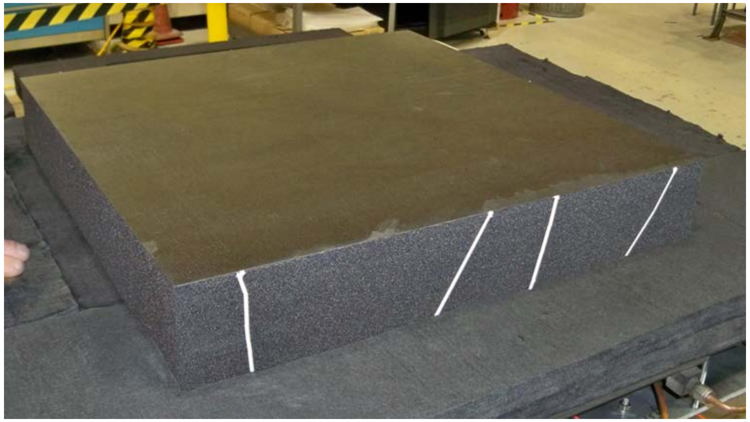




JSC Test

JSC Test Goals

- Provide system level test data that can be used to correlate the material properties used in the thermal and structural analyses
- Provide a test configuration that can be used to demonstrate repeatable performance over the course of the project



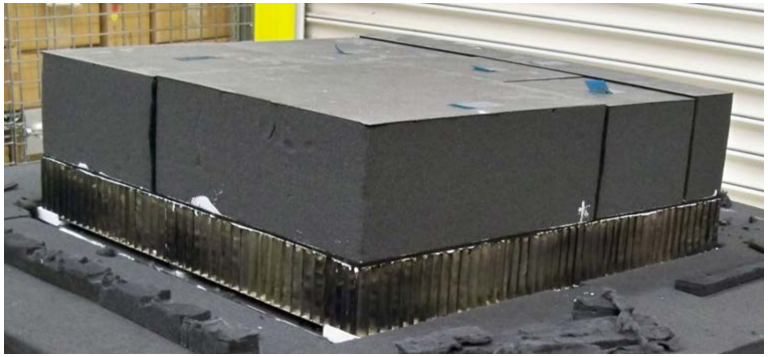
Option A test article

Timeline

- April to June 2013 - Completed

Facility

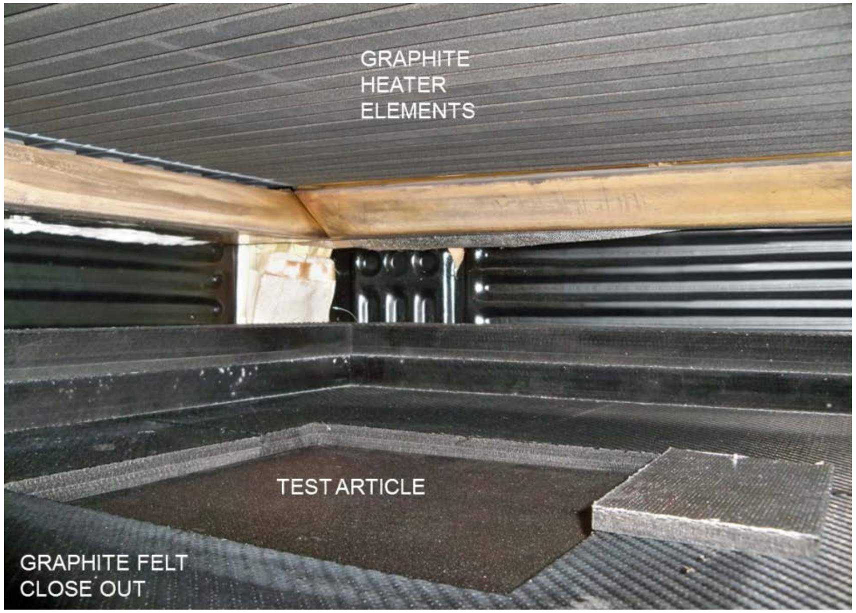
- JSC RHTF Chamber R2

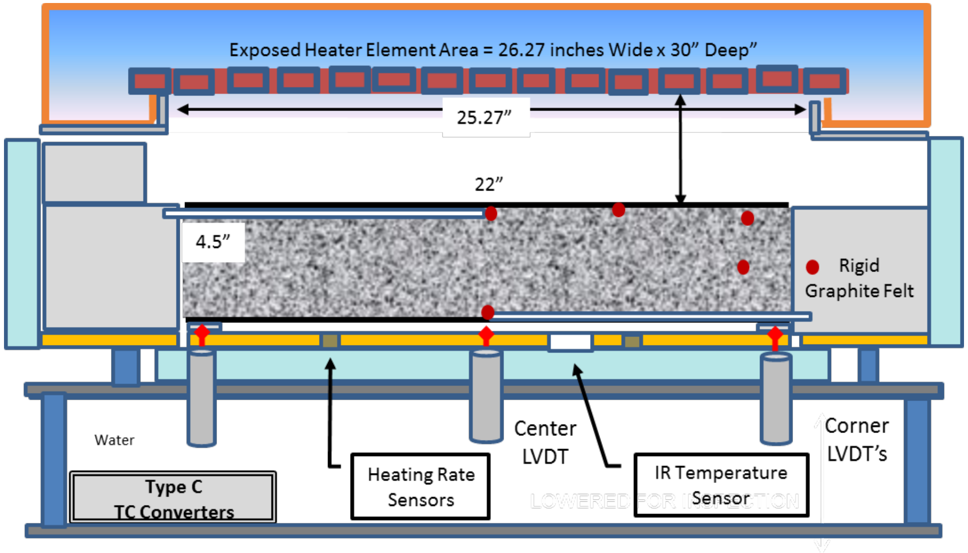


Option B test article

JSC Test Setup

- The test articles were heated from the top and cooled from the bottom
- Carbon felt around the periphery provides an insulated boundary condition



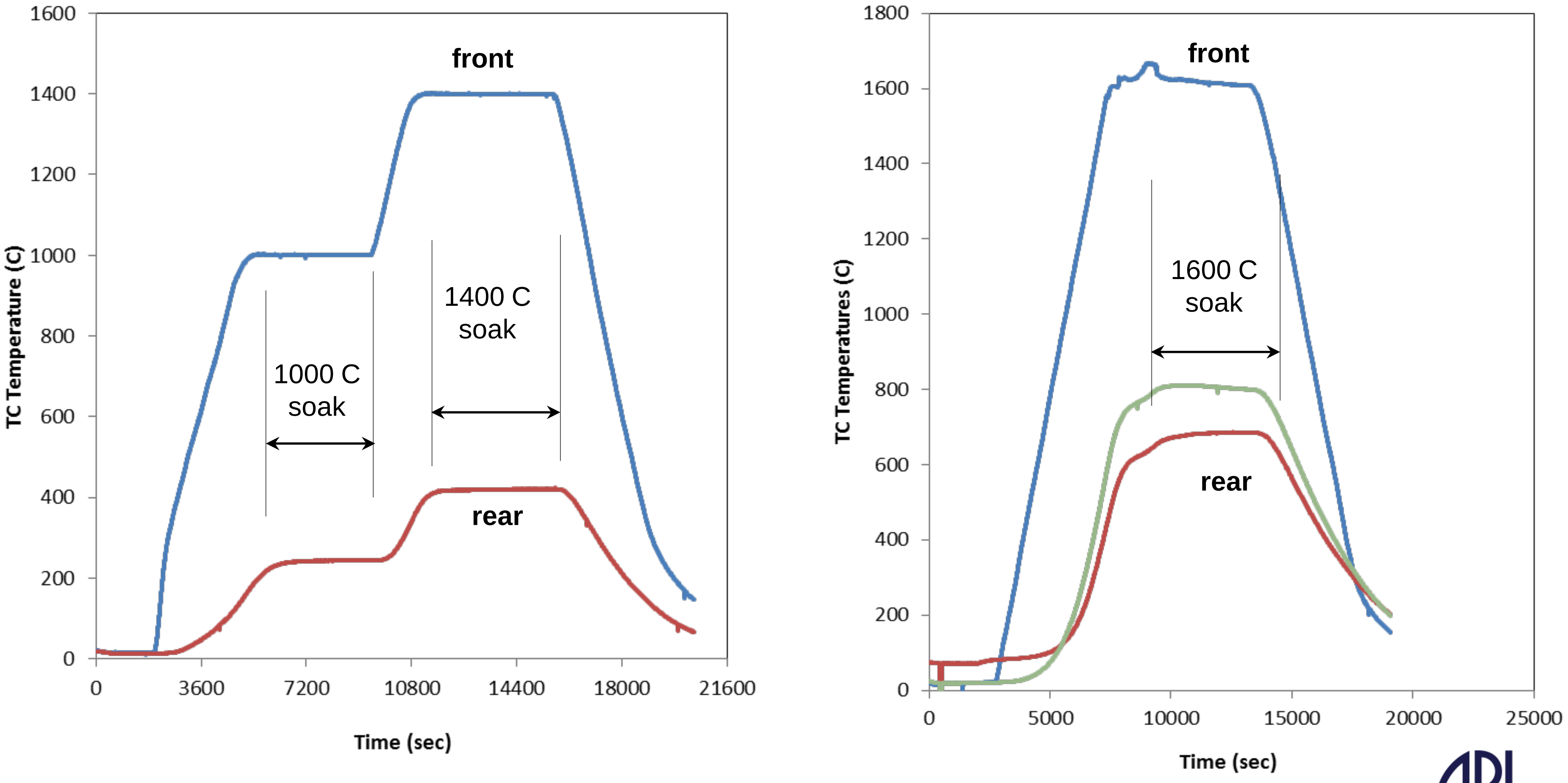


Instrumentation

- Thermal sensors:
  - TCs, pyrometer, and heat flux sensors
- Mechanical sensors:
  - LVDTs

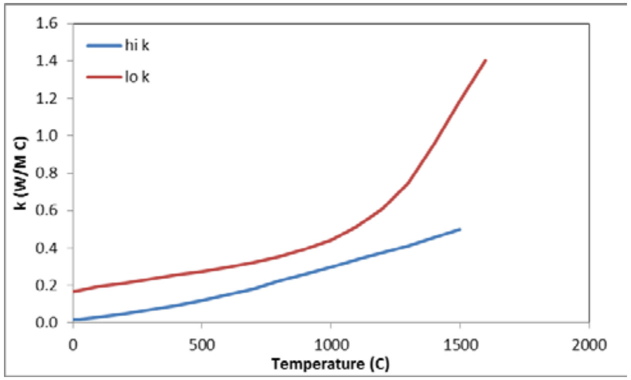
Thermal Test Data

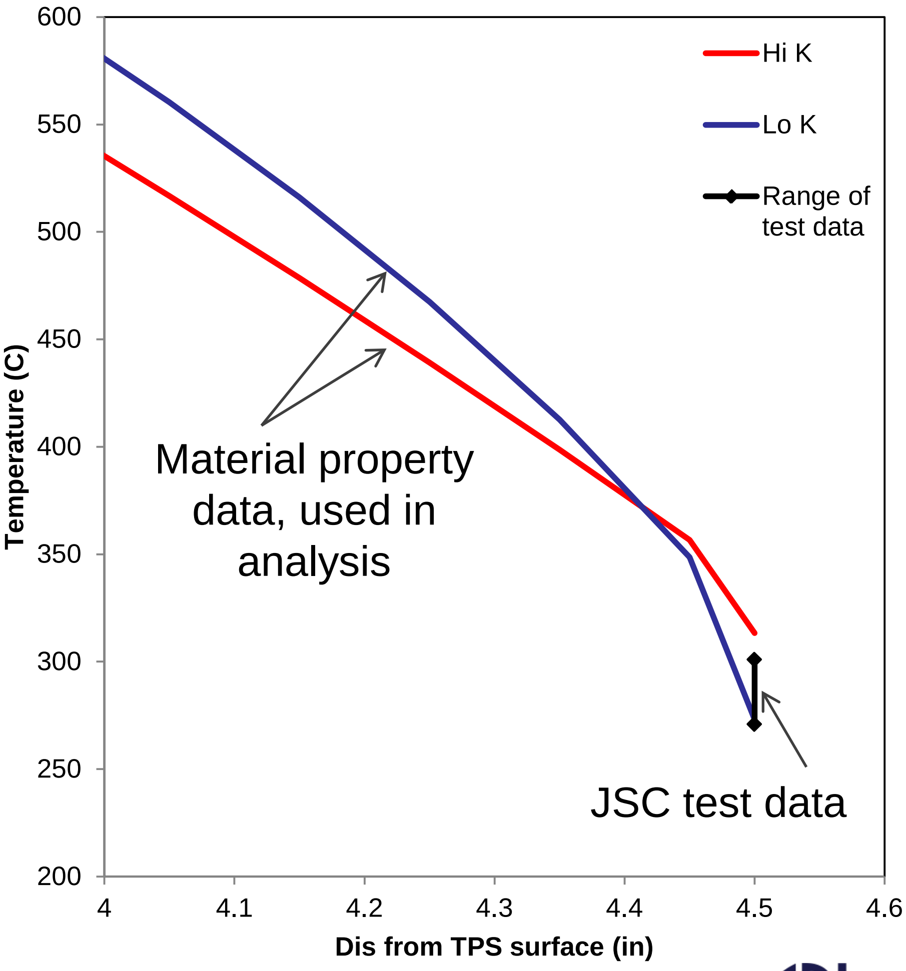
- **Test data for the soak periods were taken for the front and rear surfaces from the different plateaus when the system was reasonably stable**



TPS Thermal Conductivity Test Data

- **The calibrated heat flux sensor temperatures in the JSC test provided the best measure of bottom surface temperature**
- **The JSC test data correlate well with the min and max thermal conductivities used in the analysis**
- **The lack of temperature variation over radial distance from the panel center indicates the test achieved good 1D heat flow**



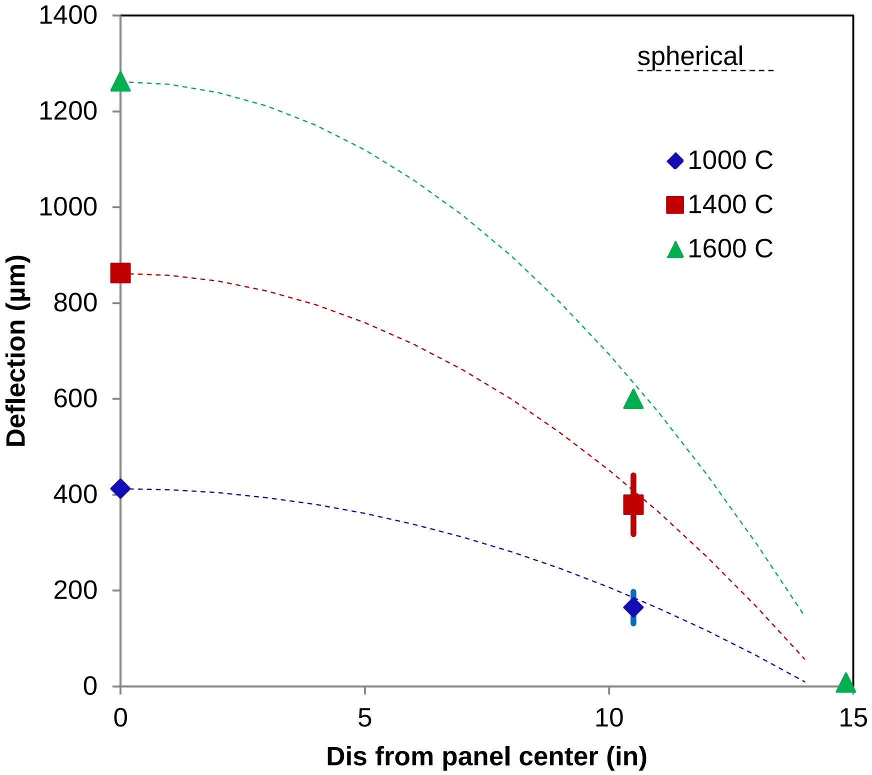


Material property data, used in analysis

JSC test data

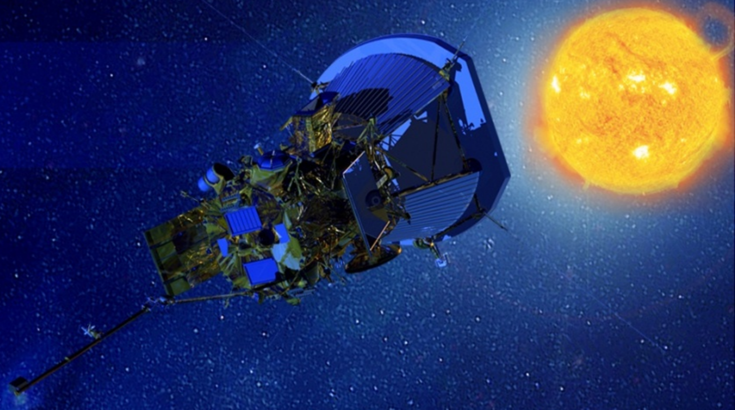
LVDT Test Data

- **TPS test article distorted to a spherical shape indicating good operation of the LVDTs and that the side boundary conditions did not significantly influence the test results**
- **LVDT data indicate the part did not fail during the test**



Solar Probe Plus

A NASA Mission to Touch the Sun



Solar Probe Plus PDR
TPS/TSA Structural Testing

APL

The Johns Hopkins University
APPLIED PHYSICS LABORATORY

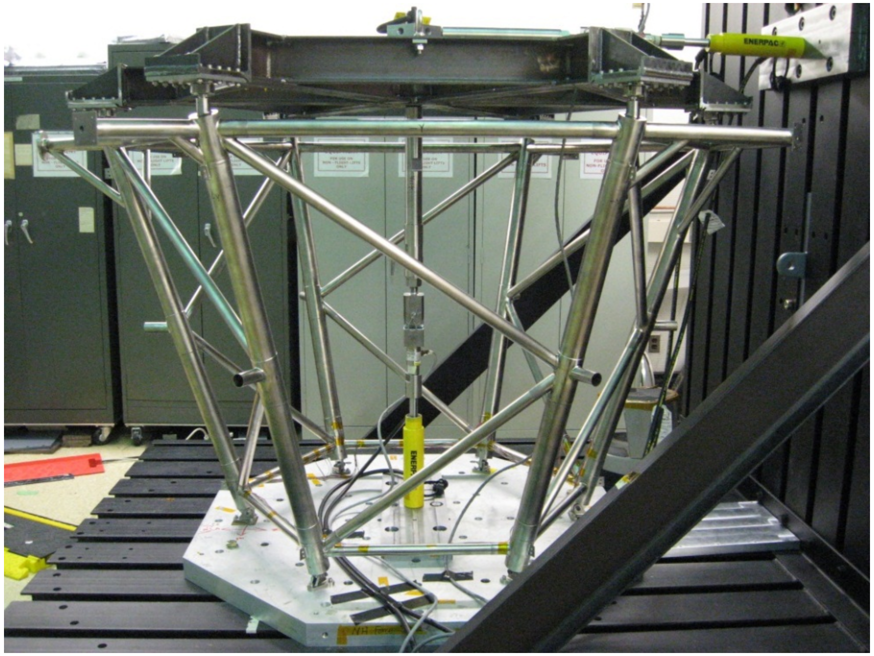
Truss Structure Assembly (TSA) Static Load Test at APL

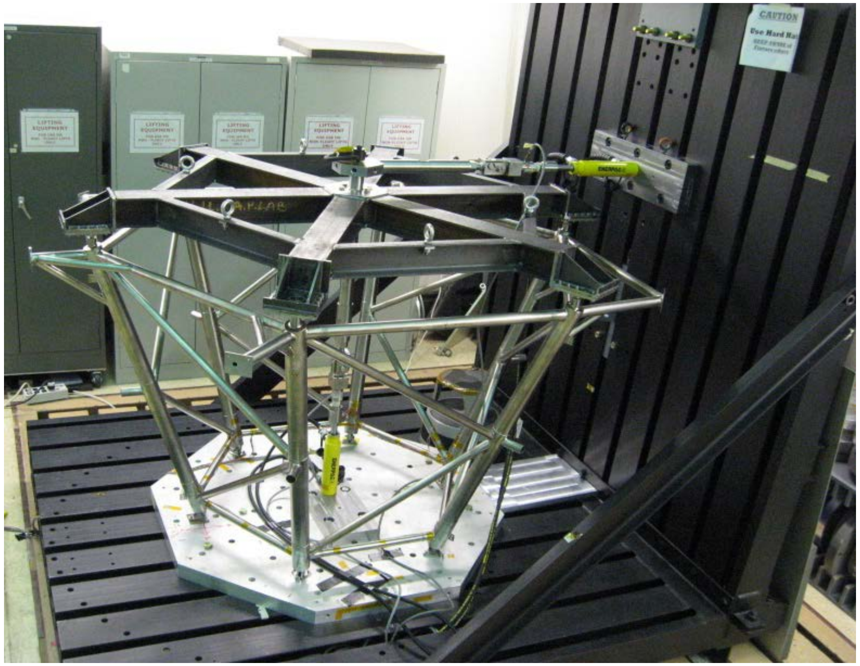
Loads

- Maximum Vertical load = +/- 5150 lbs
- Maximum Lateral loads = +/- 2900 lbs.

Results: Pass

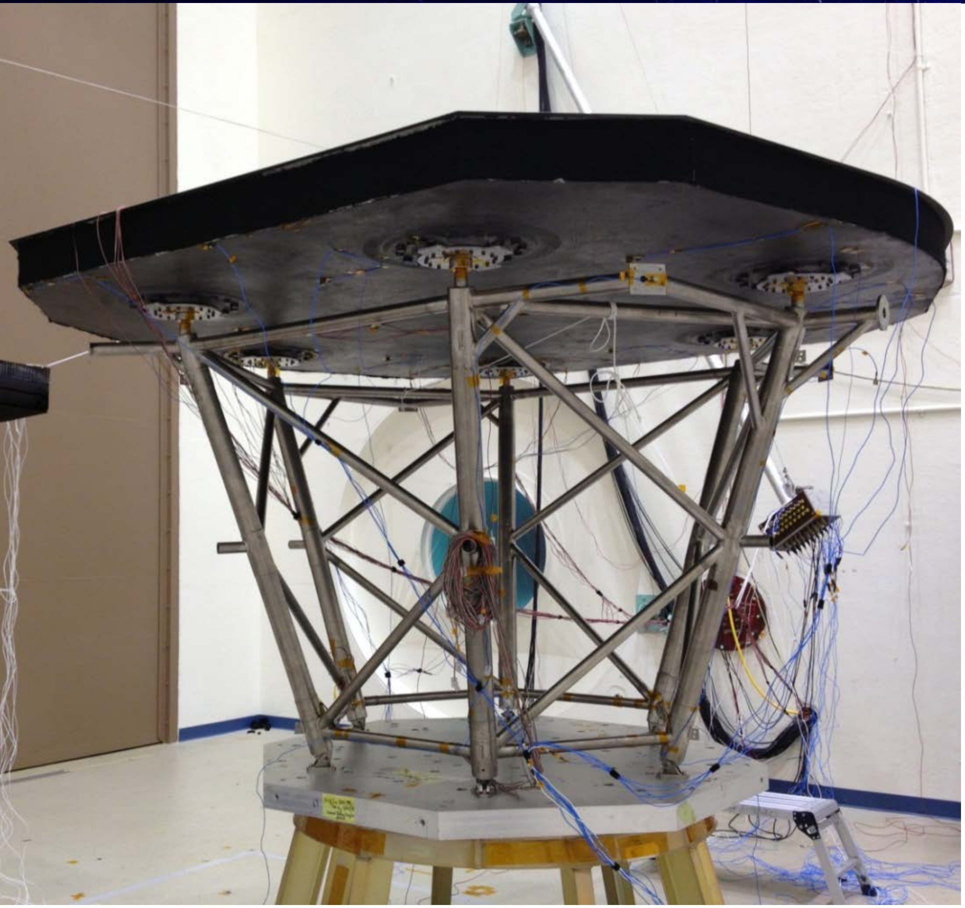
- All of the strains were within or below the estimated values, all within the elastic range, and with adequate margins of safety.





TSA Static Load Test
September 25-30, 2013

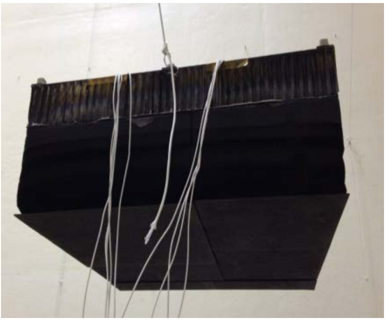
TRL-6 Acoustic Tests at NASA-GSFC

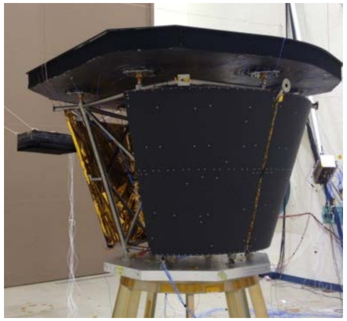


October 29, 2013

Test Findings:

1) Pass, see next chart
2) The radiators did not generate an acoustic cavity
3) After the acoustic test, a significant amount of carbon foam particles were found on the floor of the test chamber. This was probably due to both option A & B.
4) The option B test article survived the qualitative test, however one of the top carbon-carbon plates was loose.



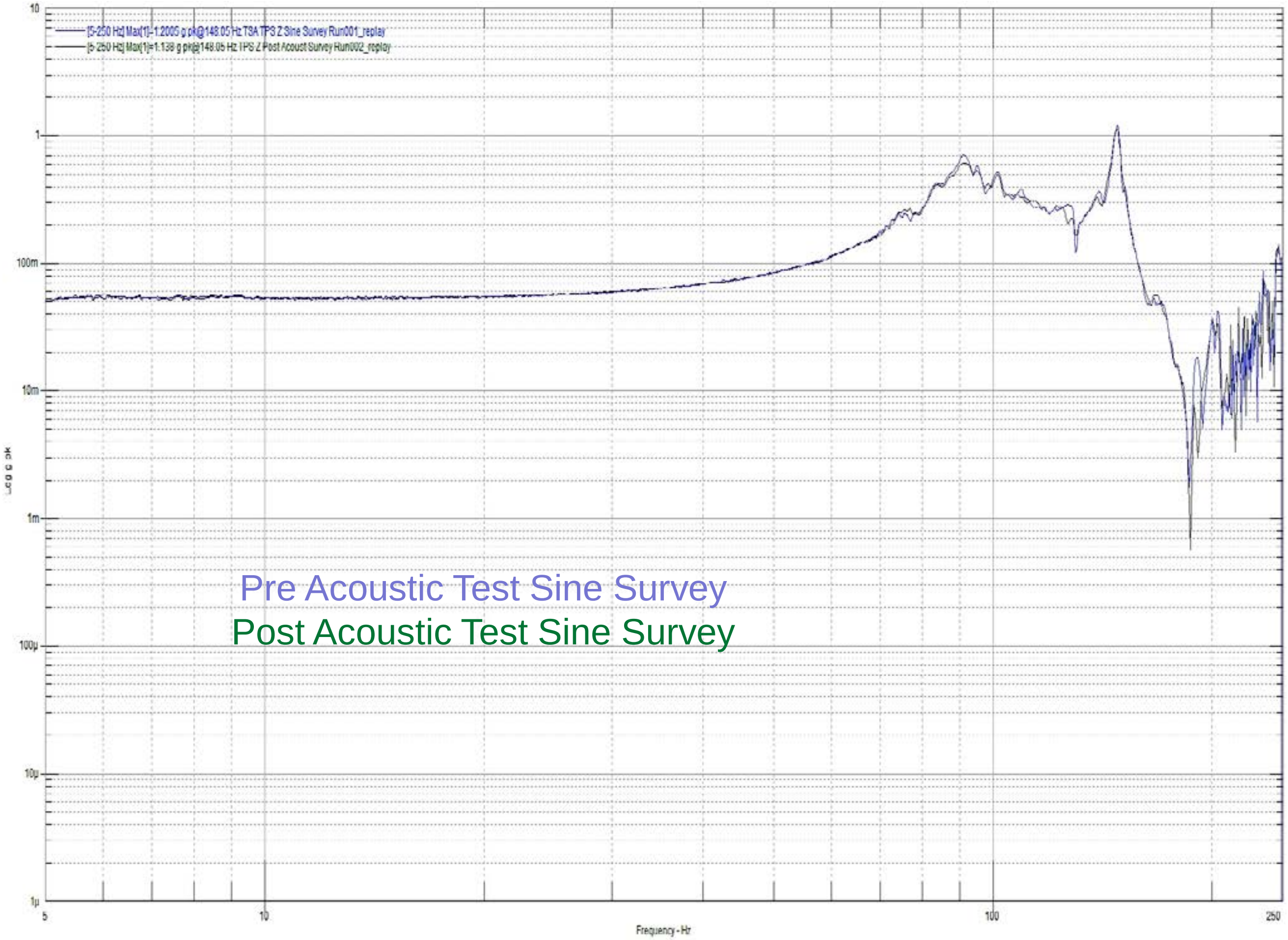


TRL-6 Z-Axis Pre-Post Sine Surveys (Acoustic)

The pre and post Z axis sine surveys were performed before and after the acoustic test sequence.

The overlays do not show any significant shift in the primary modes of the TPS/TSA subsystem, indicating there was no significant change in the overall structural strength characteristics of the test article.

Results: Pass



Pre Acoustic Test Sine Survey
Post Acoustic Test Sine Survey

TRL-6 TPS/TSA Lateral (X &Y) Axes Vibration Tests

Lateral Axes (X & Y)

- Design Limit Load 13.5g
- Test Level 17.0g

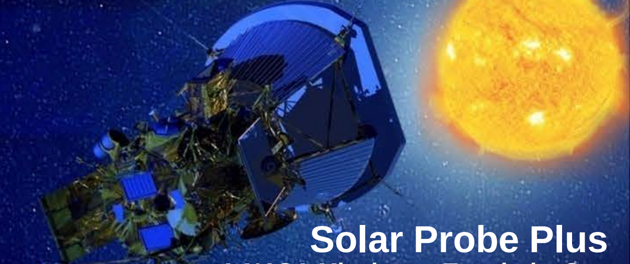
- X Axis Sine Survey
  - Pre Test: Primary Mode 30.05 Hz.
  - Post Test: Primary Mode 29.04 Hz.

- Y Axis Sine Survey
  - Pre Test: Primary Mode 31.46 Hz.
  - Post Test: Primary Mode 31.83 Hz.

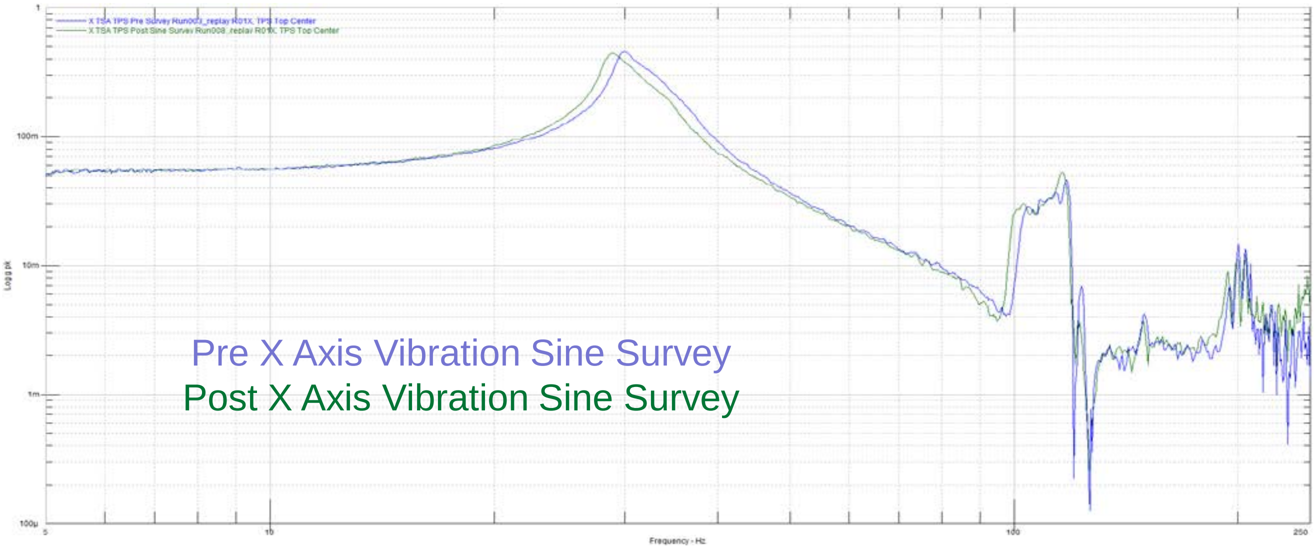
- Results:
  - Pass

November 4-5, 2013

TPS/TSA Lateral (X)Axis Vibration Test

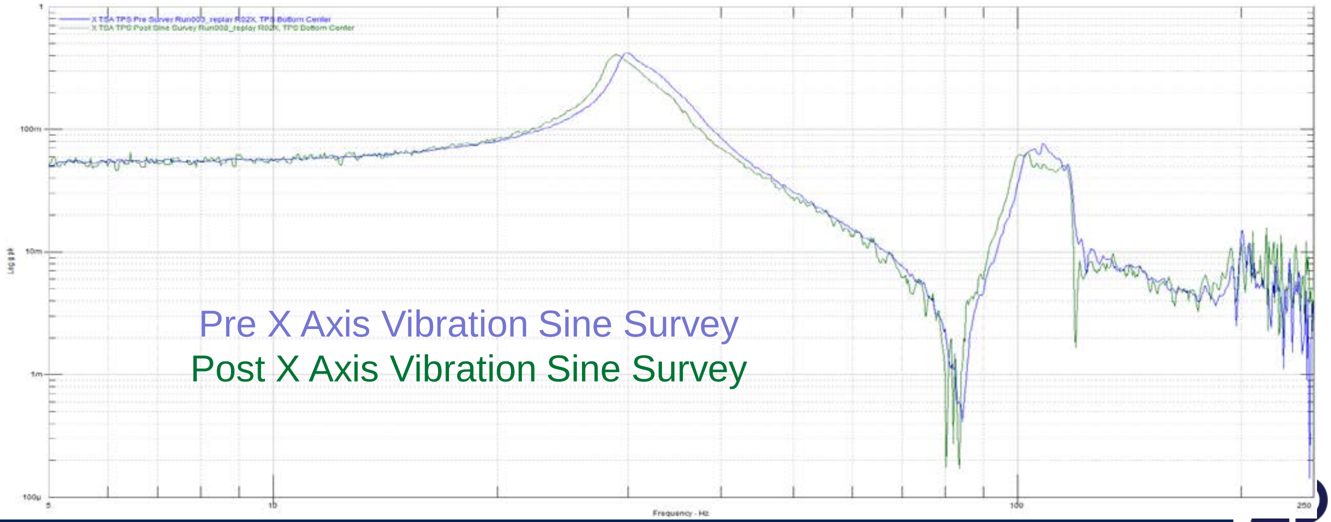


TPS Top Center X Axis
Pre and Post Surveys



Pre X Axis Vibration Sine Survey
Post X Axis Vibration Sine Survey

TPS Bottom Center X Axis
Pre and Post Surveys



Pre X Axis Vibration Sine Survey
Post X Axis Vibration Sine Survey

TPS/TSA Lateral (Y) Axis Vibration Test

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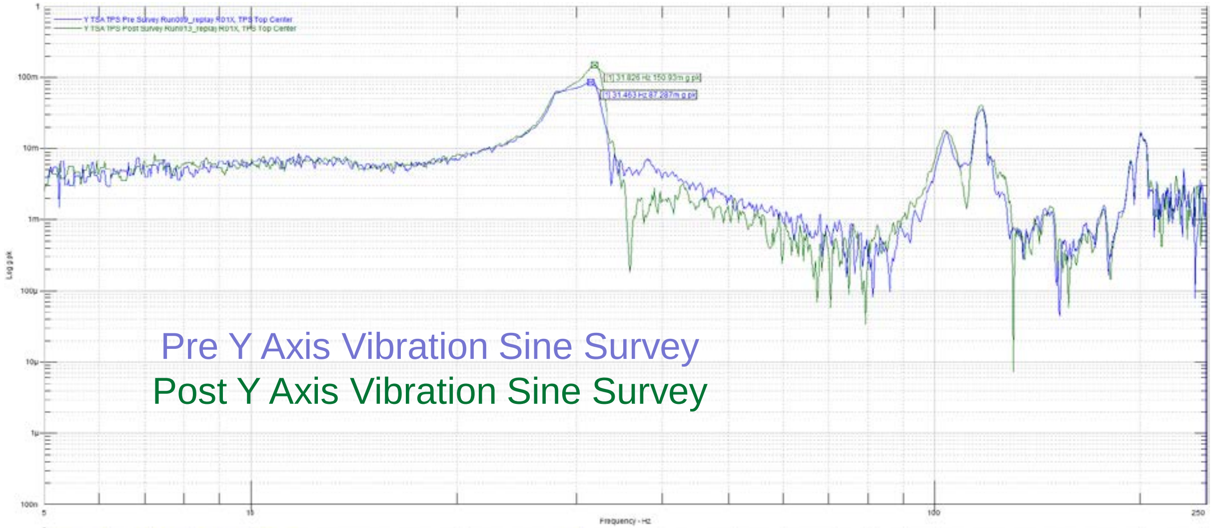
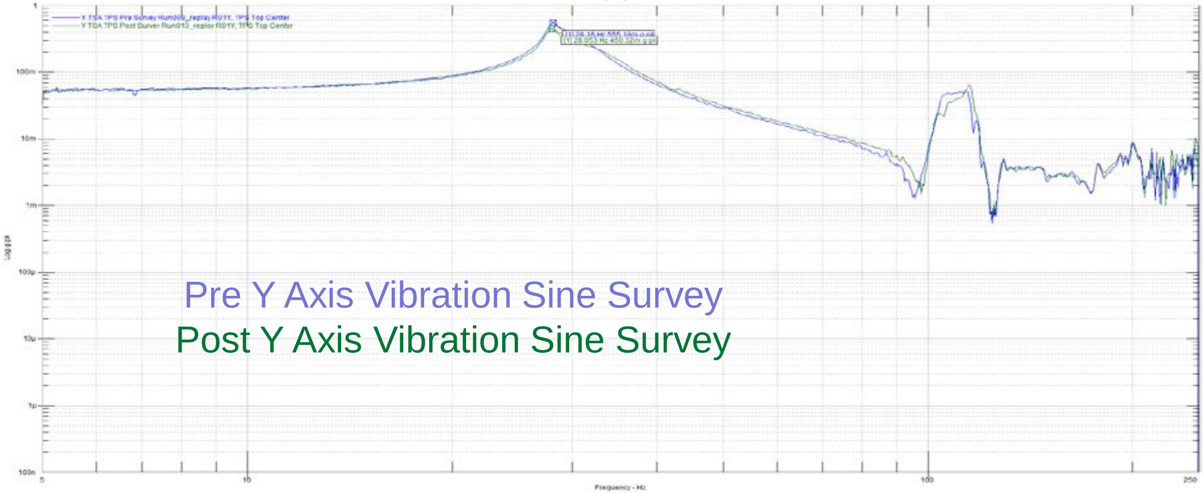
TPS Top Center Y Axis
Pre and Post Surveys



Pre Y Axis Vibration Sine Survey
Post Y Axis Vibration Sine Survey

TPS Bottom Center Y Axis
Pre and Post Surveys

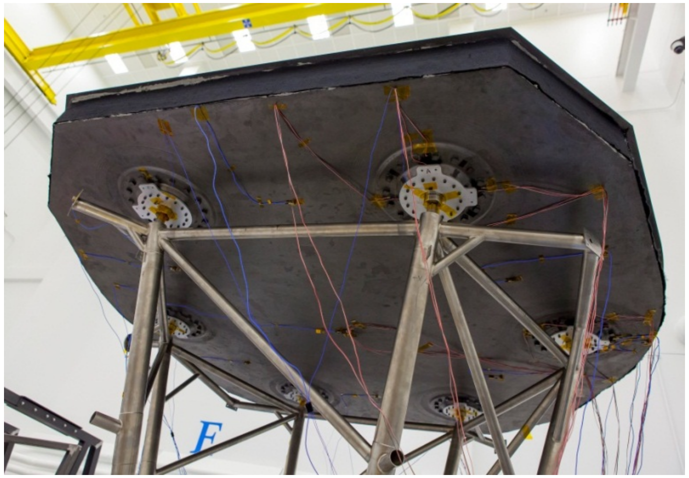


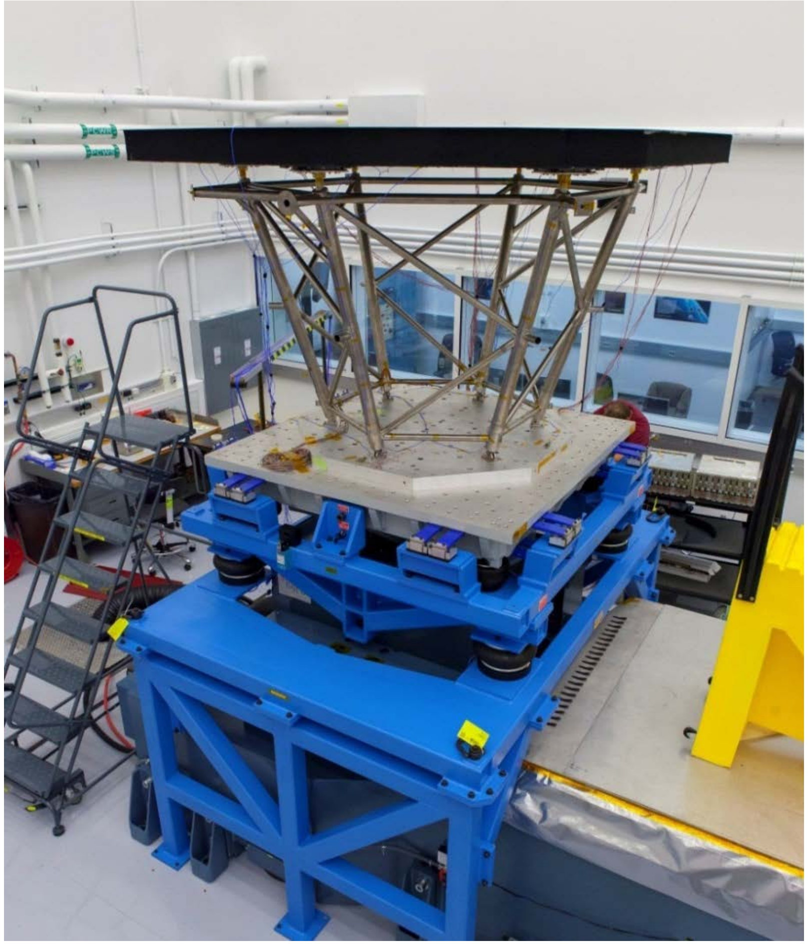
Pre Y Axis Vibration Sine Survey
Post Y Axis Vibration Sine Survey

TRL-6 TPS/TSA Thrust (Z) Axis Vibration Test (CLA) at APL

Thrust Axis (Z)

- Design Limit Load from CLA (+/-) 4.8g
- Test Level (+/-) 6g
- Pre Sine Survey:
  Primary Mode, 146.9 Hz.
- Post Sine Survey:
  Primary Mode, 146.9 Hz.
- Results:
  - TPS survived the test and remained intact
  - Model/Test correlation in process





November 7, 2013

TPS/TSA Thrust (Z) Axis Vibration Test (CLA)

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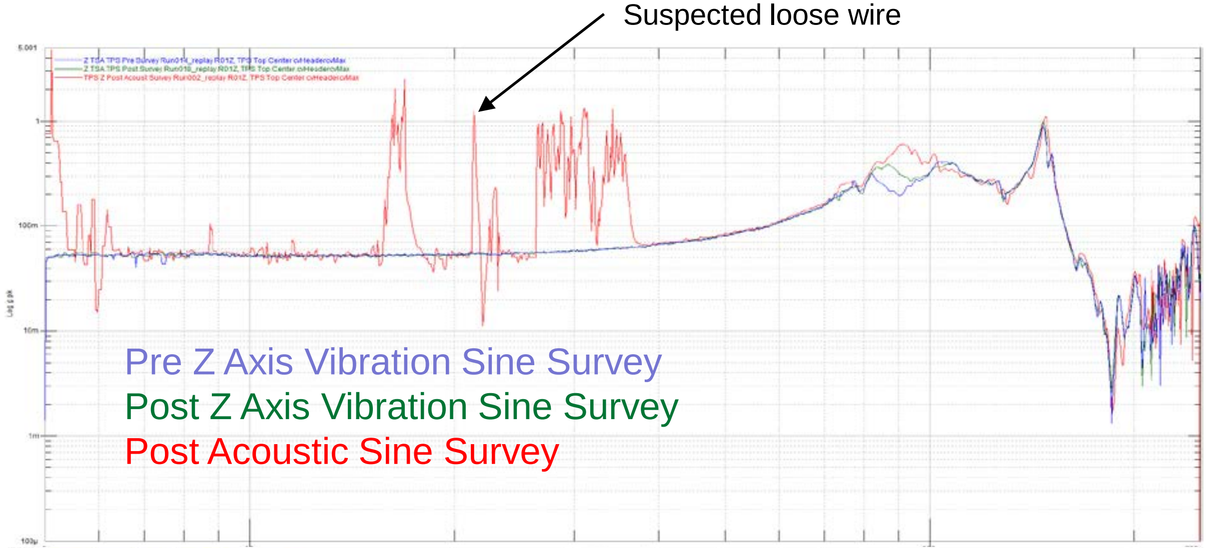
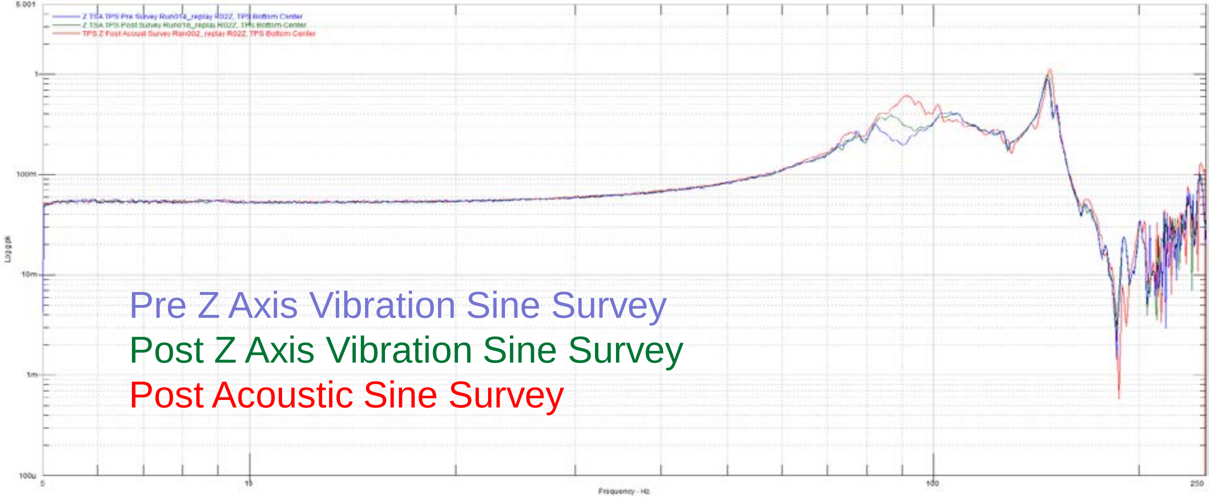
TPS Top Center Z Axis
Post Acoustic
Pre and Post Surveys



Pre Z Axis Vibration Sine Survey
Post Z Axis Vibration Sine Survey
Post Acoustic Sine Survey

TPS Bottom Center Z Axis
Post Acoustic
Pre and Post Surveys



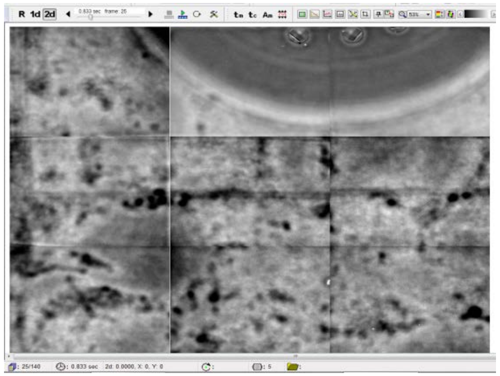
Pre Z Axis Vibration Sine Survey
Post Z Axis Vibration Sine Survey
Post Acoustic Sine Survey

NDE-Infrared Thermography

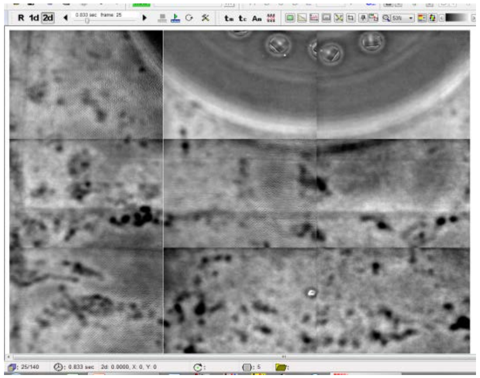
Non Destructive Evaluation

- IRT images have been taken over the length of the test program.
- Three images of one section of the bottom face sheet, taken at different points of the test program, are shown below.
- No significant changes have been noted in the IRTs taken to date.

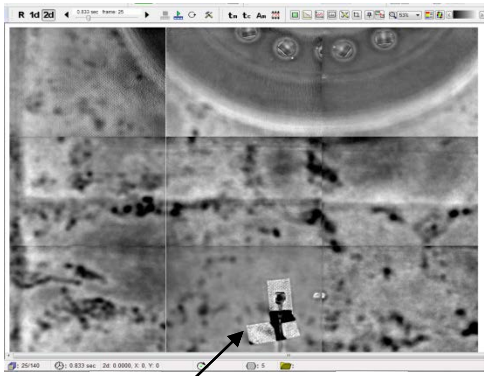
Section of TPS IRT at C-CAT



Section of TPS IRT Pre Acoustic Test



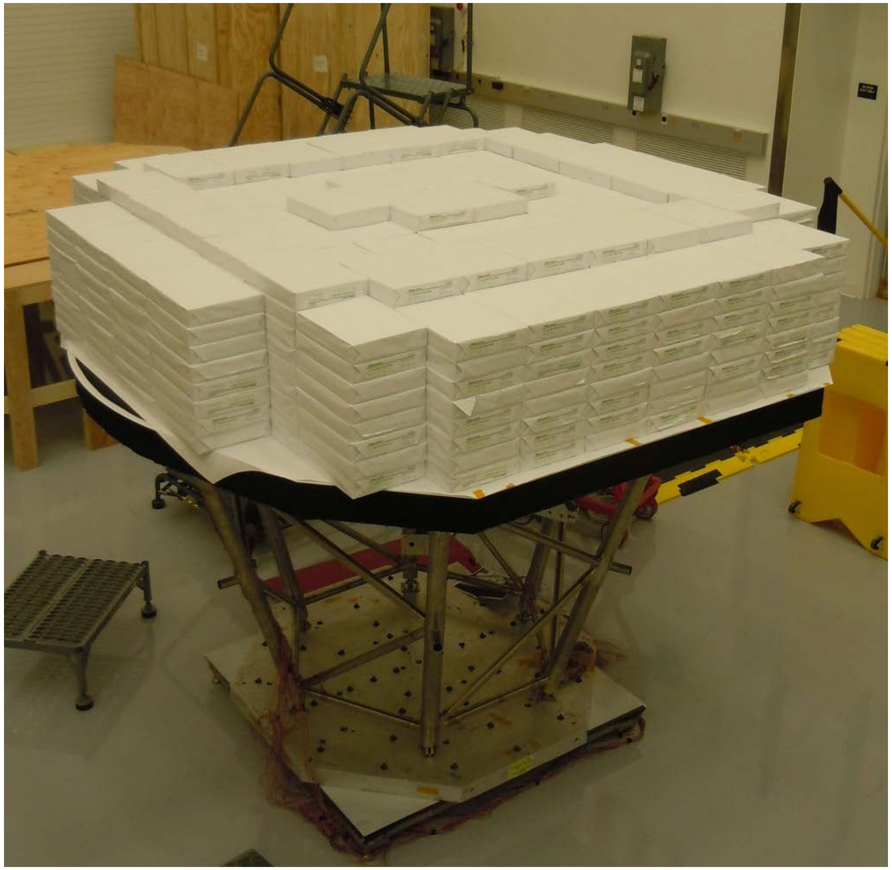
Section of TPS IRT Post Acoustic Test



Instrumentation added after Pre Acoustic Test IRT

TRL-6 TPS Static Load Test 3rd Stage Burn Out

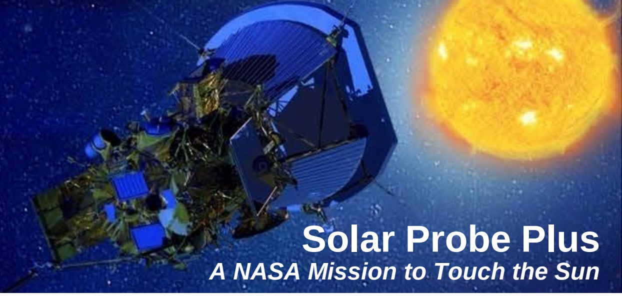
- **Axial (Z) Static Load Test**
  - 3^{rd} Stage Burn Out Load 16g
  - Test level 20g
  - Results:
    - Pass
    - The measured deflection at the center of the TPS matched the model predictions
    - The TRL-6 TPS was successfully tested to the 20g limit load



December 11, 2013

TPS Edge Closeout

- Phase B Edge Closeout Work
  - Filtering test were run on carbon felt, carbon fabric, graphite felt, and carbon mesh
  - Carbon felt selected for TRL 6 article
- Particulates observed during TRL 6 testing
  - Felt had to be removed after coating process due to contamination
  - Felt was applied at APL after delivery with limited tooling
  - Particulates were observed during acoustic test and vibration test in areas of poor edge closeout coverage
- Current/Future Work
  - Investigating tooling required to install edge post-coating and ways to protect edge during coating process
  - Contamination group investigating particulates generated and defining a requirement based on instrument needs
  - Blowdown test to be performed at APL on improved edge closeout application to prove it meets contamination and venting requirements



Major Phase C/D Activities

- TPS Qualification Unit
  - Manufacturing Complete (Second Quarter 2015)
  - Testing Complete (Third Quarter 2015)
- TSA Qualification Unit
  - Manufacturing Complete (Fourth Quarter 2014)
  - Testing Complete (Second Quarter 2015)
- TSA Flight Unit
  - Manufacturing Complete (Fourth Quarter 2015)
  - Delivery to Spacecraft (Fourth Quarter 2015)
- TPS Spare/Flight Unit
  - Cp Shift Defined (Fourth Quarter 2016)
  - Spare Manufacturing Complete (Second Quarter 2017)
  - Spare Testing Complete (Second Quarter 2017)
  - Flight Manufacturing Complete (Third Quarter 2017)
  - Flight Testing Complete (Third Quarter 2017)
  - Delivery to Spacecraft (Fourth Quarter 2017)

Conclusions

- **TPS requirements are well understood**
- **Design approach has been demonstrated through fabrication and testing of full size prototypes**
- **Design is at PDR level of maturity**
- **Key interfaces are defined**
- **Preliminary modeling and analyses results meet requirements**
- **Mass and size estimates are well substantiated**
- **Technology has been demonstrated through successful TRL-6 testing**
- **Risk areas have been identified and mitigation plans are in place**
- **Lessons learned have been reviewed and are being applied**
- **Phase C/D plans are in place**

The TPS is ready for Phase C

Solar Probe Plus

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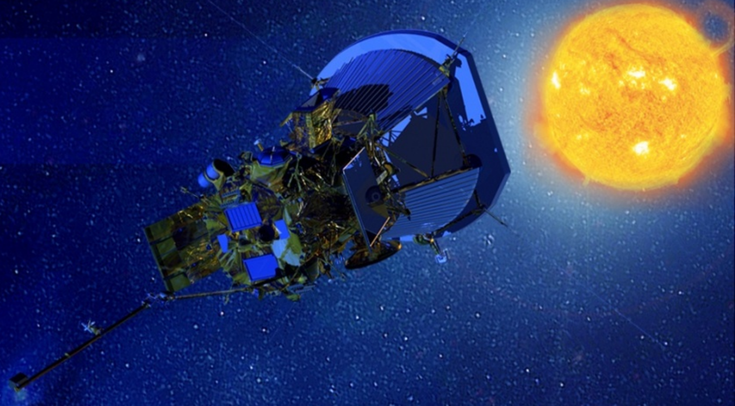

Thermal Subsystem

Elisabeth Abel
Lead Thermal Engineer

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13 – 16 January 2014

The Johns Hopkins University
APPLIED PHYSICS LABORATORY

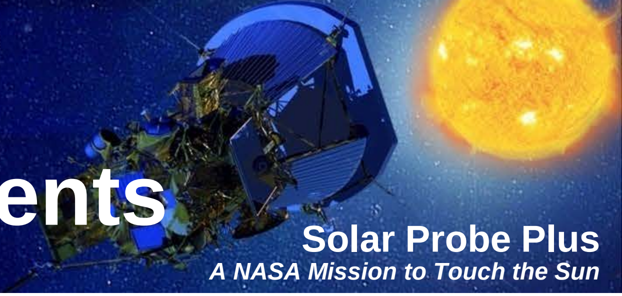
Outline

- **Thermal Subsystem Review Summary**
- **Driving Thermal Requirements**
- **Trades/Significant Changes since MDR**
- **Thermal Subsystem Design**
- **Analysis Results**
- **Verification**
- **Phase C Work**
- **Summary**

Thermal Subsystem Review

- **Thermal Subsystem PDR held November 13, 2013**
  - Review Board:
    - Mike Marley (APL), Chair
    - David Steinfeld (GSFC), SRB Member
    - Janelle Vorreiter (ATK)
  - 5 Action Items, 22 Recommendations
  - Minutes and Action Items are captured in SEM-13-4-511
  - Actions Items will be tracked in PIMS
- **Exit Criteria**
  - Verify that requirements are understood and documented ✓
  - Verify that design conforms to requirements ✓
  - Identify any open issues to be resolved as action items ✓

Driving Level 4
Thermal Subsystem Requirements

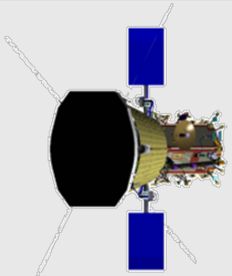
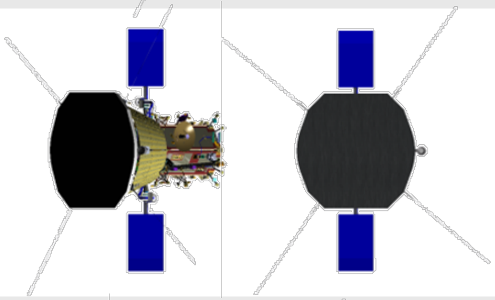
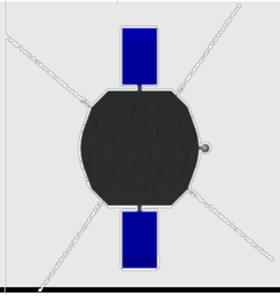


7434-9065 Level 4 Thermal Subsystem Requirements (released in PLM)

Rqmt #	Title	Requirement
THRM-1	Environments and Test Levels	Maintain component and subsystem interface temperatures within tested levels with specified margins for all phases of integration and mission operations (EDTRD)
THRM-71	Power Configuration	Maintain EDTRD interfaces for each power configuration defined in the Spacecraft System Engineering Power Loads Budget
THRM-3	Redundancy	Be single fault tolerant
THRM-4	Telemetry	Provide the spacecraft and instruments with the sufficient telemetry to detect thermal fault conditions and monitor spacecraft health
THRM-5	Mass NTE	Do not exceed a mass of 19.82 kg
THRM-6	Power NTE	Do not exceed 27.4W in PC3 (Recharge Post Rad 1&4), 15.0W in PC24 (Science 9.86Rs), and 16.1W in PC20 (Downlink 0.76AU Slew) for spacecraft thermal control and 16.2 W in PC3, 9.8W in PC24, and 16.2W in PC20 for propulsion thermal control
EDTRD	Dust Protection	MLI shall be stood off 2 inches from spacecraft panels
EMECP_011	EME	All external surfaces shall be conductive with surface resistivity under 10^5 ohms per square

Driving Thermal Requirements

Extended Spacecraft Attitudes

Solar Distance	Description / View from Sun	
1.02 AU to 0.82 AU	Aphelion	
0.82 AU to 0.7 AU	Aphelion-Umbra Variable	
0.7 AU to 9.86Rs	Umbra/ Encounter	

Driving Thermal Requirements
Transient Spacecraft Attitudes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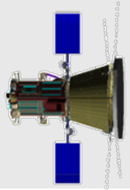
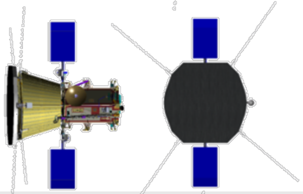
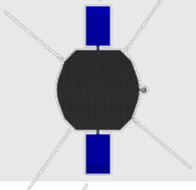
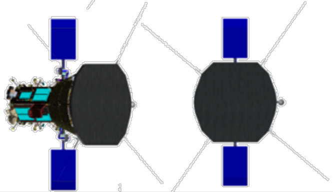
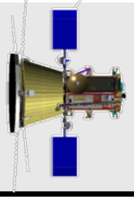
Name	View from Sun	Solar Distance	Duration
Activate Radiators 1 and 4		1.02 AU	~ 1 hr
Launch Correction		1.02 AU	≤ 2 hrs
Early Cruise TCMs		1.02 AU to 0.9 AU	< 30 mins
SWEAP Transient Slew		≥ 0.95 AU	< 40 mins
Activate Radiators 2 and 3		0.9 AU to 0.89 AU	< 1 hr

Driving Thermal Requirements
Spacecraft Thermal Dissipation (W)

Description	PC3: Recharge Post Rad 1&4 Warm-up	PC17: Downlink @ 0.76AU	PC21: Downlink @ 0.7AU	PC23: Science: 20Rs with 4hr X-band	PC24: Science: 20Rs - 9.86Rs	
Current Best Estimate (CBE) or Not to Exceed (NTE)	CBE	CBE	NTE	NTE	CBE	NTE
PSE	54.6	61.2	59.4	67.8	60.4	60.4
Battery	0.9	0.5	0.5	0.5	0.5	0.5
Actuator ECU	4.4	4.4	5.1	5.1	4.4	5.1
PDU	9.5	9.5	10.5	10.5	9.5	10.5
SACS Motor Controller	6.2	6.2	7.1	9.0	7.8	9.0
REM	12.2	12.2	14.0	14.0	12.2	14.0
RPU	13.9	13.9	16.0	21.8	18.9	21.8
IMU	27.6	27.6	29.0	29.0	27.6	29.0
Sun Sensor Electronics	5.8	5.8	3.5	7.0	5.8	7.0
Reaction Wheels	12.0	12.0	24.0	24.0	12.0	24.0
Star Tracker 1	7.4	7.4	8.9	8.9	6.0	7.2
Star Tracker 2	0.0	0.0	0.0	8.9	6.0	7.2
Ka-band EPC	0.0	8.0	8.4	0.0	0.0	0.0
Ka-band TWT	0.0	34.0	35.7	0.0	0.0	0.0
X-band EPC	0.0	0.0	0.0	3.5	0.0	0.0
X-band TWTA	0.0	0.0	0.0	19.6	0.0	0.0
Radio A	5.5	10.0	11.5	10.9	5.5	6.3
Radio B	5.5	5.5	6.3	6.3	5.5	6.3
Coax/WG	0.0	10.0	10.5	4.2	0.0	0.0
WISPR DPU	0.0	0.0	0.0	8.2	7.1	8.2
FIELDS MEP	0.0	0.0	0.0	24.6	20.6	24.6
SWEAP SWEM	0.0	0.0	0.0	5.3	4.4	5.3
Total Spacecraft Dissipation	**165.5**	**228.2**	**250.4**	**289.1**	**214.2**	**246.4**

Driving Thermal Requirements

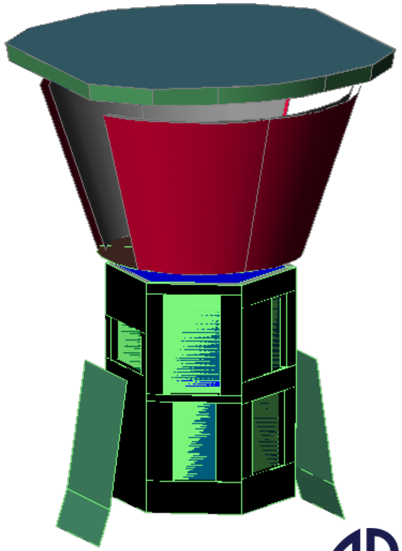
Spacecraft Thermal Interfaces

- **The thermal interfaces between the spacecraft and subsystems, instruments, and components are defined in the Environmental, Design, Test Requirements Document (EDTRD)**
- **Subsystems/Instruments**
  - Interfaces are defined using a combination of temperature boundaries, heat flow requirements, and specified thermal resistance
  - A Thermal Interface Math Model was supplied to each team and heat flows were later verified by SPP Thermal using an integrated model
  - Thermal environments are provided as part of the Thermal Interface Math Model
- **Components are specified as baseplate temperatures and verified using the spacecraft Thermal Math Model (TMM)**

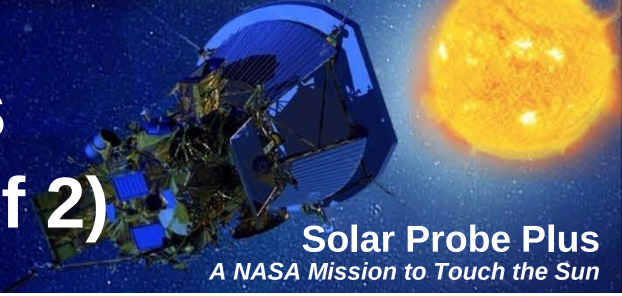
Key Thermal Interfaces with the Spacecraft:

- **SACS**
- **TPS/TSA**
- **Spacecraft Mounted Instruments**
  - **WISPR**
  - **ISIS (EPI-Lo and EPI-Hi)**
  - **SWEAP (SPAN A+ and SPAN B)**
- **TSA Mounted Instruments**
  - **SWEAP (SPC)**
  - **FIELDS (PWI Antenna, x4)**

- **Boom Mounted Instruments**
  - **FIELDS (FGM, x2)**
  - **FIELDS (V5)**
  - **FIELDS (SCM)**
- **Spacecraft Mounted Components**
  - **Battery**
  - **PSE**
  - **TWT (Ka- and X-Band, x2)**
  - **Etc.**



Driving Thermal Requirements
Component Temperature Limits (1 of 2)



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Component Name	Operational Limit (°C)	Survival Limit (°C)
Telecommunications		
High Gain Antenna	-172 to +141	-172 to +141
Fanbeam Antenna	-100 to +300 (TBR)	-100 to +300 (TBR)
Low Gain Antenna	-100 to +300 (TBR)	-100 to +300 (TBR)
Ka-band & X-band TWTs	-25 to +85	-30 to +90
Ka-band & X-band EPCs	-25 to +65	-30 to +70
Radios	-25 to +55	-30 to +60
Guidance and Control		
Inertial Measurement Unit	-25 to +65	-30 to +70
Star Tracker	-30 to +50	-35 to +55
Reaction Wheels	-25 to +55	-30 to +60
Solar Limb Sensor Interface	-25 to +65	-25 to +65
Sun Sensor Electronics Box	-25 to +65	-30 to +70
Power		
PSE	-25 to +55	-30 to +60
Battery	+5 to +35	0 to +40
Cooling System		
Motor Controller Electronics	-25 to +65	-30 to +70
Pre-Act.: Accumulator	+15 to +25	+10 to +30
Post-Act.: Accumulator	+10 to +65	+10 to +75
Flexible Cooling Lines	+10 to +150 (wet)	0 to +150 (dry)

Driving Thermal Requirements

Component Temperature Limits (2 of 2)

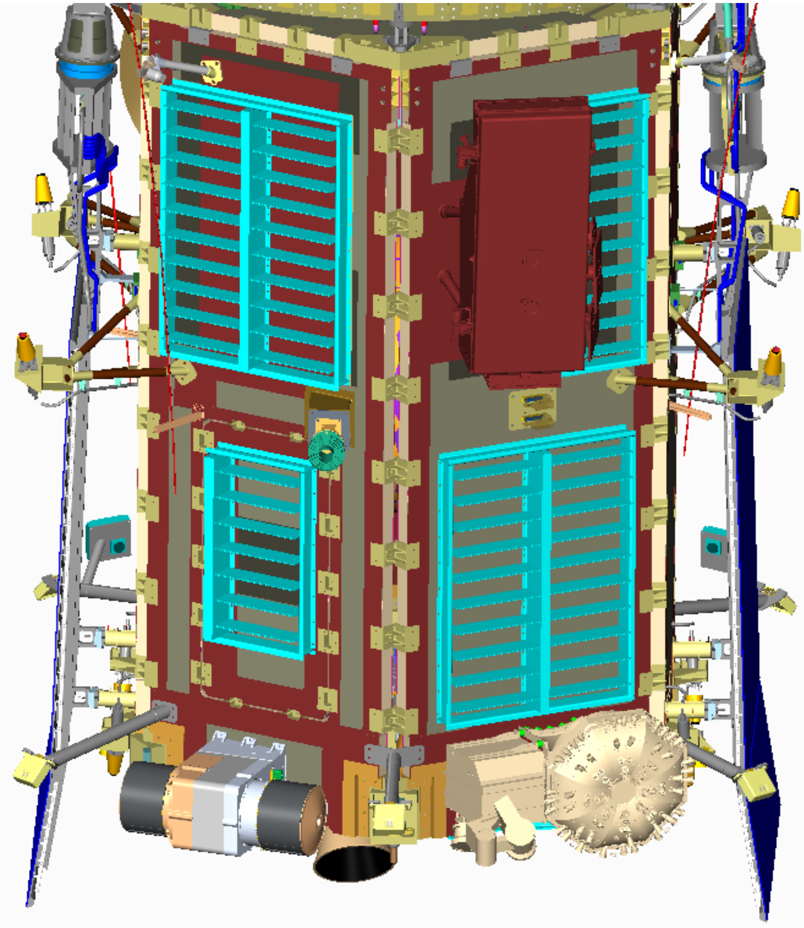
Component Name	Operational Limit (°C)	Survival Limit (°C)
Avionics		
Redundant Processor Module	-25 to +65	-30 to +70
Redundant Electronics Module	-25 to +65	-30 to +70
Power Distribution Unit	-25 to +60	-30 to +65
Remote Interface Units	-25 to +65	-30 to +70
Propulsion		
Propulsion Tank/Lines/Valves	+10 to +50	+5 to +50
Mechanical		
Solar Array Flap and Feather Actuators	-25 to +65	-60 to +100
HGA Actuator	-40 to +73	-66 to +115
Actuator ECU Solar Array and HGA	-25 to +65	-30 to +70
Magnetometer Boom	-5 to +65 (deploying)	-150 to +85
Instrument Interface		
FIELDS FGMs and SCM	-150 to +85	-150 to +85
FIELDS PWI Antennas and Pre-Amps	-130 to +240	-130 to +240
SWEAP SPC and Pre-Amps	-130 to +240	-130 to +240
ISIS EPI-Hi/Lo	-5 to +50	-5 to +50
SWEAP SPAN-A+	0 to +45	0 to +45
SWEAP SPAN-B	+5 to +50	+5 to +60
WISPR	-5 to +50	-5 to +50
WISPR DPU, FIELDS MEP & SWEAP SWEM	-25 to +65	-30 to +70

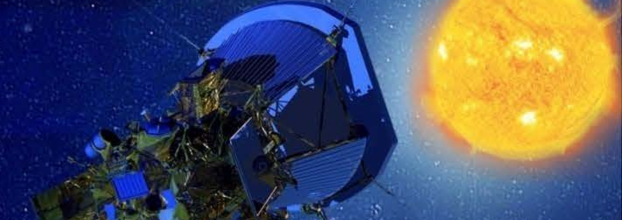
Trades/Significant Changes since MDR

- **Panel Face Sheets/Thermal Doublers**
  - MDR: Composite face sheet with K-13 thermal doubler
  - PDR: 0.008” Aluminum with mechanical doublers as required
- **Louver Assembly Sizes**
  - MDR: (2) 20-Blade , (1) 14-Blade, (1) 10-Blade and (2) 7-Blade assemblies
  - PDR: (2) 20-Blade , (3) 10-Blade and (1) 7-Blade assemblies
- **Selected Interface Temperatures**
  - Spacecraft mounted instrument interface temperature ranges have now been tailored to integrated model predicted ranges with margin
  - PDU: High operate temperature decreased from 65°C to 60°C
  - Radios (i.e. transponders) : High operate temperature decreased from 65°C to 55°C
- **Heater Configuration and Redundancy**
  - MDR: Full single fault tolerance on each heater
  - PDR: Selected reduction in heater redundancy while still maintaining single fault tolerance to decrease subsystem mass
- **Temperature Sensor Redundancy**
  - MDR: Redundant temperature sensors on all monitored components
  - PDR: Selected reduction in sensor redundancy, while still maintaining single fault tolerance, to decrease subsystem mass
    - All temperature measurements required for thermal control and autonomy are redundant

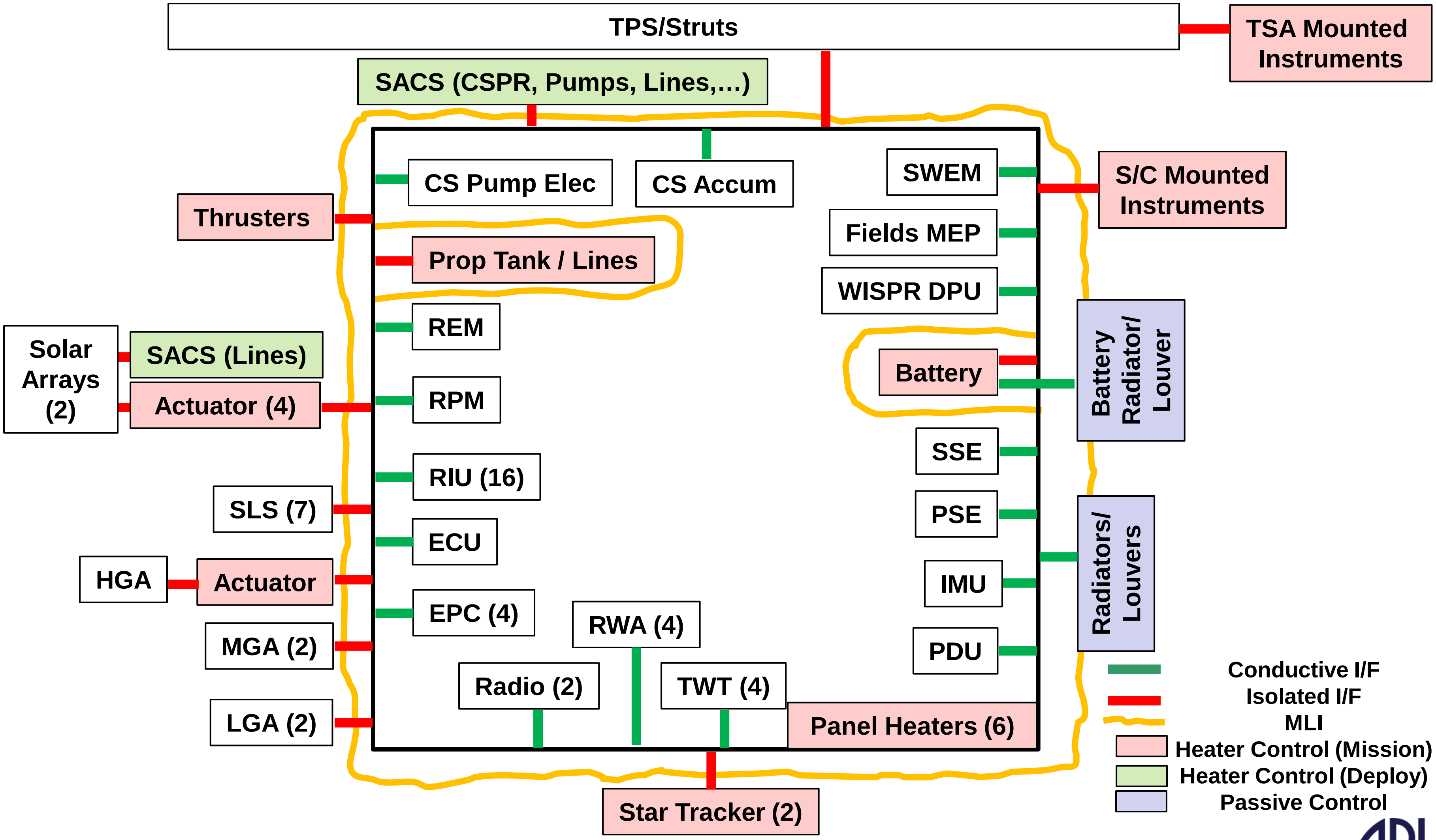
Thermal Subsystem Design

- **Isolate spacecraft from Sun/TPS and solar arrays cooling system**
  - Maintain spacecraft behind the TPS within 0.7 AU
  - Minimize thermal coupling between the TPS/TSA and spacecraft
  - Minimize thermal coupling between solar array cooling system and spacecraft
- **Louvers control heat leak**
  - Design minimizes all heat leaks through blankets, structure, etc. (ex. New Horizons)
  - Uses small fixed radiators and louvered radiators to passively adjust heat leak to space
- **Thermally link spacecraft equipment**
  - Share component dissipation to reduce required heater power
  - Radiatively couple all internal components together.
  - Limited use of doublers to spread heat





Thermal Subsystem Design
Spacecraft Thermal Block Diagram



TPS/Struts

TSA Mounted Instruments

SACS (CSPR, Pumps, Lines,…)

CS Pump Elec

CS Accum

SWEM

S/C Mounted Instruments

Thrusters

Prop Tank / Lines

Fields MEP

WISPR DPU

REM

Battery

Battery Radiator/ Louver

Solar Arrays (2)

SACS (Lines)

Actuator (4)

RPM

SSE

RIU (16)

SLS (7)

PSE

ECU

Radiators/ Louvers

HGA

Actuator

IMU

EPC (4)

RWA (4)

MGA (2)

PDU

Radio (2)

TWT (4)

LGA (2)

Panel Heaters (6)

Star Tracker (2)

🟩 Conductive I/F
🟥 Isolated I/F
〰 MLI
🟥 Heater Control (Mission)
🟩 Heater Control (Deploy)
🟦 Passive Control

Thermal Subsystem Design

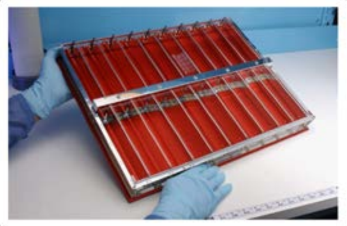
Thermal Hardware

MLI

- Spacecraft MLI (0.01 < ε* < 0.03)
  StaMet over black Kapton/
  Al Mylar/ Dacron net
- High Temp MLI (0.02 < ε* < 0.05)
  Black Kapton/embossed Al Kapton on components above the spacecraft top deck and SACS

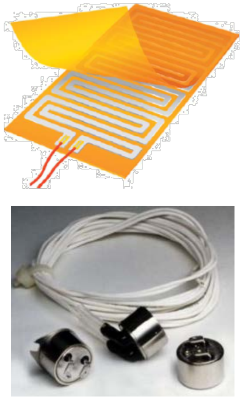
Louvers

- Sierra Nevada Corp.
- Spacecraft quantity:
  2-20 blade
  3-10 blade
  1- 7 blade



Heaters

- Kapton Etched-Foil
- Software and Honeywell 700-series thermostat controlled



Temperature Sensors

- Minco RTDs
  Qty 152, Temp Range: -100 to +100°C
- Lakeshore PT-103 RTD
  Qty 65, Temp Range -175 to +200°C

Thermal Control Coatings: Z-93C55 White Paint (EOL α/ε = 0.45/0.87)

Thermal Subsystem Design

Mass

Name	Mass CBE (kg)
Multi-Layer Insulation	8.2
Radiators (Z-93C55 White Paint)	0.26
Louvers	5.84
Doubler (Al 7075)	0.89
Heaters/RTDs	1.0
Gaskets	1.41
Total Mass (CBE):	17.59
NTE Mass Allocation:	19.82
Margin	12.8%

Thermal Subsystem Design

Heater Power (W)

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Spacecraft Heaters	PC3: Cold Recharge	PC20: Cold Ka-Band Downlink	PC24: Cold Science
Battery	3.0	2.1	2.7
S/A Feather Drive	6.1	5.8	6.5
S/A Flap Drive	2.5	2.5	2.5
Star Tracker	3.5	3.5	0.0
Internal Prop	8.2	0.0	1.2
Total S/C Heater Power	23.3	13.9	12.9
NTE	27.4	16.1	15.0
Margin	17%	17%	16%

Propulsion Heaters	PC3: Cold Recharge	PC20: Cold Ka-Band Downlink	PC24: Cold Science
Thruster Valve Heater	10.8	10.8	5.2
External Prop Line Heater	3.3	3.3	3.3
Total Prop Heater Power	14.1	14.1	8.5
NTE	16.2	16.2	9.8
Margin	15%	15%	15%

Analysis Results

Temperatures (°C) (1 of 2)

Component Name	Allowable Temperature		Temperature Prediction		Margin	
	Min	Max	Min	Max	Min	Max
Telecommunications						
High Gain Antenna	-172	141	-162	131	10	10
Ka-band TWTs	-25	85	10	75	35	**10**
Ka-band EPCs	-25	65	7	47	32	18
X-band TWTs	-25	85	11	51	36	34
X-band EPCs	-25	65	15	45	40	20
Radios	-25	55	17	41	42	14
Guidance and Control						
Inertial Measurement Unit	-25	65	29	44	54	21
Star Tracker	-30	50	-25*	36	**5***	14
Reaction Wheels	-25	55	17	45	42	10
Sun Sensor Electronics Box	-25	65	20	51	45	14
Power						
PSE	-25	55	33	44	58	**11**
Battery	5	35	10*	15	**5***	21
Cooling System						
Motor Controller Electronics	-25	65	17	45	42	20
Accumulator	10	65	20	45	10	20

* Heater Controlled

All temperatures are within limits

Analysis Results

Temperatures (°C) (2 of 2)

Solar Probe Plus

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Component Name	Allowable Temperature		Temperature Prediction		Margin	
	Min	Max	Min	Max	Min	Max
Avionics						
Redundant Processor Module	-25	65	16	48	41	17
Redundant Electronics Module	-25	65	15	50	40	15
Power Distribution Unit	-25	60	14	44	39	16
Remote Interface Units	-25	65	3	48	28	17
Propulsion						
Propulsion Tank/Lines/Valves	10	50	15*	40	**5***	**10**
Mechanical						
Actuator ECU Solar Array & HGA	-25	65	17	49	42	16
Instrument Interface						
SPAN-A+	0	45	14	34	14	11
SPAN-B	5	60	15	46	10	14
ISIS	0	45	10	30	10	15
WISPR	-5	50	6	38	11	12
FIELDS MEP	-25	65	7	46	32	19
WISPR DPU	-25	65	7	38	32	27
SWEAP SWEM	-25	65	13	46	38	19

* Heater Controlled

All temperatures are within limits

Verification

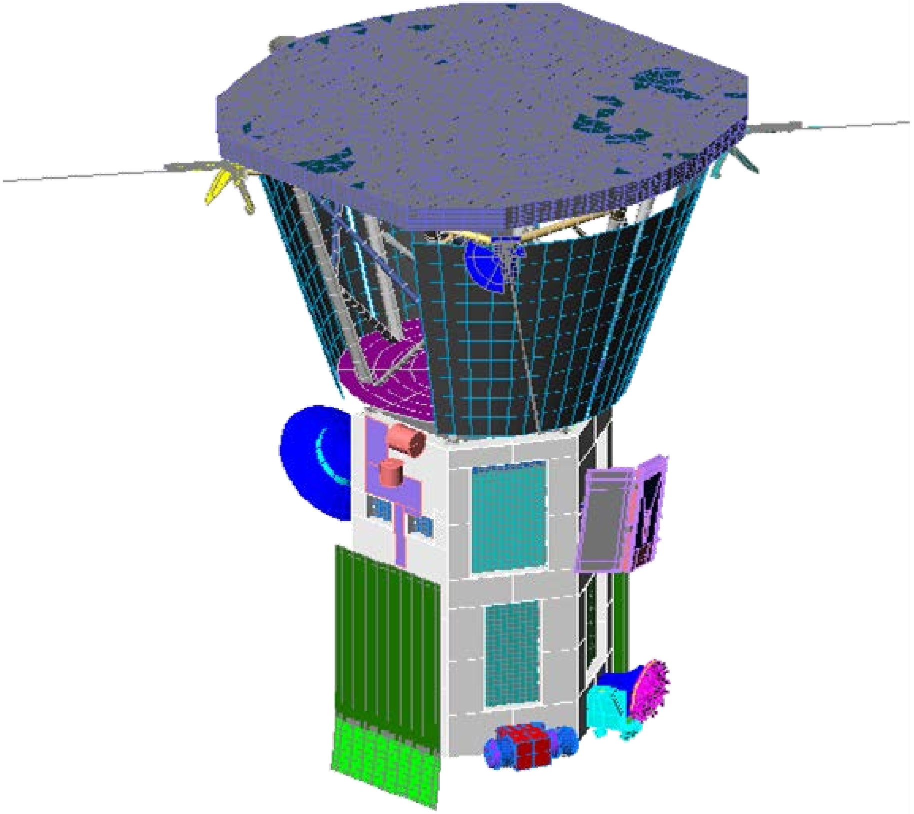
Solar Probe Plus

A NASA Mission to Touch the Sun

- **Analysis**
  - Observatory Thermal Math Model (TMM) will be correlated to test data
- **Testing**
  - **Propulsion Module Thermal Balance Test**
    - Test includes the flight propulsion module and unpopulated spacecraft panels
    - Test will verify the thermal design and heater function of the propulsion system
    - Thermal balance testing at APL
  - **Integrated Thermal Balance Test**
    - Test includes SACS (w/ simulated solar cells), TPS simulator, TSA, TSA mounted instrument simulators and spacecraft top deck
    - Test will verify the thermal design and heat flows between subsystems
    - Test will be used to correlate the thermal design and modify thermal design if necessary
  - **Observatory Thermal Balance and Thermal Cycling Test**
    - Observatory will be as flight like as possible. Will have simulator for TPS and solar cells

Phase C Work

- **Detailed Thermal Hardware Design (Draft Thermal Subsystem Spec)**
  - Louver procurement details
  - Heater pad sizing/layout
  - Sensor layout
  - Thermostat layout
  - MLI specification
- **Analysis Efforts**
  - Integrated modeling
  - Detailed component analysis
- **Testing**
  - Engineering development testing



Summary

- **All trades and engineering tests which were planned for Phase B have been completed**
- **Requirements are understood and documented**
  - Level 4 Thermal Subsystem requirements document released
  - Subsystem and component interfaces are well defined
- **Design conforms to requirements**
  - Thermal analysis results and available test data demonstrate the required margins
- **Open issues are understood and resolved as action items**
  - Subsystem PDR action items are documented in SEM-13-4-511 and tracked in PIMS
- **The Spacecraft Thermal Subsystem is ready to proceed to Phase C**

Solar Probe Plus

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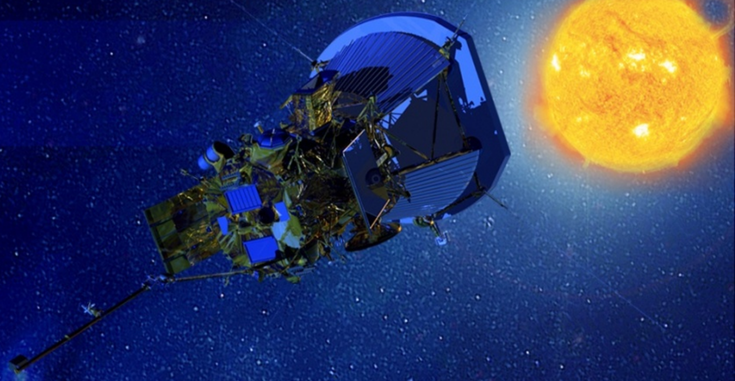

Solar Array Cooling System (SACS)

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Lead SACS Engineer
and
The Hamilton Sundstrand Division of UTAS

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13 – 16 January 2014

APL
The Johns Hopkins University
APPLIED PHYSICS LABORATORY

Solar Array Cooling System Agenda

- Driving Subsystem Requirements

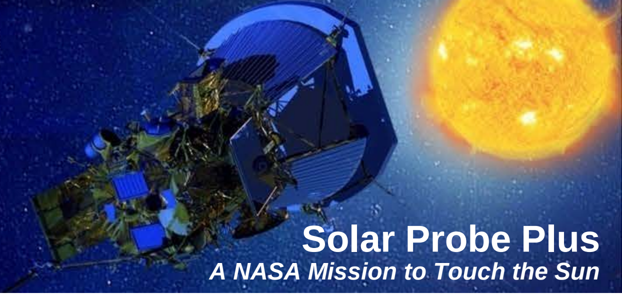
- Design Description
  - key trade results
  - Sample of analysis results
  - mass and power update

- Technology Development
  - Subsystem PDR summary
  - TRL 6 testing

- Verification

- Conclusions

Driving Requirements



Level 4 requirements derived from SPP SCRD 7434-9048

- SPP SACSRD 7434-A002 (in DOORS) and is released in PLM

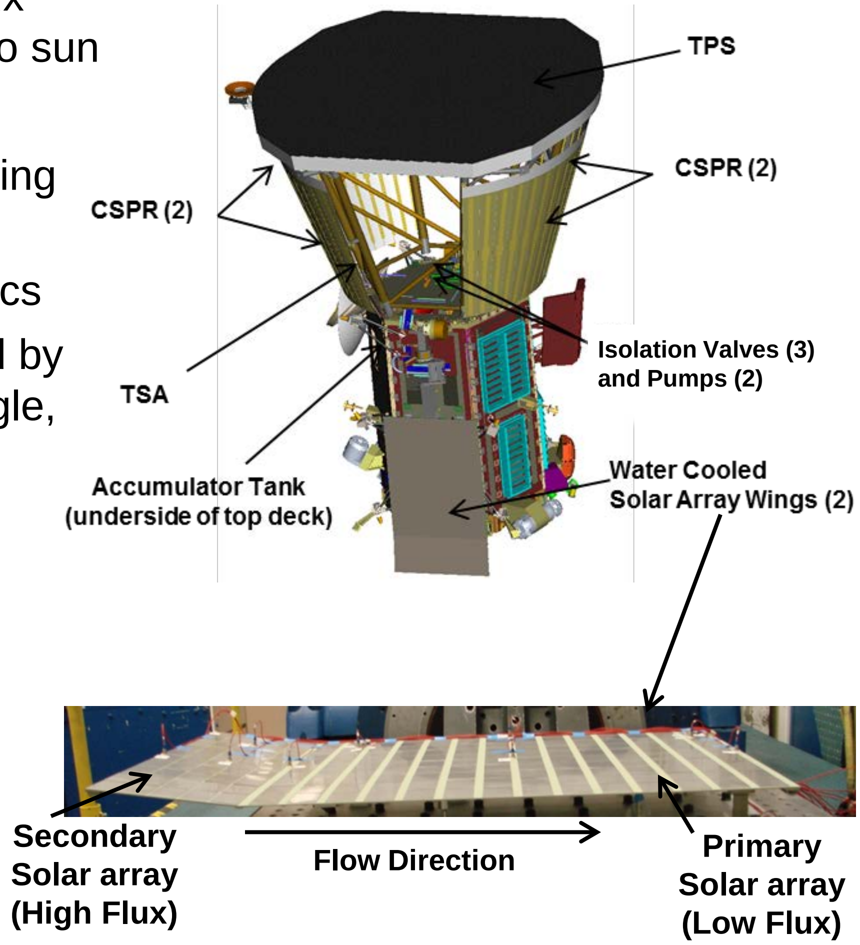
ID	Scope	Description
SACS-2	Subsystem Mass	Launch wet mass NTE ≤ 80.7 kg
SACS-7 SACS-135	Subsystem Electrical Power	Pump designed for two operational speeds, NTE: 40 W (low), 49 W (high)
SACS-6	Mission Trajectory	Mission design: perihelion, aphelion, Venus eclipses, etc.
SACS-9	Single Point Failures	Single point failures/system redundancy:
SACS-61 SACS-37	Coolant Isolation	Isolate coolant in certain parts of the subsystem for various stages of the mission
SACS-22 SACS-26 SACS-45 SACS-19 SACS-23 SACS-38 SACS-42 SACS-58	Thermal/Temperature Constraints	Driving temperature Constraints on the system: • Minimum Op. Temp. Limits • Survival Temp. Limits • Cooling System Capacity • Launch Phase Sun Incidence • Venus Eclipses • Activation Temperature • Continuous Cooling

Solar Array Cooling System

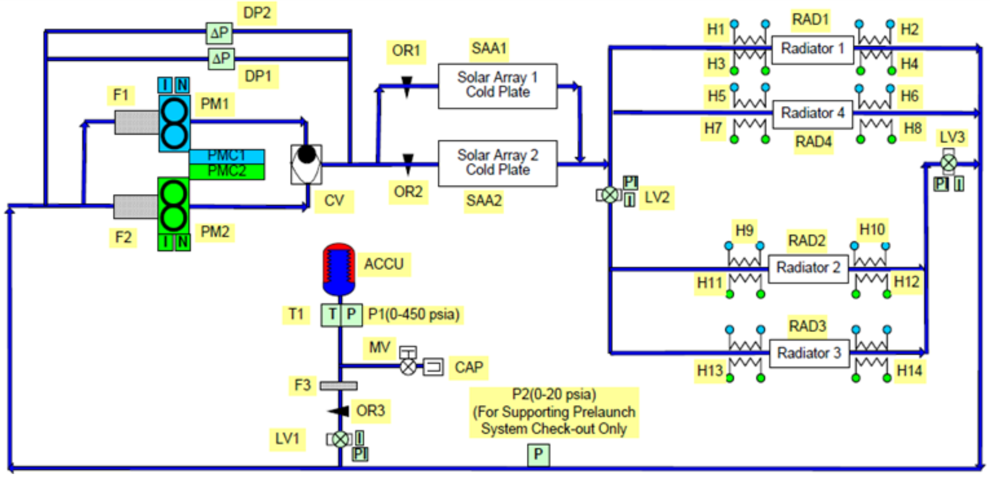
- SPP liquid cooling system dissipates high solar flux absorbed by solar array during closest approach to sun
  - 6480 W cooling system capacity at 9.86Rs
- Water pumped through solar array wings into cooling system primary radiators to dissipate heat.
- Single loop, redundant pump and control electronics
- Cooling system operating temperature determined by solar distance, spacecraft pointing, solar array angle, pump speed (2 speed)
  - Operating temp: +20C to +150C
  - Survival temp: +10C to +190C
  - Survival dry: platen: -90C, cspr: -180C
- Thermal design drivers

Hot
  - 9.86Rs – max cooling system load
  - Communication 45deg slews

Cold
  - 0.73AU – 1.02AU Aphelion
  - Venus eclipse
  - Launch, post launch activation
  - Launch correction



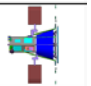
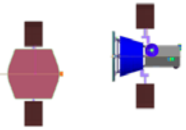
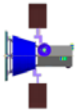
Warming the System Prior to Wetting



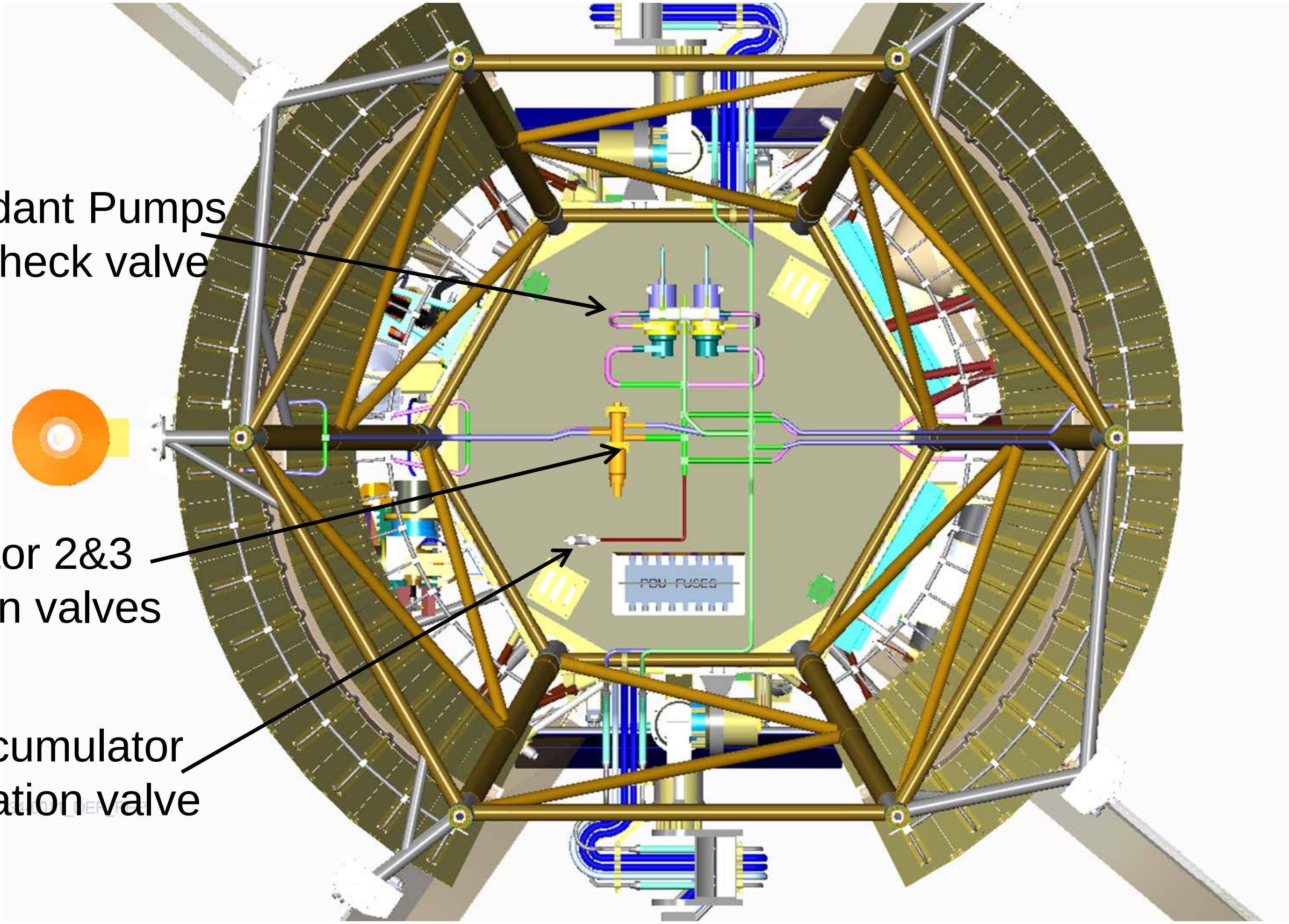
Key System Components

- Accumulator – not redundant
- Pump and Pump Electronics – block redundant
- Solar Array Platens/Cold Plates – not redundant
- Radiators – not redundant
- Isolation Valves – electrically redundant/cross strapped
- Delta Pressure Sensors – redundant/cross strapped

- Launch to Cooling System Activation two hours total:
  - Sequence completed autonomously with ground back-up/monitor
  - Ground station TBD based on launch trajectory
- Activation of cooling system radiators 2 and 3 occurs at solar distance 0.89-0.9AU (~Day 41 / Launch Correction Maneuver completed)
  - Spacecraft slew to “Activate 2&3” pointing orientation
  - Radiator 2&3 warm up to 20C prior to opening valves to flow water through radiators 2&3
  - Ground command sequence

Mission phase	Orbital distanc e	Solar view (TD thermal model)
Launch	1.02 AU	One hour Orientation unknown
Heat Cooling System radiators 1&4 simultaneously	1.02 AU	Ram side to sun 
Launch error correction	1.02 AU	Bounded S/C rotations 
Heat Cooling System radiators 2&3 simultaneously	0.90 AU	

Top Deck Packaging Looking Down

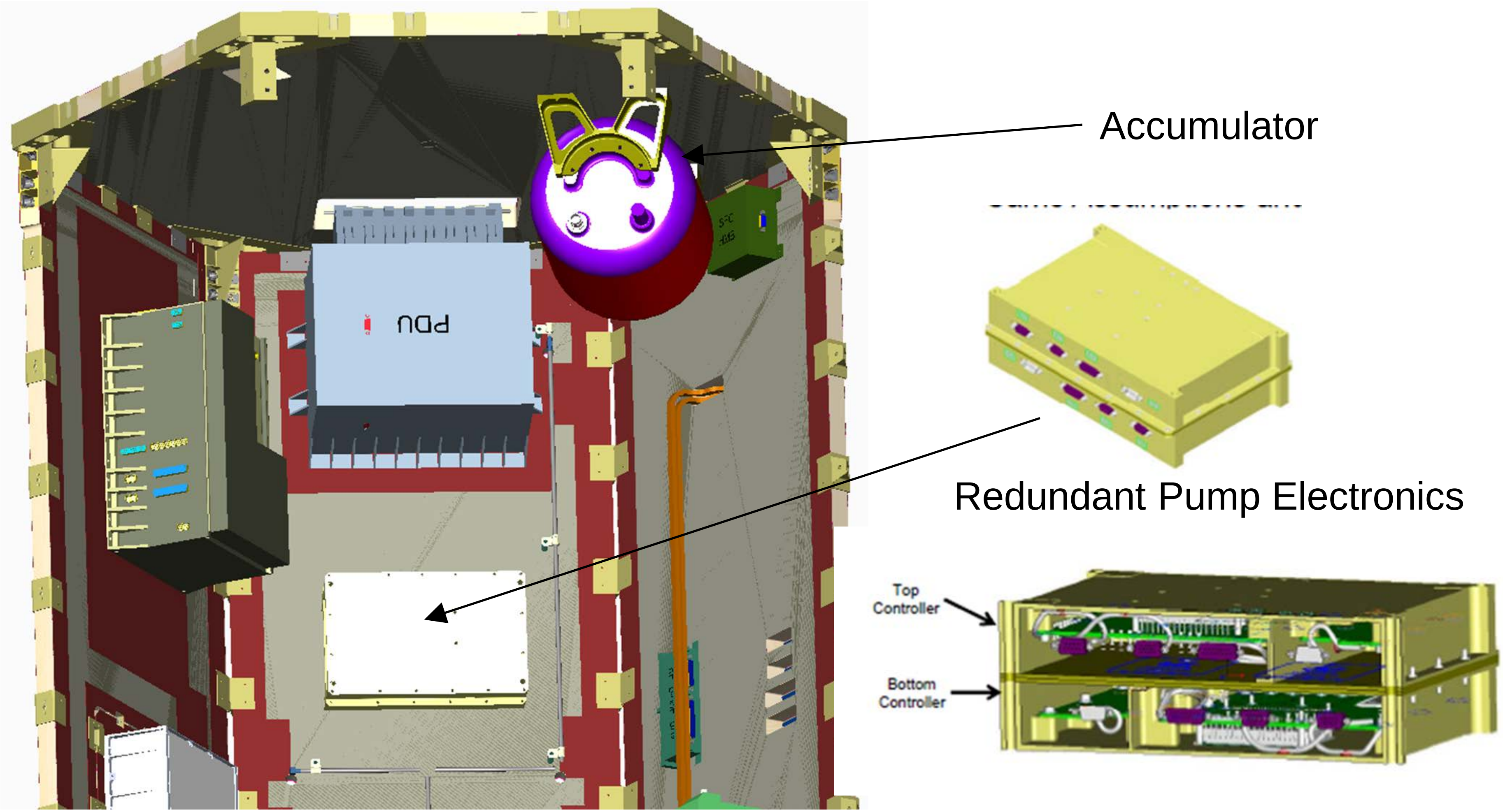


Redundant Pumps
With check valve

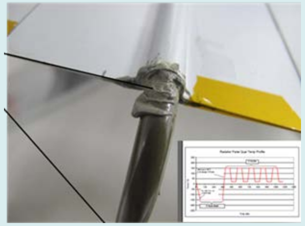
Radiator 2&3
Isolation valves

Accumulator
Isolation valve

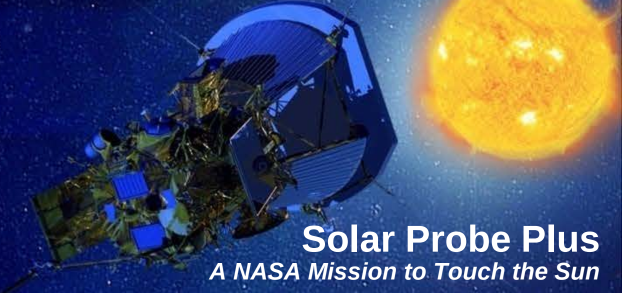
Pump Electronics on Side Panel Below top Deck



SACS Changes Since MDR (1)

MDR Baseline	PDR Baseline	Comment
Un-supported titanium tube bonded to aluminum radiator fins. Radiator fins exhibited adhesive failure at the aluminum interface 	titanium tube bonded to phosphoric acid anodize/BR-127 and mechanically reinforced aluminum radiator fins 	Trade study consisted of four radiator technology approaches that allow titanium tubes to be attached to conductive fins: reinforced bonded, Alum. Cold Spray, Al-Si-C, C-C composite. Technology trade established a reinforced bonded radiator design the most feasible from a schedule, technology risk and cost perspective. Full sized radiator assembly has successfully passed extend range thermal cycle (-180 C to +180 C)
Radiators coated with pattern of conductive white and black paint	Eliminate white paint. Radiators to be painted with Z-307 conductive black paint	Black paint helps to decrease post launch warm-up time and helps to simplify manufacturing. Eliminates uncertainty in optical properties
Accumulator designed for 300 psia charge	Accumulator designed for 400 psia charge	As charge pressure increases, weight (and volume) of the accumulator decreases. Increasing the pressure further has a minimal mass and volume benefit
Accumulator on outboard side of top deck	Accumulator moved to inboard side of top deck	Eliminates the need for heater power

Solar Array Cooling System Changes Since MDR (2)



MDR Baseline	PDR Baseline	Comment
No manifold heaters	Heaters added to manifolds	Eliminates the risk of cold spots and reduces radiator warm-up time
Single speed pump control	Discrete speed (two) pump control via programmable FPGA	Lower speed (~1/2 max flow rate) reduces power when near aphelion with no impact on solar array thermal control
Platen constructed of CP-4 and 6AL-4V titanium	Platen constructed completely of CP-4 titanium	Per NASA-STD-6016 Commercially Pure (CP) titanium shall not be in combination with 6Al-4V titanium alloy; over extended time hydride formation can occur in the weld, which can produce a brittle, catastrophic failure. Weight impact is ~ 0.9 kq increase. Identified when M&P control plan was released in late Nov. 2012.
Eight latching valves	Three isolation valves	Reduces mass and operational complexity
Flow schematic	Updated flow schematic	Includes the addition of redundant delta-P sensors, pressure transducers, and manifold heaters

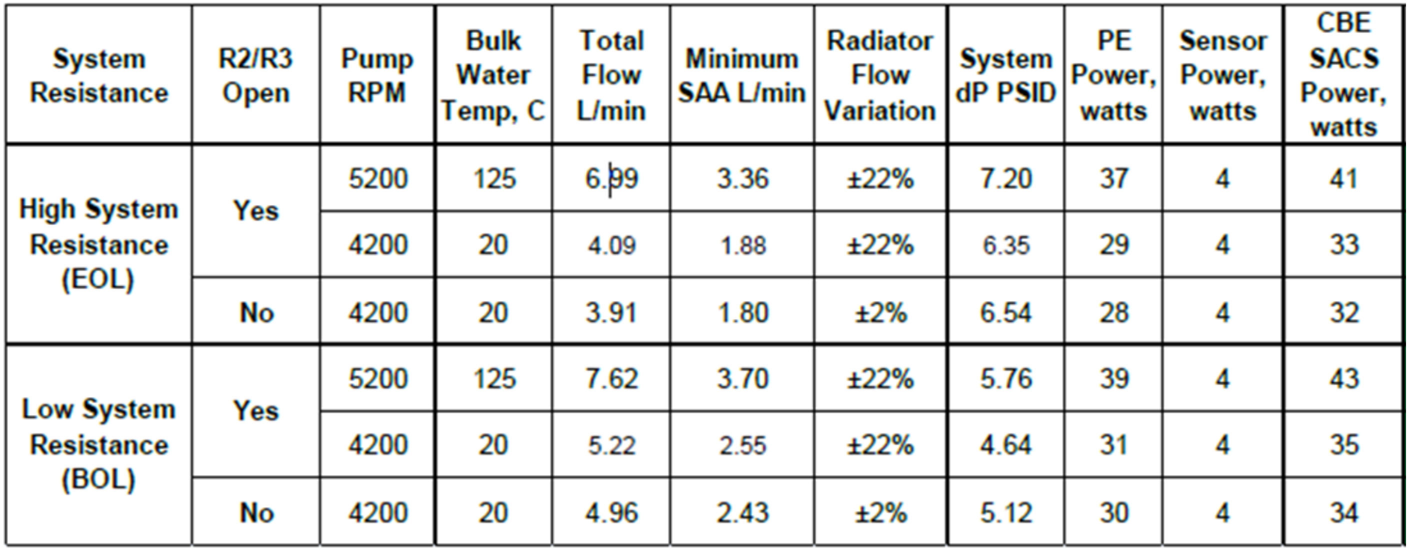
Cooling System Mass Estimates

	Qty	CBE Each (kg)	CBE Total (kg)	NTE (kg)
Cooling System Total:			72.91	80.65
Solar Array Substrate (platen)	2	11.73	23.46	25.81
Radiators(CSPR), Paint (4.4m2 total)	4	4.84	19.36	21.30
Pumps and Check Valve Assy	1	3.81	3.81	4.19
Pump Electronics	1	4.33	4.33	4.76
Accumulator	1	5.51	5.51	6.06
Accumulator Brackets	1	0.81	0.81	0.91
Isolation Valves	3	1.02	3.06	3.45
Harness, Motor Controller	4	0.24	0.96	1.08
Differential Pressure Sensors	2	0.18	0.36	0.41
Pressure Sensors	2	0.18	0.36	0.41
Fill and Drain	2	0.11	0.22	0.25
Fluid Lines	1	3.07	3.07	3.46
Flexible Cooling Lines	8	0.29	2.32	2.62
Mounting Hardware	1	0.36	0.36	0.41
Fluid	1	4.92	4.92	5.55

Summary	
CBE Total Mass (kg):	72.9
NTE Mass Allocation (kg):	80.7
Contingency	10.6%

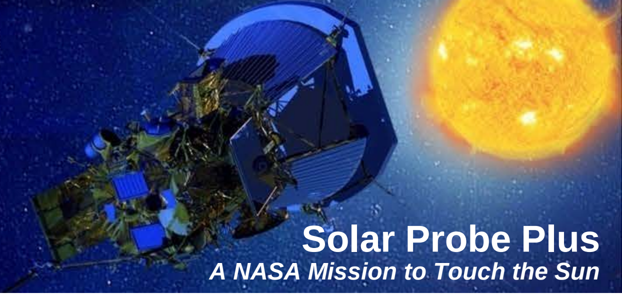
- **Cooling System CBE and NTE assume the 4.4m2 radiators and 0.69m wide platen.**
- **Mass will be adjusted based on radiator and platen size decision in early Phase C.**

Cooling System Power Estimates



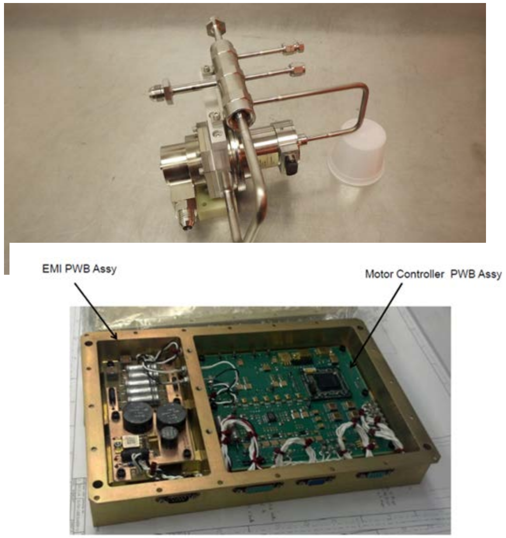
System Resistance	R2/R3 Open	Pump RPM	Bulk Water Temp, C	Total Flow L/min	Minimum SAA L/min	Radiator Flow Variation	System dP PSID	PE Power, watts	Sensor Power, watts	CBE SACS Power, watts
High System Resistance (EOL)	Yes	5200	125	6.99	3.36	±22%	7.20	37	4	41
		4200	20	4.09	1.88	±22%	6.35	29	4	33
	No	4200	20	3.91	1.80	±2%	6.54	28	4	32
Low System Resistance (BOL)	Yes	5200	125	7.62	3.70	±22%	5.76	39	4	43
		4200	20	5.22	2.55	±22%	4.64	31	4	35
	No	4200	20	4.96	2.43	±2%	5.12	30	4	34

Pump Speed	CBE Power (W)	NTE Power (W)	Contingency
Low	35	40	14%
High	43	49	14%

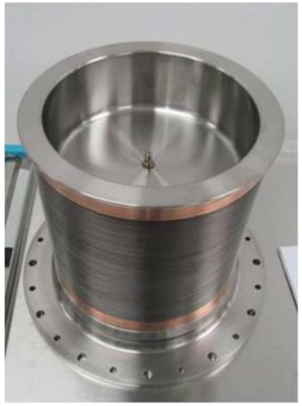


Key Hardware Development To Support TRL-6

Key Phase B development

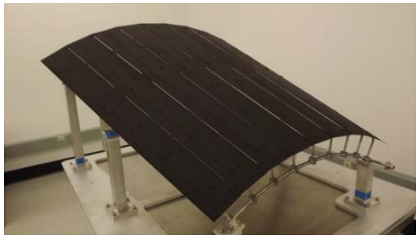


Pump assembly and Pump Controller Electronics



Welded titanium accumulator bellows

Full sized Platens/Cold Plates



Full sized Radiators

Integrated Half-System Prototype

TRL-6 Testing

SACS PDR Review Panel

Reviewer	Organization
Mechanical/Thermal Review	
Steve Rickman (Chair)	NASA/NESC, JSC
David Steinfeld (SRB)	NASA, GSFC
Henry Rotter	NASA/NESC, JSC
Gary Kinsella (SRB, dial-in)	NASA, JPL
David Persons	JHUAPL
Clint Apland	JHUAPL
Barney Gorin	GoVentures
Electrical Review	
Marty Fraeman (Chair)	JHUAPL
Paul Schwartz	JHUAPL
Steve Battel (SRB)	Battel Engineering

SACS PDR Review Summary

- **Electrical PDR (October 23, 2013)**
  - **Summary memo SEE-13-096**
    - **21 Actions / 9 Advisories**
    - **Other than the actions noted, the review board was satisfied with material as presented.**

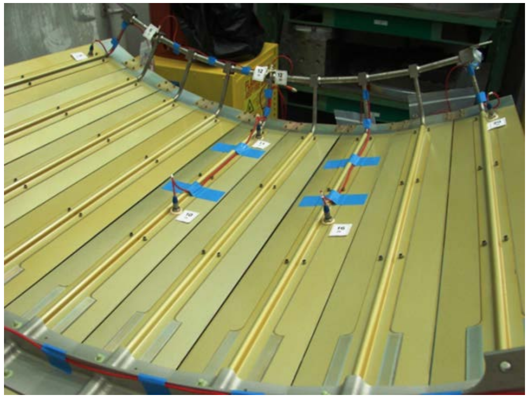
- **System PDR (December 2-5, 2013)**
  - **The review memo has been released and the conclusions from the PDR are summarized as follows:**
    - **“Comprehensive presentations were given by SACS subject matter experts and provided an excellent forum for discussion. The presenters were very responsive to questions from the review board. Review team members provided technical review and comment during the meetings and formulated notes as well as Requests for Action (RFA). RFAs could be considered as actions, concerns or recommendations. RFAs are summarized in the text below and a complete listing of RFAs is provided in the Appendix. In summary, there were 21 actions, 0 concerns, and 21 recommendations identified by the review board.”**
- **It is the unanimous opinion of the review board that all review goals were met and the maturity and system TRL-6 readiness of the SPP SACS design met the success criteria.**

Technology Assessment

Component	MDR TRL	PDR TRL	Remarks
System	5	6	Half system with full scale hardware was built and tested in relevant thermal environments during Phase B
Pump	6+	6+	Full scale pump and check valve assembly was fabricated and tested during Phase B
Radiator	5	6	Three full scale (1.0 sqm) radiators were fabricated and were structurally (unit 1 / random vib) and thermally (units 2&3 in the half system prototype) tested.
Flex Hose	6	6	Space Station Ammonia and Shuttle Freon Loop utilize Fluid Loop Flex Hoses
Solar Array Platen	5	6	Three full sized platens were fabricated and were thermally and structurally test during Phase B.
Accumulator	6+	6+	Welded titanium bellows was fabricated and used in the half system thermal prototype
Pump Electronics	4 - 5	6	Back EMF controller was successfully developed and used in closed loop with the pump during Phase B half system thermal testing

SACS Prototype Testing Summary

- Thermal test prototype has been delivered to APL for TV testing.
  - Fabricated half cooling system prototype using full size flight like components
    - Two full scale radiators (1.0 sqm each)
    - One full scale platen (0.65m wide)
    - Single string pump and controller electronics
    - Flight like welded titanium bellow used in the accumulator
    - Engineering model latching valves
  - **Half system thermal design verification test was successfully completed on November 17, 2013**
- Qualification level three axis random vibration testing:
  - Structural radiator was successfully completed on June 13, 2013
  - Structural platen was successfully completed on July 16, 2013
- Two full sized secondary and one full sized platens for EMCORE solar array testing have been delivered

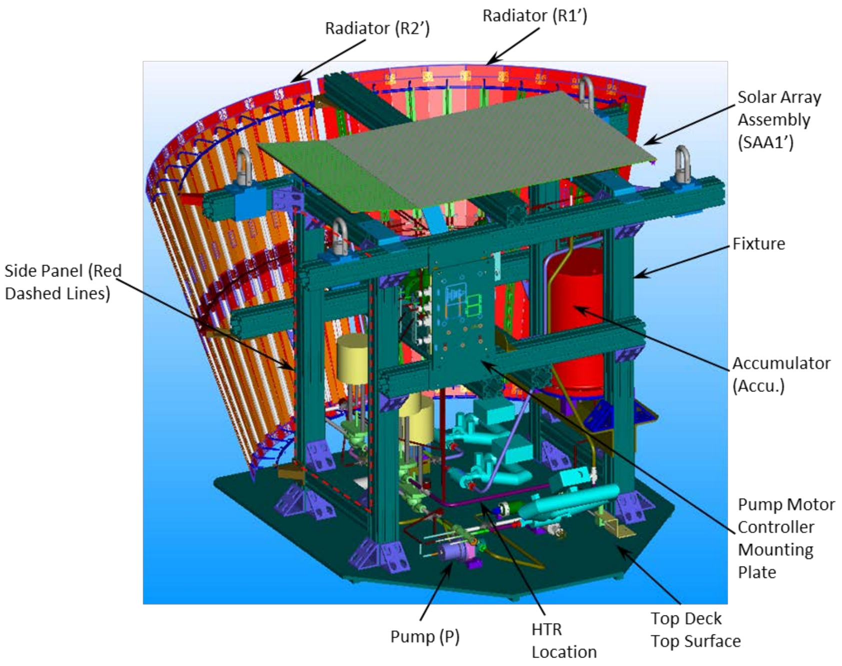


Radiator survived RV testing and extended range thermal testing

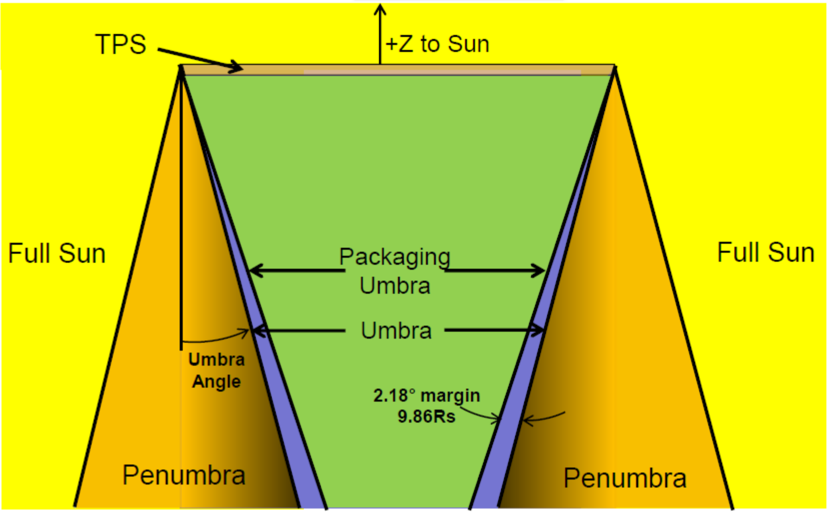
**Half size cooling system
TRL-6
thermal prototype**

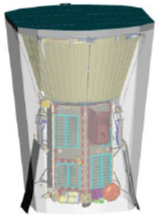
Thermal Design Verification Test (TDVT) Description

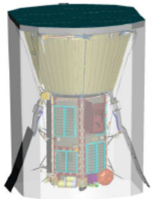
- **Key Objective – Demonstrate TRL 6 of the SPP Thermal Control System, Solar Array Cooling System (SACS)**
  - **Objective met by fabricating and testing a full-size prototype system representing half of the solar array cooling system**
- **Verified acceptable steady state and transient system thermal performance over a wide range of thermal environments representing key mission points**
  - **Near Earth aphelion**
  - **Venus eclipse**
  - **Radiator slew attitudes**
  - **Mission Perihelion**
    - **Steady State**
    - **Transients**
- **Test utilized flight prototype pump & electronics, solar array platen, welded titanium bellows accumulator and Z307 painted radiators**

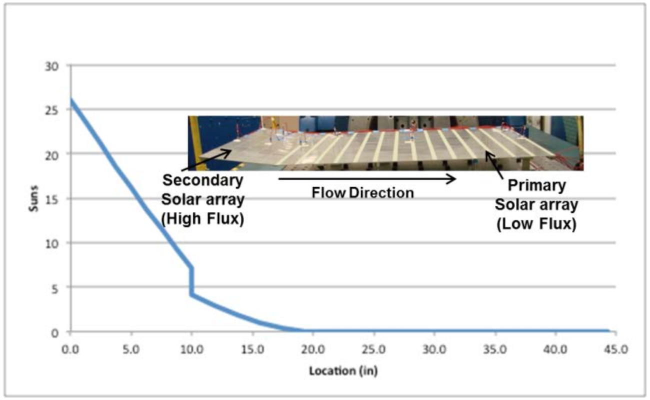


High Flux Heat Load Analysis




9.86Rs


0.25AU

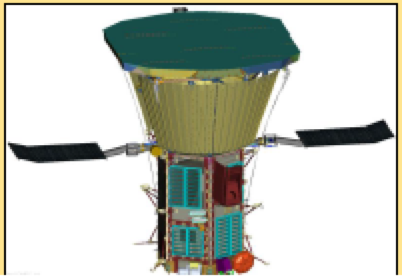


9.86 Rs
(~26 suns)

54 Rs
(~ 6 suns)

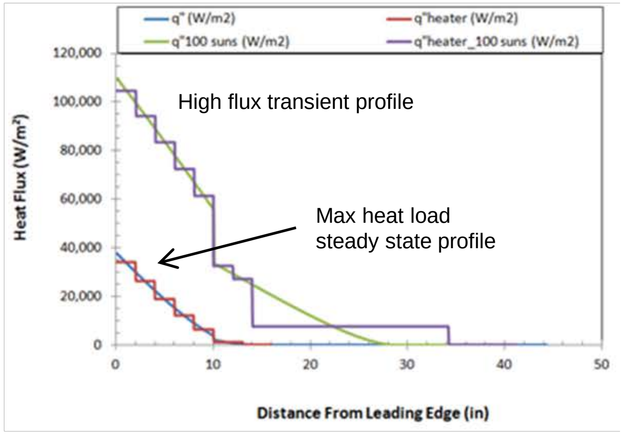
150 Rs
(~ 2 suns)

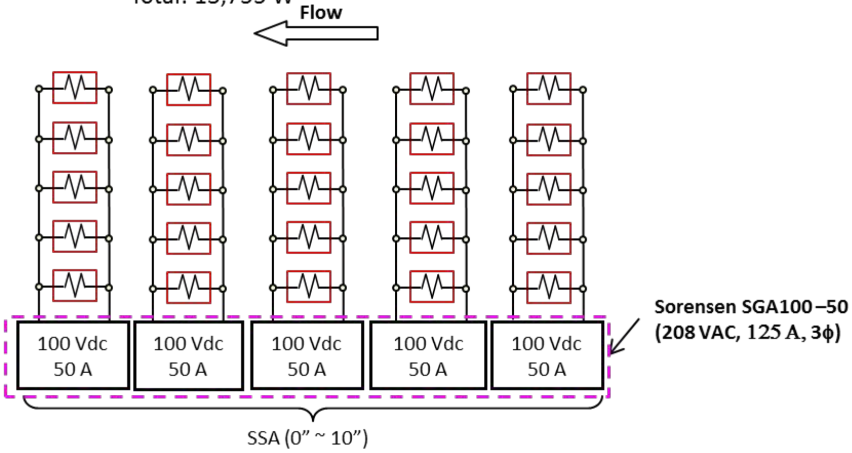
Solar Array Position

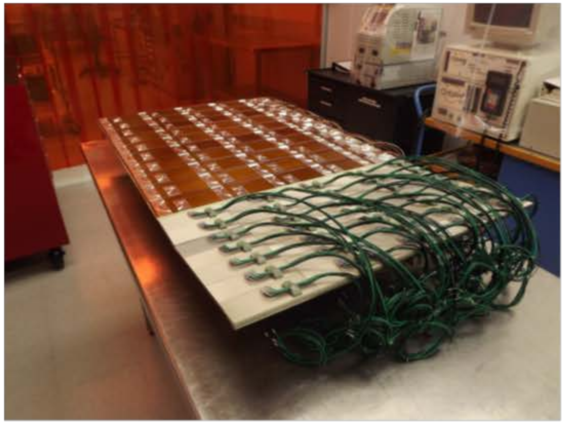


Applying Heat into the System: Platen

- Heaters:
  - Type: Ceramic (AlN) with embedded type T thermocouple
  - Quantity: 25 pcs
  - Dimensions: 5.1” (lateral direction) x 2” (flow direction)
  - Resistance/Each: 12.5 Ω/ea (Determined by 100 suns flux)
  - Wiring: Parallel within string
  - Total Resistance/String: 2.5 Ω/string
- Power Supplies:
  - Rating: 5,000 W (100 Vdc, 50 A)
  - Quantity: 5
  - Maximum Power:
    - In-Orbit:
      - Peak: 1,128 W/ea (Perihelion, First String)
      - Total: 3,240 W (Perihelion)
    - High Suns (100 suns, TBD):
      - Peak: 3,460 W/ea (First String)
      - Total: 13,755 W







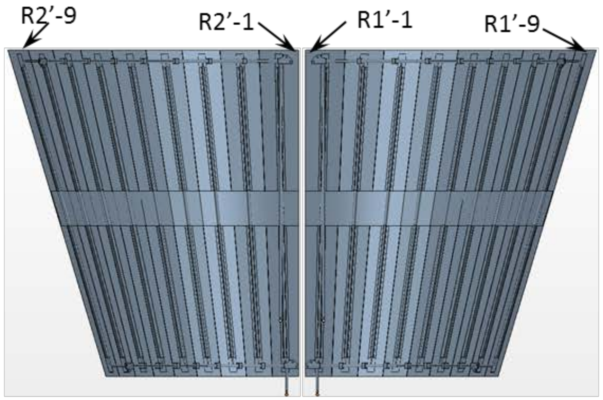
High power ceramic and conventional kapton heaters are installed on the thermal test platen to simulate the expected solar array environments

Applying Heat into the System: Radiators

Radiator Panel Heater Specifications:

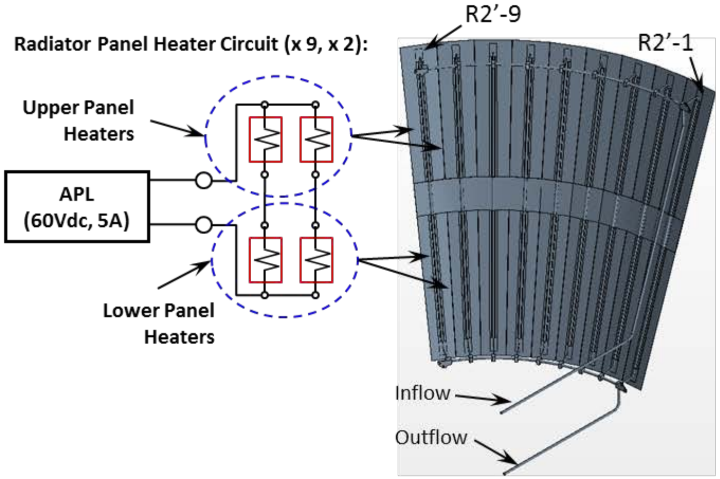
Item	Dimensions	R (Ω/ea)	R (Ω/total)	Qty.	Q_{max} (W)	Q_{min} (W)	V_{max} (Vdc)	V_{min} (Vdc)	I_{max} (A)	I_{min} (A)
Upper	1.45" x 17.6"	12.0	12.0	36	173.5	12.5	41.3	16.6	4.2	1.3
Lower	1.0" x 17.0"	8.0	8.0	36						

Kapton film heaters are installed on the thermal test radiators to simulate the expected mission environments



Interior View of R1'-R2'

Radiator Panel Heater Circuit (x 9, x 2):



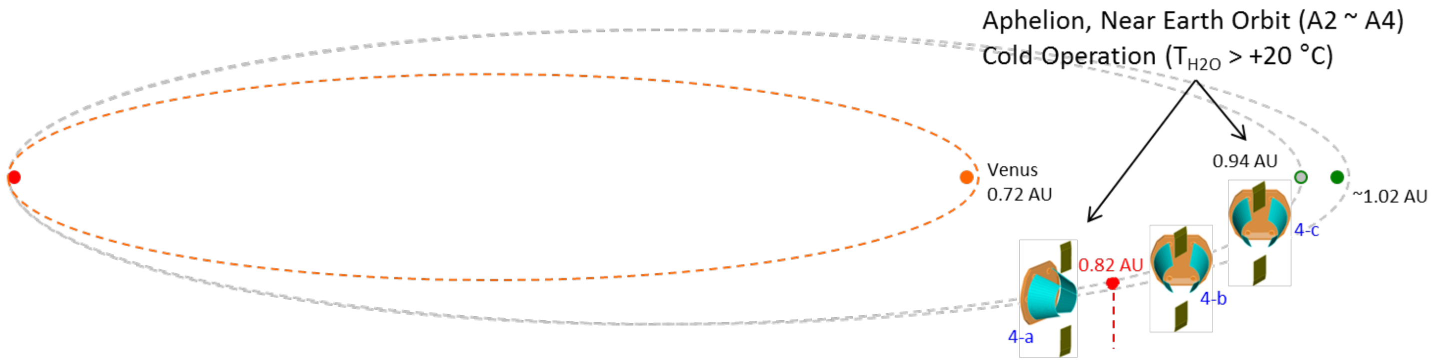
Isometric View of R2'

TDVT Test Results Summary (Cold Cases / near Aphelion)


Solar Probe Plus
A NASA Mission to Touch the Sun

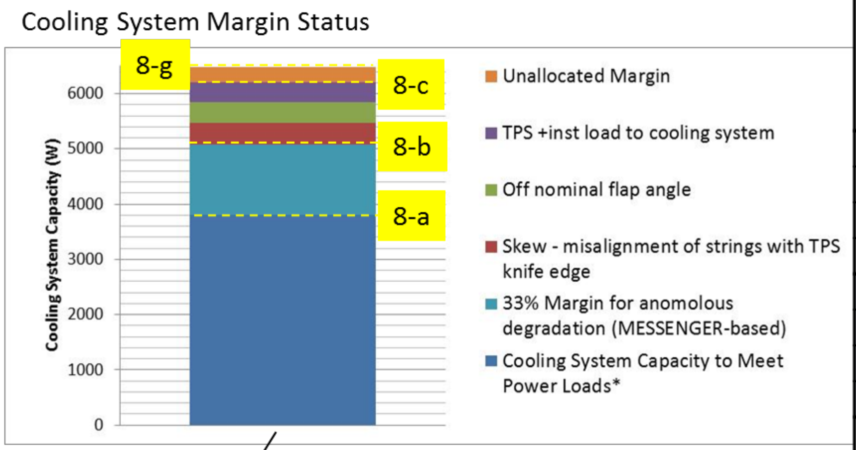
	Heat Load (W)			Water Temperature (°C)				
	Q_{SAA}	$Q_{R1'}$	$Q_{R2'}$	Pump Inlet	SAA1' Inlet	SAA1' Outlet	R1' Outlet	R2' Outlet
4-a Model	1068.5	0.0	0.0		30.1	33.9	30.1	30.1
4-a T-VAC	1085.0	0.0	0.0	32.1	32.0	35.9	31.9	32.1
Model - TVAC	(16.5)	0.0	0.0		(1.9)	(2.0)	(1.8)	(2.0)
Margin[1]	N/A			+11.9				
4-b Model	1068.5	0.0	576.2		66.6	69.6	63.9	69.3
4-b T-VAC	1069.7	0.0	567.0	66.5	64.6	68.1	62.3	66.5
Model - TVAC	(1.2)	0.0	9.3		2.0	1.5	1.6	2.8
Margin[1]	N/A			+42.3				
4-c Model	813.1	0.0	438.5		44.4	46.7	42.3	46.4
4-c T-VAC	810.0	0.0	439.5	44.0	42.5	45.1	40.8	44.2
Model - TVAC	3.1	0.0	(1.0)		1.9	1.6	1.6	2.2
Margin[1]	N/A			+20.8				

1. Margin = Lowest TVAC Water Temperature - 20 °C


Aphelion, Near Earth Orbit (A2 ~ A4)
Cold Operation (T_{H2O} > +20 °C)

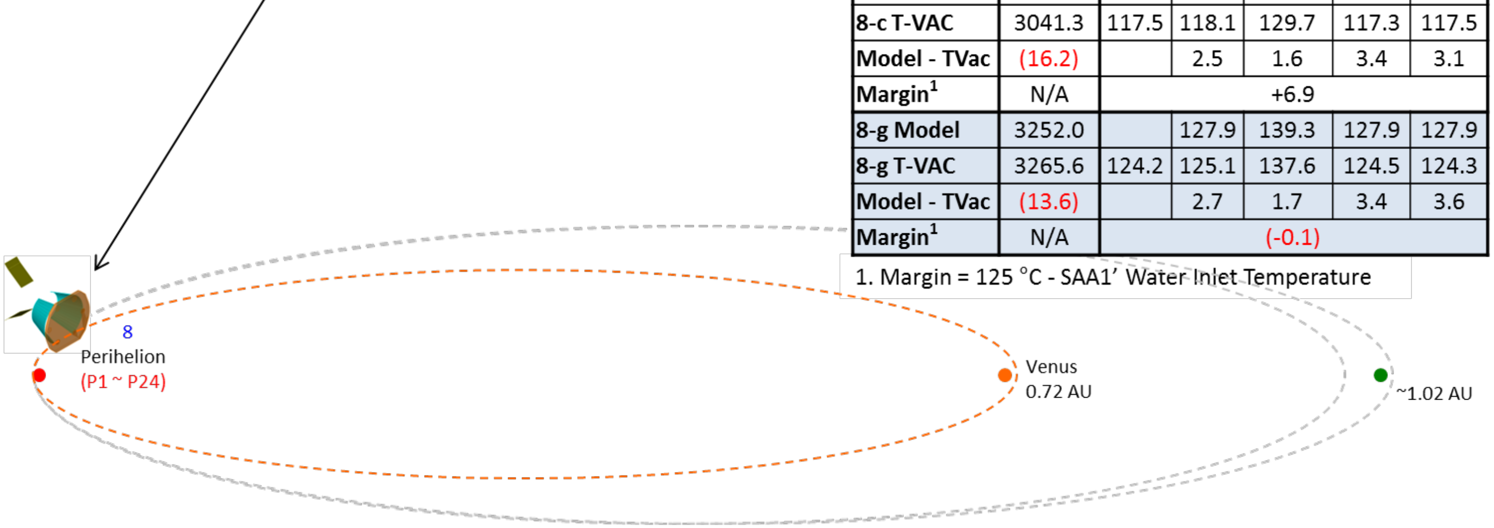
TDVT Test Results Summary (Hot Cases / near Perihelion)

Cooling System Margin Status

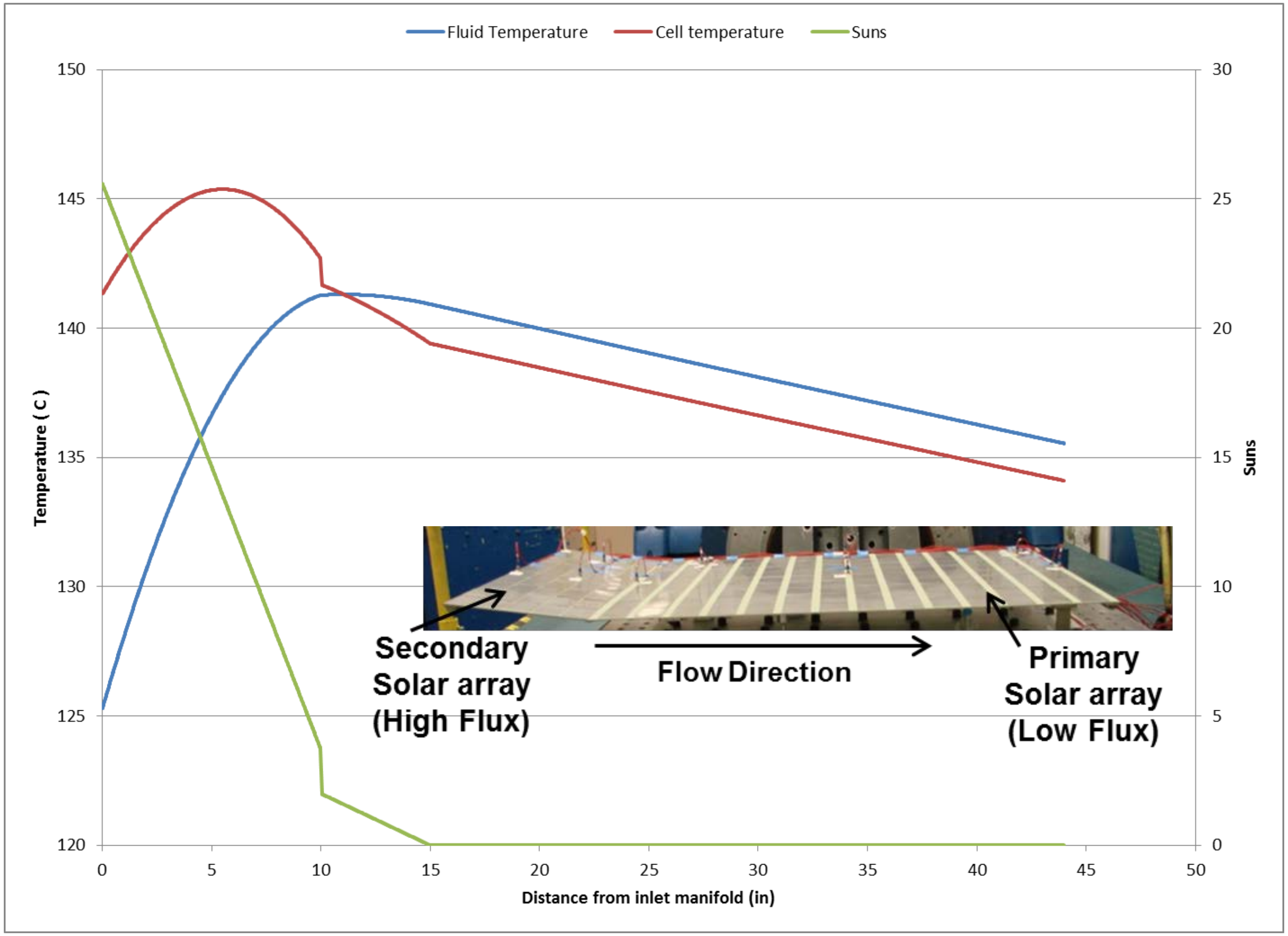


	Heat Load (W)	Water Temperature (°C)				
	Q_{SAA}	Pump Inlet	SAA1' Inlet	SAA1' Outlet	R1' Outlet	R2' Outlet
8-a Model	2056.4		84.2	91.5	84.2	84.2
8-a T-VAC	2057.8	83.3	84.1	92.0	83.7	83.4
Model - TVAC	(1.4)		0.1	(0.5)	0.5	0.8
Margin[1]	N/A	+40.9				
8-b Model	2520.9		102.9	111.8	102.9	102.9
8-b T-VAC	2541.5	102.0	102.5	112.1	101.8	102.1
Model - TVac	(20.5)		0.4	(0.3)	1.1	0.8
Margin[1]	N/A	+22.5				
8-c Model	3025.1		120.6	131.3	120.6	120.6
8-c T-VAC	3041.3	117.5	118.1	129.7	117.3	117.5
Model - TVac	(16.2)		2.5	1.6	3.4	3.1
Margin[1]	N/A	+6.9				
8-g Model	3252.0		127.9	139.3	127.9	127.9
8-g T-VAC	3265.6	124.2	125.1	137.6	124.5	124.3
Model - TVac	(13.6)		2.7	1.7	3.4	3.6
Margin[1]	N/A	(-0.1)				

[1] Margin = 125 °C - SAA1' Water Inlet Temperature



High Flux SS Temperature Profile Example : 9.86 Rs, 26 Suns



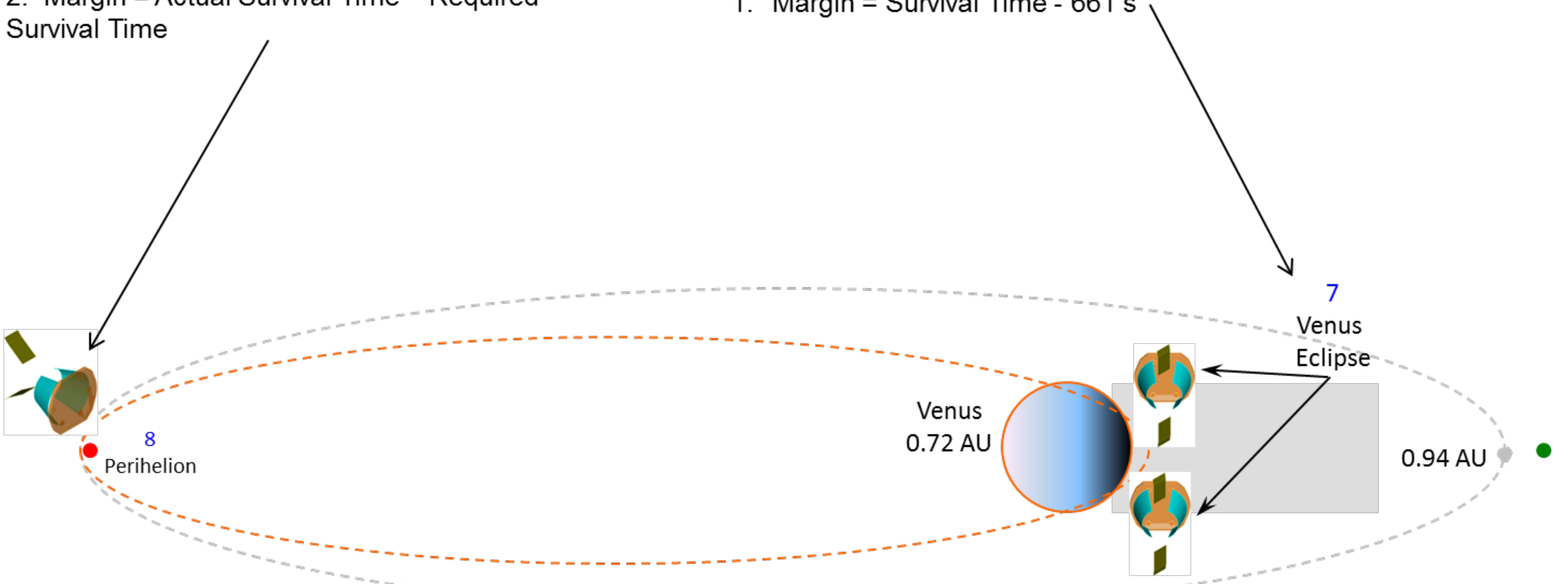
TDVT Test Results Summary (Hot & Cold Transients)

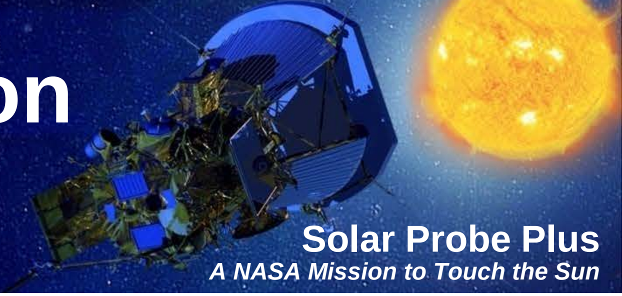
	Heat Load Q_{SAA}[1] (W)	Survival Time (mm:ss)		
		Required	Actual	Margin[2]
Case #1	16,000	00:28	05:46	05:18
Case #2	13,000	00:40	07:24	06:44
Case #3	12,000	01:20	11:50	10:30

1. Anomaly Full System Heat Load
2. Margin = Actual Survival Time – Required Survival Time

	Heat Load (W)			Survival Time (mm:ss)	Remark
	Q_{SAA}	$Q_{R1'}$	$Q_{R2'}$		
7-a	0.0	0.0	0.0	38:12	Lowest SACS Water Temperature > +20 °C , Pump On
Margin[1]	N/A			+27:11	
7-b	0.0	0.0	0.0	12:31	Lowest SACS Water Temperature > +20 °C, Pump Off
Margin[1]	N/A			+1:30	

1. Margin = Survival Time - 661 s



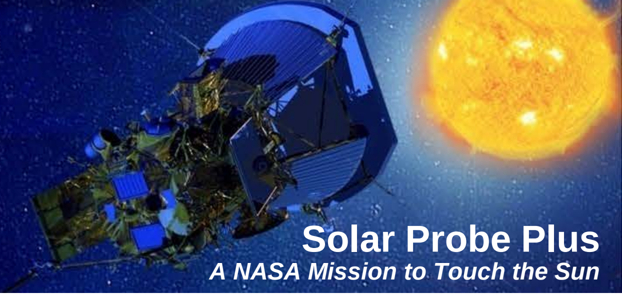


SACS Flight System Verification and Testing

- **Component level Vibration and thermal cycling**
  - Per EDTRD

- **Post flight system integration Thermal Design Verification Test**
  - Includes multi-subsystem
    - Subset of what was done during Phase B

- **System Level Observatory testing**
  - Vibration
  - Acoustics
  - Thermal Vacuum
  - System functional and performance



Phase C Work

- **Detailed Flight System Design and Manufacturing**
  - Baseline is the Phase B design

- **Integrated Analysis Working Group**
  - Begin monthly cooling system/power system working group to synchronize modeling efforts with recent thermal vacuum testing results

- **Testing**
  - Pump life test (using Phase B pump assembly)
    - Per HSSSI test plan

Conclusions

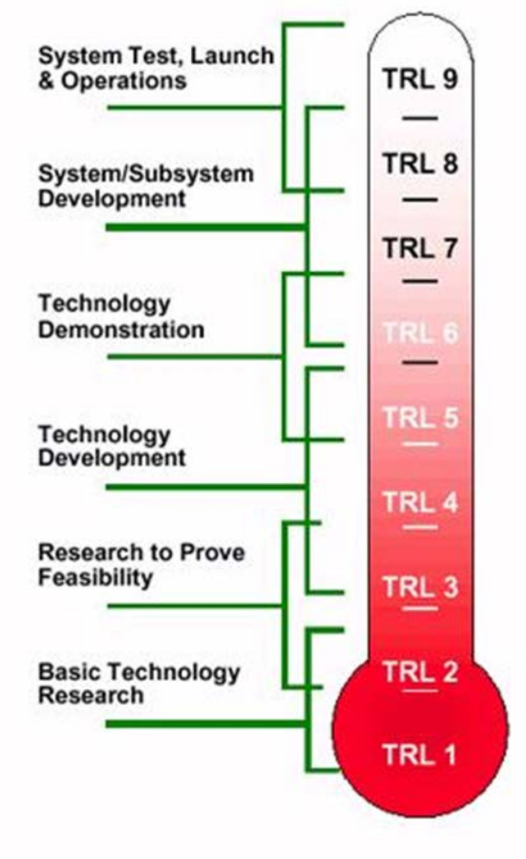
- **SACS requirements are well understood**
- **Approach to meeting requirements has been demonstrated**
- **Design is at PDR level of maturity**
- **Key interfaces are defined**
- **Preliminary modeling/analyses demonstrate compliance**
- **Mass, power, and size estimates are well substantiated**
- **TRL-6 has been assessed and is suitable for PDR level**
- **Verification approach is established**
- **Risk areas have been identified and mitigation plans are in place**
- **Lessons learned have been reviewed and are being applied**
- **Phase C/D plans are in place**

The SACS is ready for Phase C/D

Backup

TRL Definition

- • TRL 9 Actual system flight proven through successful mission operations.
- • TRL 8 Flight System completed and qualified through test and demonstration.
- • TRL 7 System prototype demonstrated in a space environment.
- • TRL 6 System Prototype Demo in Relevant Environment - By 06/23/2011 (PDR)
- • TRL 5 Component and/or breadboard validated in relevant environment.
- • TRL 4 Component and/or breadboard validated in laboratory environment.
- • TRL 3 Critical function or characteristic demonstrated (proof-of-concept).
- • TRL 2 Technology concept and/or application formulated.
- • TRL 1 Basic principles observed and reported.



SACS Description

- **The SPP Solar Array Cooling System (SACS), is a pump-driven actively cooled system comprised of three primary elements: a redundant pump package, two solar array assembly heat exchangers (cold plates), and four Cooling System Primary Radiator panels (CSPR) isolated with three latching valves to allow selective activation and wetting of the system. The heat exchangers are micro-channel etched titanium plates through which the working fluid, water, is forced via a sensor-less DC motor-driven pump to absorb waste heat. After rejecting the absorbed waste heat through the radiator panels, the cold coolant returns to the pump and completes the cycle. The back sides of each Solar Array Assembly (SAA) and each radiator panel are covered with MLI so as to minimize heat exchange with the spacecraft and to also aid in Micrometeoroids and Orbital Debris (MMOD) protection.**

ConOps (1)

- **From before launch until activation, the water necessary to wet the entire cooling system is contained in the accumulator. The accumulator is separated from the rest of the cooling system by isolation valves and it contains enough water to fill the entire cooling system once activation is completed.**
- **The accumulator uses a welded metal bellows to separate the water coolant from the integral pressure vessel that contains the gas charge to pressurize the system prior to pump activation.**
- **Within 60 minutes (TBR) after launch the spacecraft is slewed to ~45° off-TPS-normal towards radiators 1 and 4 and the SAA's are deployed and positioned nearly normal to the sun. For about 60 minutes, radiators 1 and 4, the SAA's, and critical cooling system supply and return fluid lines are warmed by solar heating augmented with strategically placed electric heaters. During this initial warming period the solar cells are producing power although coolant is not yet flowing through the wings. Once the bulk temperature of each wing and the radiators is at or above 20 C the accumulator isolation valve (SV1) is commanded open and the pump controller electronics and a single pump are activated. Water begins to flow through each of the SAA wings and radiators 1 and 4 while radiators 2 and 3 remain dry and isolated form the water flow.**

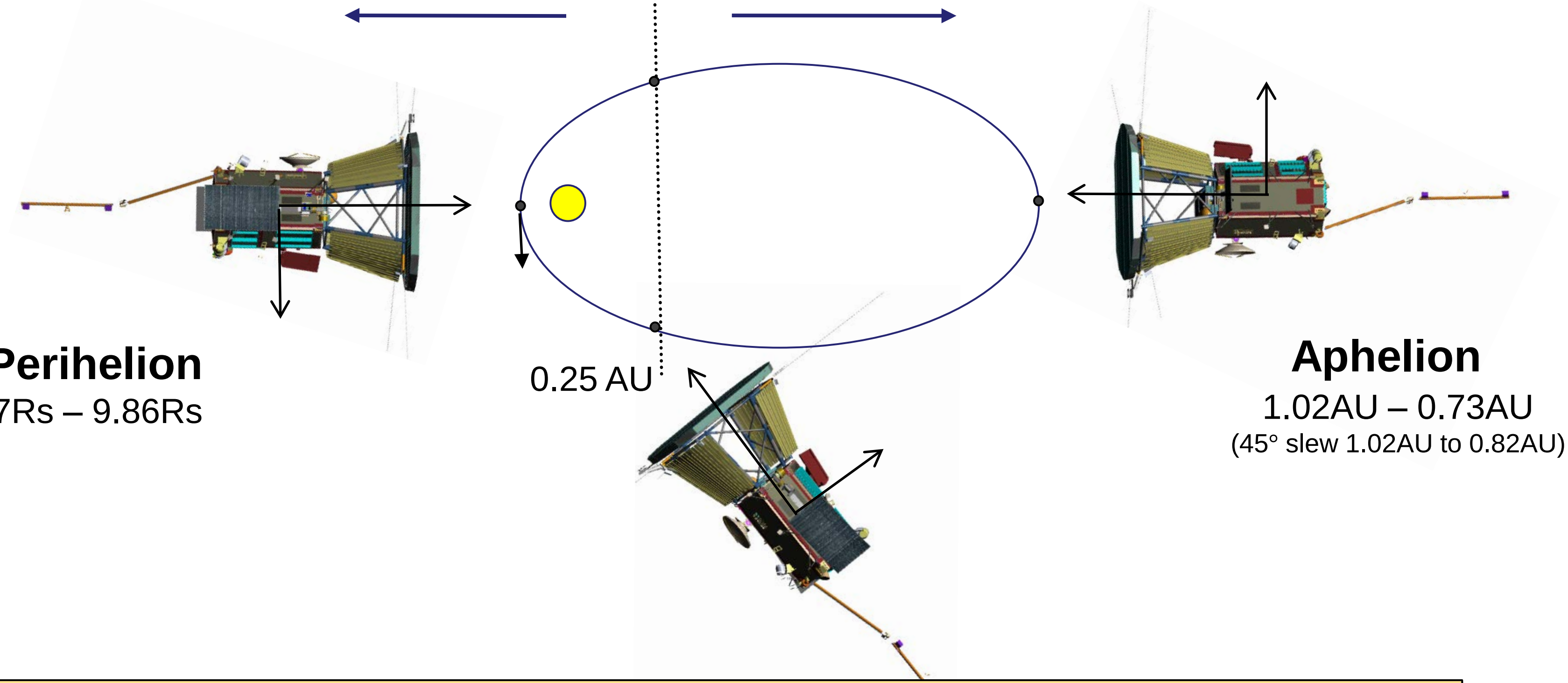
ConOps (2)

- **Later in the mission, once the orbit correction maneuver has been completed approximately 40 days from launch, the last two radiators are activated. Similar to the wetting of radiators 1 and 4, the spacecraft is slewed such that the sun is ~45° off-TPS-normal, illuminating radiators 2 and 3. The radiators are activated simultaneously by actuating the last two isolation valves once the radiators have reached 20 C. The SACS is now completely wetted and fully active. The redundant pump and redundant control electronics remain in powered-off unless a failure occurs in either the primary pump or the primary pump electronics, causing autonomy to switch to the redundant side.**
- **By performing the slew maneuvers and utilizing the waste heat absorbed from the SAA wings, the SACS requires no heater power for warming prior to radiator and SAA filling or for temperature performance enhancement nominal during operation including several 11 minute eclipses at Venus. The design and operation of the SACS must also accommodate several ~45° slews at near-Venus solar distances (~0.70 AU) to allow for antenna pointing during communication periods.**

SPP Orbit Configuration

Primary Science (~11-12 days) ←

→ Cruise/Downlink (~156-78 days)

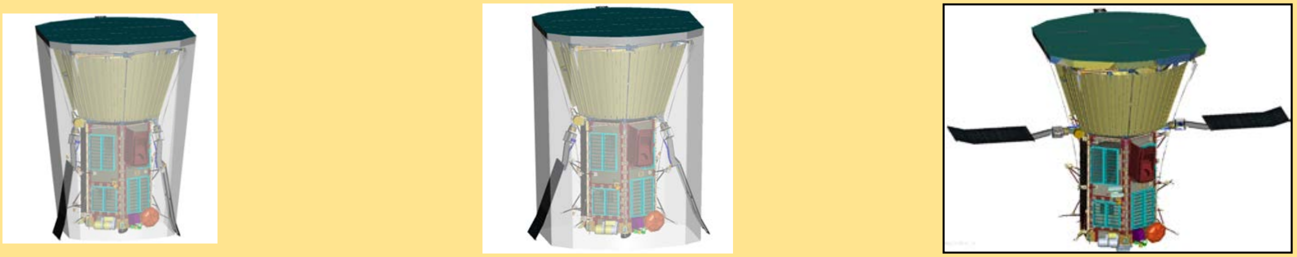


Perihelion
35.7Rs – 9.86Rs

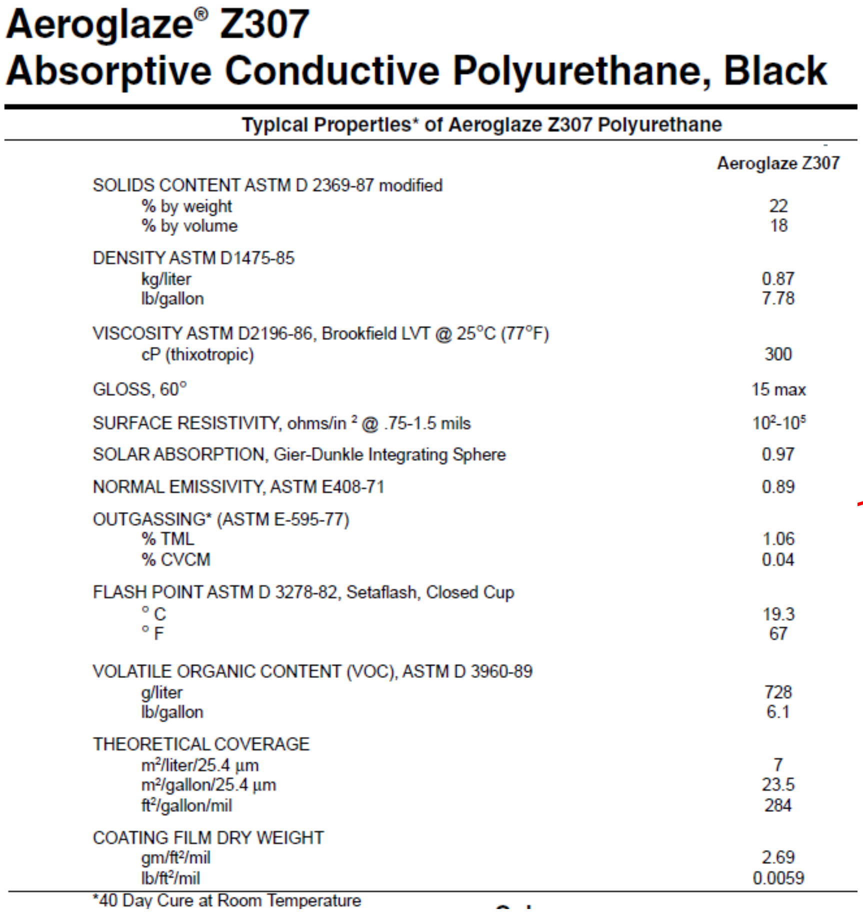
0.25 AU

Aphelion
1.02AU – 0.73AU
(45° slew 1.02AU to 0.82AU)

Solar Array Position



AEROGLAZE Z307
Electrically Conductive Black Paint

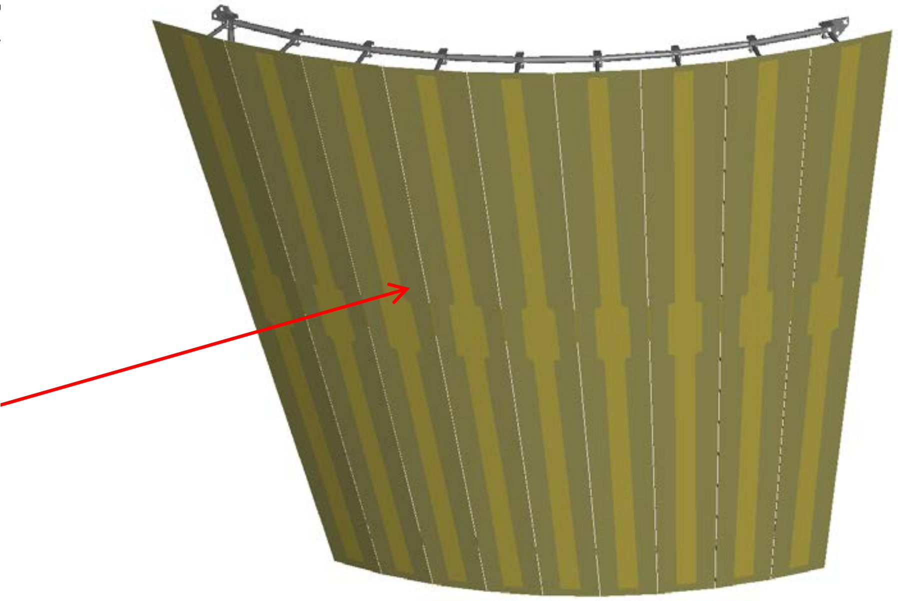


Aeroglaze® Z307
Absorptive Conductive Polyurethane, Black

Typical Properties* of Aeroglaze Z307 Polyurethane

	Aeroglaze Z307
SOLIDS CONTENT ASTM D 2369-87 modified	
% by weight	22
% by volume	18
DENSITY ASTM D1475-85	
kg/liter	0.87
lb/gallon	7.78
VISCOSITY ASTM D2196-86, Brookfield LVT @ 25°C (77°F)	
cP (thixotropic)	300
GLOSS, 60°	15 max
SURFACE RESISTIVITY, ohms/in ^{2} @ .75-1.5 mils	10^2-10^5
SOLAR ABSORPTION, Gier-Dunkle Integrating Sphere	0.97
NORMAL EMISSIVITY, ASTM E408-71	0.89
OUTGASSING* (ASTM E-595-77)	
% TML	1.06
% CVCM	0.04
FLASH POINT ASTM D 3278-82, Setaflash, Closed Cup	
° C	19.3
° F	67
VOLATILE ORGANIC CONTENT (VOC), ASTM D 3960-89	
g/liter	728
lb/gallon	6.1
THEORETICAL COVERAGE	
m^2/liter/25.4 µm	7
m^2/gallon/25.4 µm	23.5
ft^2/gallon/mil	284
COATING FILM DRY WEIGHT	
gm/ft^2/mil	2.69
lb/ft^2/mil	0.0059

*40 Day Cure at Room Temperature

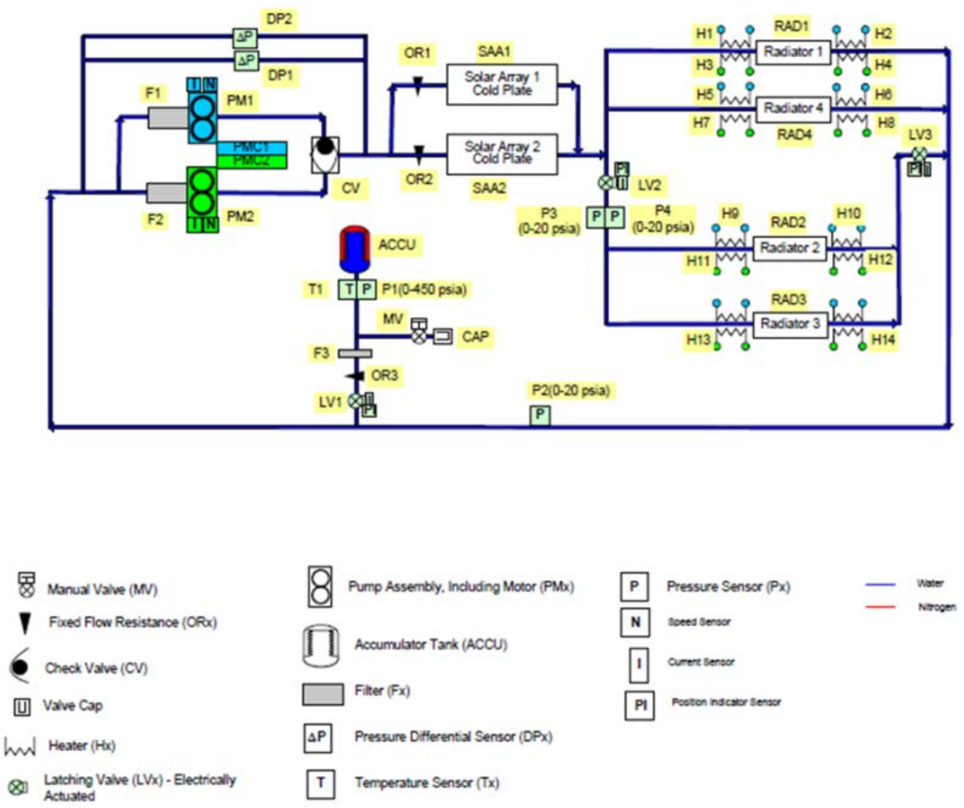


Outboard (space facing) side of each radiator will be painted black

Paint to be applied to BR-127 over phosphoric anodize

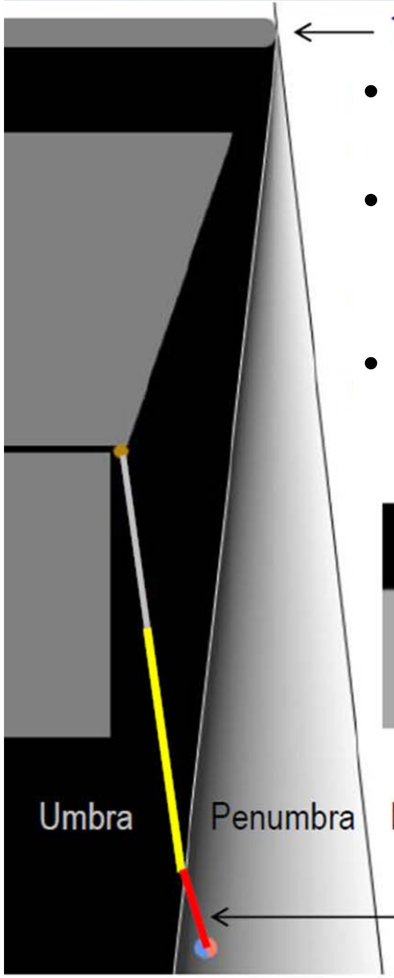
Solar Array Cooling System Flow Schematic

Current Configuration

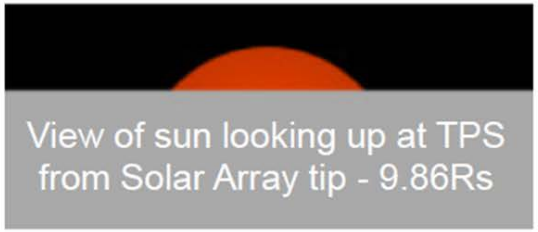


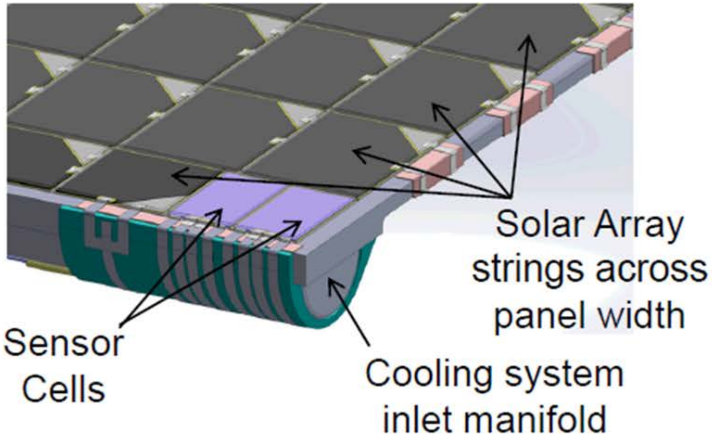
- **MDR configuration was greatly simplified during Phase B to reduce the number of valves (simplify warm up conops) and increase the ability to provide adequate autonomy for fault detection and recovery**
  - Added redundant delta-P sensors
  - Added pre-launch leak detection sensors
    - Quantity (water leak) and pressure (ambient leak)
  - Added inlet and outlet manifold heaters to assist during post launch warm-up
- **LV/Pyrovalves are used to isolate section of the system prior to need**
  - **to be actuated only once on orbit**
- **Baseline pump configuration**
  - 2 redundant pumps
    - Controllers are block redundant with pumps and are cross-strapped to each side of the s/c avionics
  - Operating conditions with one active, one in cold standby

Modeling: Treating the Sun as a $1/r^2$ point source doesn't work



- Inside of ~50 Rs the Sun cannot be accurately modeled as a uniform temperature point source
- Specialized analytical software was developed (Decker, Gaddy, Marsh) to properly account for Suns spectrum and geometry
  - especially beneficial inside of 50 Rs
- Sun model output used calculate SACS absorbed heat and predict system temperature

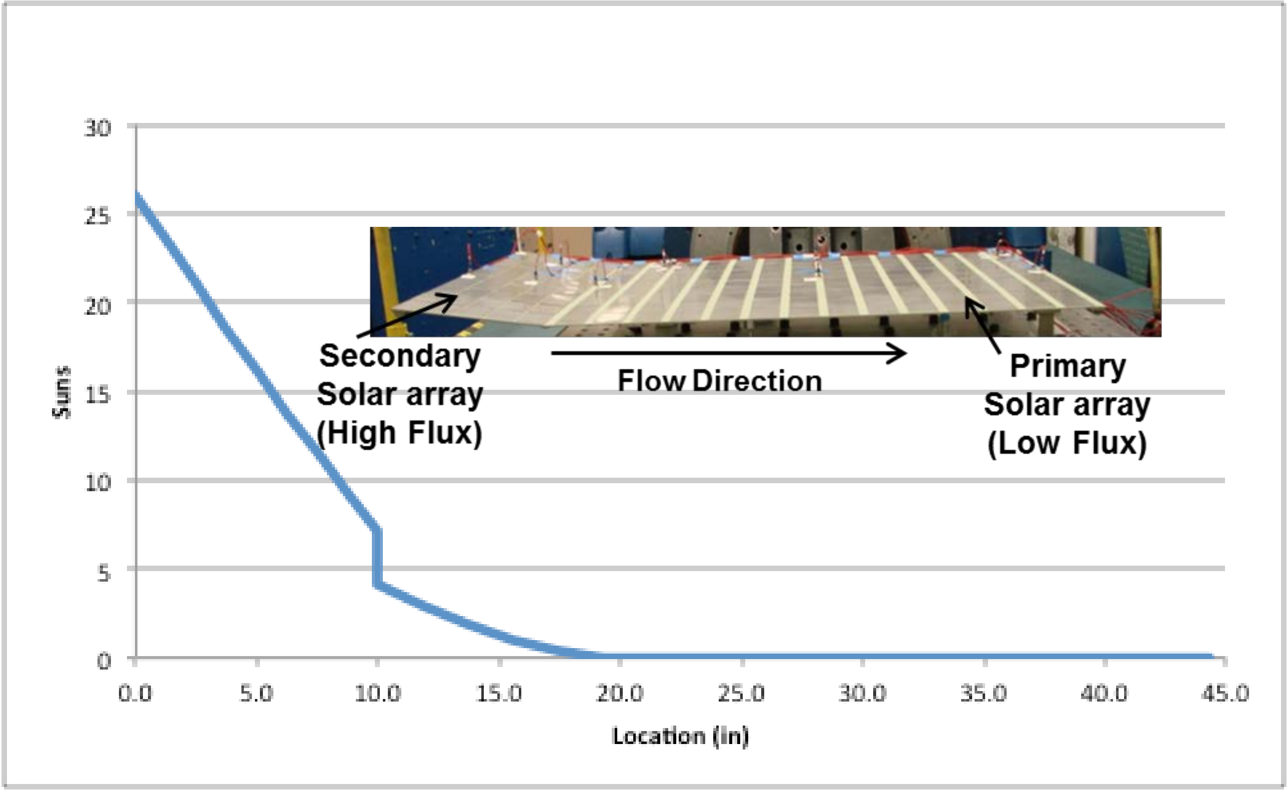




Note: Fig indicates 1 pair of sensor cells /wing corner; flight wing includes 2 pairs/wing corner

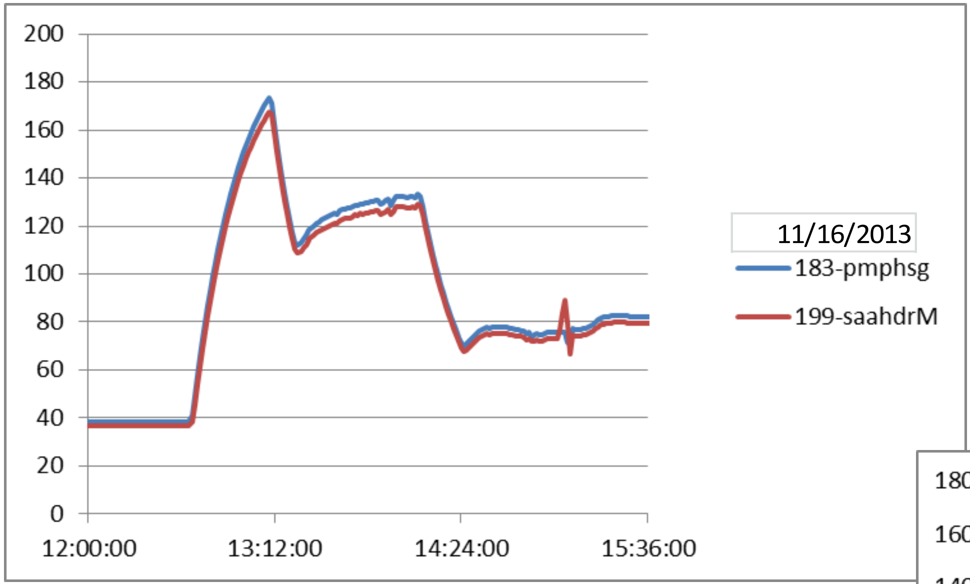
9.86 Rs Nominal Profile

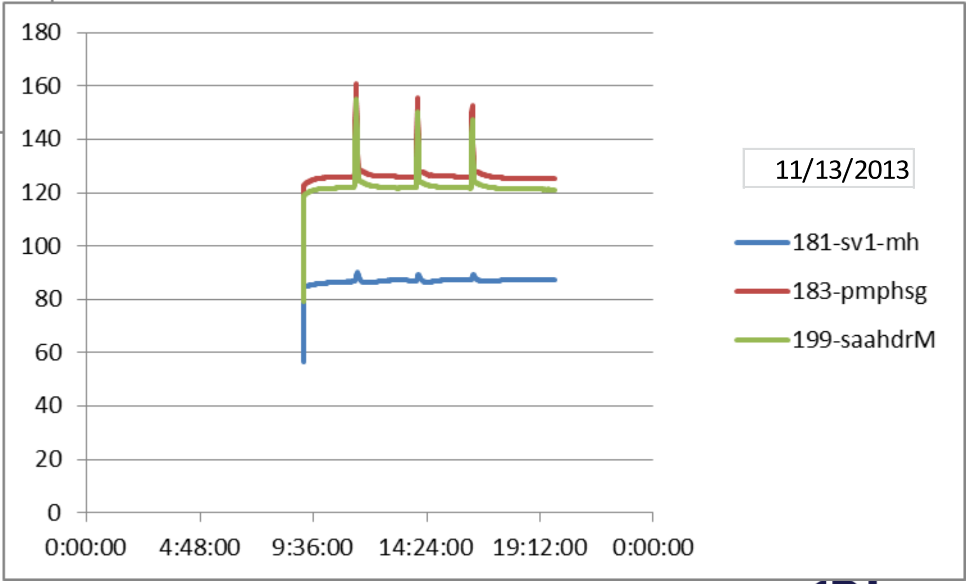
Location (in)	Suns
0.0000	26.02
1.2500	23.52
2.5000	21.04
3.7500	18.58
5.0000	16.15
6.2500	13.78
7.5000	11.48
8.7500	9.27
10.0000	7.18
10.0000	4.16
11.8745	3.01
13.7490	1.96
15.6235	1.06
17.4980	0.36
19.3725	0.00
44.3149	0.00



Typical of the heating profiles provided for thermal analysis

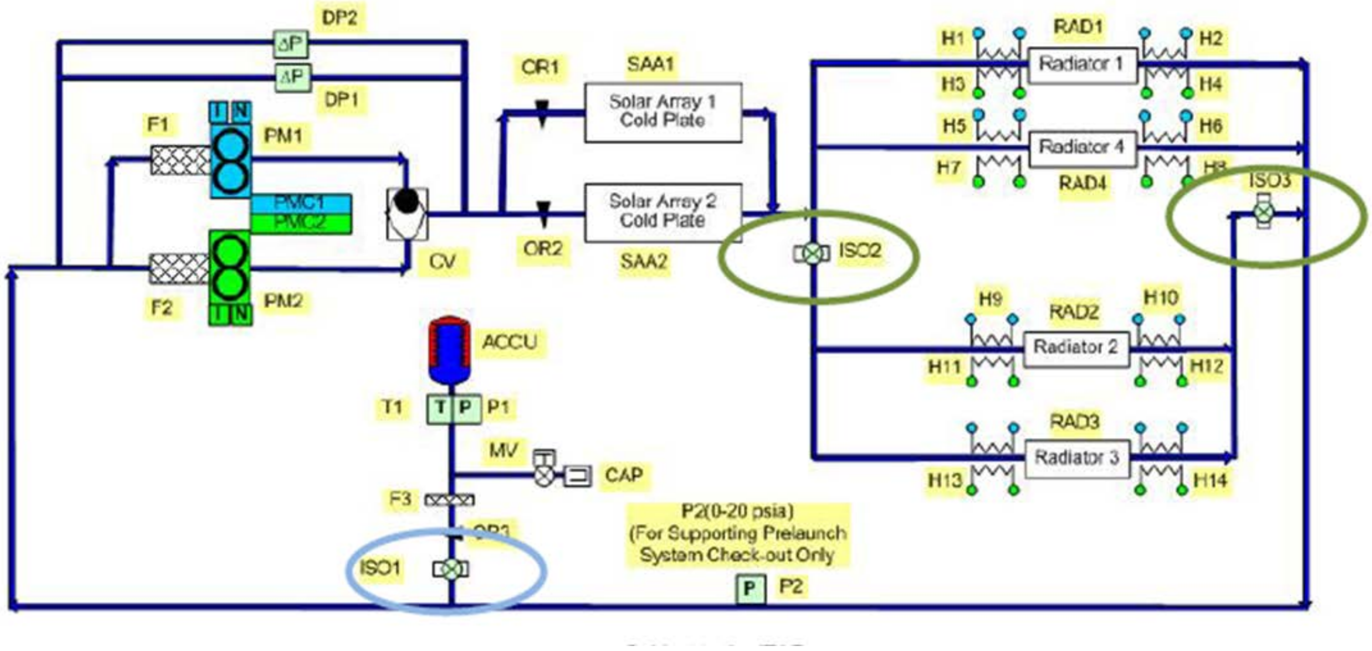
Transient Pump temperature data (C)





SACS Isolation Valves Flight Schematic

- ISO1 – Isolates system from water prior to SACS activation (60 minutes after launch)
- •ISO2 and ISO3 – Isolate RAD 2 and RAD 3 after SACS activation prior to warm-up and backfill (first 42 days of mission)



SACS Phase B Isolation Valve History

- Spring rate of bellows was 50% higher than specified

- Requires a 15V holding voltage to keep the valve closed
    - This made the valve incompatible for SV1 use (LV1 in Flight Schematic)
    - JHU/APL provided an alternate valve for Phase B testing (Moog Torque Motor)

- HS received 3 valves from supplier (SN001,SN002,SN004)
    - All valves Helium leaked checked in both directions
        - Some were tested at elevated temperatures
        - Some were subjected to “instant” surge of 300 psi gas

- SV6 (SN002) and SV7 (SN004) installed into system
    - System conditioned using 150°C water for several days with valves open

- Analysis of the Phase B TVAC system backfill procedure, reveals both SV6 and SV7 failed to isolate R2’

- SN002 was removed from the system and returned to supplier for failure investigation; replaced by SN001

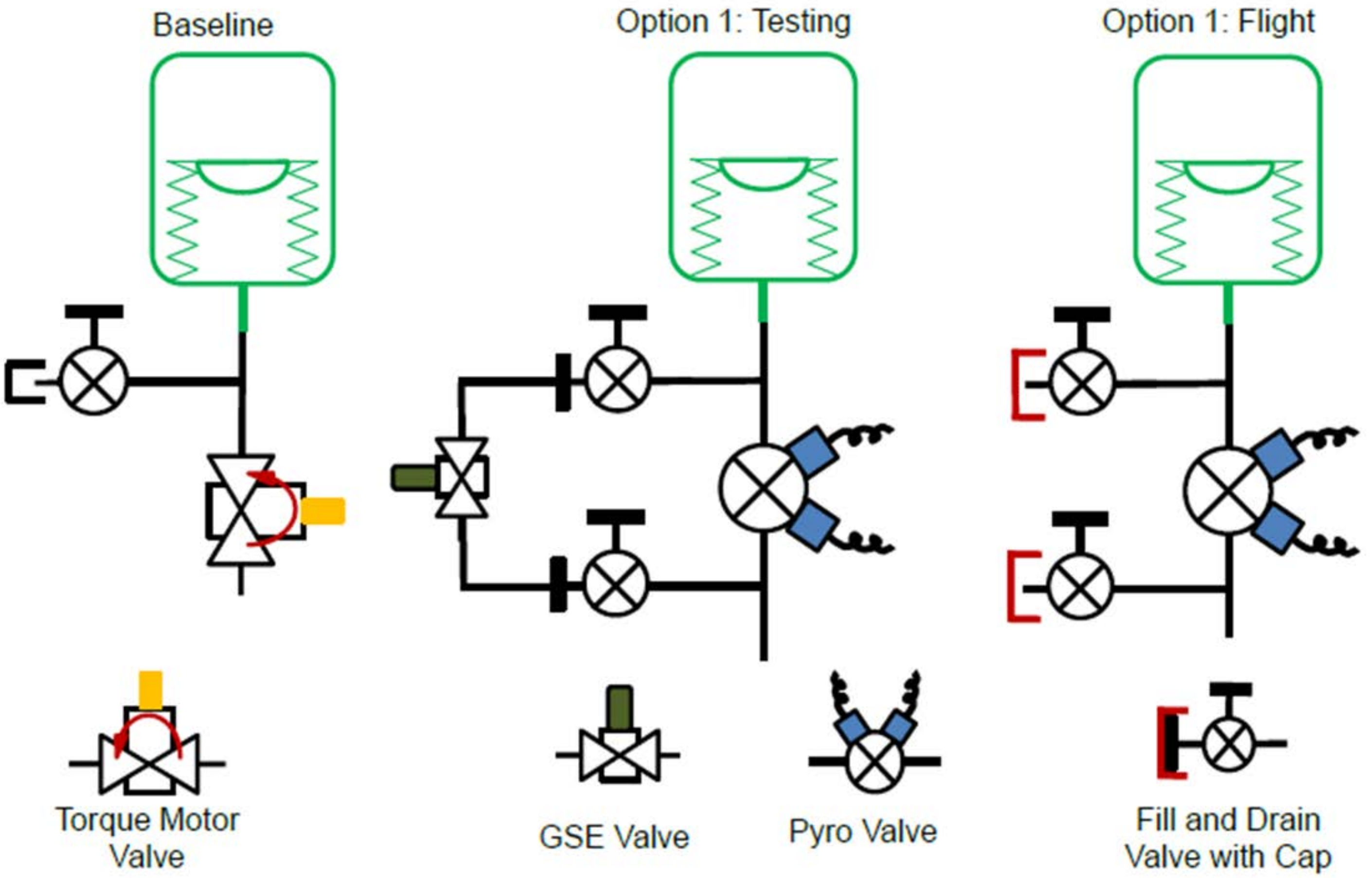
Flight SACS Isolation Valve

- **Investigate alternates including:**
  - Torque Motor valves
  - Pyro Valves
- **All wetted materials will be compatible with water for 8+ years**

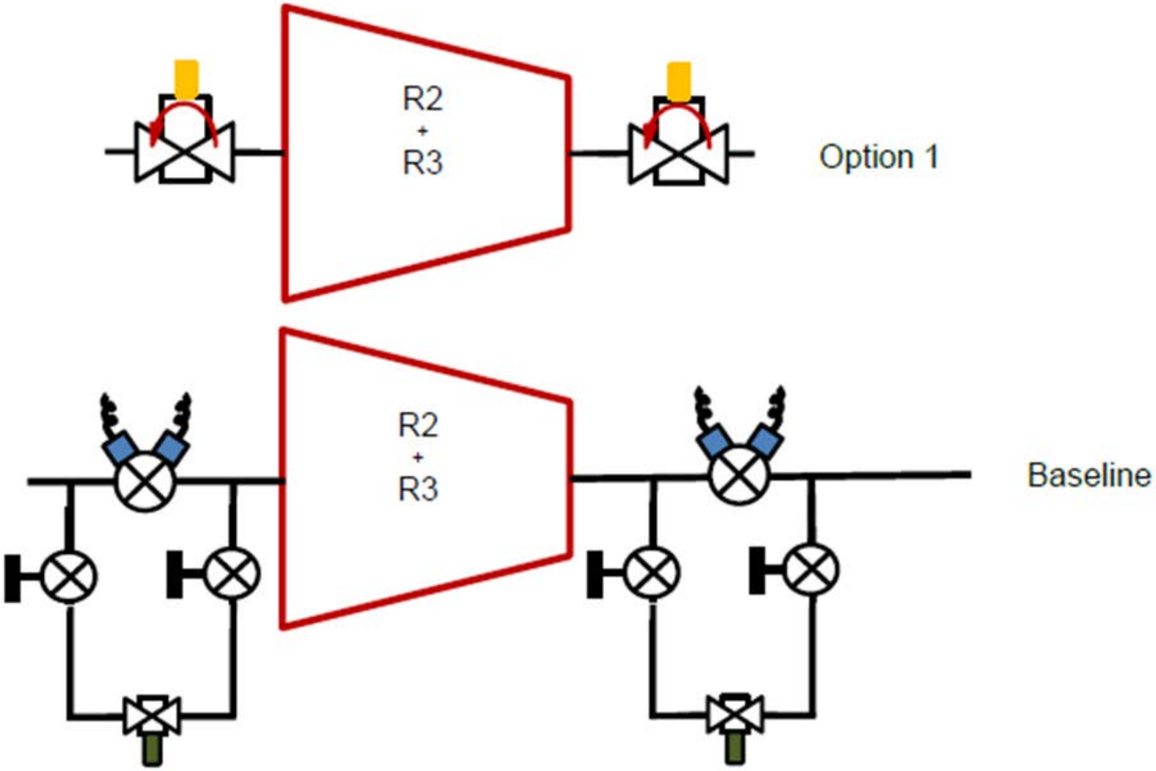
- **System Isolation Valve**
  - Isolates the accumulator from the system
  - Estimated time from system fill to valve actuation - Assume 1 month max
  - Scheme must allow
    - Evacuate system
    - Ground Performance test of the system
    - Fill the accumulator
    - Release fluid into system
  - Baseline: Torque Motor Valve

- **Radiator Isolation Valving**
  - Isolates Radiators 2+3 during startup/warm up sequence
  - Estimated time valve is pressurized until actuation - 41 days max
  - Scheme must allow
    - Evacuate system
    - Ground Performance test of the system
    - Evacuate system
    - Release fluid into Radiators
  - Seal after exposure to 150°C
  - Will see 190°C at the end of life
  - Baseline: Pyro Valves

System Inlet/ Accumulator Isolation ISO1

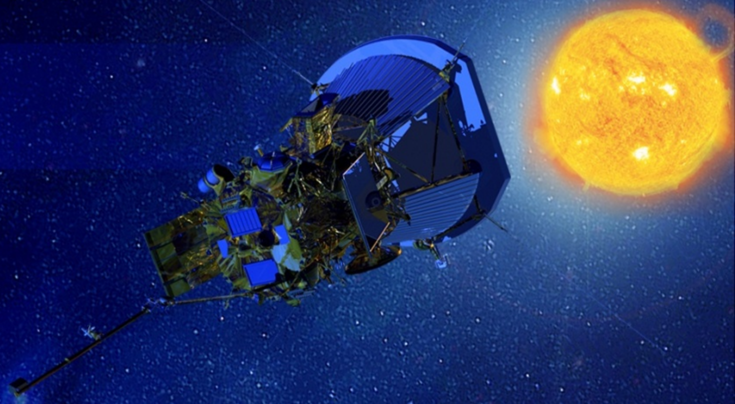


Isolation of Radiators 2 and 3



Solar Probe Plus

A NASA Mission to Touch the Sun



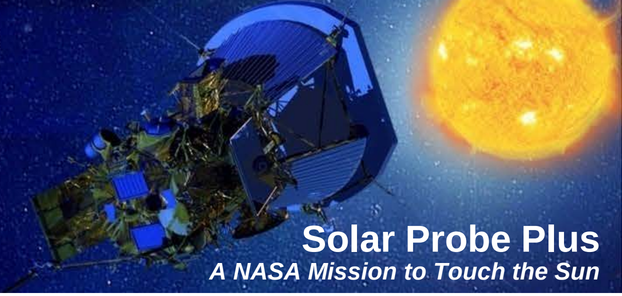
Electrical Power Subsystem

Lew Roufberg
Lead Electrical Power System Engineer

Lew.Roufberg@jhuapl.edu

13 – 16 January 2014

APL
The Johns Hopkins University
APPLIED PHYSICS LABORATORY



EPS Outline

- **Driving Requirements**
- **Block Diagram**
- **Component Configuration**
- **Battery Trade Study**
- **Power Analysis Summary**
- **Component Mass and Power Summary**
- **Verification**
- **EPS PDR Summary**
- **Phase C/D Documentation**
- **Conclusions**

Driving Requirements Summary and Implications

- **Provide power to support the S/C components per SCRD**
    - **S/A, PSE, and battery sizes**
- **Accommodate mission trajectory (9.86 Rs minimum sun distance)**
    - **S/A design and angle control**
- **Comply with the S/A thermal interface requirements per SCRD**
    - **S/A efficiency and angle control**
- **Comply with S/A angle control requirements per SCRD**
    - **High-fidelity modeling of S/A and EPS; need for EPS testbed**
- **Comply with the Electromagnetic Environment Control Plan**
    - **S/A electrostatic and magnetic cleanliness; PSE filtering**
- **Have no single point failures except those on single point failure list**
    - **Redundancy**

EPS Requirements Documents

S/C Requirements Document (Level 3) and other compliance documents

Level 4

7434-5001, SPP Electrical Power Subsystem Requirements Document (in DOORS)

Level 5

7434-5002, SPP Electrical Power Subsystem Component Requirements Document

Level 5

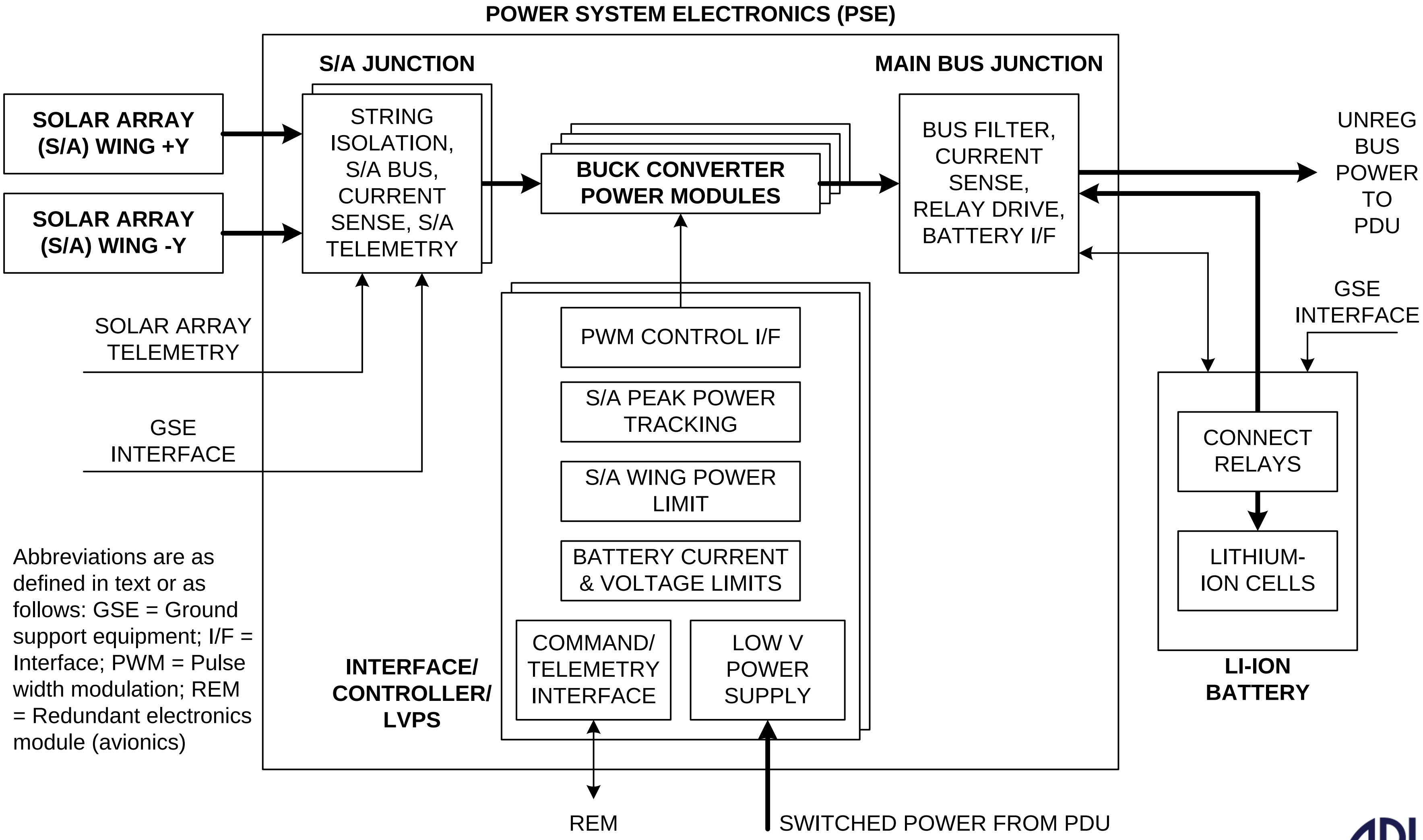
7434-5004, SPP Power System Electronics Specification and ICD
7434-5101, SPP Solar Array Phase C/D Statement of Work (includes specification)
7434-9521, SPP Battery Statement of Work
7434-9522, SPP Battery Performance Specification

All listed documents are in PLM

EPS Block Diagram

Solar Probe Plus

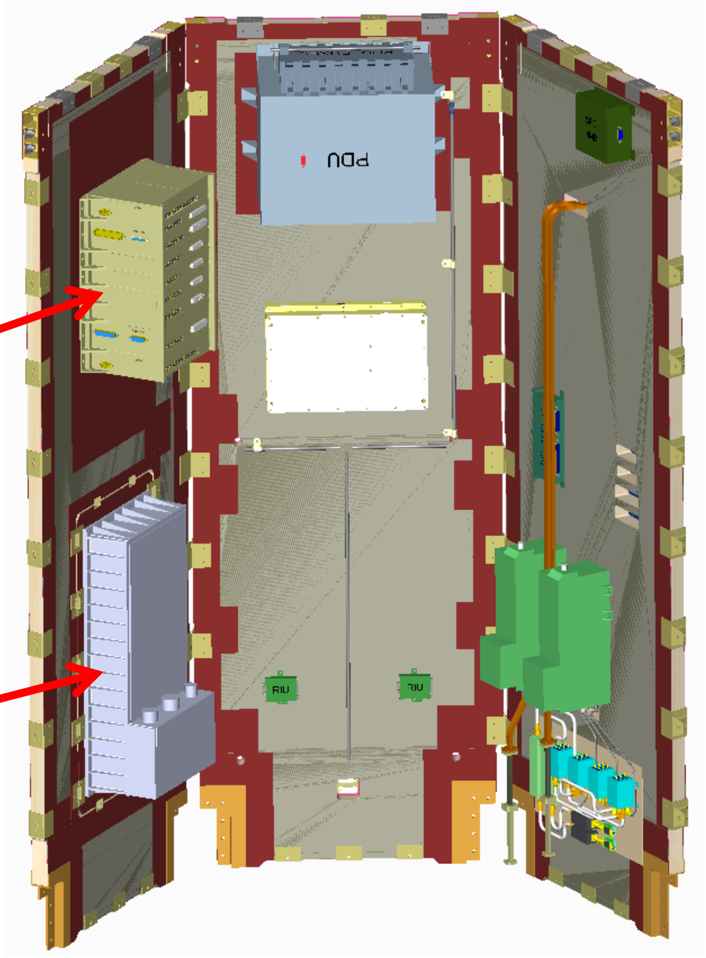
A NASA Mission to Touch the Sun



Abbreviations are as defined in text or as follows: GSE = Ground support equipment; I/F = Interface; PWM = Pulse width modulation; REM = Redundant electronics module (avionics)

Internal Component Locations

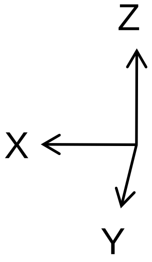
D. Napolillo 10/30/13



Power System Electronics (PSE)

Battery

-Y Inside View



Power System Electronics (PSE)

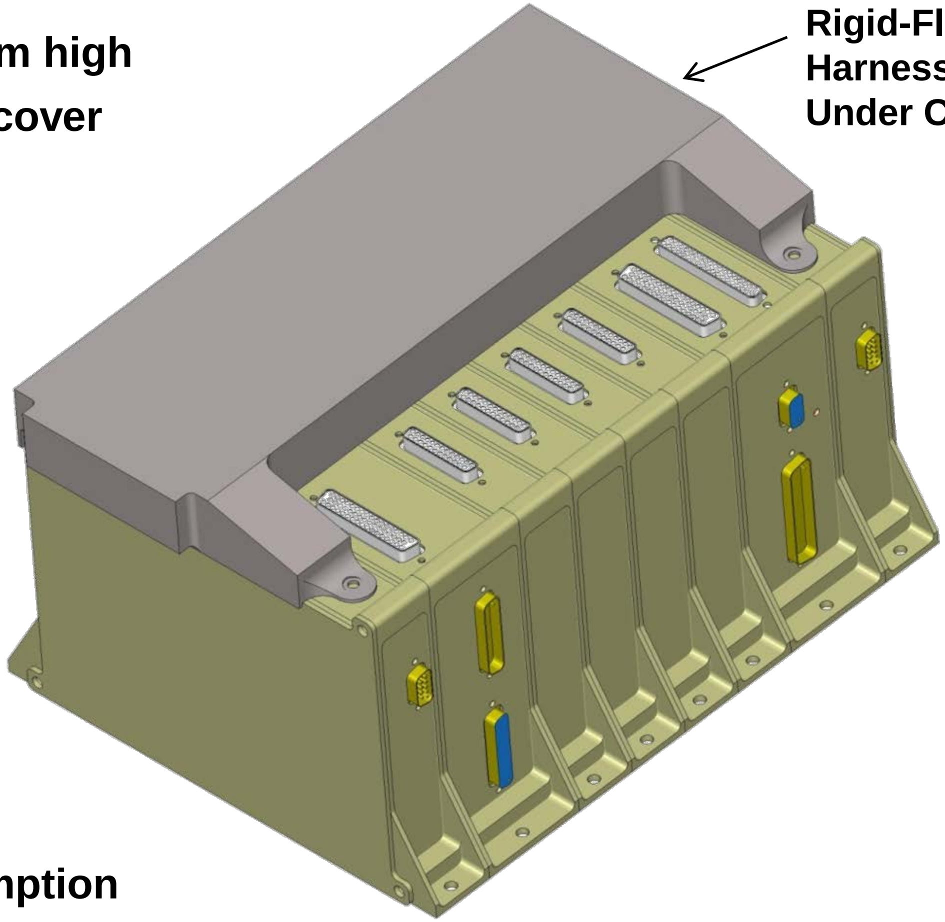
Internally Redundant

- **PSE Box Size:**
  - **31.8 cm long x 24.1 cm wide x 24.6 cm high**
  - **Including top harness keep-out and cover**

- **Slices (8 Total):**
  - **Buck Converters (4)**
  - **Interface/Controller/LVPS (2)**
  - **Main Bus Junction (1)**
  - **S/A Junction - Analog/Digital (1)**

- **Mass: 10.0 kg, CBE**
  - **Includes interslice harness & cover**

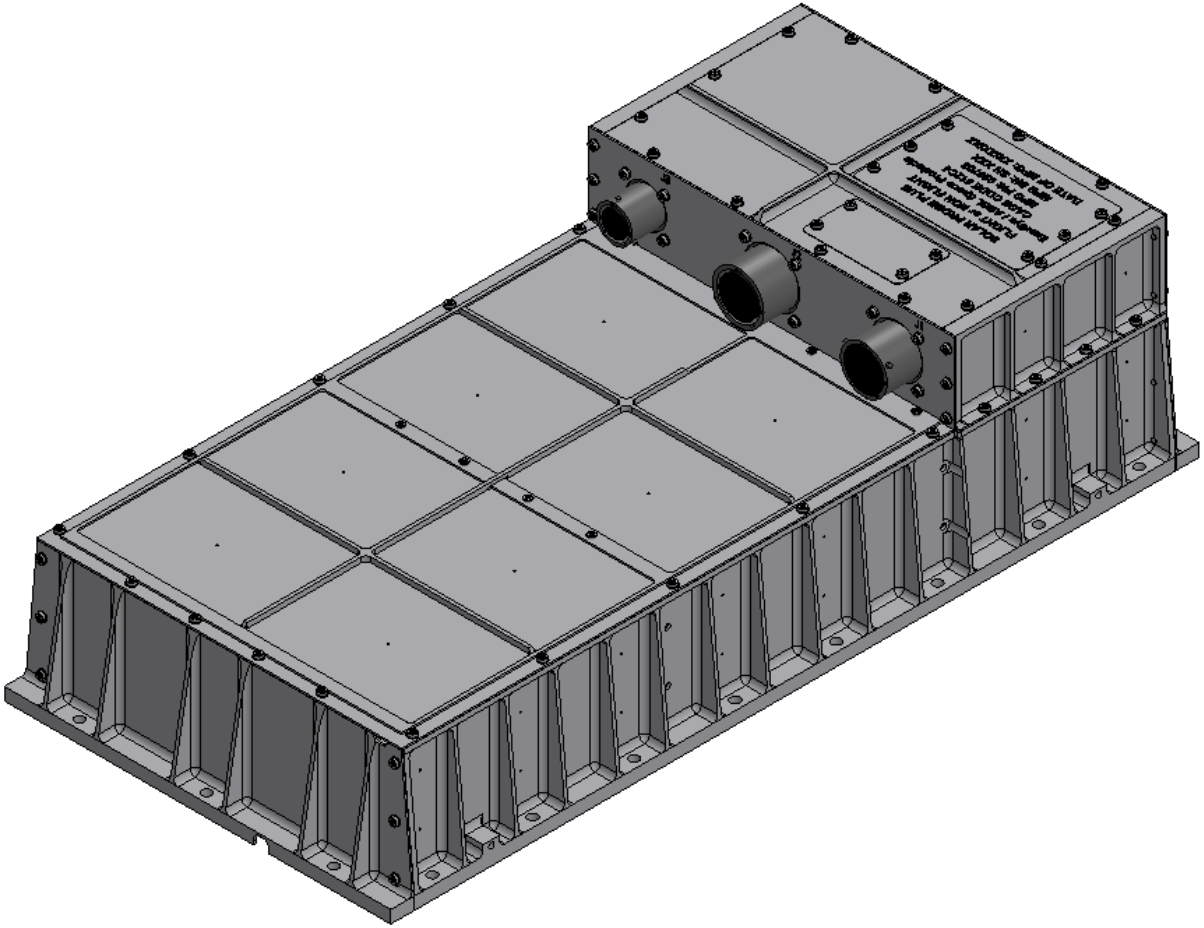
- **Thermal Dissipation 74.3 W Max**
  - **Includes 11.33 W CBE power consumption from bus and throughput losses**



Interslice Rigid-Flex Harness Under Cover

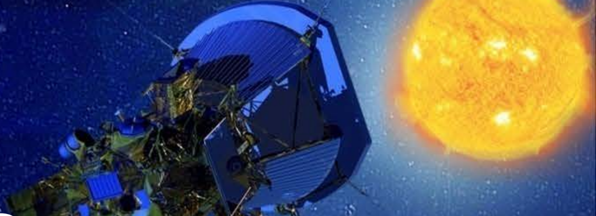
Battery Configuration

- Nameplate Capacity
    - 25 Ah
- Battery Type
    - Lithium-Ion
- Battery Supplier
    - ABSL
- Cells
    - Sony 18650HCM
- Cells/Strings
    - 8 series x 20 parallel
- Nominal Voltage Range
    - 24.0 V to 33.6 V
- Nominal Current Range
    - -16 A to 12.5 A
- Mass
    - 11.5 kg (CBE)
- Footprint
    - 48.5 cm x 24.5 cm
- Height
    - 9.5 cm cell section
    - 15.0 cm connector/relay section



Battery Trade Study

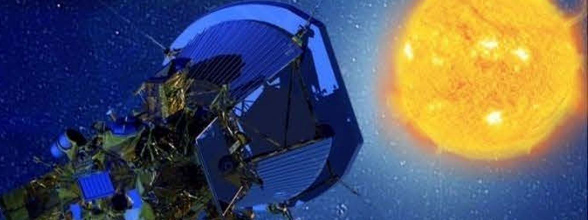
- **Analyzed “large” versus “small” cell approach**
  - **Large cells (e.g., one string of series cells with bypass switches)**
  - **Small cells (e.g., many parallel strings of smaller COTS cells)**
- **Advantages of small-cell battery for SPP:**
  - **Lower PSE mass, cost, and power consumption**
    - **No battery cell balancing and bypass circuitry required**
  - **Less impact of cell failure**
    - **Negligible effect on voltage; minimal reduction in energy**
- **Selected ABSL small-cell battery, 8s-20p configuration**
- **Considerations for using small-cell approach are recognized**
  - **Proper sizing of fuses downstream**
  - **Minimizing cell-to-cell thermal gradients**
- **NASA, DOD, and ESA have flown ABSL batteries successfully**
- **Details: SPP Trade Study: Battery Configuration, SEE-12-010, 4/16/12**



Power Summary, Driving Cases

Power Configuration Number	PC3	PC35	PC24
Component↓ /Power Configuration→	Recharge Post Rad 1&4 and SA Activation	Downlink - 0.73AU (slew)	Science: 20Rs to 9.86Rs
	Total (W)	Total (W)	Total (W)
Instruments CBE Power:	0.0	0.0	66.3
Telecommunications Total:	11.0	95.5	11.0
Guidance and Control Total:	60.8	57.9	77.4
Mechanical Total:	7.3	4.4	7.1
Power Total:	11.3	11.3	11.3
Thermal - SACS Total:	33.0	33.0	41.0
Thermal - SACS Activ Only Total:	0.0	0.0	0.0
Thermal - S/C, non-SACS Total:	23.3	13.9	12.9
Thermal - Instrument Total:	21.5	22.4	0.0
Avionics Total:	27.2	27.2	32.3
Power Distribution Total:	9.5	9.5	9.5
Propulsion (non-Therm) Total:	0.0	0.0	18.5
Propulsion Thermal (non-Tank) Total:	14.1	14.1	8.5
Spacecraft Totals			
Power CBE w/o Harness Loss	219.1	289.3	295.9
Harness Loss	3.7	4.8	4.9
Power CBE	222.7	294.1	300.8
Battery Charge	25	0	0.5
S/C - Sun Distance (AU)	1.02	0.73	0.0459
Spacecraft Pointing Orientation	Aphelion	Aphelion-Umbra Variable-Comm	Encounter
Cooling System Status	Partial	Full	Full
Available Load Power from SA (W)	342.6	379.9	420.5
Req'd Margin	25%	25%	25%
Fault Load (W)	7.4	7.4	7.4
Load with 25% Total Margin	310.8	375.1	383.9
Power Reserves	87.5	78.4	111.8
Actual Margin	39.27%	**26.65%**	**37.17%**

- **Minimum power margin 26.7%**
- **Requirement at PDR is 25.0%**



Analysis Results and Requirements Compliance Summary

Parameter	Requirement	Worst-Case Analysis	Comply
Minimum Power Margin	25.0%	26.7%	Yes
Minimum Energy Margin, Normal Conditions	20.0%	36.6%	Yes
Minimum Energy Margin, Fault Condition	10.0%	22.2%	Yes
Maximum Bus Voltage at Load	35.0 V	34.2 V	Yes
Minimum Bus Voltage at Load *	22.0 V	25.4 V	Yes

* Instruments required to operate down to 24.0 V

Mass, Power, Size Summary

- **EPS team has high confidence in meeting NTE mass and power requirements**

Component / Parameter	**Not-to-Exceed (NTE)**	**Current Best Estimate (CBE)**
Solar Array (Electrical Add-on) Mass (kg)	10.63	9.00
Battery Mass (kg)	12.97	11.50
PSE Mass (kg)	11.28	10.00
PSE Power Consumption (W)	13.60	11.33

Component	**Dimensions**
Solar Array Wing	Primary section: 87.1 cm x 65.0 cm Secondary section: 25.4 cm x 65.0 cm Cant angle between sections: 7.4°
Battery	48.5 cm long x 24.5 cm wide x 15.0 cm high
PSE	31.8 cm long x 24.1 cm wide x 24.6 cm high (incl. top harness keep-out)

Notes: (1) S/A mass, size, and power values herein are based on 65 cm wing width. Systems Engineering is carrying mass and size for 69 cm width as a contingency; final size selection planned for April 2014.
(2) PSE power consumption values are are as indicated in load power budget and do not include throughput losses; maximum total PSE heat dissipation including power consumption and throughput losses is estimated to be 74.3 W (included in S/A sizing and thermal analysis).

EPS Verification

- Compliance with EPS requirements verified per EPS Verification Plan
  - 7434-5005

- Verification includes:
  - EPS power analysis
  - EPS failure modes and effects analysis (FMEA)
  - EPS simulations using Simulink models
  - EPS testbed testing using PSE, S/A simulator, battery, and GSE
  - Component (S/A, PSE, battery) level verifications

EPS Testbed

- EPS testbed =
  + PSE (power system electronics)
  + SAS (dynamic solar array simulator)
  + Battery (or battery simulator)
  + EPS GSE (including load simulator & PSE command/telemetry I/F)
  + Mini-MOC (mini mission ops center incl. command/telemetry database)
  + Avionics hardware and G&C truth models (in Phase C)

- EPS testbed evolves throughout development and supports:
  - PSE breadboard testing
  - S/A angle control testing (at EPS and S/C system levels)
  - PSE EM/FM testing
  - Compatibility testing of PSE with avionics
  - Verification of compliance with EPS requirements

- Autonomous S/A angle control has been demonstrated on EPS testbed
  - Using PSE breadboard hardware in the loop and simulators
  - Successfully completed – see S/A angle control presentation

EPS PDR

- **Conducted November 18 & 19, 2013 at APL**

- **Review Board (External to Project):**
  - **Dan Gallagher, EPS PDR Chair (Power System Engineer, JHU/APL)**
  - **Tom Kerslake (SPP SRB; NASA/GRC)**
  - **Amri Hernández-Pellerano (NASA/GSFC)**
  - **Melyane Ortiz-Acosta (NASA/GSFC)**

- **Summary Memo: SEE-13-095**

- **Review board unanimously agreed EPS PDR success criteria have been met**

- **Action Items**
  - **16 total (14 assigned to EPS team)**
  - **Responses in work**

Phase C/D Documentation

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- **PSE Parts Application Stress (Derating) Analysis Reports**
- **Thermal Analysis Reports**
- **Structural Analysis Reports**
- **Worst-Case Analysis Reports**
- **EPS Design Review Presentations (EPS CDR and component reviews)**
- **Limited-Life Items List**
- **EPS Performance Trending Plan**
- **GSE Design Documentation (Hardware and Software)**
- **GSE Certification Test Procedures**
- **Component Test Procedures and Test Scripts**
- **Test Vectors (or suitable verification files for FPGAs)**
- **Component Test Reports**
- **EPS Test Report**
- **Battery Handling, Operations, and Maintenance Plan/Procedure**
- **Solar Array Handling, Testing, Inspection, and Cleaning Plan/Procedure**
- **Command/Telemetry Handbook and Database Inputs**
- **EPS I&T Procedures (power up/down, CPT, mission sim, constraints)**
- **Mission Operations Plan Inputs**

Conclusions

- EPS requirements are well understood
- Approach to meeting requirements has been demonstrated
- Design is at PDR level of maturity
- Key interfaces are defined
- Preliminary modeling/analyses demonstrate compliance
- Mass, power, and size estimates are well substantiated
- TRL has been assessed and is suitable for PDR level
- Verification approach is established
- GSE requirements are defined
- Risk areas have been identified and mitigation plans are in place
- Lessons learned have been reviewed and are being applied
- Phase C/D plans are in place

The EPS is ready for Phase C

EPS Backup

EPS Requirements Summary - 1

Voltage, Energy, Power

ID	Title	Requirement: The EPS shall…	Description/ Clarification	Compli-ance	Verif. Method
EPS-1	Bus Voltage	under normal conditions maintain the unregulated bus voltage within the range of 22 V to 35 V as measured at the input to each spacecraft (S/C) component.	Maximum voltage drop allocation between battery and input to each S/C component is 2.8 V.	Comply	Test Analysis
EPS-3	Energy Margin	be designed such that battery state of charge (SOC) is no less than 20% under worst-case normal (no failures) conditions and no less than 10% following the worst-case single point failure.	SOC is defined in 7434-5002.	Comply	Analysis
EPS-4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 105, 106	Load Power and Configurations	provide power to support the S/C components for all conditions throughout the mission as defined in the SCRD Table 3.5-1 and the EDTRD Table 2-1, with the worst-case failure and degradation consistent with time in the mission, without violating the solar array (S/A) and cooling system temperature limits, within battery energy margin constraints.		Comply	Test Analysis

EPS Requirements Summary - 2

S/C & S/A Orientation and Illumination

ID	Title	Requirement: The EPS shall…	Description/ Clarification	Compli-ance	Verif. Method
EPS-14, 15, 16, 17, 18	S/C and S/A Orientation	comply with the S/C and S/A orientation requirements per the SCRD, including S/A deployment, articulation, and TPS umbra dimensions.		Comply	Analysis Inspection
EPS-19	Orbit and Sun Distance	accommodate the mission design trajectory as specified in SEG-13-005 "Alternative Solar Probe Plus Mission Design."	Heliocentric orbit where aphelion varies from 1.02 AU at launch to 0.73 AU and perihelion varies from 35.7 Rs to 9.86 Rs.	Comply	Analysis
EPS-20	Venus Flyby Eclipse	accommodate a maximum post-launch eclipse duration of 661 seconds during Venus flybys.	Load power requirements during Venus eclipse are referenced by EPS-4.	Comply	Test Analysis
EPS-21	S/A Shadowing from Antennas	accommodate S/A shadowing from the FIELDS electric field antennas.		Comply	Analysis

EPS Requirements Summary - 3

S/A Angle Control and EPS Testbed

ID	Title	Requirement: The EPS shall…	Description/ Clarification	Compli-ance	Verif. Method
EPS-22, 23, 24, 25, 26, 27, 28, 108, 109, 110	S/A Angle Control	comply with the S/A angle control requirements per the SCRD.	EPS provides S/A angle control algorithms to be implemented in G&C software residing in the avionics.	Comply	Test Analysis
EPS-29	EPS Testbed	provide an EPS testbed - including PSE, dynamic solar array simulator, test battery, and Simulink models of S/A and angle control algorithms - to support EPS level testing and system level testing of autonomous S/A angle control and S/A safing.	EPS testbed minimizes risk by allowing early verification of interfaces with other subsystems/disciplines and minimizing differences between test and flight configurations.	Comply	Test

EPS Requirements Summary - 4

S/A Sensors and Thermal Interface

ID	Title	Requirement: The EPS shall…	Description/ Clarification	Compli-ance	Verif. Method
EPS-30	S/A Temperature Sensors	include temperature sensors within 10 cm (TBR) of each end of each platen manifold (inlet and outlet) of each S/A wing to measure temperature to an accuracy of +/- 5 deg C and report in telemetry at 5 Hz rate.	Temperature sensors are used to trend performance and detect out-of-limit temperatures.	Comply	Test Analysis
EPS-31	S/A Sensor Cells	include sensor cells on the outboard corners of each S/A wing to measure sample-cell short-circuit current and open-circuit voltage and report in telemetry at 5 Hz rate to allow estimation of irradiance to +/- 6% and temperature to +/- 15 deg C.	Sensor cells are used to trend performance, detect out-of-limit irradiance and temperature, and support calibration of the S/A angle potentiometers and determine safe angles in flight. The sensor cells will be calibrated in flight.	Comply	Test Analysis
EPS-33, 34, 35, 37, 38, 111	S/A Thermal Interface	comply with the S/A thermal interface requirements per the SCRD, including temperature limits and heat load into the S/A cooling system.		Comply	Analysis

EPS Requirements Summary - 5

Fault Management

ID	Title	Requirement: The EPS shall…	Description/ Clarification	Compli-ance	Verif. Method
EPS-39	Single Point Failure Tolerance	have no single point failures except those on the single point failure list.		Comply	Analysis
EPS-40	Battery SOC Estimate	provide an estimate of battery SOC in telemetry at 5 Hz rate for use by Fault Management to initiate a low battery SOC response and/or transition between S/C operational levels.		Comply	Test
EPS-112	Side Switching	switch to the redundant side upon command (via PDU power switches to the LVPS on PSE A & B sides).	This supports S/C side switching within the allocated time prior to commanding the S/A to a safe angle and/or other fault responses.	Comply	Test
EPS-41	Health Check on Redundant Side	ensure that health checkout of redundant side does not interfere with operation of primary side.		Comply	Test

EPS Requirements Summary - 6

S/A Safing; Fault Injection; Command/Telemetry I/F

ID	Title	Requirement: The EPS shall…	Description/ Clarification	Compli-ance	Verif. Method
EPS-42, 43, 44, 45, 114, 115, 116, 117	S/A Safing	comply with the S/A safing requirements per the SCRD.	The EPS team provides inputs to tables of irradiance thresholds and safe angles.	Comply	Test Analysis
EPS-118	Fault Injection for Testing	have a test program that takes into account that the S/C will be capable of over-writing subsystem telemetry with injected values during testbed/subsystem testing and S/C testing.		Comply	Test
EPS-46	Command and Telemetry Interface	communicate with the avionics redundant electronics module (REM) for commands and telemetry over block-redundant serial digital interfaces in accordance with the Spacecraft Electrical Interface Control Document (ICD).		Comply	Test

EPS Requirements Summary - 7

Mass, Power Consumption, Interfaces

ID	Title	Requirement: The EPS shall…	Description/ Clarification	Compli-ance	Verif. Method
EPS-48	Mass	comply with the following not-to-exceed component mass allocations: S/A (electrical add-on) 10.63 kg, battery 12.40 kg, and PSE 11.28 kg.	12.8% margin/contingency is included in each of these not-to-exceed values.	Comply	Test
EPS-49	Power Consumption	comply with the following not-to-exceed component power consumption allocation: PSE 13.6 W.	20% margin/contingency is included in this not-to-exceed value for power drawn from the unregulated bus; throughput losses in the EPS are accounted for in the EPS power analysis.	Comply	Test
EPS-50	S/C Electrical ICD	comply with the Spacecraft Electrical ICD.		Comply	Inspection
EPS-51	S/C Mechanical ICD	comply with the Spacecraft Mechanical ICD.		Comply	Inspection
EPS-52	GSE Interface	interface with the electrical ground support equipment via the S/C umbilical and test connectors in accordance with the Spacecraft Electrical ICD.		Comply	Test

EPS Requirements Summary - 8

Life and Environment

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ID	Title	Requirement: The EPS shall…	Description/ Clarification	Compli-ance	Verif. Method
EPS-53	Mission Life	be designed to operate through all mission phases for a total lifetime in orbit of 7 years.		Comply	Analysis
EPS-54	Storage	be designed to allow 3 years of storage and/or testing prior to launch.	For the battery, this time period starts when the battery is delivered from subcontractor to APL.	Comply	Analysis
EPS-56	Environmental Design and Test	comply with the Environmental Design and Test Requirements Document, 7434-9039.		Comply	Test
EPS-57	Electromagnetic Environment	comply with the Electromagnetic Environment Control Plan, 7434-9040.		Comply	Test
EPS-58	Contamination Control	comply with the Contamination Control Plan, 7434-9011.		Comply	Test Inspection

Trade Study Summary

Completed in Phase A

- **EPS architecture** (peak power tracking rather than direct energy transfer)
- **PSE power processing topology** (buck converters between S/A and bus)
- **S/A junction boards/functions location** (in PSE instead of separate box)
- **PSE digital control location** (local to PSE rather than remote in Avionics)
- **PSE digital control implementation** (state machine rather than software)

Updated and Completed in Phase B

- **Battery configuration** (ABSL “small-cell” battery 8s-20p)

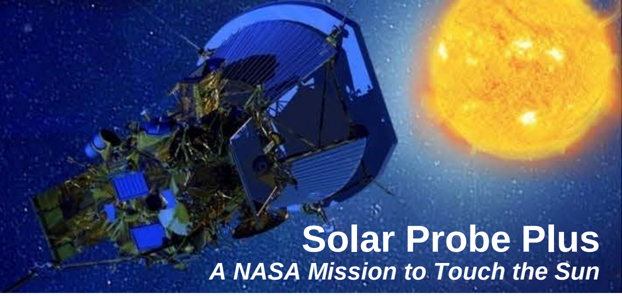
Significant Changes Since MDR

Item / Parameter	MDR	PDR
Solar array Primary section cell stack Secondary section cell stack Total mass of cell laydown	 "Semi-standard" TBD (ceramic or semi-std) 5.9 kg	 Ceramic (interposer) Ceramic (interposer) 9.0 kg
Battery Capacity Mass Design approach Manufacturer	 20 Ah 11.1 kg "Large-cell" design APL (using Yardney cells)	 25 Ah 11.5 kg "Small-cell" design ABSL (using Sony cells)
PSE box quantity	Two boxes	One internally-redundant box
PSE printed wiring board quantities	Buck converter - 6 S/A junction - 2 Bus junction - 1 Command/telemetry - 2 Controller - 2 LVPS - 2 Battery interface - 2	Buck converter - 4 S/A junction analog - 1 S/A junction digital - 1 Bus junction - 1 Interface/controller/LVPS - 2 Rigid-flex harness - 1
PSE functions	Battery cell balancing and bypass included	No battery cell balancing and bypass required with "small-cell" battery
PSE mass	14.4 kg	10.0 kg
PSE power consumption	19.00 W	11.33 W
S/A angle control algorithm	S/A power-control mode only	Added S/A temperature-control mode

Redundancy

- **PSE**
  - 4-for-3 module redundancy for buck converters (S/A power conversion)
    - Hot-redundant - all operate in parallel
  - Redundant current sensors (parallel paths)
  - S/A string blocking diodes are block redundant with S/A strings
  - Single S/A bus and battery bus (unregulated bus) – mitigation addressed
  - A-side/B-side redundancy for other portions of PSE:
    - Low voltage power supply, command & telemetry, controller
- **Solar Array**
  - All requirements (including margin) are met with failure of any S/A string
    - Impact on S/A cooling system heat load has been taken into account
- **Battery**
  - 20 parallel strings of cells
  - All requirements (including margin) are met with failure of any string

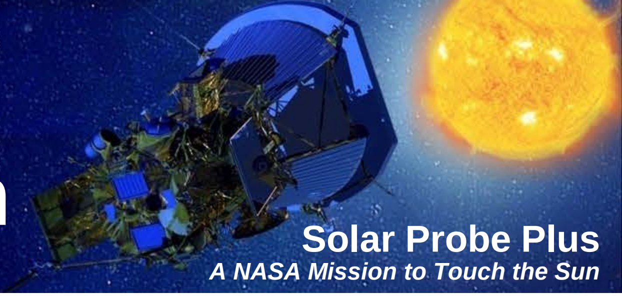
Mission-Critical Single Point Failures



- **EPS is designed to “have no single point failures except those on the single point failure list”**

- **Exceptions to be included on the approved single point failure list:**
    - **Short circuit of unfused portion of the unregulated bus (battery bus)**
    - **Short circuit of the S/A power bus (node where S/A power is combined)**

- **These “golden nodes,” with suitable mitigation, are not unusual for NASA S/C**

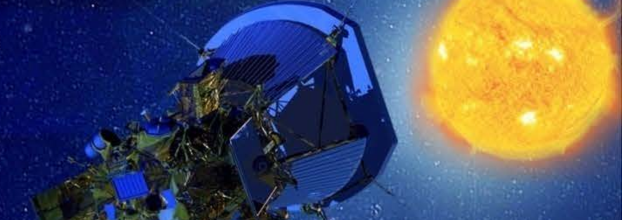


Short Circuit Failure Mitigation

- **Extra physical spacing between power and return/ground**
- **Connector contacts separated between power and return/ground**
- **Conformal coating**
- **Double insulation**
- **High-potential testing of critical wiring harnesses**
- **Inspection of critical areas prior to box close-out**
    - **Mission Assurance and Engineering inspections**
- **Above items are typical for previous spacecraft**

EPS Summary Status Map

Completion status is relative to PDR level



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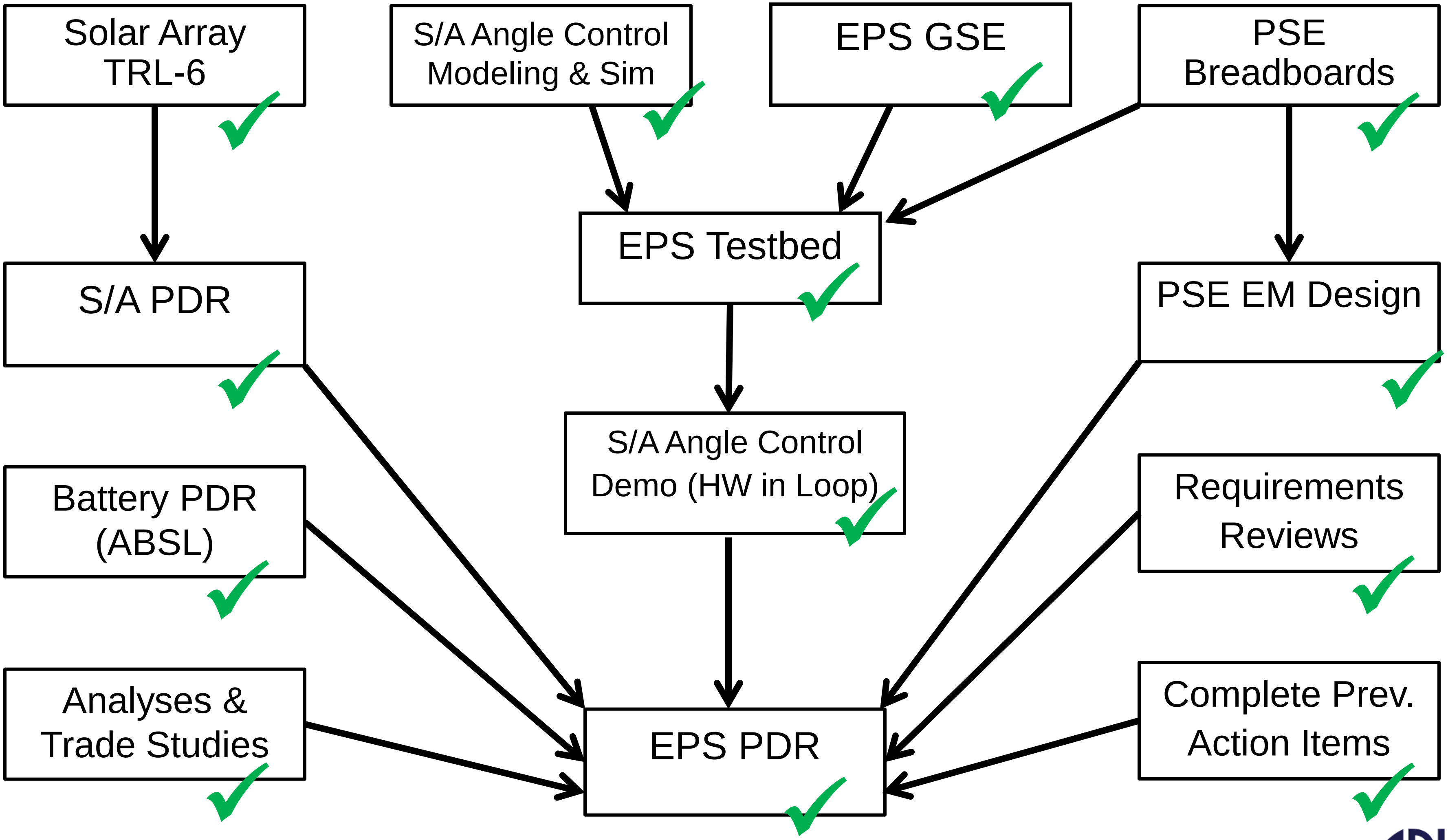


Solar Array TRL-6 ✓

S/A Angle Control Modeling & Sim ✓

EPS GSE ✓

PSE Breadboards ✓

S/A PDR ✓

EPS Testbed ✓

PSE EM Design ✓

S/A Angle Control Demo (HW in Loop) ✓

Battery PDR (ABSL) ✓

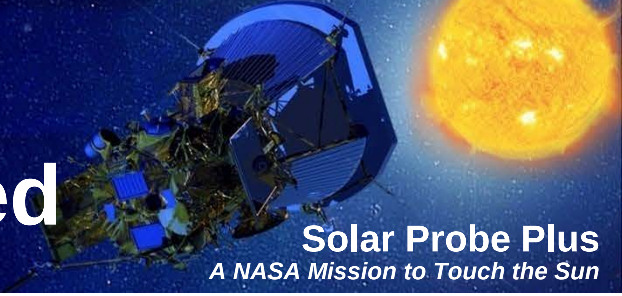
Requirements Reviews ✓

Analyses & Trade Studies ✓

Complete Prev. Action Items ✓

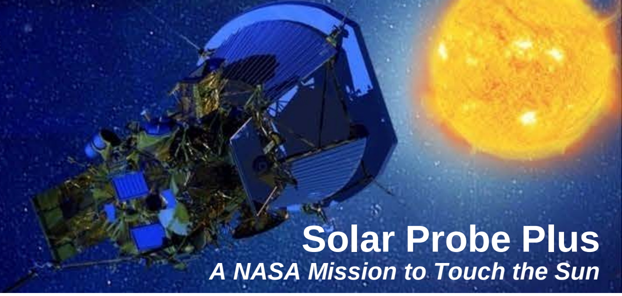
EPS PDR ✓

EPS Summary Status, continued



- **Completed EPS development plan (SOW, schedule, staffing, cost)**
- **EPS requirements baselined in DOORS and document released in PLM**
- **Updated EPS energy balance model**
    - **Including losses and heat dissipation estimates**
- **Updated estimates for component mass, power, size**
- **Completed SOW/specs for S/A and battery**
- **Completed S/A angle control peer review**
    - **Including EPS models, algorithms, and results of integrated simulations with G&C models**
- **Updated PSE slice functional allocations**
- **Developed detailed command/telemetry list**
- **Completed preliminary failure modes and effects analysis**
- **Completed preliminary verification plan**

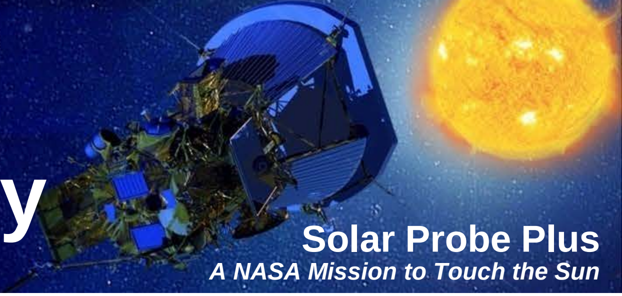
EPS Reviews Held in Phase B



- **EPS PDR – 11/18/13 - 11/19/13**
- **S/A PDR – 11/6/13**
- **EPS Requirements Peer Review – 7/25/13**
- **PSE Requirements Peer Review – 7/26/13 - 7/30/13**
- **PSE Packaging Concept Working Review – 8/22/13**
- **S/A Angle Control Peer Review – 8/7/13**
- **Battery Design Peer Review – 11/21/13**

- **Other related reviews**
  - **Fault Management Peer Review – 7/21/13 & 7/22/13**
    - **Includes S/A Operations and Safing review**
  - **S/A cooling system**
    - **Electrical PDR – 10/23/13**
    - **Mechanical/Thermal PDR – 12/3/13 - 12/5/13**

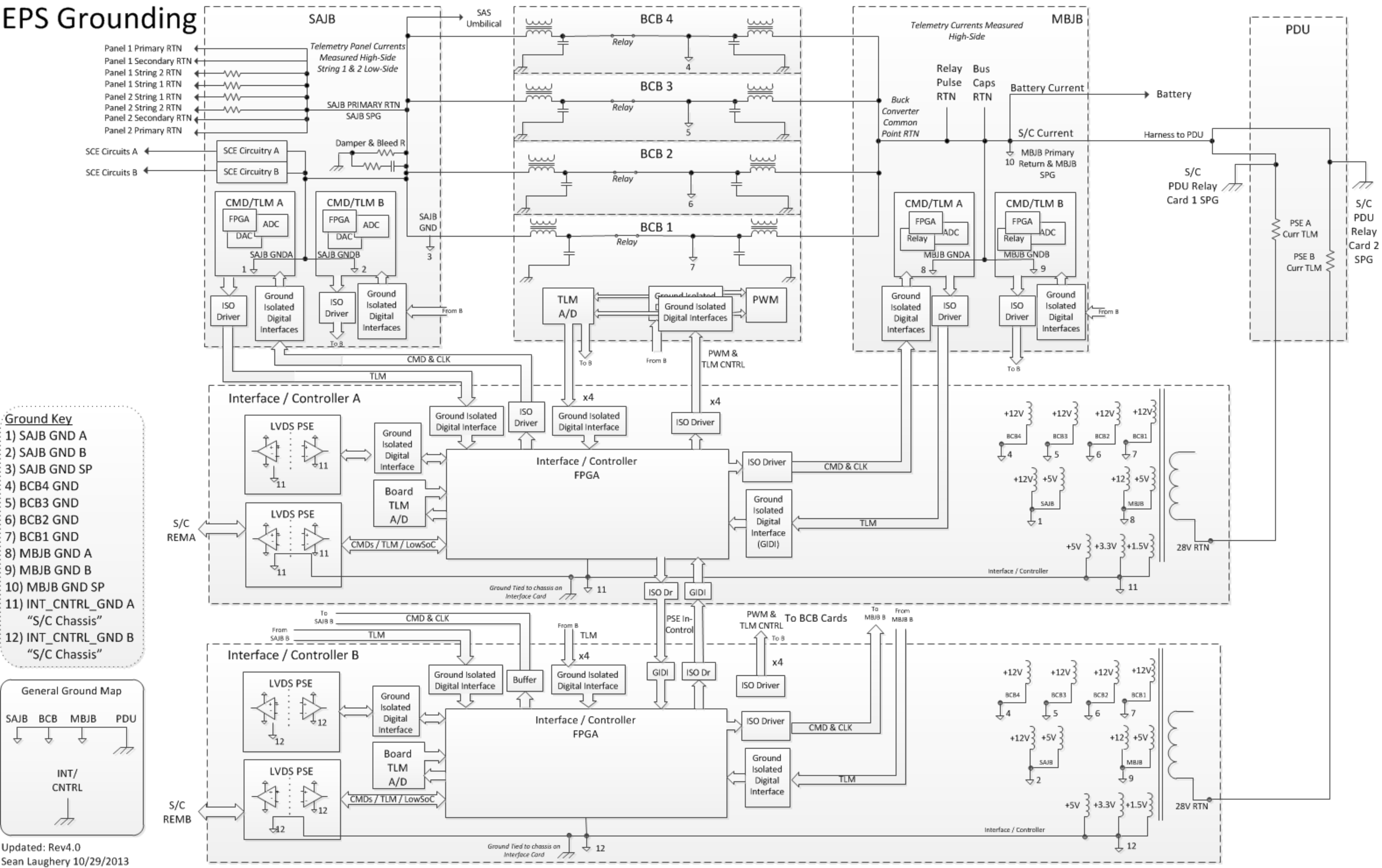
Action Items in PIMS - Summary



- **SPP EPS Pre-MDR Peer Review**
  - **Action Item Closure Status**
    - **Total: 11**
    - **Approved and closed: 11**
    - **Open: 0**
  - **Action items closed per SEE-13-078 (9/9/13)**
  - **All action items approved and closed in PIMS**
  - **All recommendations addressed in memo**

- **SPP EPS Portion of MDR**
  - **No action items assigned to EPS**

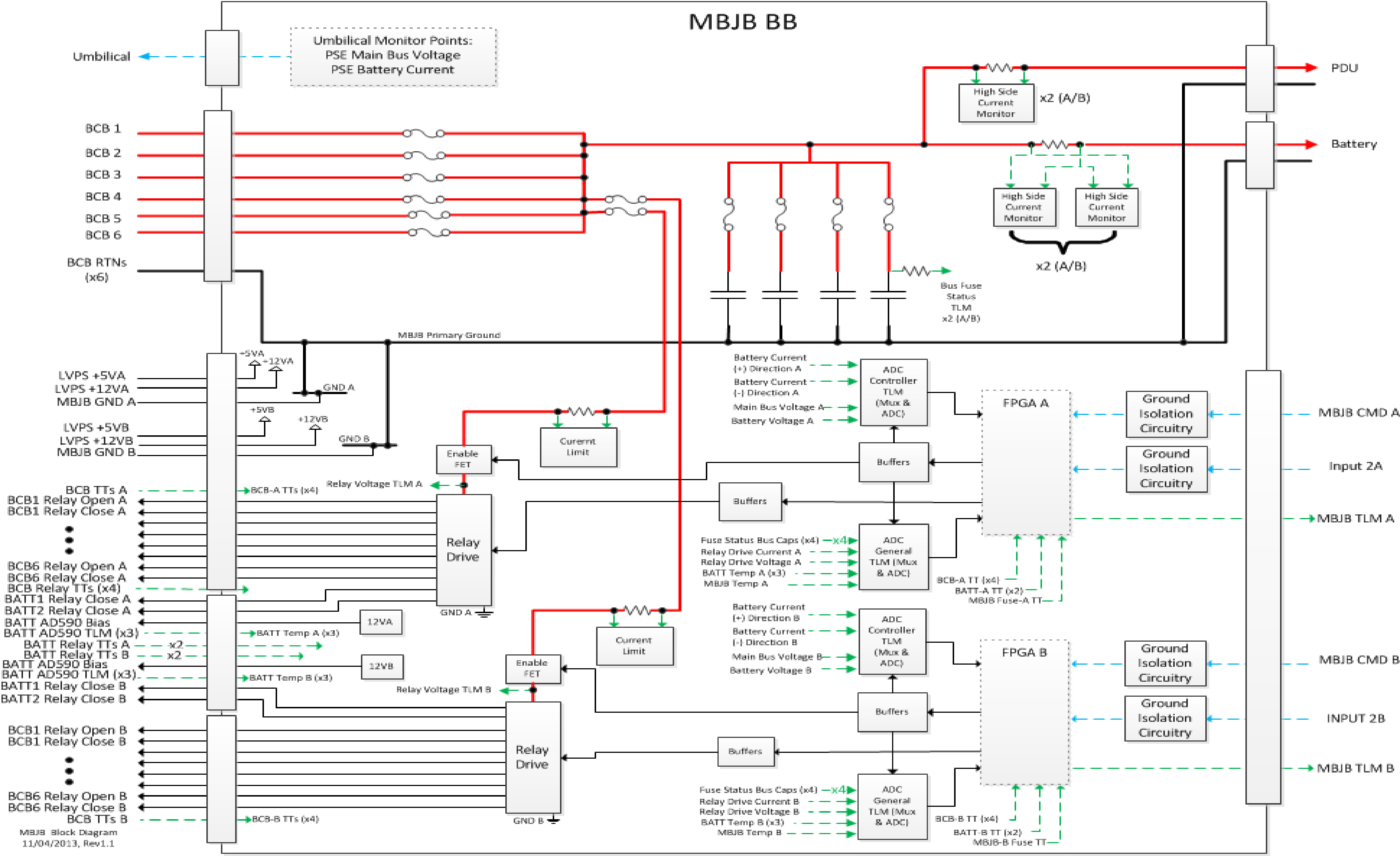
PSE Grounding Block Diagram



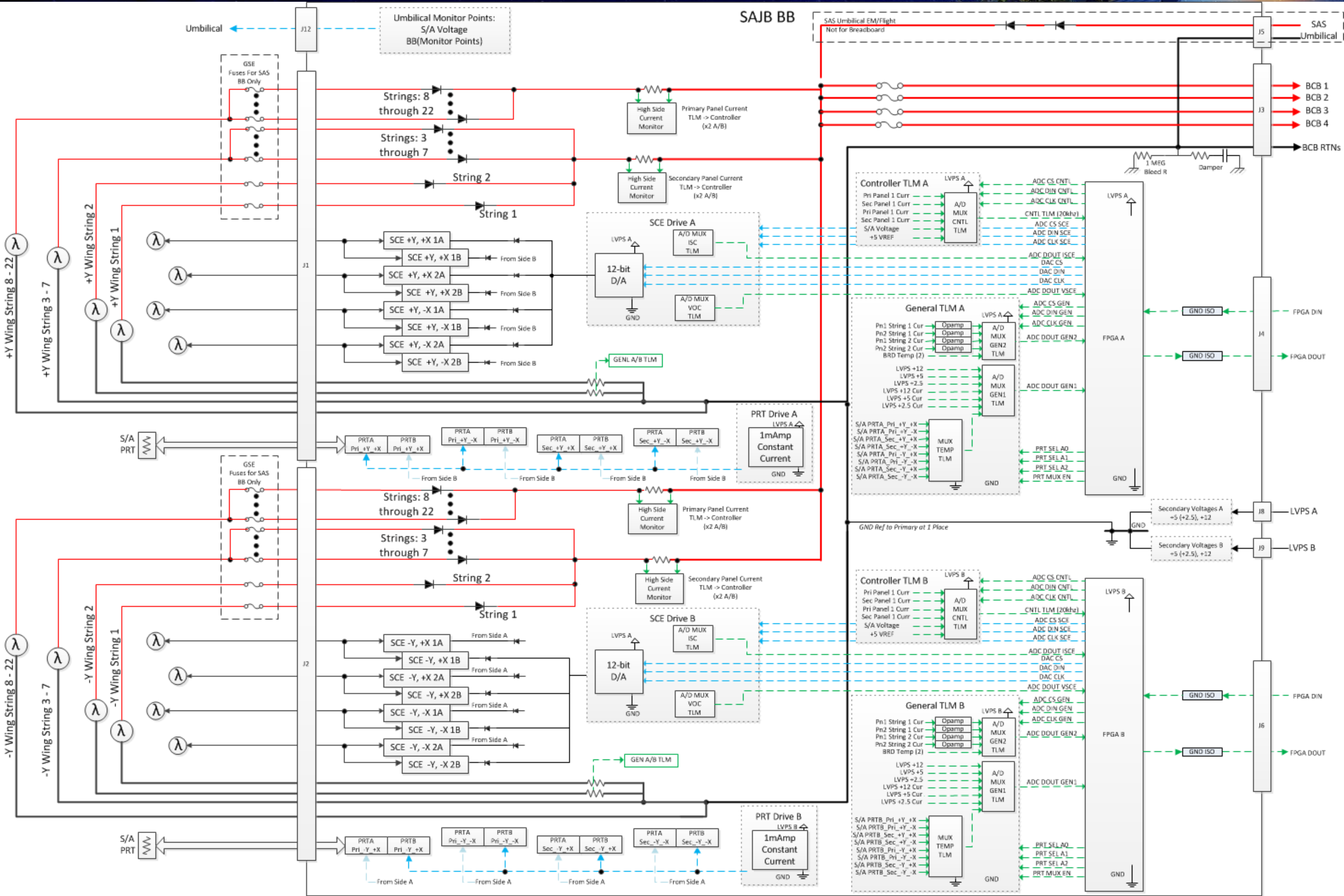
Ground Key
1) SAJB GND A
2) SAJB GND B
3) SAJB GND SP
4) BCB4 GND
5) BCB3 GND
6) BCB2 GND
7) BCB1 GND
8) MBJB GND A
9) MBJB GND B
10) MBJB GND SP
11) INT_CNTRL_GND A "S/C Chassis"
12) INT_CNTRL_GND B "S/C Chassis"

Updated: Rev4.0
Sean Laughery 10/29/2013

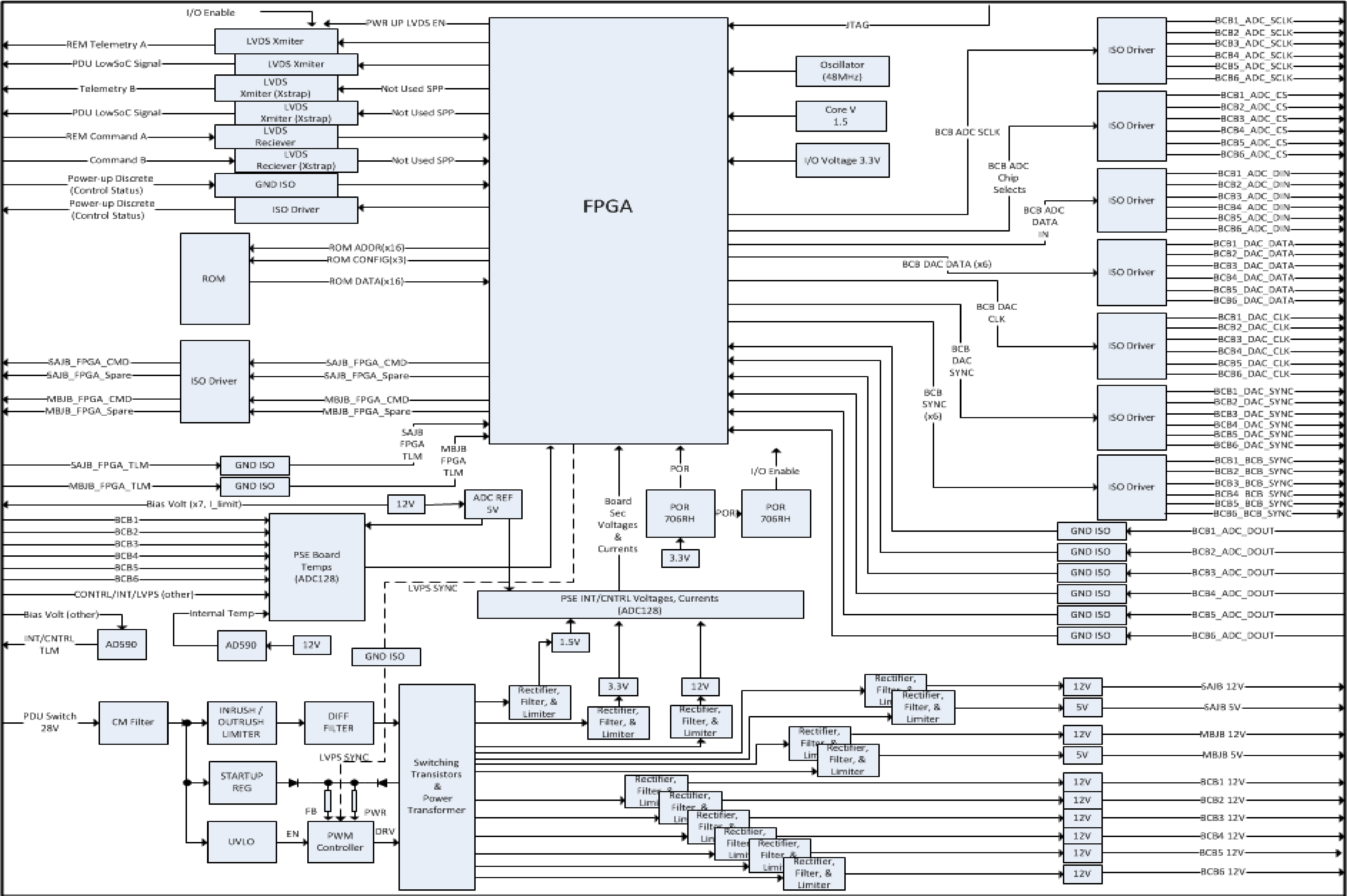
PSE MBJB Block Diagram



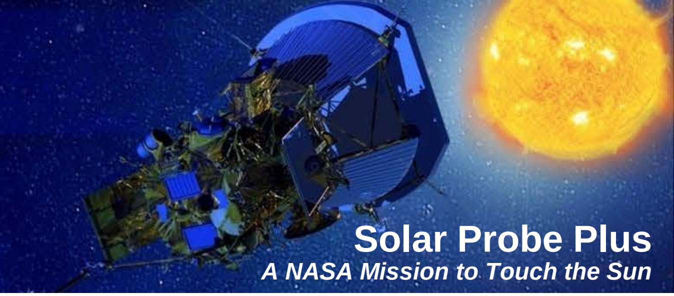
PSE SAJB Block Diagram



PSE ICL Block Diagram



PSE Buck Converter Board Block Diagram



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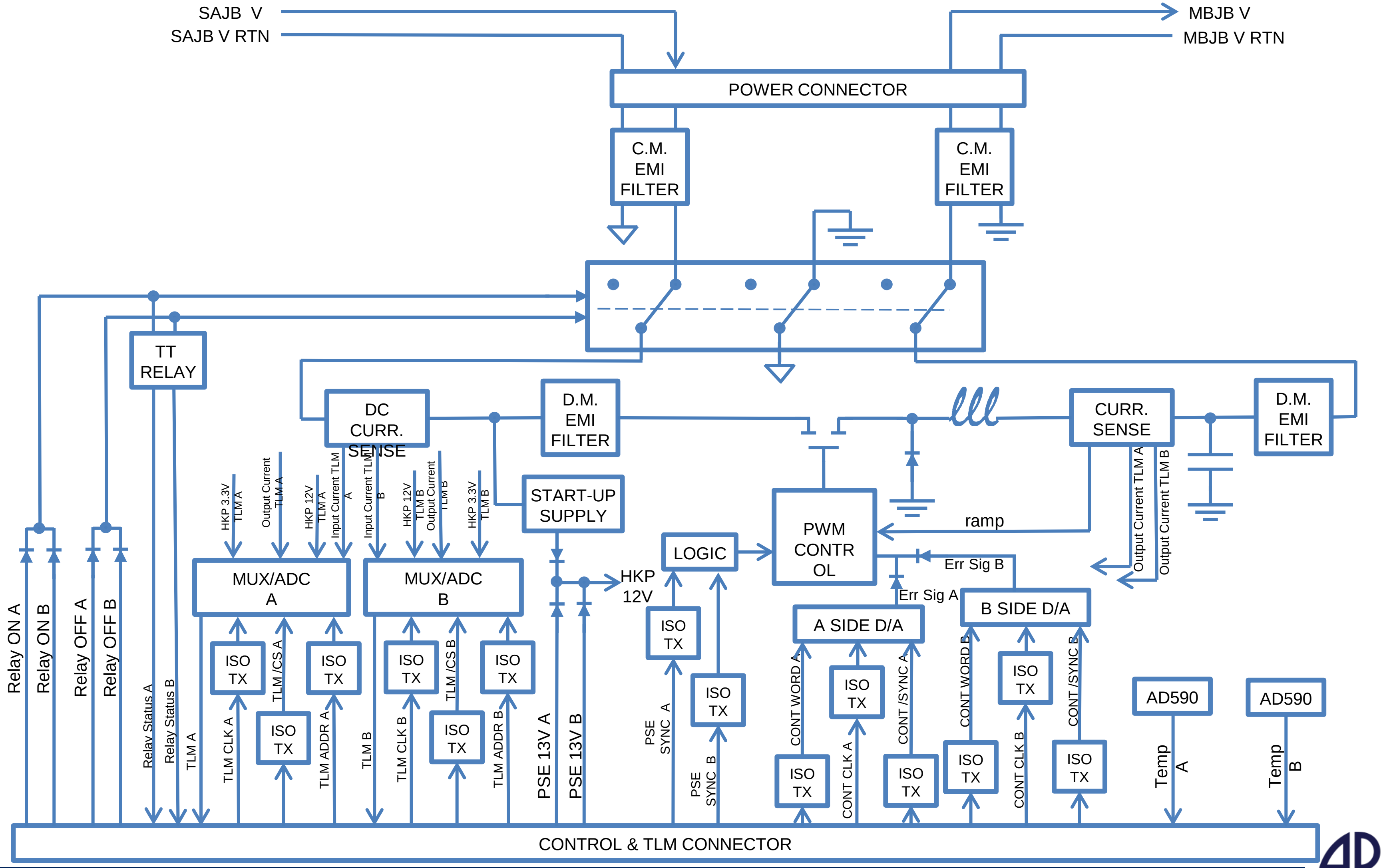
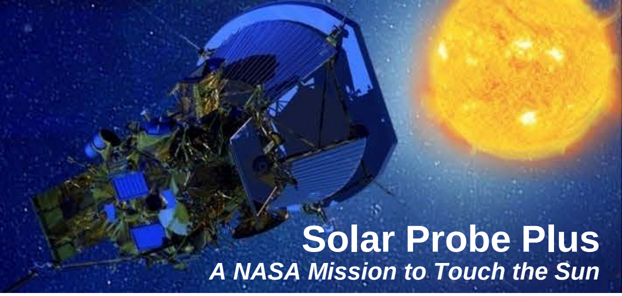




Battery Discharge Cases

Power Configuration #	PC1	PC2	PC4	PC5	PC25	PC29	PC31	PC33
Power Configuration Description	Launch	Warm-up and Activate Rad 1&4 and Solar Array	Catbed Warm Up for Launch Error Correction	Launch Error Correction	Safe Mode-Solar Array, <0.5AU	Venus Eclipse	TCM (non-launch correction); 1.02AU	TCM EOM; 0.72AU - 0.34AU
BOM/EOM	BOM	BOM	BOM	BOM	EOM	EOM	EOM	EOM
Duration (Minutes)	60	60	60	120	15	12	30	30
S/A Power Minimum (W)	0.0	319.7	376.0	376.0	0.0	0.0	376.0	507.8
Load Power Maximum (W)	169.0	414.9	358.8	417.6	361.5	350.8	450.7	450.7
Battery Power (Worst Case) (W)	-174.8	-139.9	-29.4	-91.3	-382.0	-370.2	-126.7	-7.6
Battery Discharge Rate (C)	0.250	0.200	0.042	0.130	0.546	0.529	0.181	0.011
Starting SOC Description	Near "Full"	End of PC1	Near "Full"	End of PC4	"Depressed"	Near "Full"	Near "Full"	Near "Full"
Starting SOC Minimum (Wh)	570.6	395.8	570.6	541.2	251.0	417.4	417.4	417.4
Change in SOC (Worst Case) (Wh)	-174.8	-139.9	-29.4	-182.7	-95.5	-74.0	-63.3	-3.8
Depth of Discharge (%)	25.0%	45.0% *	4.2%	30.3% *	13.6%	10.6%	9.0%	0.5%
Quantity of Cycles	1	1	1	1	< 5	3	19	23
End of Discharge SOC Minimum (Wh)	395.8	255.9	541.2	358.5	155.5	343.3	354.1	413.6
End of Discharge SOC Minimum (% of Rated)	56.5%	36.6%	77.3%	51.2%	22.2%	49.0%	50.6%	59.1%
End of Discharge Battery Voltage Minimum (V)	30.9	30.0	31.9	30.7	28.2	29.8	29.9	30.6
Bus Voltage (at Loads) Minimum (V)	28.1	27.2	29.1	27.9	25.4	27.0	27.1	27.8

Consecutive Consecutive

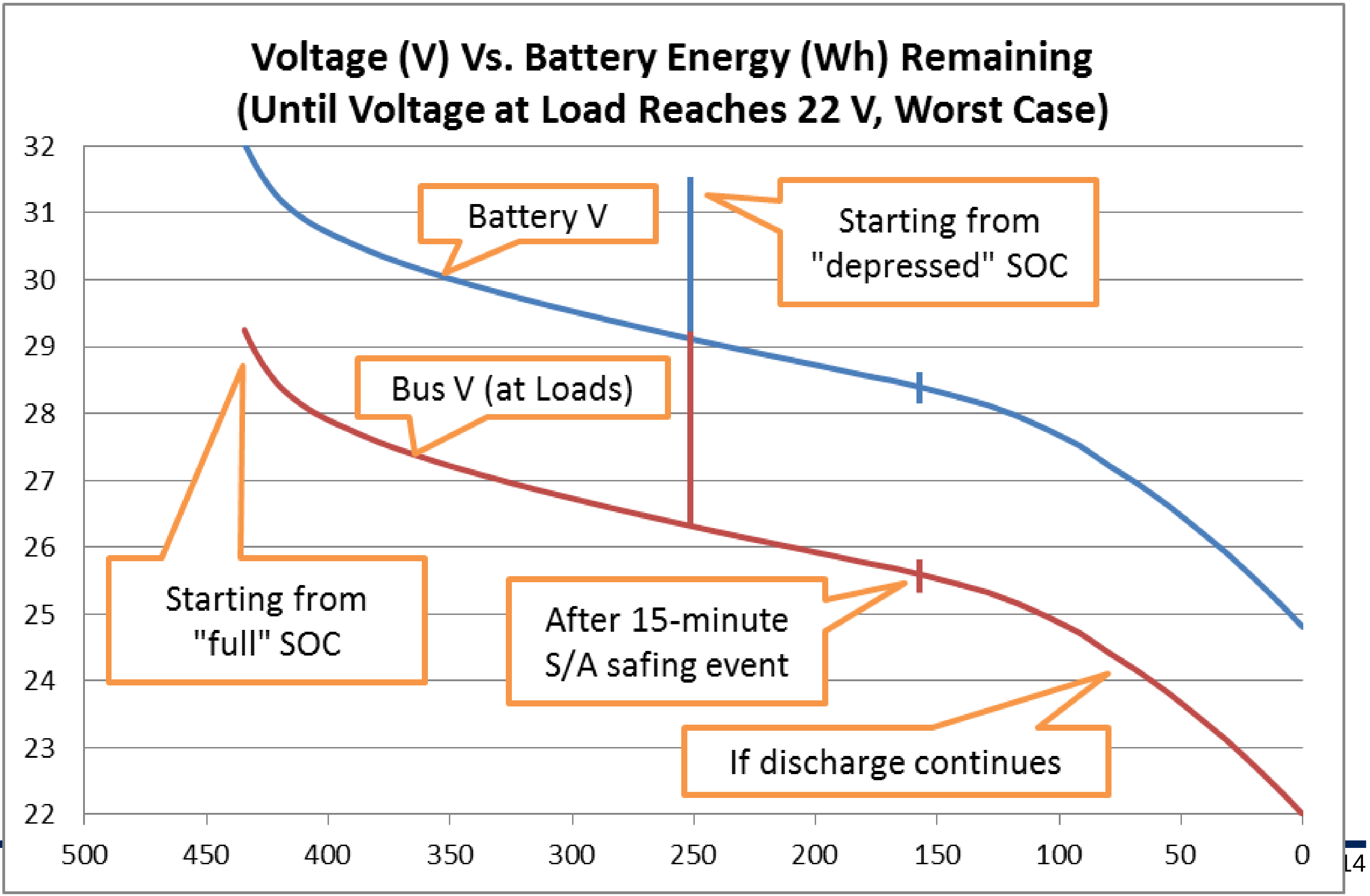
- Relative SOC "near full" assumed to be at 95%
- Safe mode assumed to start with the battery at a depressed SOC
  - Applicable during autonomous closed-loop S/A angle control
- End-of-discharge SOC % is relative to rated energy, 700 Wh

* Includes DOD from preceding power configuration

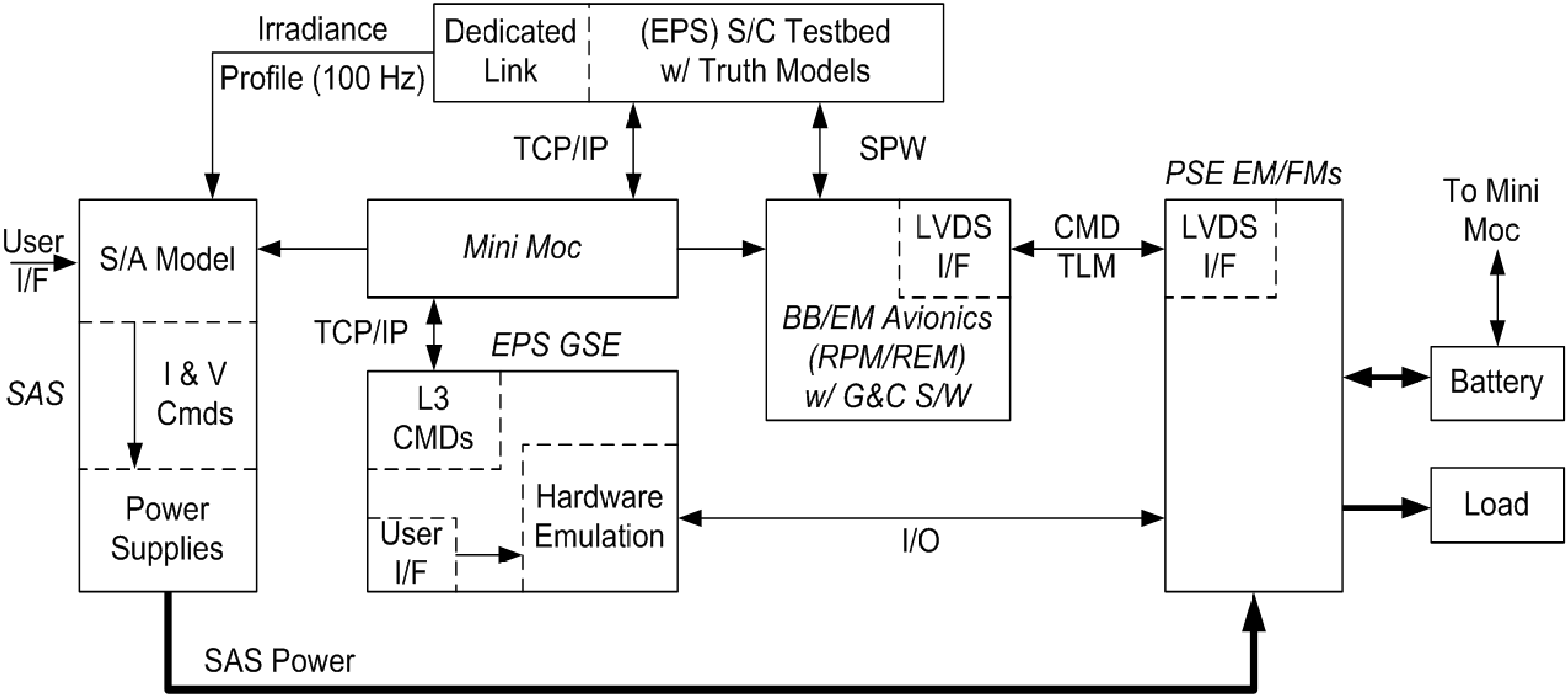
Data as of EPS PDR 11/2013

Battery Energy Margin

- At end of life, minimum battery SOC is about 251 Wh under normal conditions
- Minimum SOC after S/A safing event is 156 Wh
- At max load (w/ margin) of 440 W, battery can support load for ~20 minutes

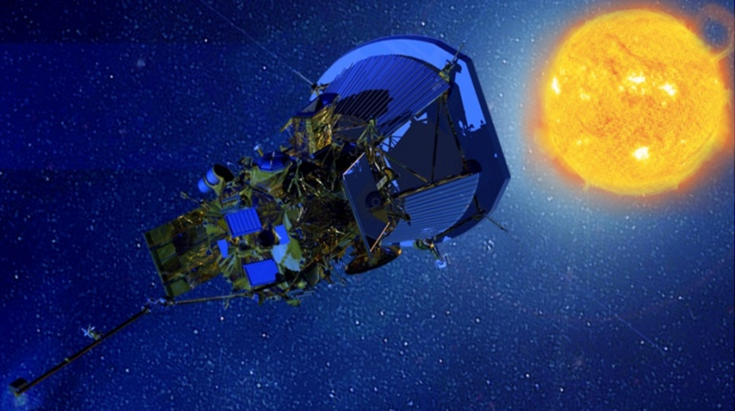


EPS Testbed (Phase C)



Solar Probe Plus

A NASA Mission to Touch the Sun



Solar Array

Ed Gaddy
Lead Solar Array Engineer

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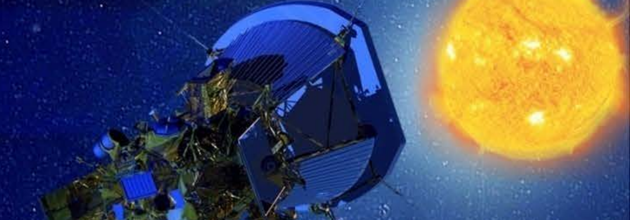
13 – 16 January 2014

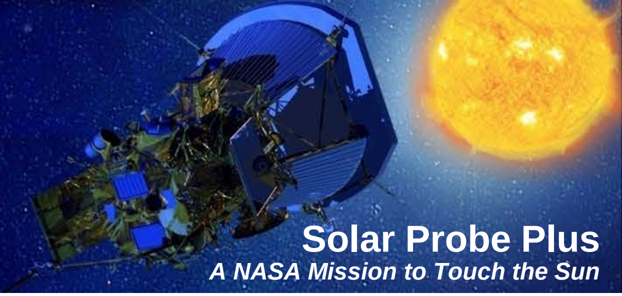
APL
The Johns Hopkins University
APPLIED PHYSICS LABORATORY



Outline

- Configuration
- Environment -> increase TRL level
- Requirements
  - Withstand the environment including non-nominal ~70 suns
  - Power, analysis technically challenging
  - Thermal load to cooling system
  - Mass (wing width)
  - Electrostatic Cleanliness
  - Magnetic Cleanliness
  - Provide signals for array temperature and irradiance
- TRL 6 test results
- Additional test results
- Special equipment
- Summary of upcoming testing

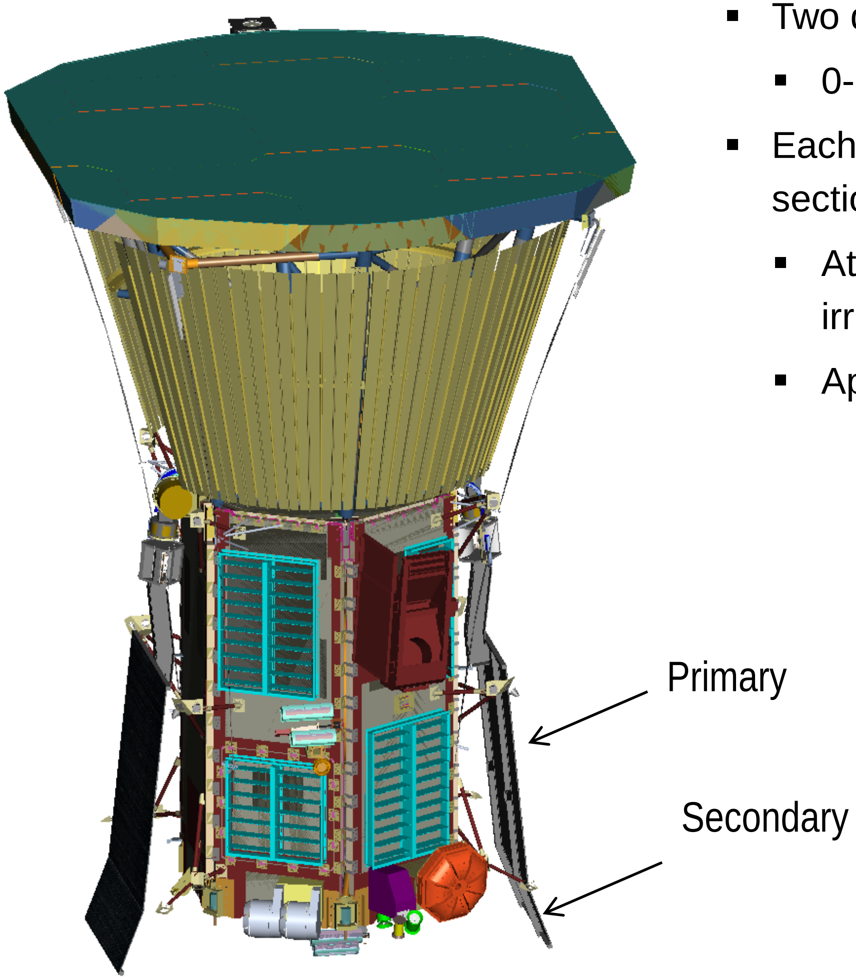
Configuration

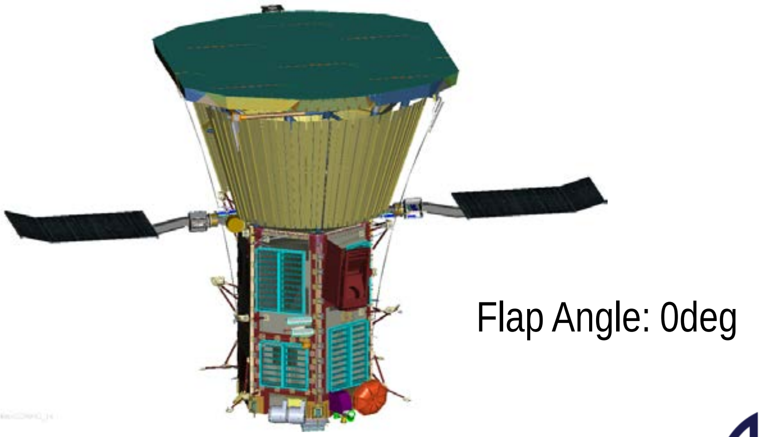


Configuration

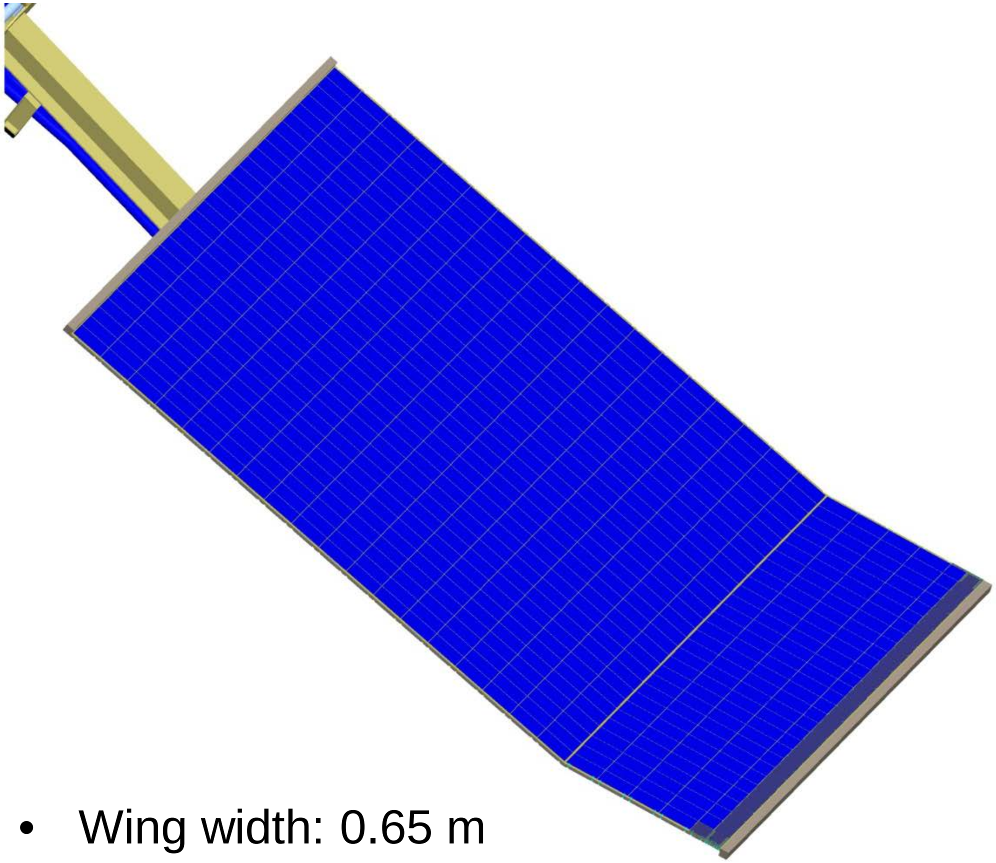
Configuration
Wings

- Two deployable, articulated solar array wings
  - 0-88º flap and ±85º feather
- Each wing includes a primary section and a smaller secondary section at a fixed cant angle
  - At 9.86Rs, the secondary absorbs about 90% of the incident irradiance
  - Approximate peak suns into cells, 25.





Configuration
Overview of front of wing



- Wing width: 0.65 m
- Primary length: 0.8715 m
- Secondary length: 0.2538 m

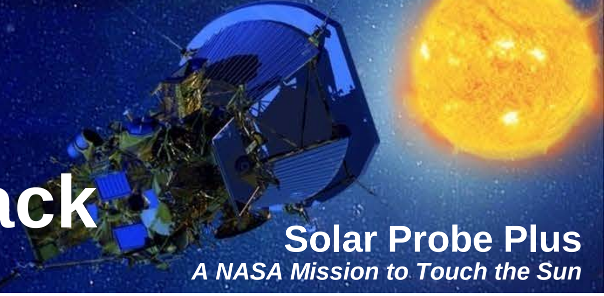
Both primary and secondary cells carry Emcore cells based on ZTJ technology.

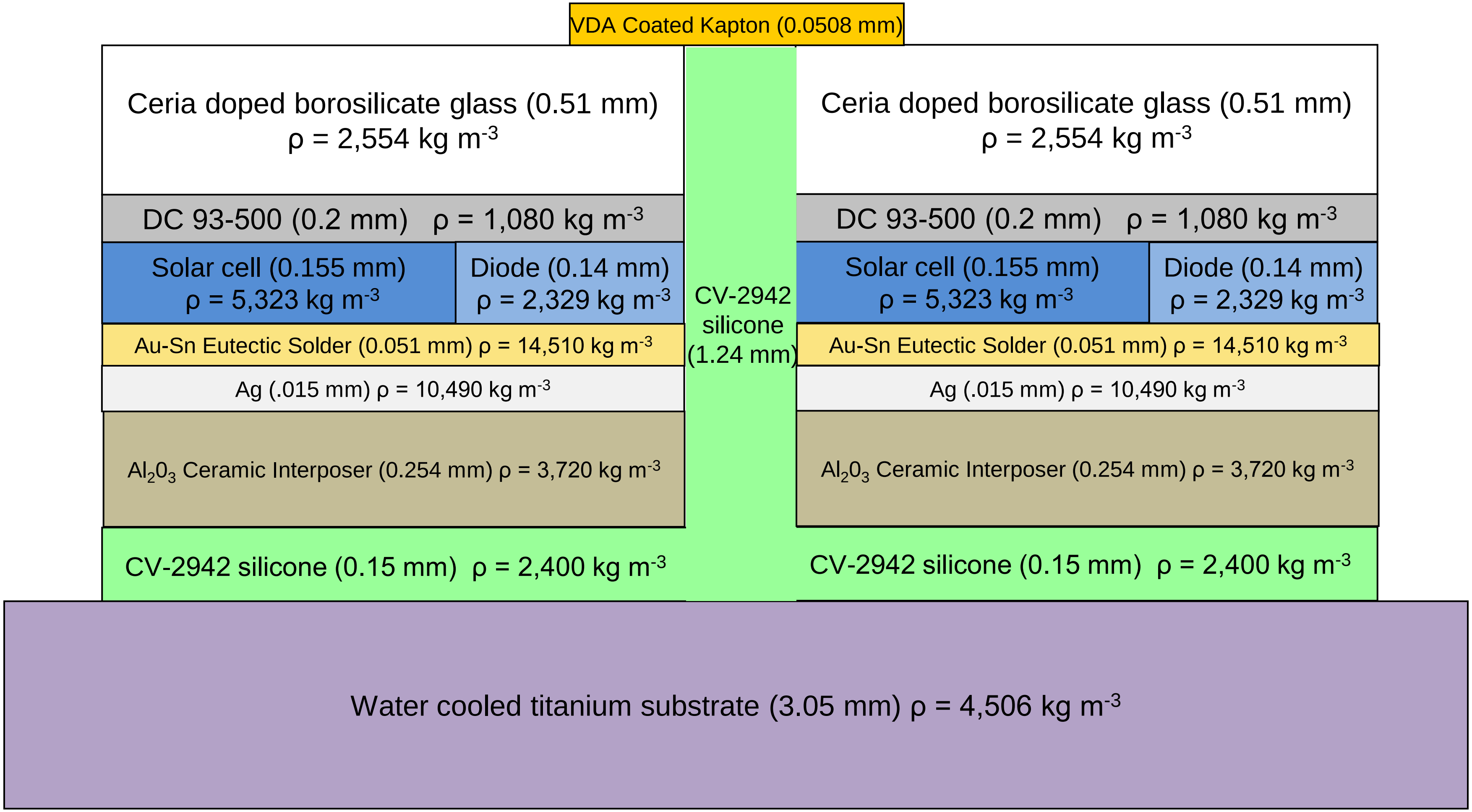
Cell stacks for both are optimized for thermal conductance using high thermal conductivity adhesive and alumina insulators

Electrical connections are made with Au-Sn eutectic solder rather than welding

Substrates (platens) are liquid cooled. Water from radiators enters the outboard edge and exits from the inboard edge

Configuration
High Thermal Conductance Cell Stack





VDA Coated Kapton (0.0508 mm)

Ceria doped borosilicate glass (0.51 mm) ρ = 2,554 kg m^{-3}

DC 93-500 (0.2 mm) ρ = 1,080 kg m^{-3}

Solar cell (0.155 mm) ρ = 5,323 kg m^{-3}

Diode (0.14 mm) ρ = 2,329 kg m^{-3}

Au-Sn Eutectic Solder (0.051 mm) ρ = 14,510 kg m^{-3}

Ag (.015 mm) ρ = 10,490 kg m^{-3}

Al_20_3 Ceramic Interposer (0.254 mm) ρ = 3,720 kg m^{-3}

CV-2942 silicone (0.15 mm) ρ = 2,400 kg m^{-3}

CV-2942 silicone (1.24 mm)

Ceria doped borosilicate glass (0.51 mm) ρ = 2,554 kg m^{-3}

DC 93-500 (0.2 mm) ρ = 1,080 kg m^{-3}

Solar cell (0.155 mm) ρ = 5,323 kg m^{-3}

Diode (0.14 mm) ρ = 2,329 kg m^{-3}

Au-Sn Eutectic Solder (0.051 mm) ρ = 14,510 kg m^{-3}

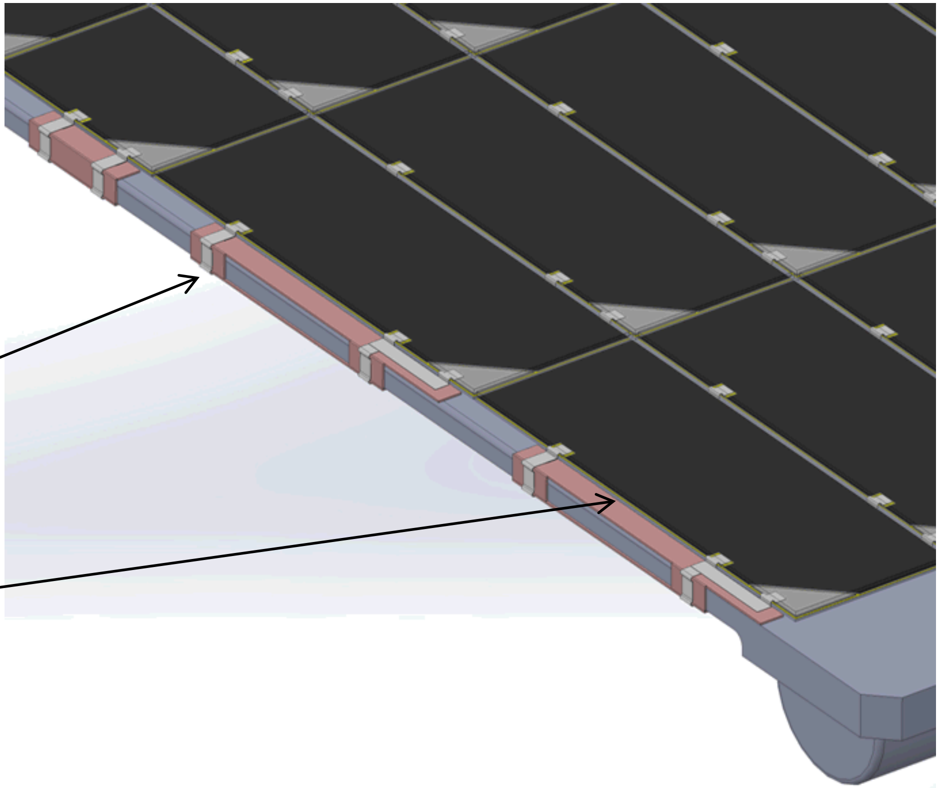
Ag (.015 mm) ρ = 10,490 kg m^{-3}

Al_20_3 Ceramic Interposer (0.254 mm) ρ = 3,720 kg m^{-3}

CV-2942 silicone (0.15 mm) ρ = 2,400 kg m^{-3}

Water cooled titanium substrate (3.05 mm) ρ = 4,506 kg m^{-3}

Configuration
HTCCS wrap around conductors

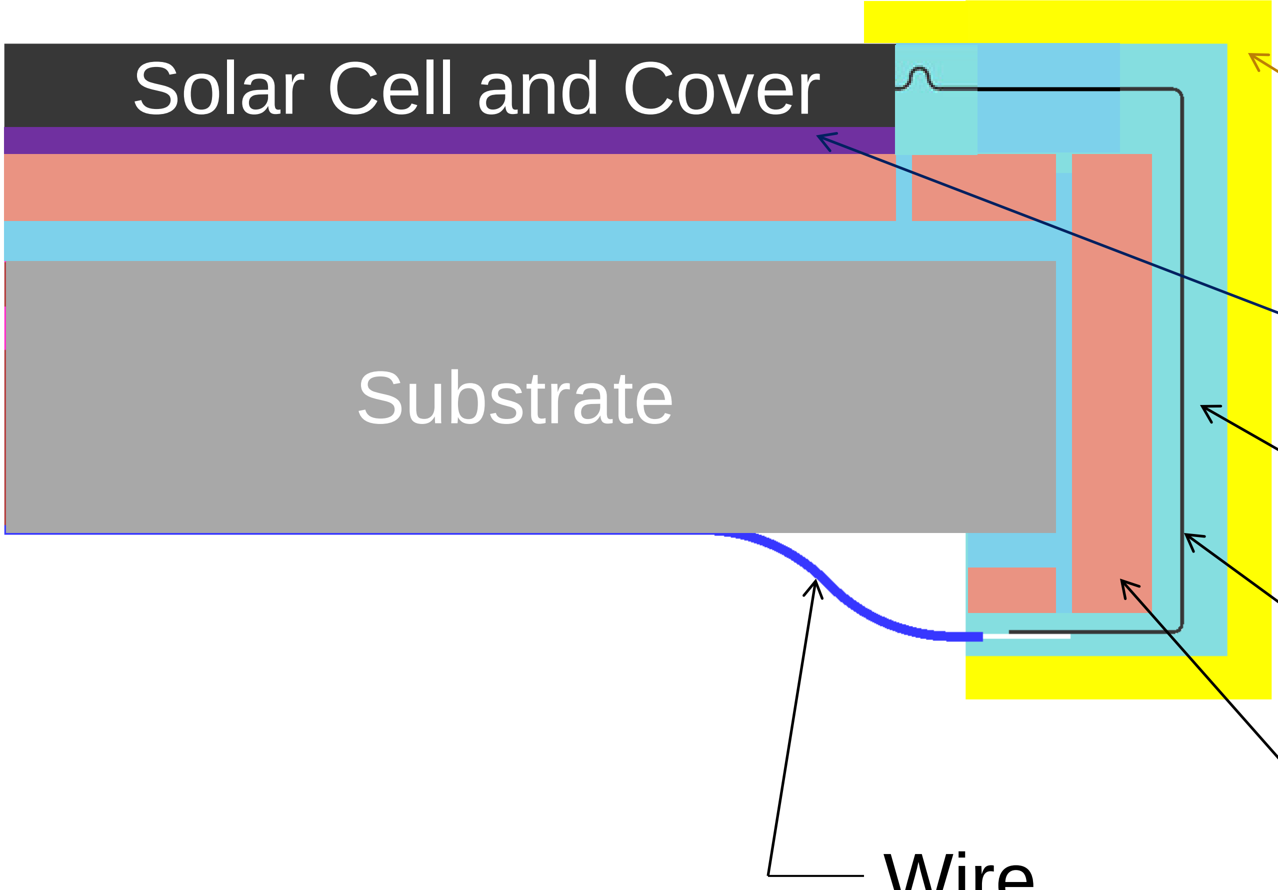


Not shown: VDA Kapton is glued over exposed conductors using CV 2942

conductors shown in gray

ceramic insulators shown in red

Configuration
HTCCS wrap around



Solar Cell and Cover

Substrate

Kapton coated with VDA

Au Sn solder

CV 2942

Interconnect

Ceramic

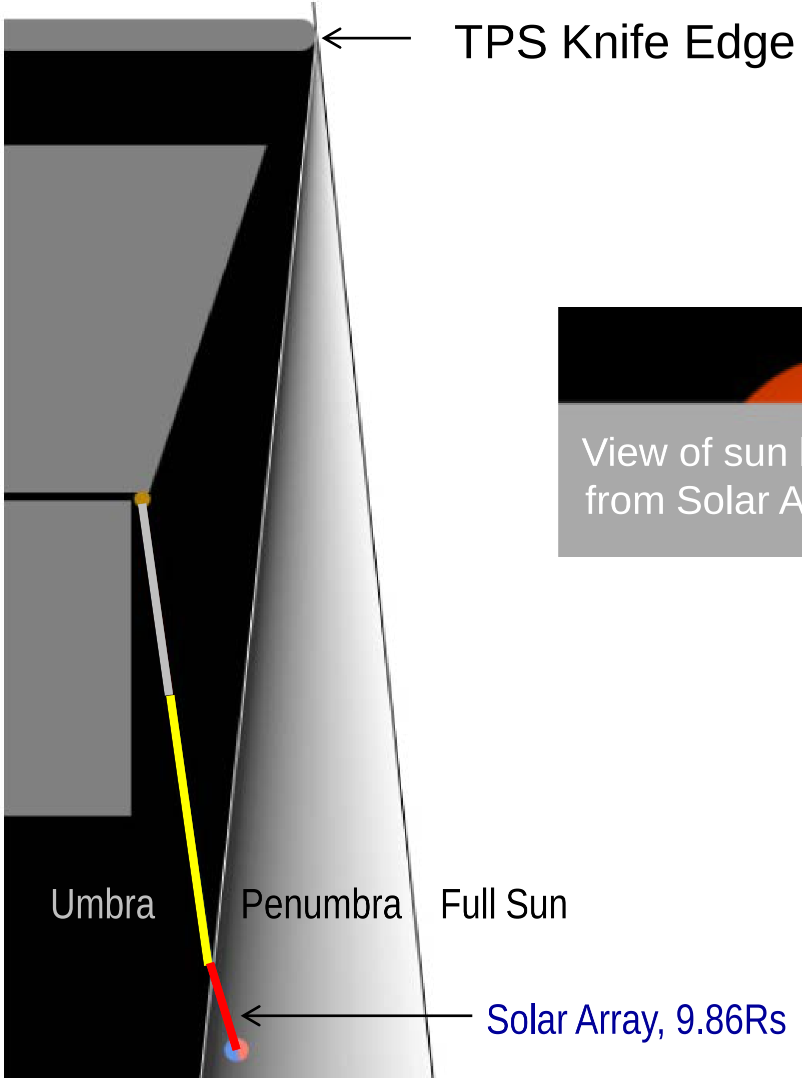
Wire

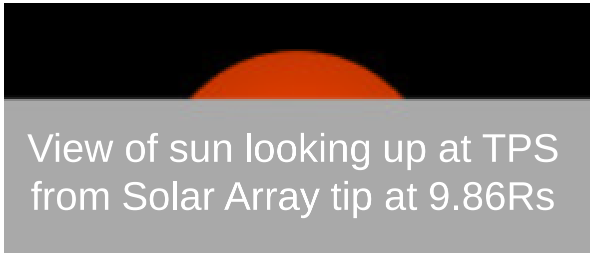
Environment

Environment

Environment

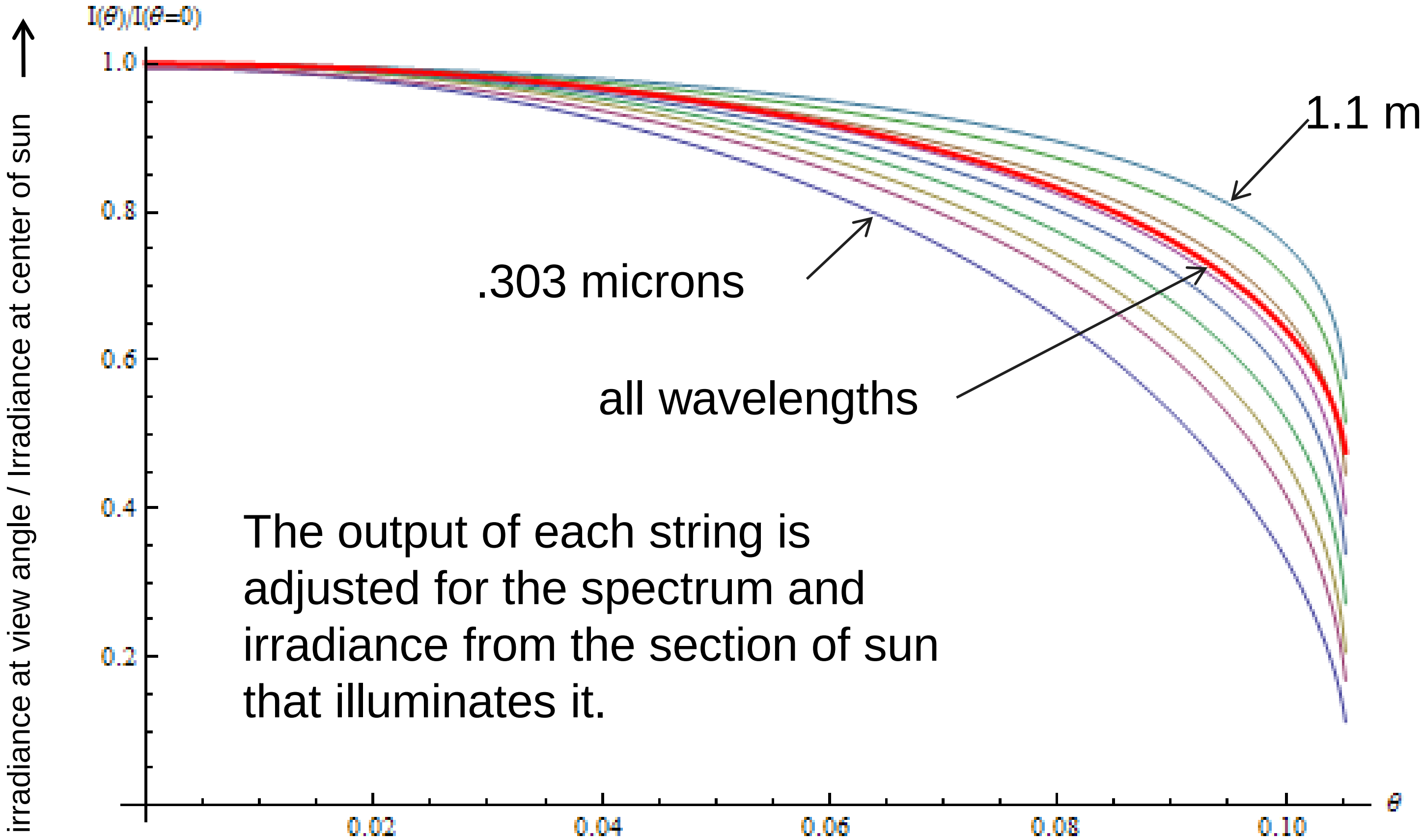
Array’s view of the sun at perihelion




View of sun looking up at TPS from Solar Array tip at 9.86Rs

Environment

the limb is redder and dimmer than the entire sun



1.1 microns

.303 microns

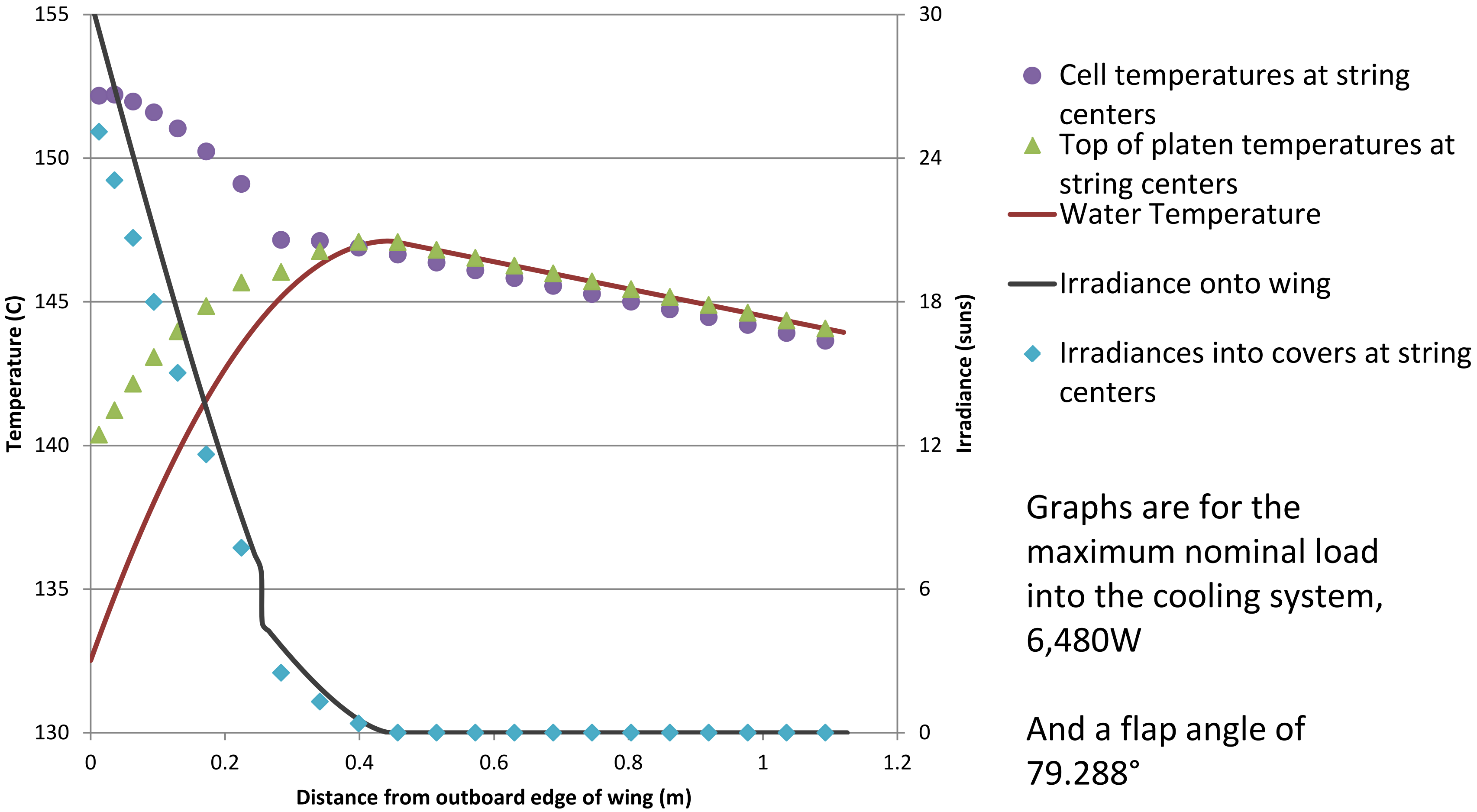
all wavelengths

The output of each string is adjusted for the spectrum and irradiance from the section of sun that illuminates it.

View angle from sun's center at 0.0442 AU

Environment

Temperature and irradiance at EOL perihelion



Graphs are for the maximum nominal load into the cooling system, 6,480W

And a flap angle of 79.288°

Environment

- **Approximately 200,000 sun hours predicted for the most outboard section of the wings. A 15 year GEO mission is exposed to ~ 131,400 sun hours.**
- **Less than 0.2% of the mission occurs at > 25 X AM0**
- **Greater than 92% of the mission occurs at < 10X AM0**
- **Non-nominal irradiance up to 70 suns for up to ~30 seconds.**
- **Sun spots, coronal mass ejections, plages, and faculae have been reviewed; they will have minimal or no impact on the array.**

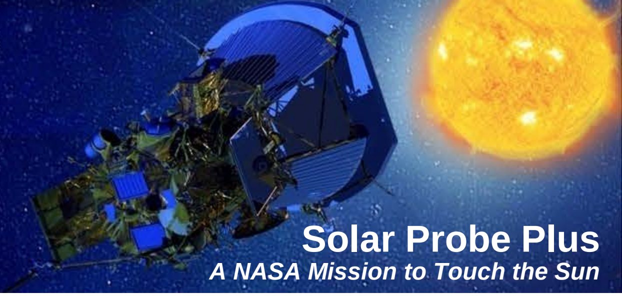
Environment

- **Solar flares will emit charged particles that will impact array performance. Proton fluence goes approximately as $r^{-1.5}$. Protons are the dominate source of charged particle degradation.**

- **Thermal cycling.**
  - **Launch sequence: +20C to -80C to +20C (note: wings not flooded)**
  - **Cycles due to 24 orbits around sun: 10C to 154C to 10C**
  - **Cycles due to slews: 100 (TBR) from 50C to 150C to 50C**

- **Dust**
  - **Reduces cell area and correspondingly the output**
  - **Shorts between the cell and the substrate**
  - **Cell shunts**
  - **Effect is a primarily theoretical computation, the flight dust velocities cannot be achieved in test.**

- **Antennas shadow the wings during slews**



Requirements

Requirements

Requirements

- Power (with CBE loads):
  - A minimum of 439 W at 6.96 years at 0.7 AU
  - A minimum output of 365 W on first day of launch

- Load to cooling system:
  - No more than 5,343 W to the cooling system from irradiance on the array
    - 600 W allocated for skew
    - 450 W from the TPS
    - 534 W from the instruments
    - (447) W to the power system
    - 6,480 W total to the cooling system

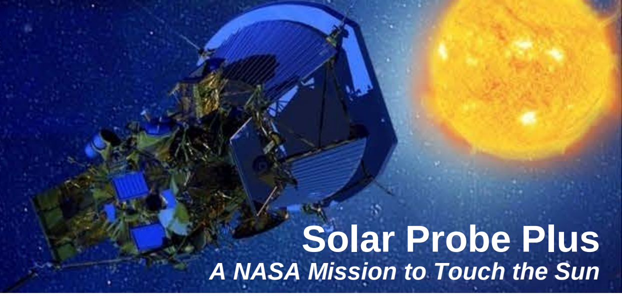
- Mass: less than 4.5 kg with CBE + 25% loads.

- Wing width: less than 0.65 m with CBE + 25% loads.

Requirements (continued)

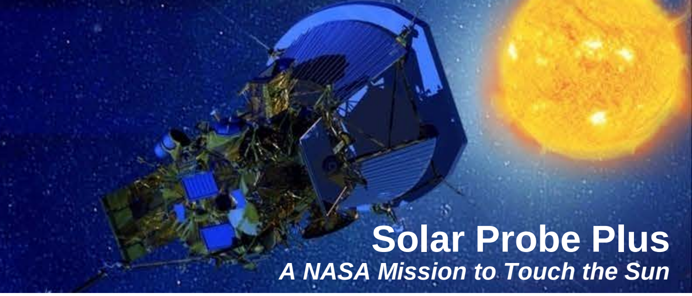
- **Electrostatic cleanliness: Present less than 10 volts to space**
- **Magnetic cleanliness:**
    - **Back-wiring is required**
    - **No magnetic material or components other than 6.9 g of Kovar**
- **Provide signals for over irradiance and over temperature**
- **Reliability: Meet power, electrostatic cleanliness and magnetic requirements after seven years in orbit**
- **Derived requirements: such as number of thermistors, wire maximum temperature, number of sensor cells etc.**

Power Analysis



POWER ANALYSIS

Power Analysis Degradation Factors



- **The irradiance and temperature are available from calculations that were used to produce previous slides.**
- **In addition, the factors tabulated below are used:**

Factor	Amount (%)	How computed over trajectory	Improvements to be made
Test uncertainty	2	Constant	None
Assembly	0.5	Constant	None
Charged particles to current	1	Linear with time	None
Charged particles to voltage	8	Linear with time	None
Micrometeorites and debris	1	Linear with time	None
Thermal cycling	0.5	Linear with time	Taken after first cold cycle
Diode loss	0.7 v	Constant	Correct for temperature

Power Analysis
Degradation Factors continued

- **the degradation factors tabulated below are used (continued):**

Factor	Amount (%)	How computed over trajectory	Improvements to be made
Covering	0.0	Constant	None (data is taken from CICs)
UV	2.0	Linear over time	Exponential saturating “early”
Contamination	1.0	Linear over time	None
Antenna shadowing	3.5	Only in “comm” attitude	To be updated to account for roll about x-axis.
Anomalous on primary	17	From ESH on MESSENGER	To be updated with new SPP ESH computation
Anomalous on secondary	33		

Power Analysis
Anomalous degradation


Solar Probe Plus

A NASA Mission to Touch the Sun

- **Anomalous degradation of spacecraft that have previously operated at high irradiance and high temperature has happened in all cases. The reason for this is thought to be due to either or both of:**
  - **Outgassing**
  - **Cover to cell adhesive darkening.**
- **Measuring values for degradation of CICs as a consequence of outgassing and cover to cell adhesive degradation are difficult**
  - **How much outgassing will accumulate on the cover surfaces and how much it will degrade are impossible to accurately determine from experiment**
  - **The degradation of the cover to cell adhesive is difficult because there is no good simulator for the UV produced by the sun and because the wavelengths that trigger the degradation are unknown.**
  - **Because of this, we have predicted the degradation of the SPP array on the degradation of the MESSENGER array as a function of Equivalent Sun Hours.**

Power Analysis
Computation methodology

Data provided by Emcore was used to craft functions that predict Voc, Isc, Vmp, and Imp over the range of irradiance and temperature of interest

Average differences between measured data and predictions are within 0.2%

The “points” defined by Voc, Isc and Pmp are used to predict I-V curves at required irradiances and temperatures

Power Analysis
Results near or at aphelion

Power Configuration	Description	Power Required (W)	Power Predicted (W)	Antenna Shadowing	Margin** (%)
PC 3	After launch, after cooling system fill	351.6	388	No	10.4
PC 20	0.761 AU aphelion at 5.01 years	425.6	449	Yes	5.5
PC 21	0.70 AU at 6.96 years	425.5	458	Yes	7.6
PC 35	0.731 AU at aphelion at 6.99 years	425.6	431	Yes	1.3

* Analysis assumes 17% anomalous degradation on primary, 33% on secondary

** Margin of Predicted Power over Power Req'd. Power Req'd includes 25% margin on loads.

Power Analysis
PC 24b with failed string

9.86 Rs with 6.87 years of degradation, string failed on +Y

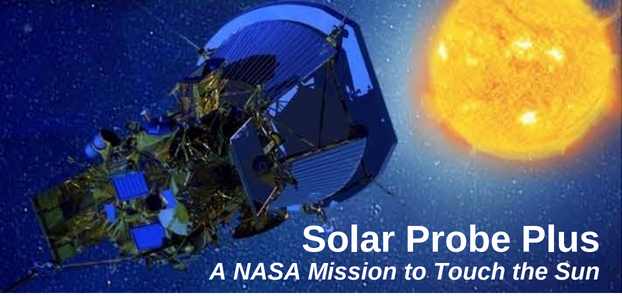
Qcs (W)	5,917			6,480			6,243		
Anomalous Deg. (%)	33			33			33		
Inlet water temp. (C)	120			132			152		
Wing	+Y	-Y	Both	+Y	-Y	Both	+Y	-Y	Both
Flap angle (degrees)	79.8	79.8		79.5	79.5		79.3	79.3	
Power (W)	207	240	447	219	259	478	245	285	529
Outlet water temp.(C)	130	130		144	144		165*	165	

*case is run to 165C to account for measurement inaccuracy. the nominal limit is 160C.

Mass Estimate

Mass Estimate

Mass Estimate
Add on mass per wing



Solar Probe Plus
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Item	Mass (g)
VDA Kapton	4.8
Coverglasses	932.7
DC 93-500	165.8
Cells	532.2
Diodes	9.0
Interconnects	6.9
CV 2942	426.0
Wire	649.9
Connectors	186.8
Ceramic	984.0
Solder	511.9
Sub-Total	4410
Reserve	90
Total	4500

Electrostatic Cleanliness

Electrostatic Cleanliness

Electrostatic Cleanliness

- **The primary’s coverglasses are coated with indium tin oxide (ITO) and grounded.**

- **The spaces between the primary’s coverglasses are covered with VDA coated Kapton that is grounded. This tape also grounds the ITO on the covers**

- **During nominal operation, the secondary is always illuminated.**
  - **This prevents charge build up as UV knocks off the electrons**
  - **There is some shine through of cell voltages.**
    - **NASCAP analysis shows that small areas of the array will range between 13.2 V and 34.3 V. This does not have a significant effect on instrument measurements. Effects are limited to very close to array.**
    - **Accepted by the scientists.**
  - **The spaces between the secondary’s coverglasses are covered with VDA coated Kapton that is grounded.**
  - **The secondary is not illuminated during earth and Venus eclipses. This has been analyzed to determine if destructive ESD will occur. It will not.**

Magnetic Cleanliness

Magnetic Cleanliness

- **The wings shall use no magnetic components with the exception of Kovar interconnects having a total mass of less than 6.9 g.**

- **The strings shall be back wired to minimize magnetic field generation.**

- **This configuration has been submitted to the instrument team and found to be acceptable.**

Robustness and Reliability

- **Numerous coupons and larger test articles have been tested at the required irradiance and temperatures.**
- **The wings have redundant sensor cells on each outboard corner to sense irradiance**
- **The wings have temperature sensors under the inlet and outlet manifolds to sense water temperature.**
- **Spacecraft fault management safes the wing if they encounter:**
  - **Too high of a water outlet temperature**
  - **Too high irradiance**
  - **Too low water inlet temperature**

TRL

TRL-6

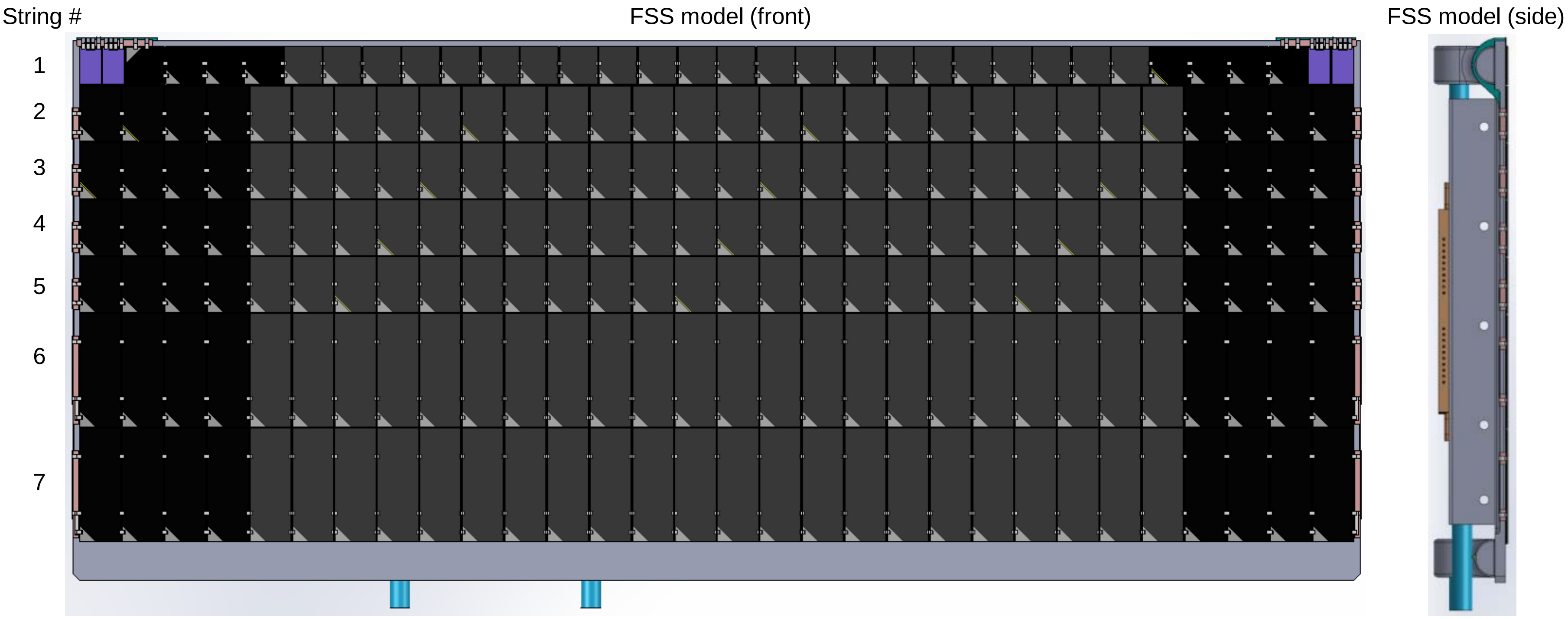
TRL-6 Environmental Exposure Overview

- **Humidity exposure: flight wings and qualification wing will not be exposed to the humidity environment.**
- **Thermal vacuum soak for 48 hours at 164 ºC to simulate outgassing bake-out that will undoubtedly be required for flight panel**
- **Thermal cycling**
  - **2 cycles from -80 C to 10 ºC to mimic first thermal cycle occurring just after launch**
  - **36 cycles from 10 ºC to 164 ºC to simulate the 24 thermal cycles resulting from the orbit and Venus eclipse cycles.**
- **Nominal irradiance and temperature exposure for 45 hours to simulate operation near perihelion.**
  - **A gradient between 0 suns at the inboard edge and 34 suns at the outboard edge and 125 ºC inlet water temperature**
- **Output measured at skewed irradiance (if this occurs in flight, it will be caused by miss alignment between the TPS edge and the wing outboard edge)**
- **Off nominal irradiance**
  - **29 suns at the inboard edge to 63 suns at the outboard edge and 125 ºC water temperature**

TRL-6 Functional Tests

- **Measurement of output under large area pulsed solar simulation**
- **Measurement of Voc versus temperature at 1 AM0 (a check for delaminations)**
- **Diode string dark I-V curves**
- **Visual Inspection**
- **Electroluminescence inspection**
- **Insulation resistance**
- **Ground resistance of VDA Kapton**

TRL-6 Full Size
Secondary Test Article



- Test panel: 27×65 cm^2; vs. flight panel: 25×65 cm^2 w/o outlet/inboard manifold
- 7 strings × 30 CICs: 1 small (3.25 cm^2), 4 med (5.4 cm^2), 2 large (11.38 cm^2)
- 4 sensor CICs (2.09 cm^2) at ends of outboard-most string #1
- VDA Kapton (not shown) over CV2942 grout & panel edges, grounded

Test panel reproduces the secondary portion of a full wing.

TRL-6 Test Results

- **The full size secondary passed all tests except thermal vacuum cycling in which approximately 1% of the solder joints opened and small cell cracks appeared on 27% of the CICs.**
  - **Test of four TRL-5 coupons and other coupons did not open any solder joints. This is a new development.**
  - **Due to inherent redundancy and due to bypass diodes, the flight array would have performed satisfactorily with the opened solder joints.**
  - **The cell cracks remained small during the environmental exposures and did not cause a degradation in power.**
  - **No change in performance of strings without solder failures.**
- **The issues were addressed by changing the method of soldering from thermode heating to hot gas reflow. The later heats the cell better, which is where the solder joints failed, and reduces pressure.**
- **A delta TRL-6 panel was fabricated and thermal vacuum cycled**
  - **No solder failures**
  - **Cell cracking reduced from ~3 mm to < 1 mm. Thermal cycling the panel 50 times from 10C to 164C did not cause additional degradation.**
  - **Cell cracks are within Emcore's standard criteria for acceptance**
- **This demonstrates compliance with TRL-6. Additional tests are planned to refine and improve the existing design.**

Additional Tests

- ESD-wrap around coupon tested at Glenn showed the design to be fully tolerant of the expected plasma environment.
  - Performed 46 ambient cycles from -70 C to 180 C with no degradation
  - No measurable change in string performance at STC.
- A 10,000 Equivalent sun-hour test at Boeing Radiation Effects Laboratory showed no significant dependence of degradation rate of cover to cell adhesive as a function of different covers. This may not be a "true" result due to outgassing that confounds the test results.
- A 10,000 equivalent sun-hour test at JAXA showed no significant variation in degradation rate as a function of temperature between 120 C and 240 C at 10 X AM0.

Additional Tests

- **Cell output measured as a function of temperature and irradiance**
  - **Secondary CIC output measured at 1, 20, and 35 suns at temperatures from 10 ºC to 180 ºC**
  - **Secondary CIC output measured at 1 and 75 suns at angles from 0º to 80º at 28 ºC and 180 ºC.**
  - **Primary CIC output measured at 1, 5, and 10 suns at temperatures from 10 ºC to 180 ºC**
  - **Primary CIC output measured at 1 and 5 suns at angles from 0º to 80º at 28 ºC**
- **Cell output measured as a function of proton and electron fluence**
- **Cell spectral response measured as a function of temperature.**
- **Two coupons built and tested to demonstrate methods of improving packing factor.**
- **Cross sections of coupons to check cell adhesive for voids.**

Special Equipment

- **High irradiance solar simulators**
- **Cooling cart to provide test substrates with cooling water to flight specifications**
- **Heliostat and special vacuum chamber to obtain required irradiance.**

Summary of Planned Testing

- **Determine whether cell stacks with landings perform better than cell stacks with notches.**
  - **Comparison to be performed on two half-sized primary panels.**
  - **These tests are to compare the advantages of the landing and the notched ceramic configurations**
    - **Does the landing configuration:**
      - **Provide for easier repair**
      - **Reduce or eliminate cell cracks**
      - **Result in quicker and higher yield fabrication**

- **Re-build the second full size secondary and redo the TRL-6 test suite. Re-build may have notched or landing depend on prior test results**

- **Execute the S-112 Solder Qualification Suite**

Summary of Planned Testing (2)

- **Perform tests to determine the temperature and time required to thoroughly outgas the flight wings.**
- **Four point bend tests and acoustic tests on the TRL-6 coupon**
- **Cell removal and replacement refinement with subsequent exposure to environments.**
- **Empirically assess the effect of cell to cell planarity**
- **Refine analyses and experiments to determine the effect of irradiance skew and out of flatness**
- **Characterize the sensor cell output over the applicable ranges of irradiance, temperature, and charged particle damage.**
- **Thorough acceptance tests on the qualification wing and flight wings (detailed in backup chart)**

Status of Array PDR

- **Solar Array PDR held on November 6, 2013**
- **PDR Board Members**
  - **Dennis Dillman, GSFC, Co-chair**
  - **John Lyons, GSFC, Co-chair**
  - **Steve Battel, SPP Standing Review Board**
  - **Tom Kerslake, SPP Standing Review Board**
  - **Mark Stan, Emcore**
- **The review team agreed that the design was at a PDR level-of-maturity.**
- **The review team also agreed that the testing to date supported a piecewise satisfaction of the requirement to be at TRL 6 by the Mission PDR.**
- **10 actions received**

Ready for Phase C

- **The solar array requirements are well understood**
- **Plans to meet requirements are in place**
- **The design is at PDR level of maturity**
- **Key interfaces, excepting those related to wing width, are defined**
- **Thorough modelling demonstrate compliance with requirements**
- **Mass, power, and size estimates are well substantiated and accurate**
- **Testing to TRL-6 is completed**
- **Verification plans are established**
- **GSE requirements are defined**
- **Risk areas are identified and mitigation is in place**
- **Phase C/D is thoroughly planned**

The Solar Array is ready for Phase C

Backup

Backup

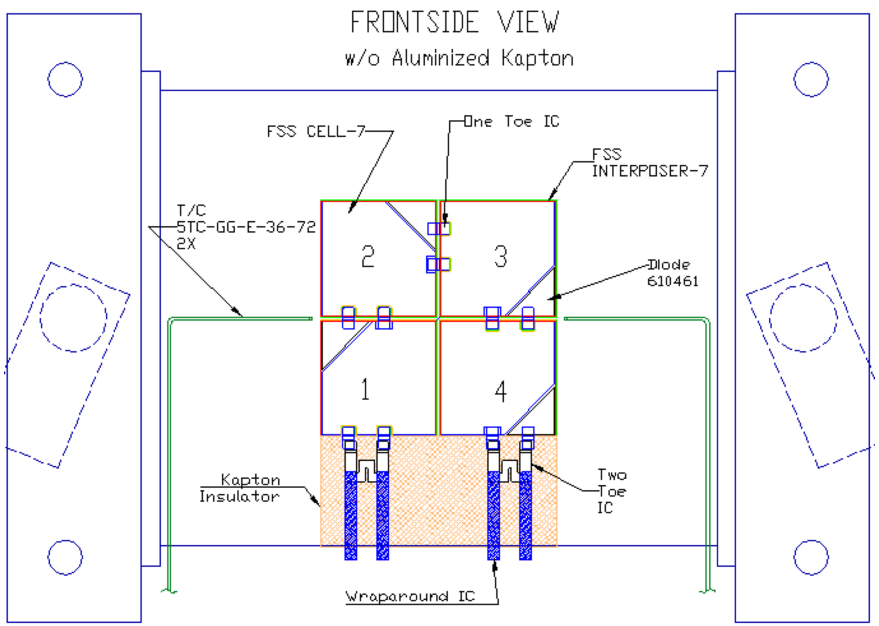
TRL-5 Test Overview

- **Humidity exposure: flight wings and qualification wing will not be exposed to the humidity environment.**
- **Nominal irradiance and temperature exposure for 45 hours to simulate nominal operation near perihelion.**
  - **Nominally 34 suns and a nominal164C with 125C water inlet temperature.**
- **Thermal vacuum soak for 72 hours to simulate outgassing bake-out that will undoubtedly be required for flight panel**
- **Thermal cycling**
  - **5 cycles from -70 ºC to 10 ºC to mimic first thermal cycle occurring just after launch**
  - **41 cycles from 10 ºC to 180 ºC to simulate the 24 thermal cycles resulting from the orbit and Venus eclipse cycles.**
- **Off nominal irradiance**
  - **> 70 suns with 125 ºC water inlet.**
- **Specifics varied slightly from test article to test article from the above**

Four TRL-5 Tests Were Conducted

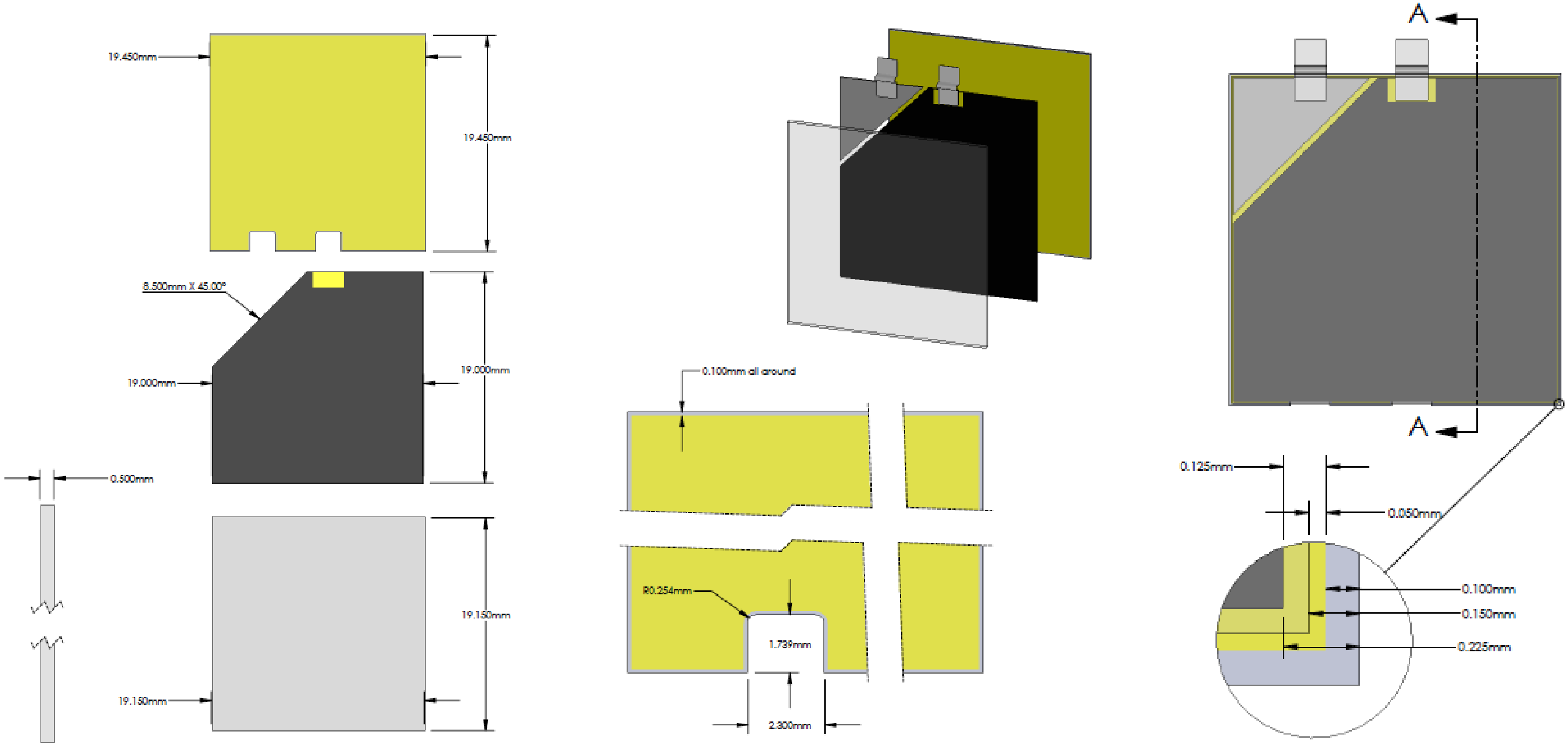
- **All coupons used four 4 cm^2 CICs on water cooled substrates**
  - **Two coupons, a pathfinder and a follower, using semi-standard cell stacks were tested. Failures occurred during 34 sun irradiance or thermal vacuum bake or thermal vacuum cycling**
  - **The coupon using a high thermal conductance cell stack (HTCSS) with a landing on the ceramic passed.**
  - **The coupon using HTCCS with notched ceramic passed.**
    - **Degradation of ~0.3% in current subsequent to environmental exposure**
    - **No significant change to coupon appearance**

Notched TRL-5 Coupon

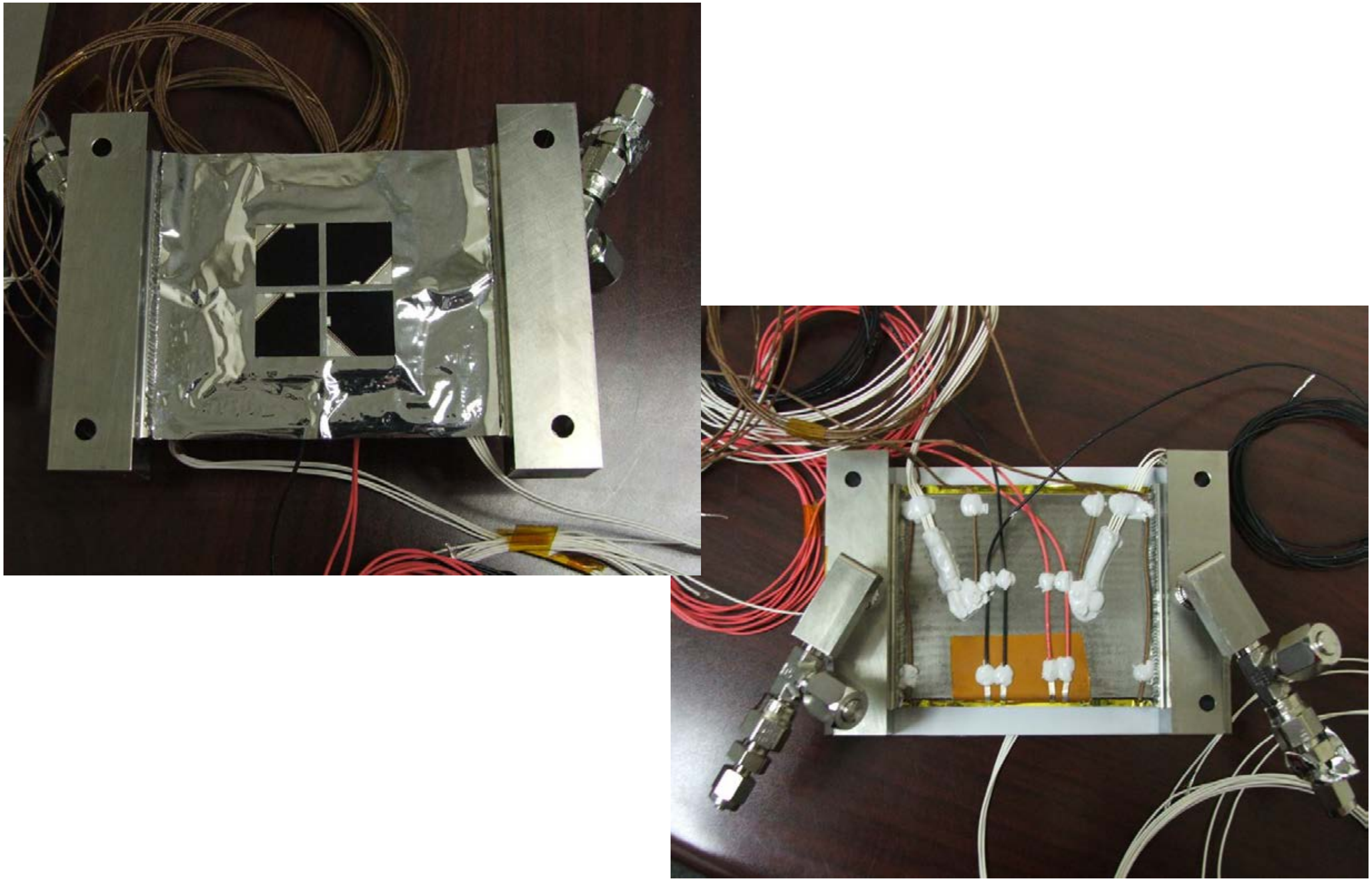


- CTJ/ZTJ 3.25 cm^2 cells
- Si bypass diodes in cropped corners
- CMG-AR-0.020 glass w/ DC93-500
- Four 3.8 cm^2 CICs in series string
- Single-toe ICs, AuSn-soldered
- IC loop embedded in grout
- Cells attached to notched 0.010” Al_2O_3
- CV-2942 lay-down adhesive, grout
- T/Cs on front, back of substrate
- Two Lakeshore PRTs on back side
- VDA Kapton over grout and T/Cs
- Single-toe wrap-around ICs
- Water-cooled H-S substrate from APL

Notched Cell Stack



Notched TRL-5 Coupon



Key Trades

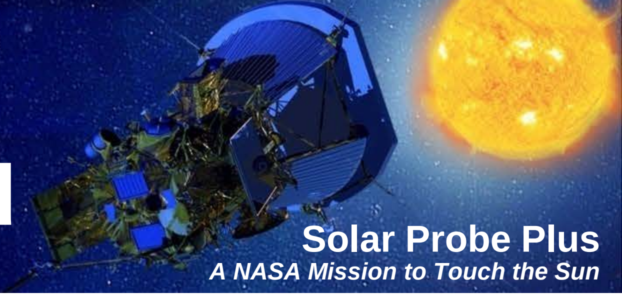
Key Trades

Key Trades

- **Method of insulating solar cells from substrate:**
  - **Semi-Standard. This is close to the standard method. It consists of a Kapton insulator between the substrate and the cells**
    - **Uses a high thermal conductivity Kapton**
    - **Uses a high thermal conductivity adhesive, CV 2942**

  - **High thermal conductance cell stack (HTCCS). This replaces the Kapton with an alumina insulator coated with silver to which the cell is soldered.**
    - **Landing insulator**
    - **Notched insulator**
    - **(Will described these later)**

Key Trades
HTCCS* versus Semi-Standard



<table>
<tr><th></th><th>HTCCS*</th><th>Semi-Standard</th></tr>
<tr><td>Fabrication ease</td><td>★</td><td></td></tr>
<tr><td>Mass</td><td></td><td>★</td></tr>
<tr><td>Resistance to dust and micrometeorite penetration</td><td colspan="2">★</td></tr>
<tr><td>Cell temperature</td><td>★</td><td></td></tr>
<tr><td>Heritage</td><td colspan="2">★</td></tr>
<tr><td>Load to cooling system</td><td>★</td><td></td></tr>
<tr><td>Reliability</td><td>★</td><td></td></tr>
<tr><td>Overall</td><td>★</td><td></td></tr>
</table>

* Also known as CPVI, concentrator photovoltaic inspired

Flight Acceptance Tests

- 1 Measure mass to ± 0.01 g
- 2. Measure cell to cell planarity and determine whether it is within the limits determined in Section 17
- 3. Functional tests and visual inspections
- 4. Output at 1 AM0 versus temperature
- 5. Output from the primary at TBD suns at TBD temperature
- 6. Functional tests and visual inspections
- 7. Output at 1 AM0 versus temperature
- 8. Output from the secondary at TBD suns with graded irradiance at TBD temperature.
- 9. Humidity Test (2 weeks)
- 10. Functional tests and visual inspections
- 11. Output at 1 AM0 versus temperature
- 12. Thermal Vacuum Bake for 72 (TBD) hours at TBD temperature measuring VCM per S-112
  2 thermal vacuum cycles from -80C to +10C
  41 thermal vacuum cycles from 10C to 164C
  300 thermal vacuum cycles from 55C to 150C (TBD)
- 13. Functional tests and visual inspections
- 14. Output at 1 AM0 versus temperature
- 15. Measure mass to ± 0.01 g
- 16. Acoustic Exposure, levels per the EDTRD
- 17. Functional tests and visual inspections
- 18. Output at 1 AM0 versus temperature
- 19. 45 hour HIHT-Vacuum Test using a Heliostat as an irradiance source
- 20. Functional tests and visual inspections
- 21. Output at 1 AM0 versus temperature
- 22. Non-Nominal High Irradiance Exposures to 40 suns (TBD)
- 23. Functional tests and visual inspections
- 24. Output at 1 AM0 versus temperature
- 25. Expose the flight wings to 10 suns (TBD) for 80 hours
- 26. Functional tests and visual inspections
- 27. Output at 1 AM0 versus temperature
- 28. Non-Destructive Arc Sensitivity Tests
- 29. Measure mass to ± 0.01 g
- 30. Functional tests and visual inspections
- 31. Output at 1 AM0 versus temperature

Solar Array Angle Control Overview

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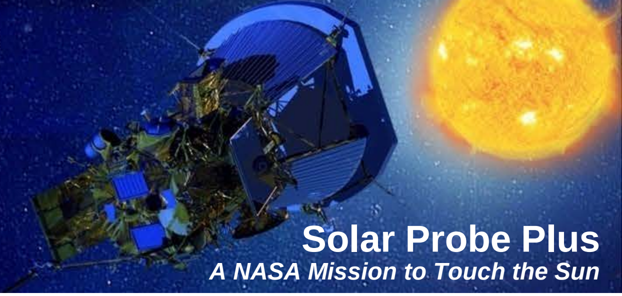
13 – 16 January 2014

The Johns Hopkins University
APPLIED PHYSICS LABORATORY

S/A Angle Control Review

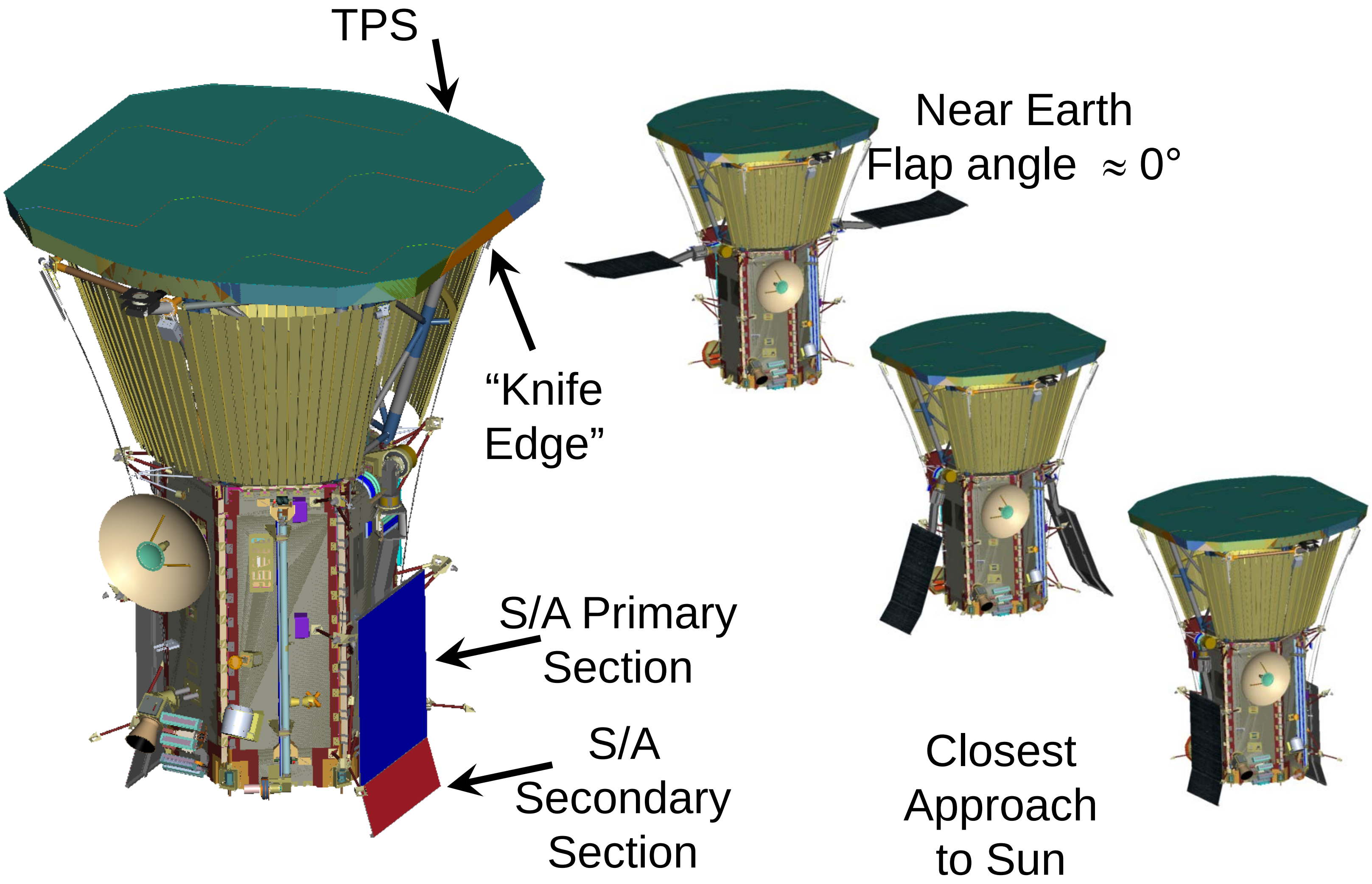


- **S/A angle control peer review was held on August 7, 2013**
  - Covered the control concepts and models in detail
  - 9 action items: 7 closed, 2 open (in review)
- **S/A Angle Control was reviewed at the EPS PDR, November 19, 2013**
- **Multi-disciplinary team contributed**
  - G&C, Power, Solar Array, Systems, Thermal, Operations & safing
- **Requirements flow down from the EPS subsystem**
- **Additional model details and implementation are reviewed through the G&C subsystem**
- **Nominal S/A angle control is the focus of this overview**
  - Safing conditions were covered in the fault management PDR in May, 2013

Solar Array Angle Control

- **SPP uses autonomous closed-loop S/A 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
  - Prevent S/A cooling system from freezing
- **Goals:**
  - Optimize S/A temperature (minimize degradation)
  - Minimize S/A drive motion (power and mechanical wear)
  - Minimize battery cycling (minimize degradation)

Solar Array Configuration



TPS

“Knife Edge”

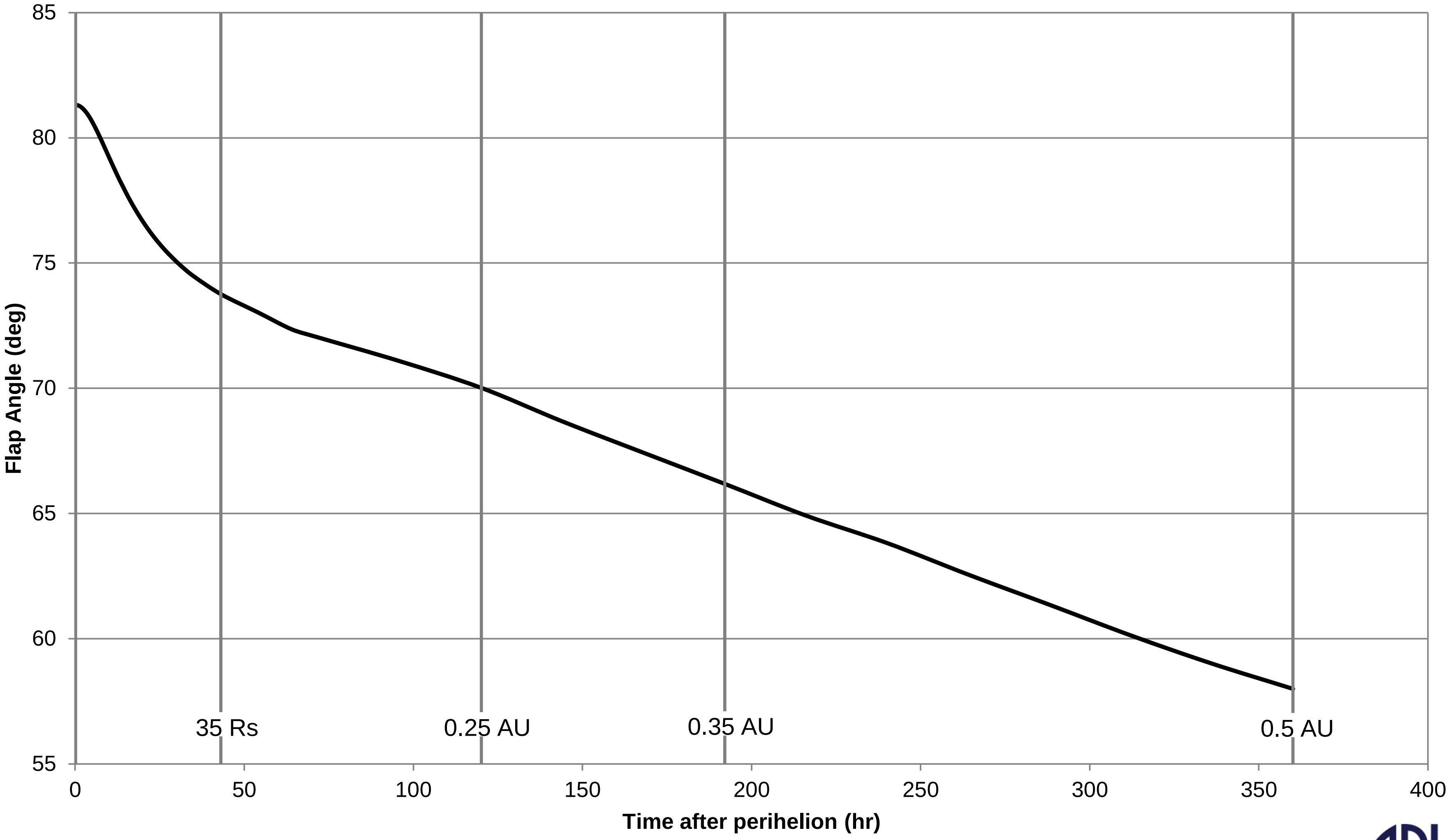
S/A Primary Section

S/A Secondary Section

Near Earth
Flap angle ≈ 0°

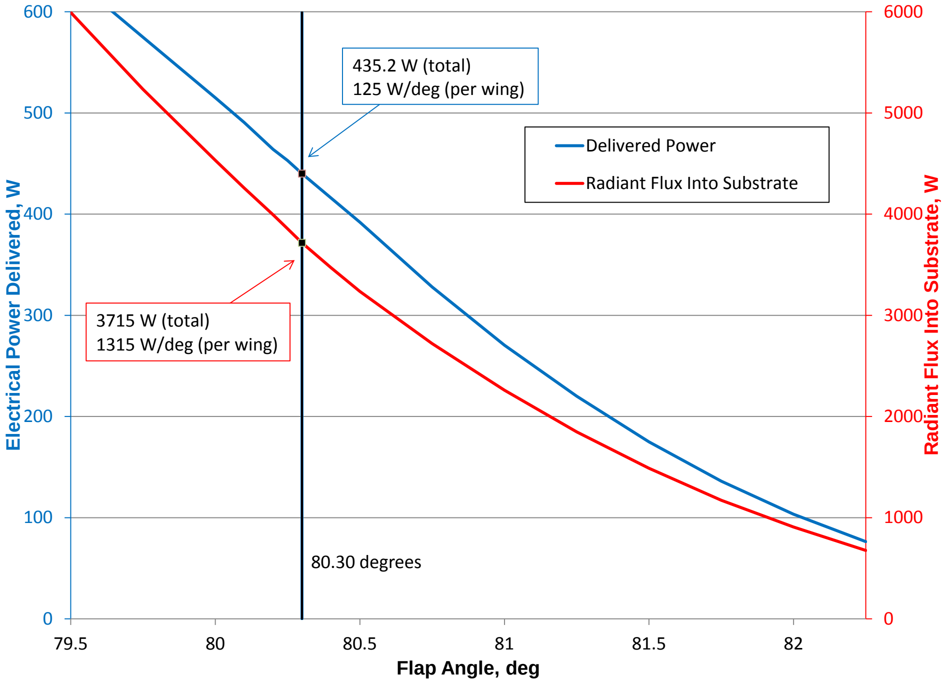
Closest Approach to Sun

Notional Flap Angle vs. Time



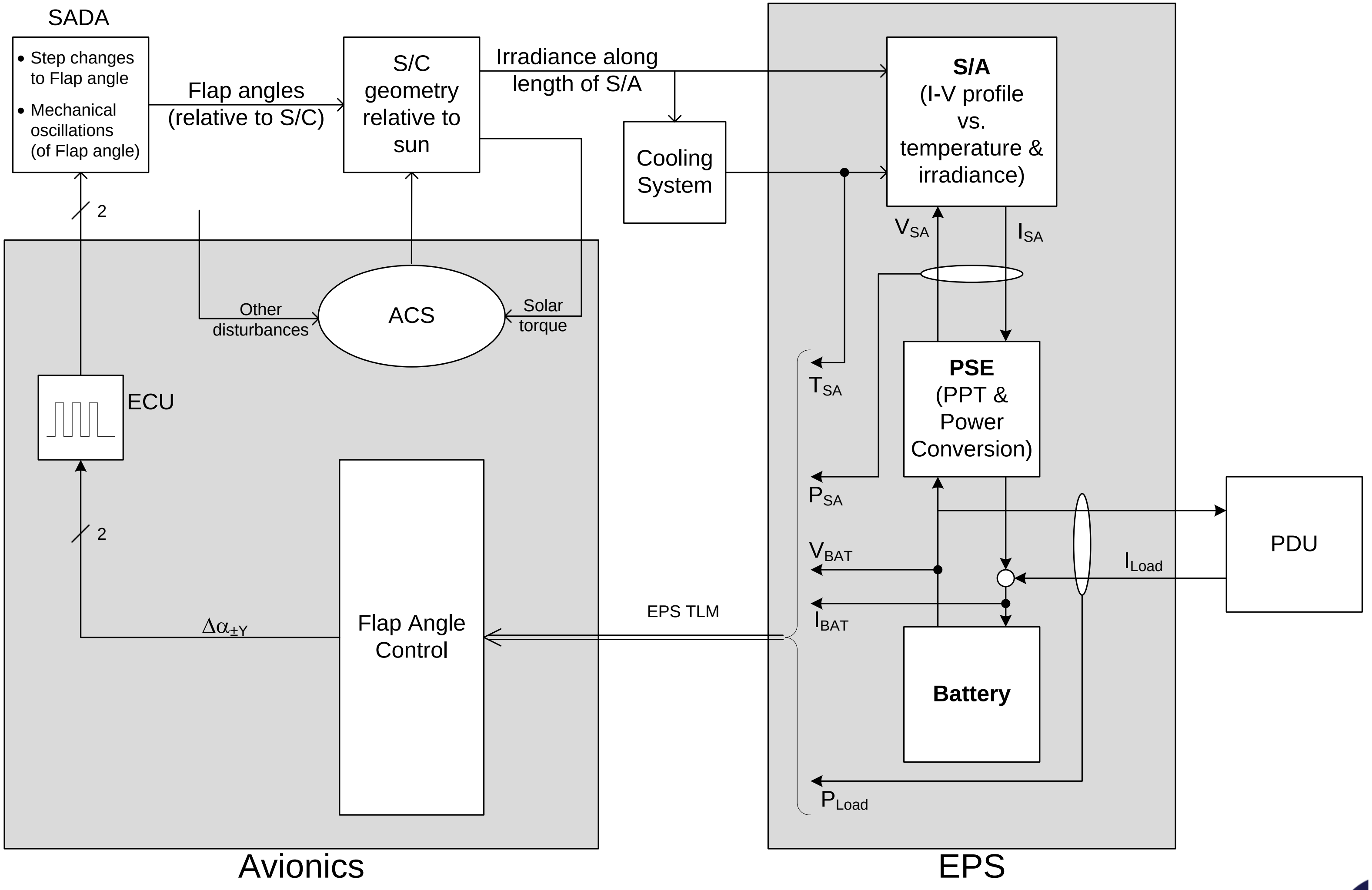
Autonomous Close-loop Control

- **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

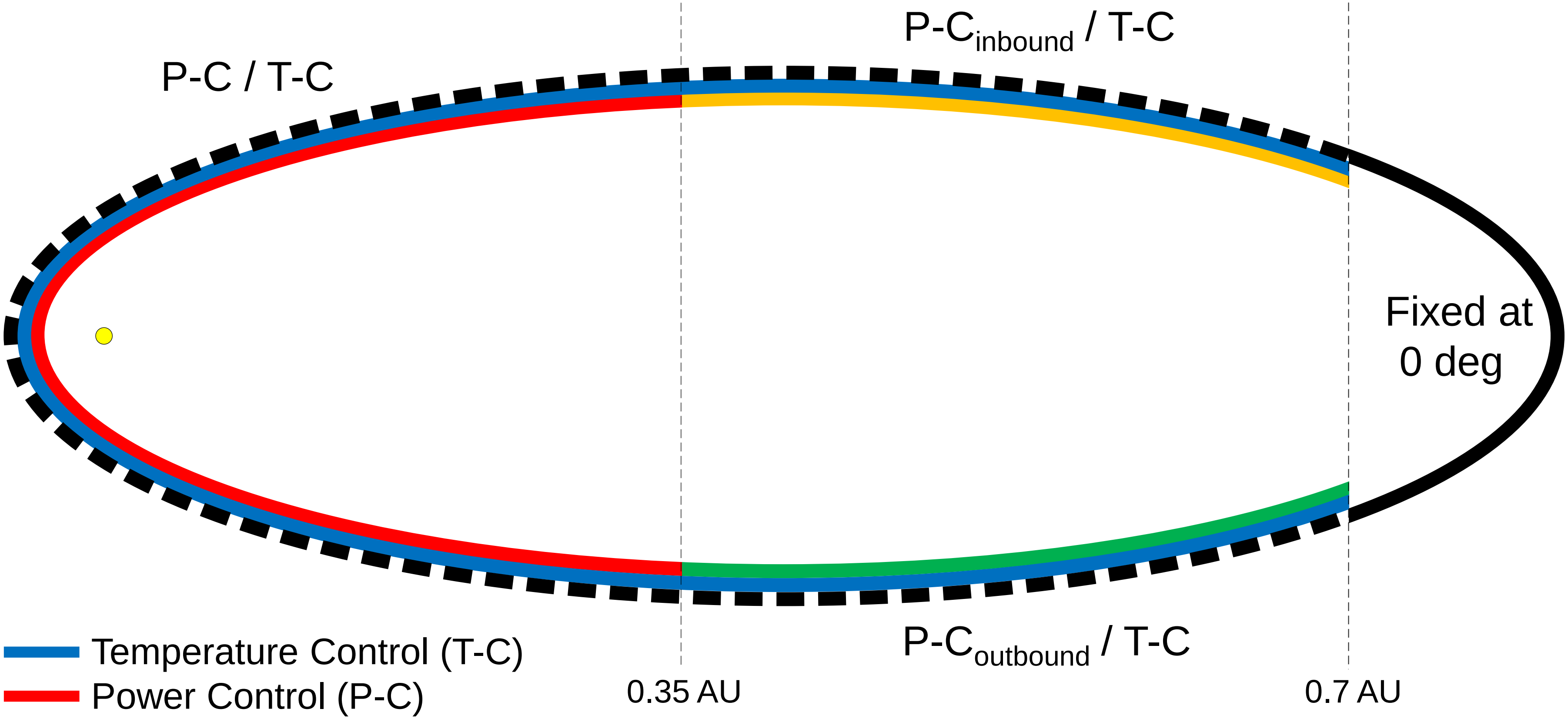


- **Power Control**
  - Minimize irradiance and temperature on S/A to meet S/C power demands
- **Temperature Control**
  - Achieve a minimum water temperature while preventing water from freezing
- **The flap angles are independently controlled to equalize power on each wing**

Solar Array Angle Control Block Diagram



S/A Flap Angle Control Modes



P-C / T-C

P-C$_{inbound}$ / T-C

Fixed at 0 deg

P-C$_{outbound}$ / T-C

0.35 AU

0.7 AU

🟦 Temperature Control (T-C)
🟥 Power Control (P-C)
🟩 Power Control – Outbound
🟨 Power Control – Inbound
⬛ Fixed Angle
▪▪▪ Fixed Angle (intended for safing)

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 – 0.7 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
    - **Use knowledge of PPT to determine if angle is adequate**
- **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**

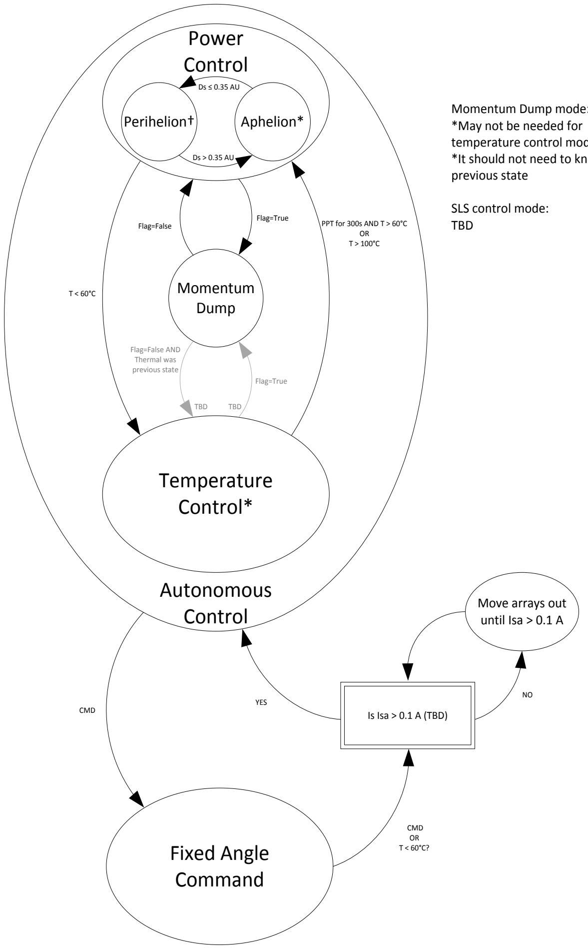
Temperature Control

- **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
  - Include/analyze an ‘auxiliary’ mode to ensure smooth transition between P-C and T-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
    - The wide range is due to variations in solar distance and efficiency of cooling system
  - If the average S/A loading is less than required the temperature control stays active longer

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

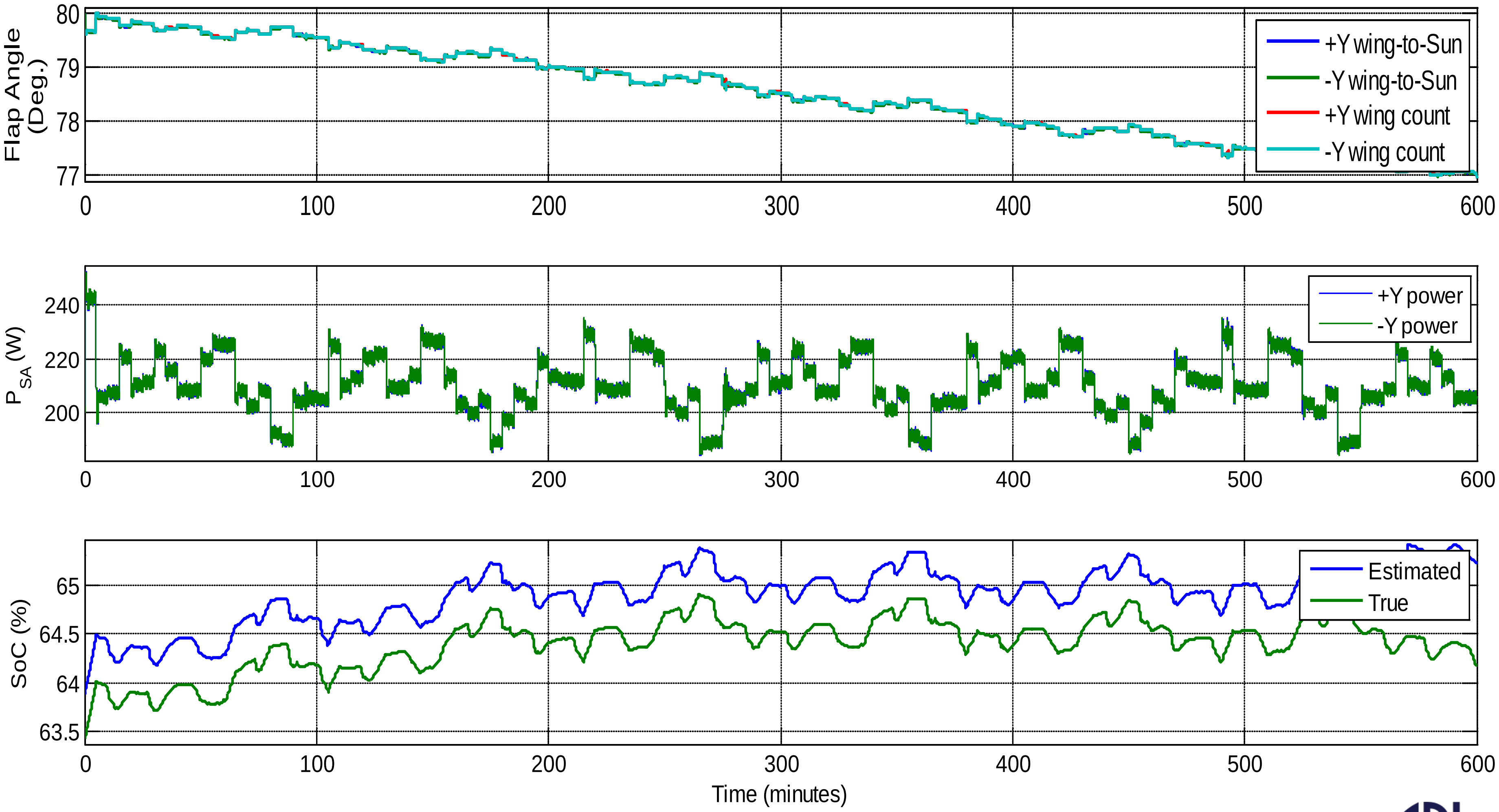
- **All integrated in G&C's Matlab/Simulink model**

Simulation Methods and Scenarios

- **Transient conditions**
  - Trajectory Correction Maneuvers
  - Wheel desaturation
  - Load changes
  - State transitions
  - Safing and operations
- **Stability**
  - Stand-alone control loop at a given operating condition
    - **Linearized modeling of system plant and control loops**
  - Monte Carlo Simulations
    - **Stability over a wide range of operating conditions with entire S/C G&C models**
    - **Sensitivity and Trending analysis**
- **Power and Thermal parameters and margins**
- **Design and control optimization**

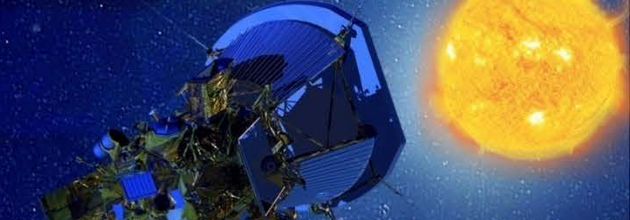
Transient Example

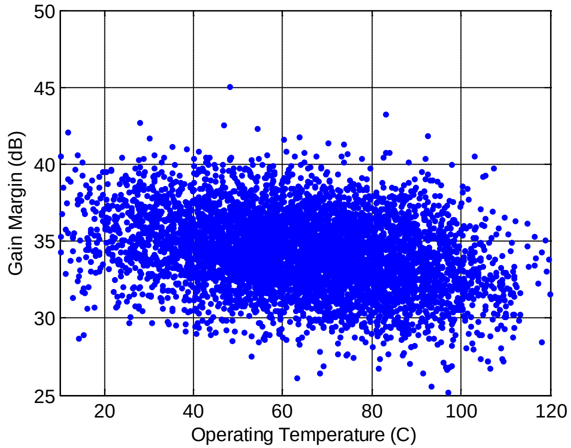
Power control starting at 9.86 R_S

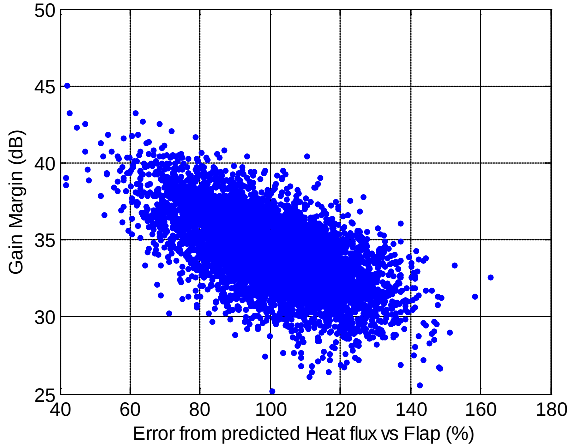


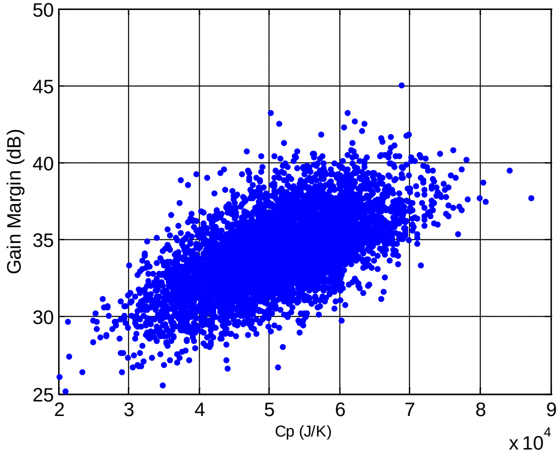
Monte Carlo Stability Example

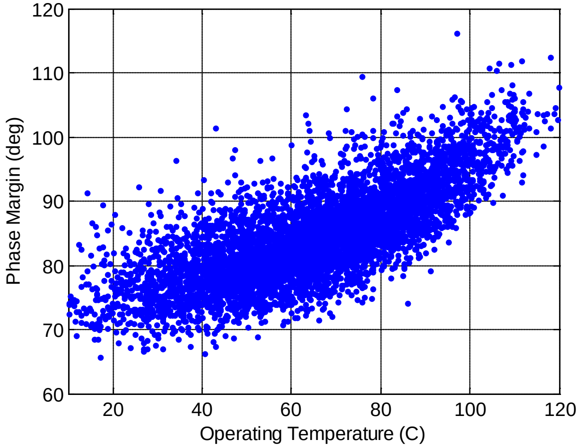
Gain and Phase Margin for three temperature control parameters

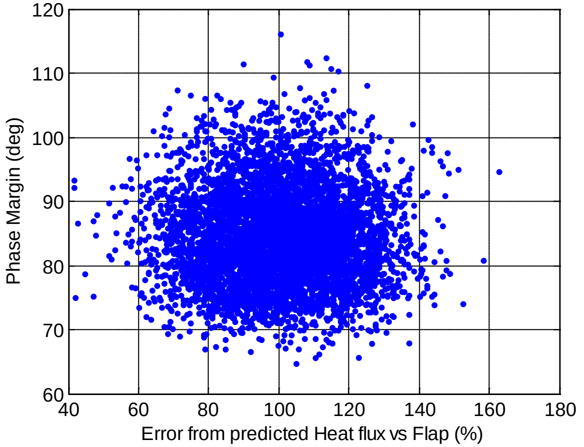


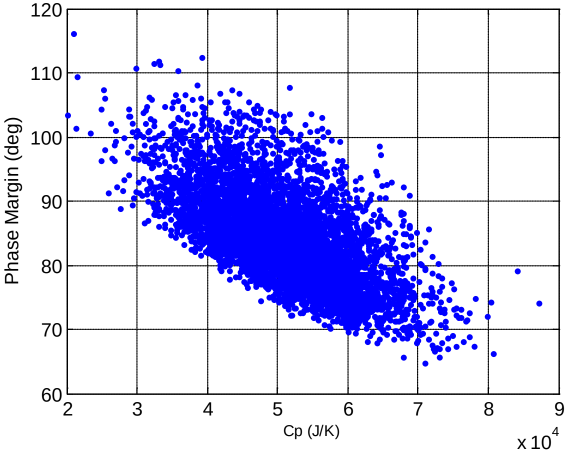












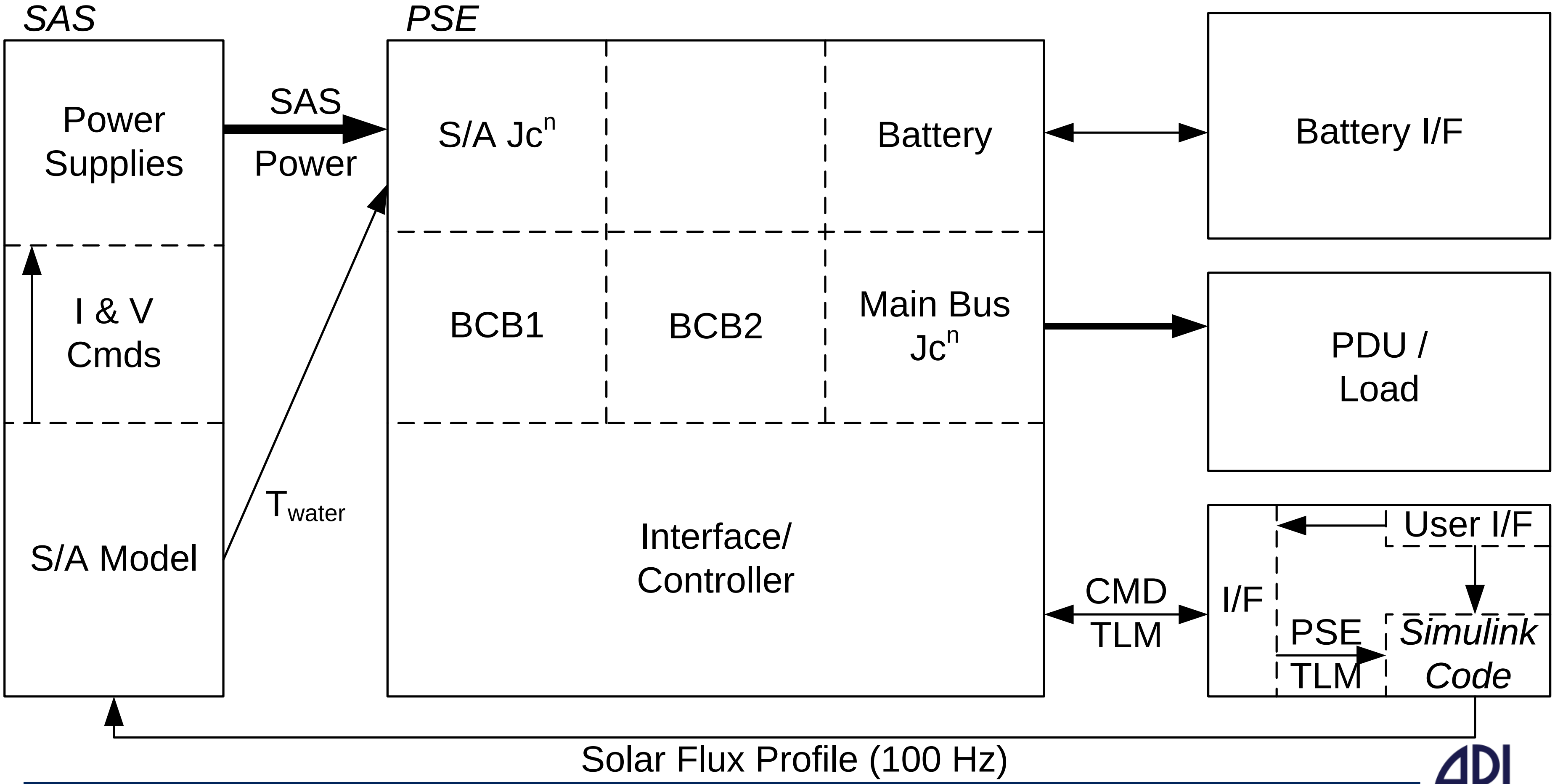
Verification and Validation of Solar Array Angle Control

- **Solar Array Simulator (SAS)**
  - Dynamic SAS will be independently verified to be as flight like as possible to match solar arrays in expected environment
- **Battery**
  - Battery simulator utilizes code to represent flight like battery
  - Test / EM battery can also be used in testing
- **EPS testbed with hardware-in-the-loop**
  - Hardware
    - **Dynamic SAS**
    - **Battery simulator or test battery**
    - **PSE power processing (breadboards and engineering models)**
    - **Avionics breadboards**
  - Software
    - **Truth models**
    - **G&C control logic (including S/A angle control)**
      - Initially resides in EPS GSE then evolving to Avionics

EPS Development Testbed

Integrated G&C models w/ EPS hardware

- **EPS hardware-in-the-loop testbed demonstrated closed loop control of solar array flap angles**



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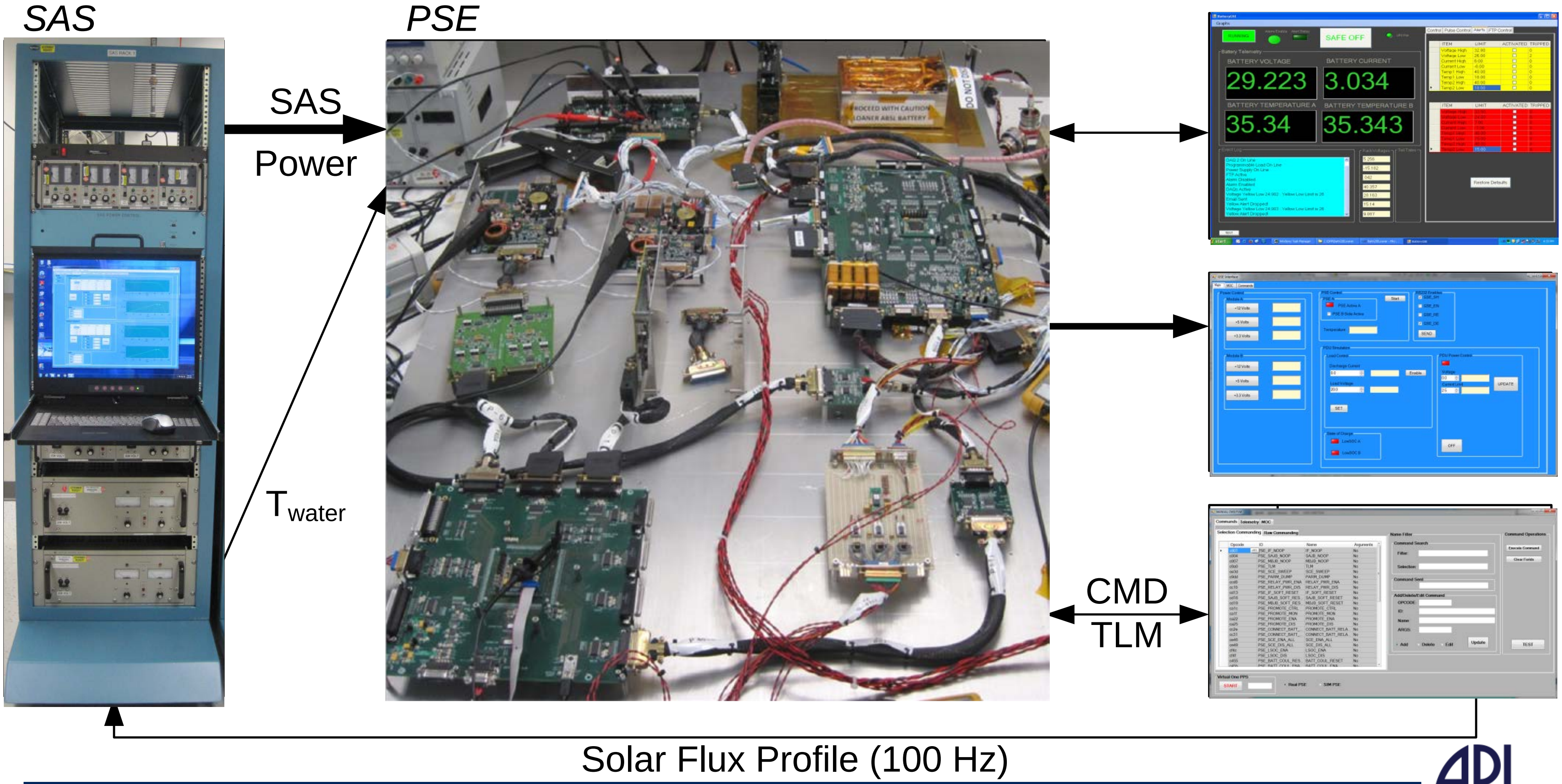


Battery Telemetry

BATTERY VOLTAGE	BATTERY CURRENT
29.223	3.034

BATTERY TEMPERATURE A	BATTERY TEMPERATURE B
35.34	35.343

ITEM	LIMIT	ACTIVATED	TRIPPED
Voltage High	32.80	☐	0
Voltage Low	26.00	☐	2
Current High	6.00	☐	0
Current Low	-6.00	☐	0
Temp1 High	40.00	☐	0
Temp1 Low	18.00	☐	0
Temp2 High	40.00	☐	0
Temp2 Low	18.00	☐	0

Event Log

```
DAQ 2 On Line
Programmable Load On Line
Power Supply On Line
FTP Active
Alarm Disabled
Alarm Enabled
DAQs Active
Voltage Yellow Low 24.902 : Yellow Low Limit is 26
Email Sent
Yellow Alert Dropped!
Voltage Yellow Low 24.903 : Yellow Low Limit is 26
Yellow Alert Dropped!
```

Rack Voltages

5.256
-15.182
.042
40.357
28.163
15.14
9.087

Phase C/D Future Work

- **Continue to refine control algorithms for fast-rate conditions, e.g.**
  - Wheel desaturation
  - Trajectory Correction Maneuvers
  - ‘Fast’ S/C slew rates

- **Simulate models to determine**
  - Stability
  - State transitions
  - Limiting/stressing cases
  - Safing operations
  - Testing conditions

- **Test and verify angle control algorithms with EPS EM and Avionics hardware**

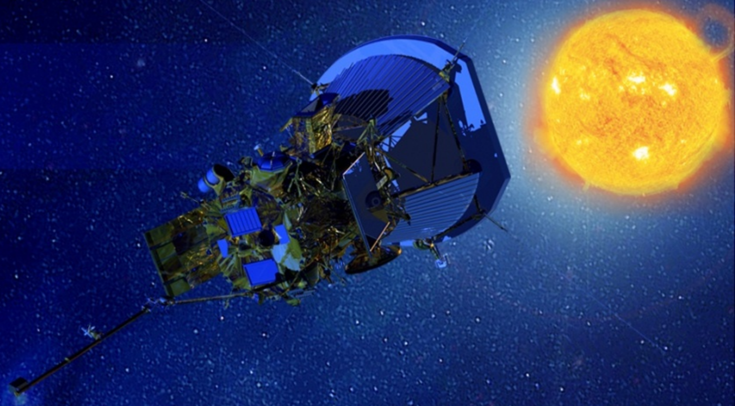
Summary

- **S/A angle control is a multidisciplinary function spanning inputs from many systems**
  - Electrical power, Guidance and control, Thermal/cooling, Mechanical
- **Solar array angle control is integrated within G&C models and software**
- **EPS models are created in MATLAB/Simulink to verify feedback of control**
  - Solar Arrays, PSE, Battery and S/A actuators
- **Two main modes of autonomous control are implemented**
  - Power Control: minimizes irradiance (and temperature) on arrays
  - Temperature Control: maintains minimum temperature of water
  - Autonomous transitions between modes
- **Models have demonstrated a stable system**
  - Preliminary hardware results confirm stability
- **EPS hardware-in-the-loop testbed demonstrated closed loop control of solar array flap angles**

Solar array angle control is ready for Phase C

Solar Probe Plus

A NASA Mission to Touch the Sun



Guidance & Control Subsystem

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Lead G&C Engineer

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13 – 16 January 2014

APL
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APPLIED PHYSICS LABORATORY

Guidance and Control Agenda

- **System Implementation**
  - Block diagram, basic functions, hardware & software
- **Requirements**
  - Review status and driving requirements summary
- **Performance analysis summary**
  - Attitude knowledge, encounter pointing control, maneuver execution accuracy
- **G&C Hardware**
  - Vendor options and procurement status
  - Mass and power estimates
  - Actuators – placement and key issues
    - Reaction wheel availability
  - Sensors – placement and key issues
    - Solar limb sensor development and demonstration of TRL 6
- **Verification and test plans**

SPP G&C System Summary

- **Close-loop, 3-axis stabilized control system**

- **Determines and controls spacecraft attitude**
  - Enforces attitude-related safety constraints (e.g. point TPS to Sun)
  - Manages momentum since reaction wheels are used

- **Points articulated devices**
  - High-gain antenna (HGA)
  - Solar arrays - geometry, power, and thermal-based closed-loop algorithms developed in collaboration with EPS (power) team

- **Executes trajectory correction maneuvers**
  - Imparts translational velocity change (ΔV) for trajectory control

- **Hardware**
  - Star trackers
  - IMU – gyros and accelerometers
  - Solar limb sensors (new) and digital Sun sensors (standard)
  - Reaction wheels
  - Thrusters
  - (HGA and array drives)
- **Flight software**
  - Implements functions at left
  - 1 Hz and 50 Hz tasks
    - Control functions in 50 Hz task
    - Other functions in 1 Hz task
  - Hardware interface rates

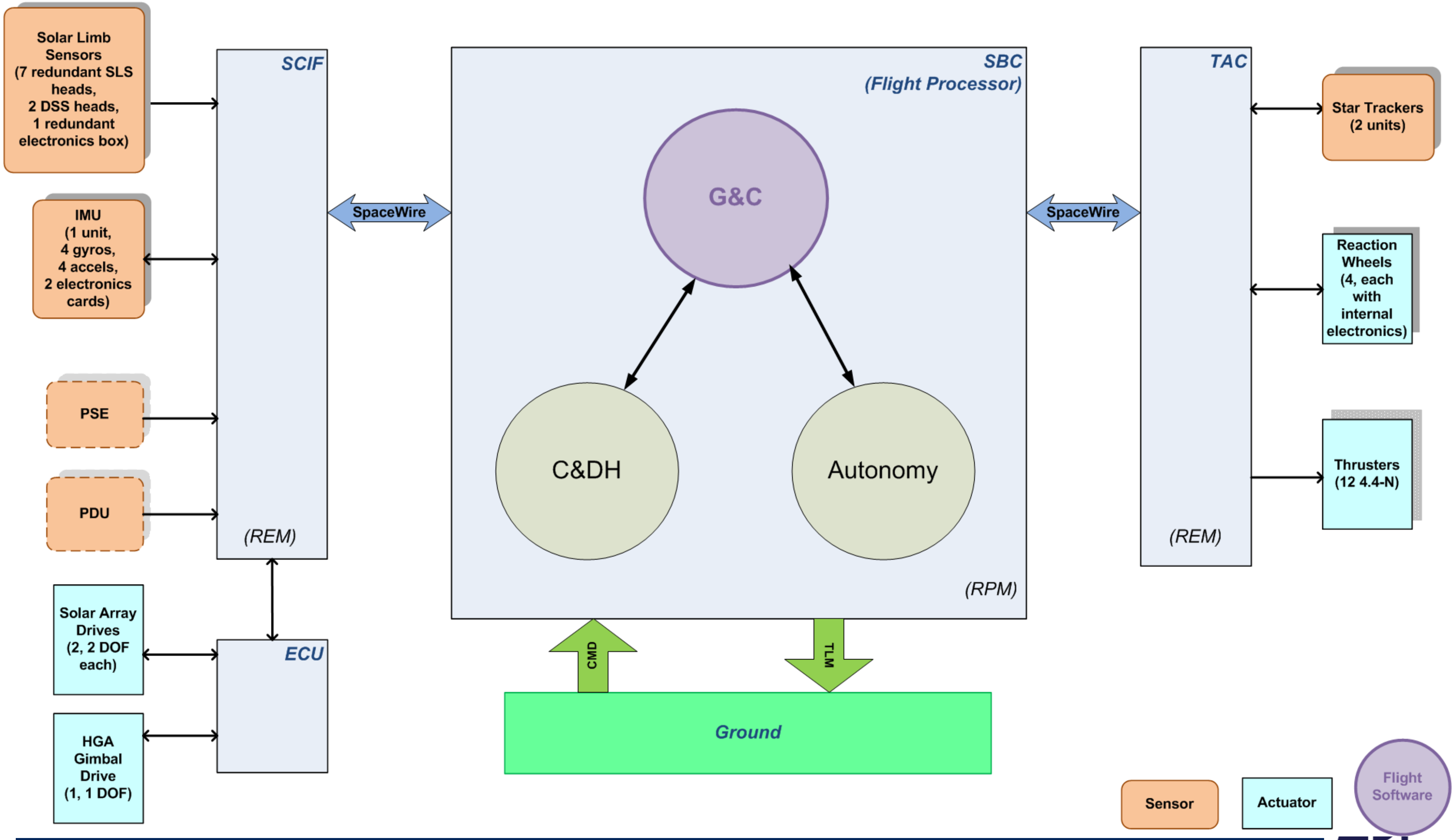
Star trackers 10 Hz	IMU 100 Hz
Sun sensors 5 Hz	Thrusters & wheels 50 Hz
HGA and array drives 1 Hz	

- **Stand-alone simulation and testbed software for ground analyses and testing**

G&C Block Diagram

Solar Probe Plus

A NASA Mission to Touch the Sun



Guidance and Control
Phase B Reviews

- **G&C requirements review held on July 22, 2013**
  - Review board: Wayne Dellinger, Sarah Flanigan (APL-SEG), Neil Dennehy (GSFC)
  - 11 action items, 13 recommendations
  - 9 of 11 action items are closed; 2 are open pending further analysis
  - References:
    - SEG-13-019 SPP G&C Requirements Peer Review Minutes, August 6, 2013
    - SEG-13-037 Closure of Action Items from SPP G&C Requirements Peer Review, December 2013

- **G&C requirements document approved and released on November 15, 2013** (7434-4909 SPP G&C Requirements Document, Rev -)

- **G&C PDR held on November 12, 2013**
  - Review board: Dan O'Shaugnessy, Sarah Flanigan (APL-SEG), Steve Collins, Ed Swenka (JPL), Neil Dennehy (GSFC)
  - 8 action items, 14 recommendations
  - Reference: SEG-13-035 Solar Probe Plus Guidance and Control Subsystem Preliminary Design Review Action Items and Recommendations, December 4, 2013

G&C Driving Requirements

- **General capabilities**
  - Turn between and maintain nominal, mission default, and special event attitudes (includes detumble, commissioning activities)
    - Autonomous transitions between nominal attitudes in the absence of sequences or other pointing command input
    - Ability to command transitions to special event attitudes, attitudes for communication passes, TCMs, and calibration activities

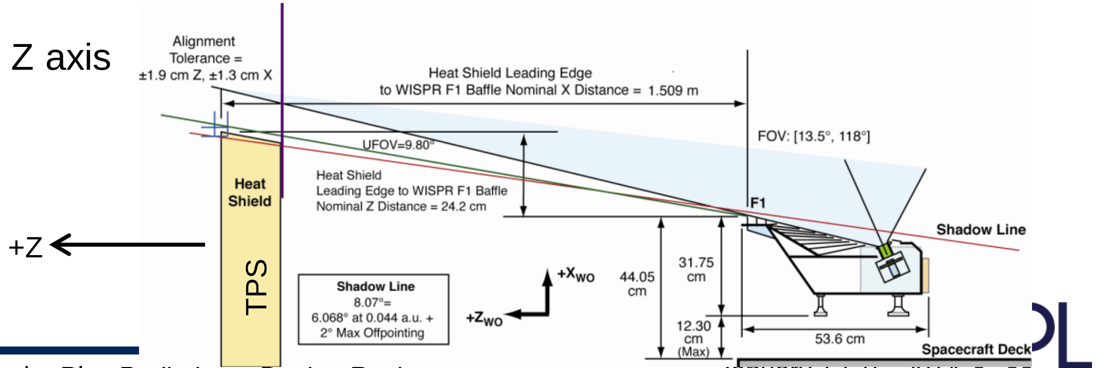
- **Nominal System Performance**
  - Attitude knowledge and control for science data collection
  - Attitude knowledge and control for spacecraft operations (e.g. solar array and cooling system operation, communications)
  - Maneuver execution accuracy for TCMs

- **Fault management**
  - Support for critical fault detection and responses
  - G&C mode definition and interaction with fault management mode transitions (safe↔operational)

G&C Performance Requirements
Attitude Knowledge and Control
WISPR Instrument ≤ 0.25 AU

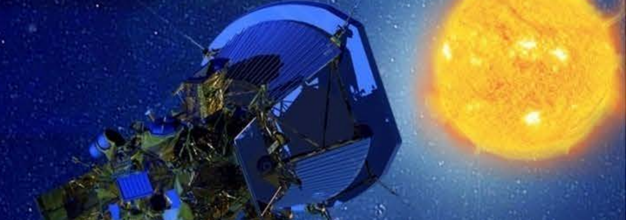
Requirement Source	Line of Sight	Required Accuracy	
	Pointing Knowledge		
WISPR	Optical Z axis	1.2 arcmin (0.02°) (3-σ)	
	About optical Z axis	3.4 arcmin (0.057°) (3-σ)	
	Pointing Control		
WISPR pointing accuracy	Optical Z axis	6 arcmin (0.1°) (3-σ)	
	About optical Z axis	60 arcmin (1°) (3-σ)	
WISPR pointing jitter	Optical Z axis	0.8 arcmin (0.013°) (3-σ)	Jitter Window Durations 20 s 9.86 Rs - 0.11 AU
	About optical Z axis	3.4 arcmin (0.057°) (3-σ)	40 s 0.11AU – 0.25 AU
WISPR pointing windowed stability	Optical Z axis	1.6 arcmin (0.27°) (3-σ)	Stability Window Durations 4 min 9.86 Rs – 0.07 AU
	About optical Z axis	3.4 arcmin (0.057°) (3-σ)	8 min 0.07 – 0.11 AU 16 min 0.11 – 0.174 AU 80 min 0.174 – 0.25 AU

The target direction for the WISPR optical Z axis is the Sun.
Applies for solar distance ≤ 0.25 AU



WISPR = Wide-Field Imager for Solar Probe Plus

G&C Performance Requirements Attitude Control - Spacecraft



Requirement Source	Line of Sight	Required Accuracy
Pointing Control		
Spacecraft pointing accuracy < 0.25 AU (encounter pointing orientation)	+Z axis to Sun +X to ram	30 arcmin (0.5°) TBD (instrument science, < 20°) 1200 arcmin (20°) (safety)
Spacecraft pointing accuracy 0.25 – 0.82 AU (umbra & aphelion umbra variable pointing orientations)	+Z axis to Sun	296 – 337 arcmin (4.93 – 5.62°) (umbra limit + 2° margin)
Spacecraft pointing accuracy 0.7– 0.82 AU (aphelion umbra variable pointing orientation)	Sun at specified angle between +Z and 45° from +Z towards -X	+/-180 arcmin (3°) around target direction in XZ plane and out of XZ plane
Spacecraft pointing accuracy > 0.82 AU (aphelion pointing orientation)	Sun at 45° from +Z towards -X	+/-180 arcmin (3°) around target direction in XZ plane and out of XZ plane
Jitter for solar array illumination stability	Z axis	3 arcmin (0.05°) (3-σ) Jitter Window Duration 60 s 9.86 Rs - 0.7 AU

G&C Performance Requirements
Maneuver Execution Accuracy

- TCM error specification uses Gates model that includes fixed and proportional magnitude and pointing errors, each specified as a normal distribution
  - Magnitude errors act in the direction of the target ΔV
  - Pointing errors can be in any direction perpendicular to the target direction
  - Proportional errors are scaled by the magnitude of the target ΔV

Table entries are 3-σ values

Target ΔV Magnitude	Fixed Magnitude Error	Proportional Magnitude Error	Fixed Pointing Error	Proportional Pointing Error
0.005 – 90 m/s	1 mm/s	2%	1 mm/s (per axis)	20 mrad (per axis)

G&C Requirements
Fault Management

- **Keep the spacecraft bus within the umbra of the TPS when spacecraft orientation should be encounter or umbra**
- **Keep the spacecraft at the proper tilt of Sun from +Z towards –X axis when spacecraft orientation should be aphelion or aphelion-umbra variable**
  - Including over a 24-hour period without star tracker data

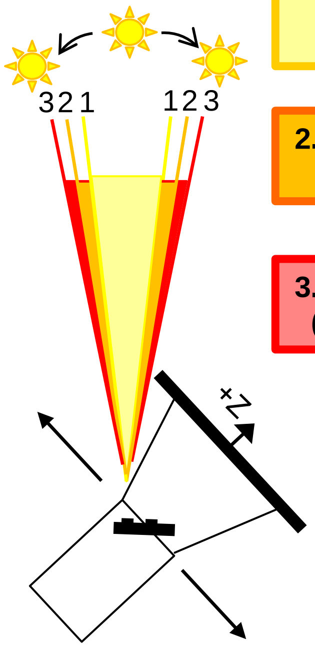
- **Provide Sun-relative attitude control using sensors for external detection of attitude deviations**
  - Solar limb sensors for encounter and umbra orientations
  - Digital Sun sensors for aphelion and aphelion-umbra variable orientations
- **Provide diagnostic telemetry including indications for critical faults associated with attitude deviations (umbra violation orange warning and aphelion thermal violation)**

- **Support actions and timing budgets for avionics side switch, processor reset, and safe mode demotion with processor switch and solar arrays to safe positions**
  - Autonomous transitions to mission default attitudes on demotion to safe mode and while in safe mode
  - Ability to command rotation about Sun line for communication with Earth for Safe Mode – Earth Acquisition

Attitude Deviations Defined as Critical Faults

Deviation from Aphelion or Aphelion-Umbra Variable Orientation

Aphelion Thermal Violation



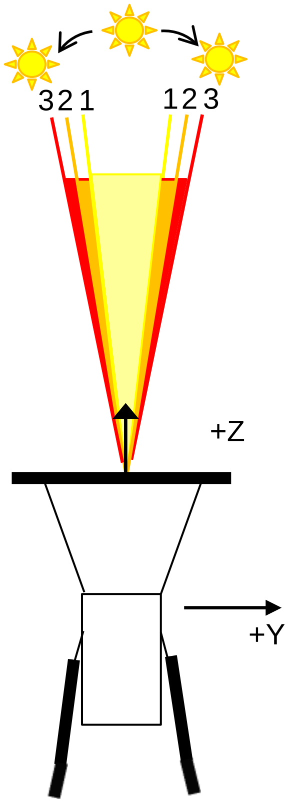
1. Sun direction deviation boundary from DSS measurements (G&C action)

2. Aphelion Thermal Violation Boundary (Autonomy action)

3. Aphelion S/C Safety Limit (Sun +/-5° from target direction)

Deviation from Umbra or Encounter Orientation

Umbra Violation Orange Warning



1. SLS Sun detection boundary (G&C action)

2. Orange Warning Boundary (Autonomy action)

3. Umbra Violation Boundary (S/C Safety Limit, +Z-Sun angle = 2.18° at 9.86 Rs)

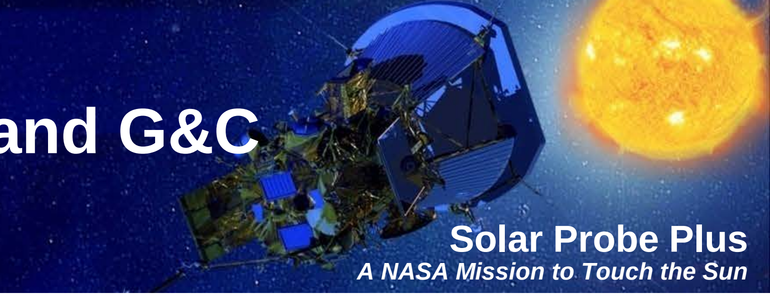
G&C Phase B Performance Analyses

- Analysis focused on nominal scenarios associated with driving requirements:

Scenario	Driving Requirements	Other Requirements
Attitude Control < 0.25 AU Wheels Thrusters (momentum dumps)	WISPR – pointing accuracy, jitter, windowed stability Spacecraft Safety – pointing accuracy, jitter	ISIS, FIELDS – pointing accuracy SWEAP – jitter
Attitude Knowledge	WISPR – pointing knowledge As needed to support attitude control requirements (from pointing budgets)	ISIS, FIELDS pointing knowledge
Maneuver Execution	Proportional and fixed magnitude and pointing errors	

- Monte Carlo simulations run for each scenario
  - Parameters varied for
    - Spacecraft mass properties
    - Sensor alignments and measurement error sources (e.g. gyro bias drift)
    - Actuator alignments and performance factors (e.g. wheel friction)
    - Environmental disturbances such as solar radiation pressure
  - Used former baseline SPP trajectory with minimum perihelia for last 3 orbits at 9.5 Rs

Attitude Knowledge and Control: Top-Level Requirements, Budgets, and G&C Allocated Performance Metrics



- **Error budgets developed for driving knowledge and control requirements**
  - G&C attitude knowledge and control contributions allocated from these budgets
  - Simulation results compared with allocated values in budgets, not top-level requirements (shown in slides 7-9)

- **WISPR pointing knowledge**
  - Top-level requirement met by combination of in-flight calibration (WISPR-star tracker) and post-processing of telemetered attitude data
  - G&C allocation for on-board attitude knowledge accuracy in fiducial frame is 51 arc-s (0.85 arcmin, 0.0142°) 3-σ
    - Includes star tracker-IMU relative alignment, measurement accuracies for star tracker and IMU, estimator performance

- **WISPR pointing control during perihelion passage**
  - G&C allocation for on-board attitude knowledge accuracy in spacecraft body frame is 139.2 arc-s (2.32 arcmin, 0.0387°) 3-σ
    - Adds alignment of fiducial frame to spacecraft body frame to error sources for fiducial frame attitude knowledge listed above
  - G&C allocation for on-board attitude control is 0.0833° (5 arcmin) on wheels and 0.33° (20 arcmin) on thrusters
    - Adds factors influencing control performance to attitude knowledge error sources
  - G&C allocations do not include ephemeris or time conversion errors

G&C Performance Analyses
Attitude Knowledge

- Simulations for estimated attitude accuracy using different combinations of star tracker and gyro measurements
  - Measurement combinations:
    - All gyros and star trackers (nominal perihelion configuration)
    - All gyros and 1 star tracker
    - 3 gyros and 2 star trackers
    - 3 gyros and 1 star tracker
  - Basic scenario: holding encounter pointing orientation (+Z to Sun) at minimum perihelion distance (9.5 Rs)
  - Attitude error statistics collected over 1-hour period

Fiducial Frame Attitude Estimation Accuracy	**S/C Body Frame Attitude Estimation Accuracy**
Requirement 51 arc-s	Requirement 139.2 arc-s
Max error in fiducial X/Y/Z axes 19.22/9.88/16.07 arc-s	Max error in body frame X/Y/Z axes 122.62/122.96/159.8 arc-s

- Simulations for attitude propagation after star tracker data drops out
  - Both star trackers active for 30 minutes, then disabled
  - Simulation continued for 24 hours with estimator propagating attitude using gyro rate data
  - Estimated attitude solution accuracy exceeded G&C allocation and top-level requirement for many cases
    - Likely due to modeling and treatment of gyro bias uncertainty
    - Work on-going to identify driving error sources and improve filter performance

S/C Body Frame Attitude Propagation after Star Tracker Drop Out
Top-level control requirement < 0.5° over 24 hours (1800 arc-s)
Majority of cases have max errors < requirement on X/Y/Z body axes
Many cases have max error exceeding requirement, ~3600 arc-s in worst cases

G&C Performance Analyses

Attitude Control

- Simulations for control using wheels between momentum dumps
  - Basic scenario: holding encounter pointing orientation (+Z to Sun, +X to ram) at 6 different solar distances: 0.0442 (9.5Rs), 0.0580, 0.0900, 0.1420, 0.2120, 0.2500 AU
    - Distances selected to span jitter and windowed stability periods in WISPR pointing stability requirements
  - Attitude control statistics collected over 800 second period

Holding Encounter Attitude using Wheels
Budgeted allocation for pointing accuracy met at all solar distances (WISPR)
Jitter requirements met for all solar distances (WISPR, SWEAP, spacecraft)
Windowed stability requirement met for WISPR optical X & Y axes for all solar distances; requirement about WISPR optical Z axis exceeded for some smaller solar distances (See table on next slide)

- Simulations for control using thrusters during momentum dump & transition back to wheel control after dump
  - Basic scenario for wheel control at 9.5 Rs with momentum level increased to induce autonomous momentum dump using thrusters
  - Attitude control statistics collected during dump while on thruster control, in transition period immediately after last thruster firing, and after transition when settled back on wheel control

Attitude Control During and After Momentum Dumps
Budgeted allocation for pointing accuracy on thrusters (20 arcmin) met during dump and in transition period
Transition to wheel control after last thruster firing: ~30% of cases settled within 1 sec after last thruster firing, remainder settled in less than 60 sec (Transition period is time for +Z-Sun angle to return to lower allocation for wheel control)
Budgeted allocation for pointing accuracy on wheels (5 arcmin) met after transition period

Attitude Control Performance
WISPR Pointing Metrics Summary
(WISPR Optical X, Y, Z Axes, 3-σ)

Jitter windows:
20 sec, 0.046 – 0.11 AU;
40 sec, 0.11 - 0.25 AU;

Stability windows:
240 sec (4 min), 0.046 – 0.07 AU
480 sec (8 min), 0.07 – 0.11 AU
960 sec (16 min), 0.11 – 0.174 AU
4800 sec (80 min), 0.174 – 0.25 AU

Solar Distance	**Accuracy (arcmin, 3-σ)**			**Jitter (arcmin, 3-σ)**			**Windowed Stability (arcmin, 3-σ)**		
(AU)	X	Y	Z	X	Y	Z	X	Y	Z
0.0442	3.4838	3.4625	4.4386	0.0331	0.0327	0.5797	0.1751	0.1682	5.7920
0.0580	3.4844	3.4618	4.1194	0.0313	0.0304	0.4658	0.1575	0.1516	4.8884
0.0900	3.4838	3.4626	3.7104	0.0303	0.0294	0.2659	0.1386	0.1282	2.8875
0.1420	3.4849	3.4625	3.5858	0.0396	0.0379	0.2505	0.1305	0.1194	1.6022
0.2120	3.4850	3.4625	3.5341	0.0394	0.0379	0.1664	0.1274	0.1162	0.9371
0.2500	3.4849	3.4627	3.5232	0.0393	0.0380	0.1537	0.1268	0.1159	0.7648
G&C Pointing Accuracy Budget Allocation				WISPR Pointing Stability Requirements					
	5	5	5	0.8	0.8	3.4	1.6	1.6	3.4

G&C Performance Analyses
Maneuver Execution Accuracy

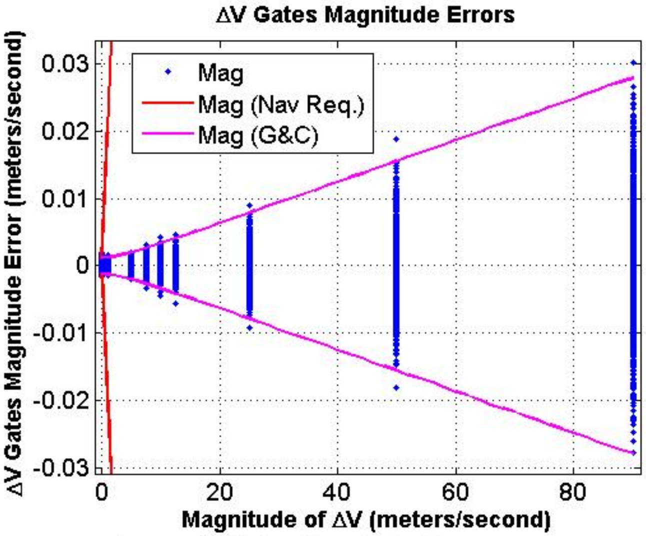
- Simulations for TCM 1 – large magnitude, “turn and burn”
  - Basic scenario: turn spacecraft to point A or B thruster set in ΔV direction
  - Perform 90 m/s ΔV maneuver using closed-loop burn guidance; accelerometer feedback used to determine when ΔV target is reached and burn is terminated

TCM 1
Maximum total pointing error 0.2°; maximum total magnitude error 2.0 mm/s; easily meets current requirement
Mean additional fuel usage for attitude control and pulsing logic to implement ΔV is 19.3% more than continuous firing of 4 thrusters aligned with ΔV direction until ΔV magnitude is reached

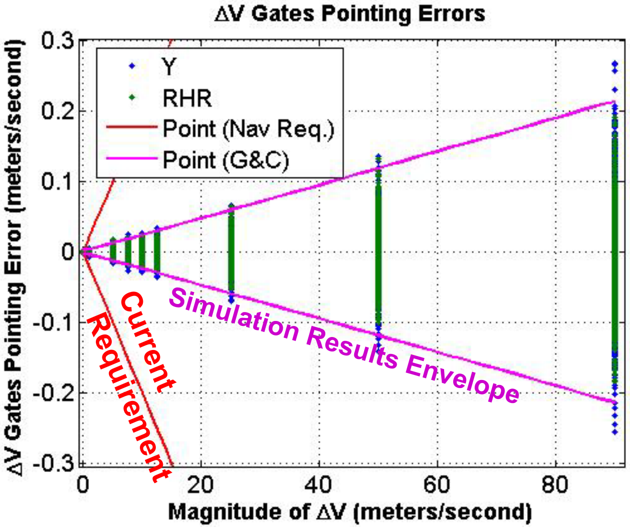
- Simulations for other statistical TCMs – varying magnitude, “component burns”
  - Basic scenario: hold umbra attitude (+Z to Sun) with angle between ΔV and +Z axis varying from 0 to 180°; combined pulsing of thrusters in groups B & C or A & B to achieve ΔV in target direction
  - 11 separate cases for ΔV magnitudes of 0.005, 0.010, 0.025, 0.1, 1.0, 5.0, 7.5, 10, 12.5, 25, 50 m/s
  - Perform maneuver using closed-loop burn guidance with accelerometer feedback as for TCM 1

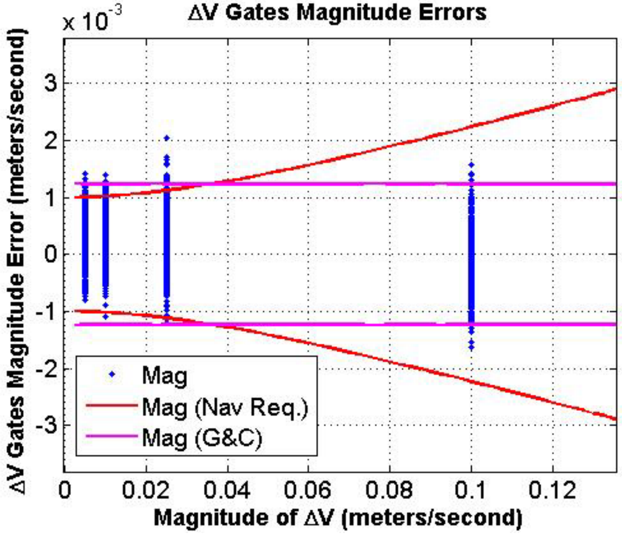
TCMs holding +Z to Sun
Pointing and magnitude accuracy requirements met for Δ magnitudes > 5 cm/s
Current requirements not met for ΔV magnitudes below 5 cm/s Work on-going with mission design and navigation teams to revise requirement and determine smallest TCM magnitude needed
Mean additional fuel usage for attitude control and pulsing logic with 2 thruster groups to implement ΔV is 56% more than continuous firing of 4 thrusters aligned with ΔV direction

G&C Performance Analyses
Maneuver Pointing and Magnitude Errors

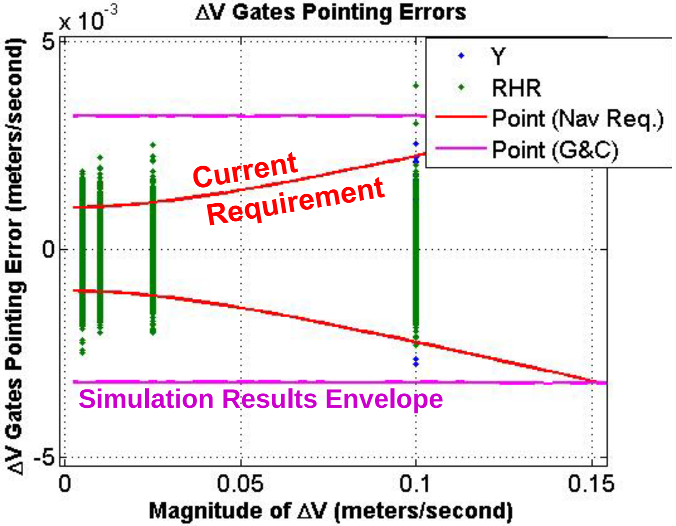


Performance results from simulations well within **current requirement** for larger magnitude ΔVs





Performance results outside **current requirement** for smaller magnitude ΔVs



SPP G&C Hardware Procurement Status

Solar Probe Plus

A NASA Mission to Touch the Sun

- **Attitude control components procured by G&C team from commercial vendors – star trackers, IMU, Sun sensor system, reaction wheels**
- **Propulsion system, solar array and HGA drive actuators and associated electronics procured by other teams**
- **Vendor proposals for flight hardware solicited and reviewed as part of development of SPP Phase C/D proposal to NASA (May-October 2013)**
  - Representative units carried in spacecraft baseline configuration for design purposes in phase B

Component	Candidate Vendors
Star trackers	*Selex ES – AA-STR* Sodern - Hydra
IMU	*Northrup Grumman - SSIRU* Honeywell - MIMU
Sun sensors	*Adcole*
Reaction Wheels	*Rockwell Collins* – Update of RSI 1.6-33/60A Honeywell – Constellation HR10

- **APL documents revised and vendors requested to update proposals for final selection (February-March 2014)**
- **Vendors selected and contracts initiated for flight hardware (& associated test equipment) at start of phase C (March-April 2014)**
  - Star trackers, IMU, and reaction wheels remain competitive procurements
  - Adcole will continue as the sole-source vendor for Sun sensor system
- **Flight hardware deliveries scheduled between November 2015 and April 2016**

G&C Hardware Mass

G&C total mass allocation: 27.94 kg CBE 30.08 kg NTE

G&C component mass estimates:

	Qty	CBE Each (kg)	CBE Total (kg)		Assumed Baseline Unit	Heritage
Guidance and Control Total Mass Estimate			27.871 27.940	Nominal Max		
IMU	1	7.8	7.8		SSIRU Northrop-Grumman	MESSENGER, Deep Impact, SBIRS
Star Tracker	2	2.5	5.0		AA-STR Selex ES (Galileo Avionica)	Proba-2, Alphasat
Reaction Wheels	4	< 3.2	< 12.8		Rebuild former small wheel design for SPP Rockwell Collins Deutschland (Teldix)	Update of RSI 1.6-33/60A
Reaction Wheel Metglass Shields	4	0.03	0.12			MESSENGER, STEREO
Solar Limb Sensors Electronics box	1	1.0	1.0		New design for SPP Adcole	Similar to electronics for other Adcole Sun sensor systems
Solar Limb Sensors Detector heads	7	0.093 0.10	0.651 0.700	Nominal Max	Custom design for SPP Adcole	None – TRL 6 development
Digital Sun Sensor heads	2	0.25 0.26	0.50 0.52	Nominal Max	Standard DSS Adcole	MESSENGER, Stereo, numerous other missions
Sun Sensor System (box + SLS heads + DSS heads)	1		2.151 2.220	Nominal Max	Custom system for SPP Adcole	

G&C Hardware Power

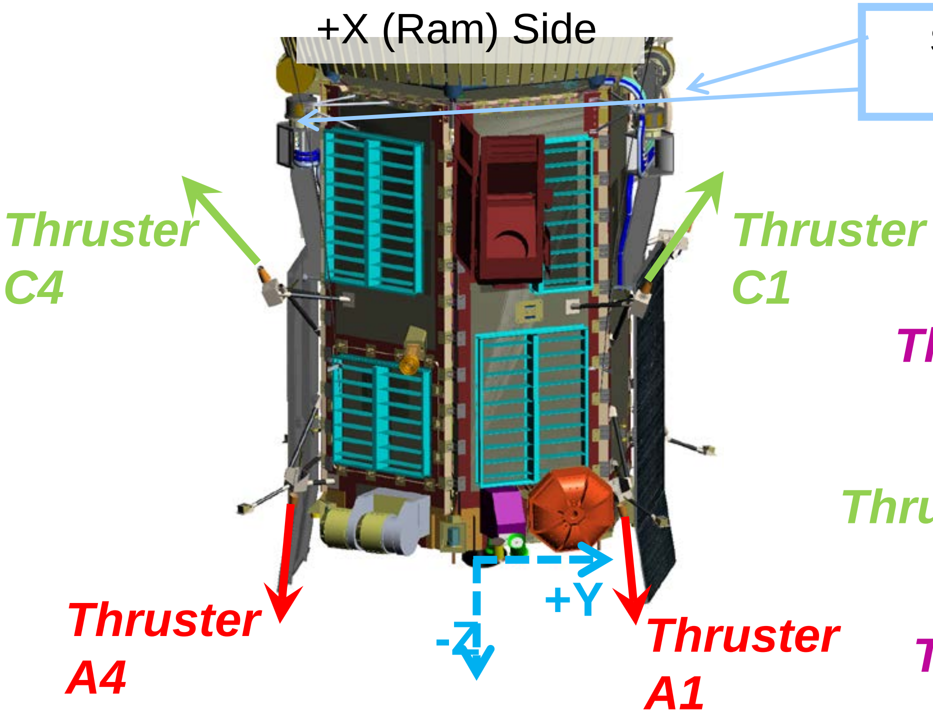
G&C component power estimates:

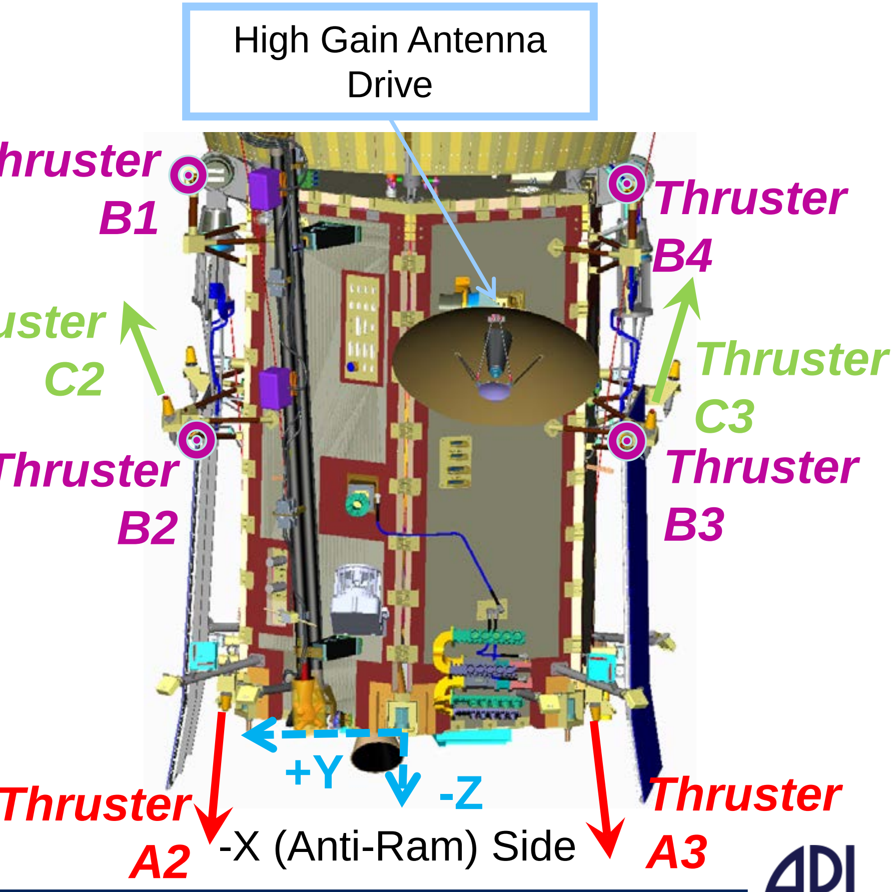
	Qty	CBE Each (W)	Assumptions	Assumed Baseline Unit
IMU	1	29.0 27.6	4 gyros + 4 accels on 4 gyros on, 4 accels off (gyro heaters off)	SSIRU Northrop-Grumman
Star Tracker	2	6 9 13	@ 20 C @ 40 C @ 60 C	AA-STR Selex ES (Galileo Avionica)
Reaction Wheels	4	11	Estimated max power at max speed and torque is 35 W for smaller wheels; Carrying smaller steady-state power value based on MESSENGER & Stereo wheel operational experience	Rebuild former small wheel design for SPP Rockwell Collins Deutschland (Teldix)
Sun Sensor System (box + SLS heads + DSS heads)	2	 2.4/2.9 3.5/4.2 3.7/4.6 1.8/2.4 2.7/3.4 2.9/3.8	2 SLS heads illuminated @22 V @32 V @35 V No SLS heads illuminated @22 V @32 V @35 V	Custom system for SPP Adcole

Consistent with current spacecraft power loads budgets

- ***Multiple configurations with specific assumptions on operating temperatures, voltages, number of units powered on***

G&C Actuators
Exterior: Thrusters
(Solar Array and HGA Drives)





Note: Arrows denote exhaust directions. Thrust directions are opposite exhaust directions.

G&C Actuators
Thruster Configuration

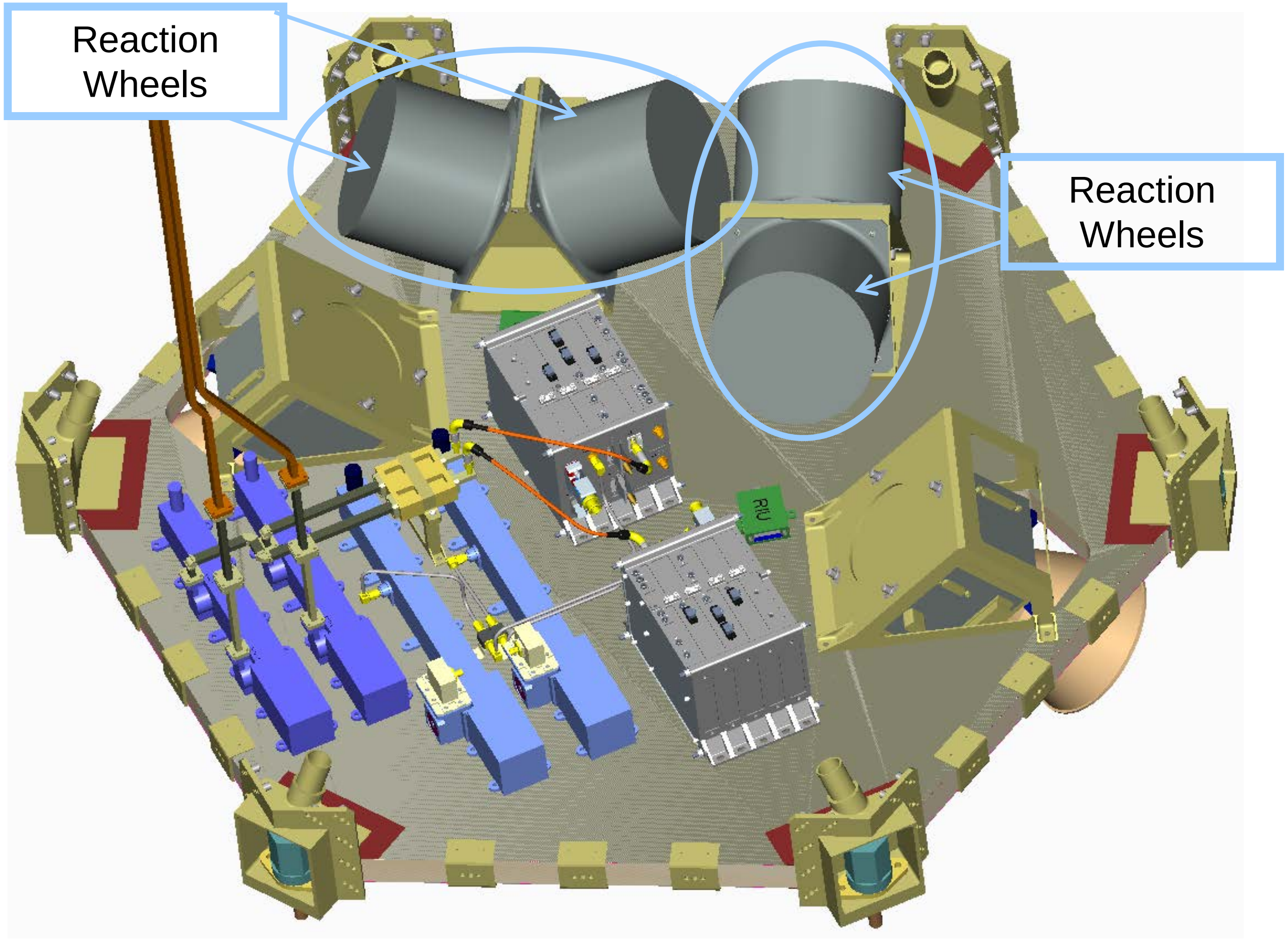
- Mono-prop, blow-down propulsion system with 1 fuel tank and 12 thrusters
  - All thrusters are 4.4N (1 lbf)
- Thrusters are grouped in 3 sets of 4 thrusters each: A, B, C
  - Placement and grouping driven by:
    - Need to perform ΔV in any inertial direction while keeping +Z pointed to Sun (TCMs)
    - Science team preferences to avoid firing thrusters towards Sun or along ram direction during science data collection (momentum dumps)

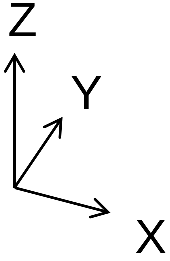
- Assuming ideal alignment, when all 4 thrusters in one group are firing simultaneously:
  - A group produces net thrust along s/c +Z axis
  - B group produces net thrust along s/c +X axis
  - C group produces net thrust along s/c –Z axis

  - A thrust directions are canted at 20° off from +Z axis
  - B thrust directions are canted at 10° off from +X axis
  - C thrust directions are canted at 30° off from –Z axis

- One group of thrusters is sufficient for attitude control only; the other two groups provide redundancy and tolerance to a single thruster failure

G&C Actuators
Interior: Reaction Wheels





Inside Bottom Deck

G&C Actuators
Reaction Wheel Availability

- Wheels chosen as primary actuators to meet science pointing accuracy and jitter requirements
- Spacecraft mass and power margins dictate small wheel size
- Options based on SPP RFP responses:

	RCD **Former RSI 1.6-33/60**	**RCD** **Modified RSI 2-75/60**	**RCD** **Re-build of RSI 1.6**	**Honeywell** **Constellation HR10 (Model CS1004L)**
	Initial Phase B Baseline	RCD Proposal	RCD ROM Estimate *Current Phase B Baseline*	Honeywell Proposal
Maximum Momentum Storage (Nms)	1.6	2	1.6	4
Maximum torque (mNm)	33	75	33	40
Maximum power (W)	28	75	35	70
Mass (kg)	2.45	3.4	< 3.2	4.4 (< 4.7)
Size Diameter (mm) Height (mm)	 135.5 110	 222 85	 < 145 <120	 294 135

G&C Actuators
Reaction Wheel Selection Status

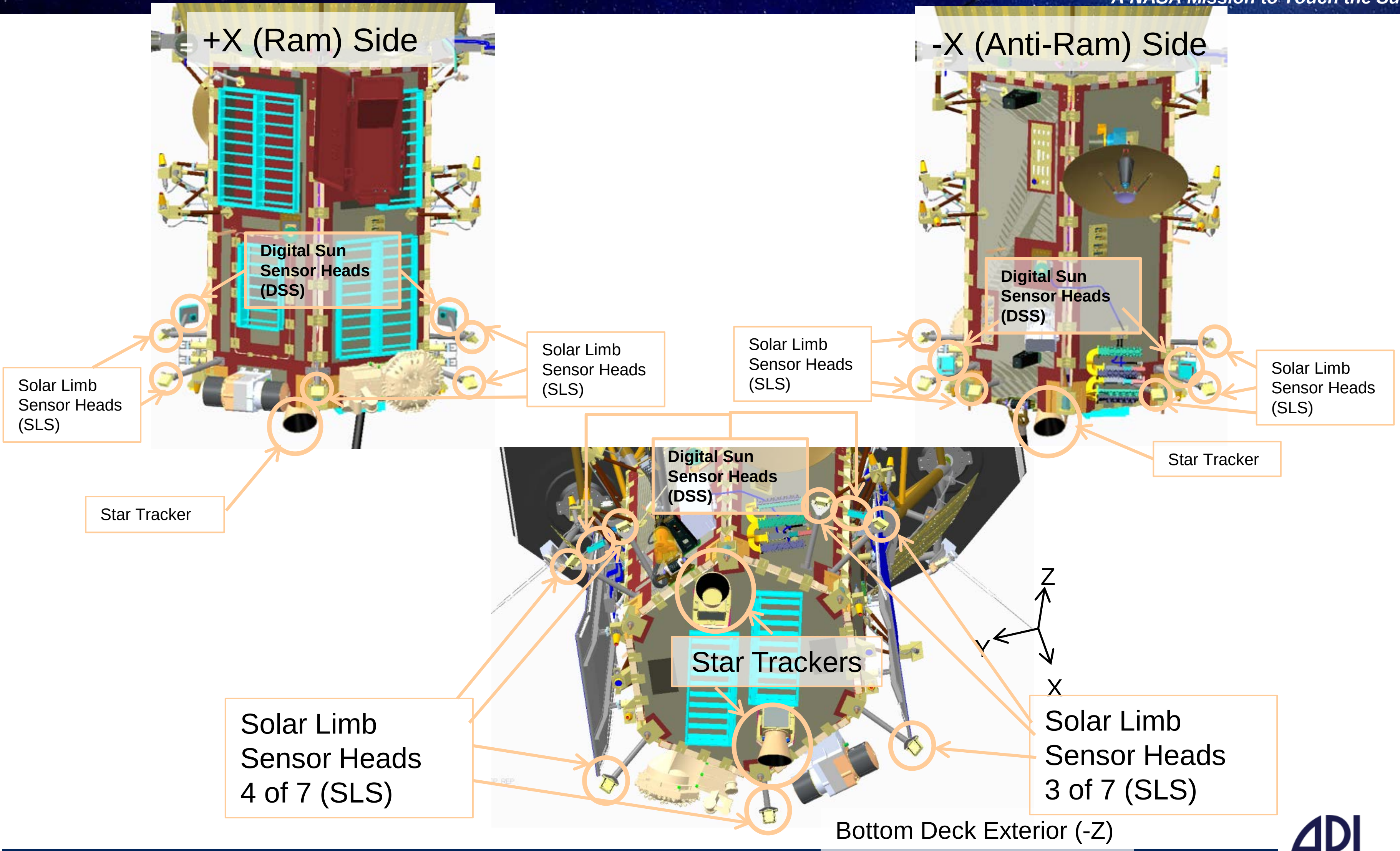
- Difficult to fit Honeywell or modified RCD RSI wheels on bottom deck
- Mass, size, and power higher than desired

- Honeywell proposal did not include changes to off-the-shelf HR10 wheel

- RCD has confirmed that RSI 1.6-33/60 wheels are obsolete and there are no immediate plans to replace or redesign the electronics
  - RCD recommended a larger wheel - modified RSI 2-75/60
- APL requested RCD to consider effort and cost for near re-build of RSI 1.6-33/60 or equivalent small wheel
  - ROM cost and basic configuration received in October 2013
  - Full proposal requested in December, expect response in January or February 2014
    - Will include building and life testing an EM wheel to qualify design
- ROM cost for re-build of RSI 1.6 wheels included in phase C/D proposal
- Schedule can accommodate longer procurement duration

- Project risk in place for reaction wheel availability since March 2013 (SPP-60 Reaction Wheel Procurement)
  - Mechanism for monitoring trades on wheel selection with vendors and spacecraft engineering team

G&C Sensor Placement
Exterior: Star Trackers, Sun Sensors



+X (Ram) Side

Digital Sun Sensor Heads (DSS)

Solar Limb Sensor Heads (SLS)

Solar Limb Sensor Heads (SLS)

Star Tracker

-X (Anti-Ram) Side

Digital Sun Sensor Heads (DSS)

Solar Limb Sensor Heads (SLS)

Solar Limb Sensor Heads (SLS)

Star Tracker

Digital Sun Sensor Heads (DSS)

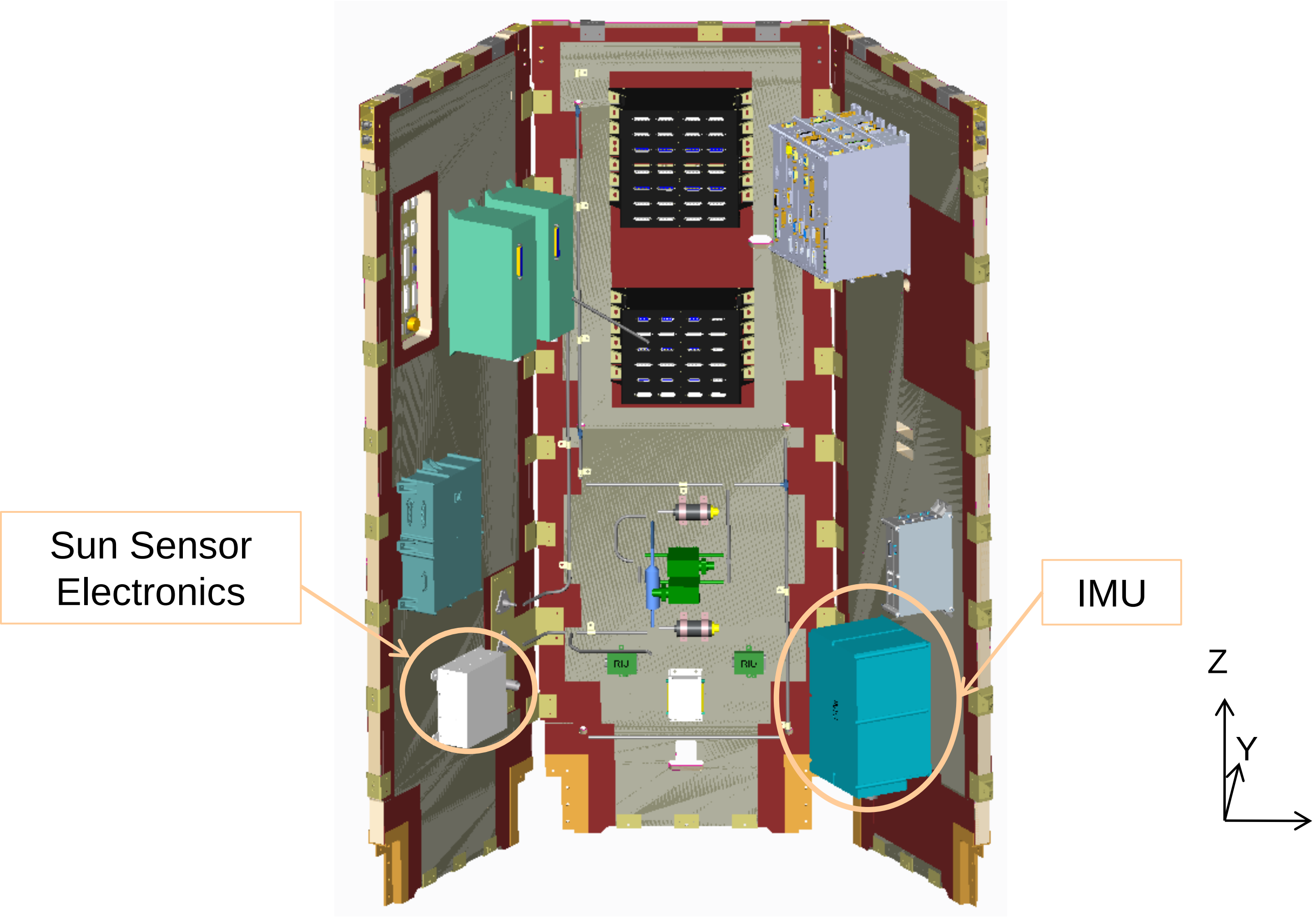
Star Trackers

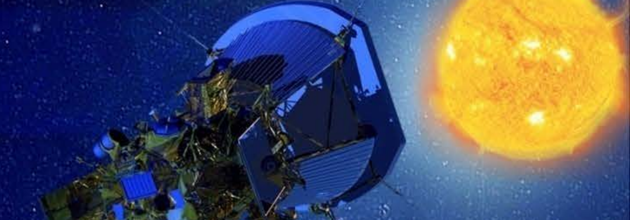
Solar Limb Sensor Heads 4 of 7 (SLS)

Solar Limb Sensor Heads 3 of 7 (SLS)

Bottom Deck Exterior (-Z)

G&C Sensor Placement
Interior: IMU, Sun Sensor Electronics





SPP Challenges for G&C Sensors

- **Star Tracker**
  - Increased background level from dust, but attitude solutions still possible
  - Proton fluence level during periods of high solar activity will make tracker unable to generate attitude solutions
    - System must accommodate tracker drops out up to 24 hours in duration

- **IMU**
  - Gyro rate errors must be limited to allow accurate propagation of attitude during tracker outages

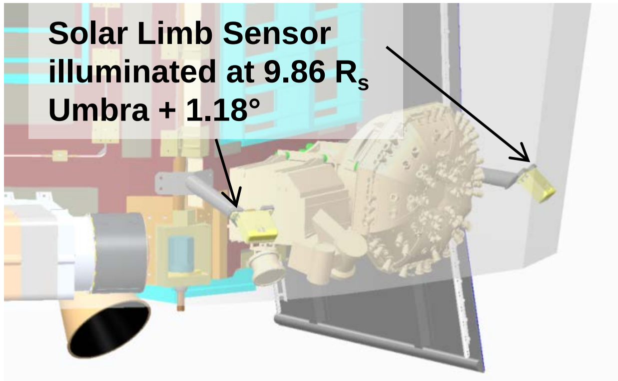
- **Sun sensor system**
  - Sensor complement required to provide Sun direction information over full range of solar distance (1 AU to 9.86Rs) and planned range of spacecraft attitudes
    - Operation at high illumination, high temperature (perihelia) and no illumination, low temperature (in umbra at nominal attitude or at aphelion)
  - Solar limb sensors - new concept and custom design for SPP
  - Digital Sun sensors – standard design with long heritage

Sun Sensor System Overview

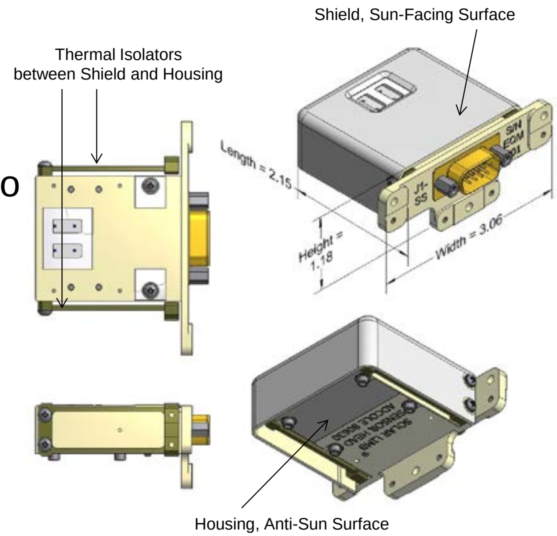
- Sun sensor system is included to externally detect deviations from nominal attitudes - pending umbra violation or aphelion thermal violation
  - Provides tolerance to faults with star trackers, on-board ephemeris and time models
- Sun angles or direction readings used to detect critical faults associated with attitude deviations
    - “Umbra violation orange warning”
    - Aphelion thermal violation warning
- Solar limb sensor (SLS) heads are placed around the perimeter of the bottom deck to detect deviations from encounter and umbra pointing orientations
  - Do not provide full Sun direction vector; only provide measurements once attitude has drifted from nominal
- Digital Sun sensor (DSS) heads are placed on the –X side to detect deviations from aphelion or aphelion-umbra variable pointing orientations
  - Provide full Sun direction vector and will give measurements at nominal & off-nominal orientations
- Used as primary sensors for Sun-relative attitude control (contingency system operation – “G&C safe mode”)

Solar Limb Sensor Design

- TPS edges serve as one boundary for SLS head fields-of-view; partial Sun disk extends beyond TPS edge as attitude deviates from encounter orientation (TPS to Sun)

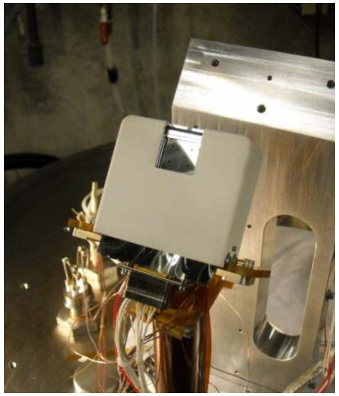

Solar Limb Sensor illuminated at 9.86 R_s Umbra + 1.18°

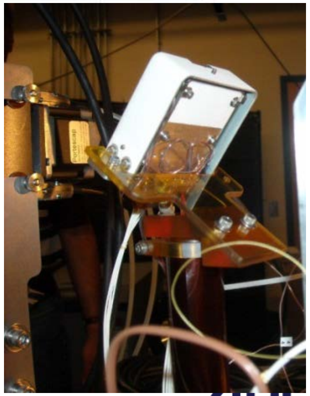
- Sun presence and intensity measured at two locations in each head
  - Differential intensity between two locations used to derive offset angle in boresight plane when partial Sun disk is visible (small Sun offset angles)
  - Cross-angle information not provided



ADCOLE

- Design features for operation at hot and cold extremes:
  - Aluminum shield covers housing with solar cells
  - Shield and part of housing painted with low solar absorption and high emissivity white paint
  - Shields isolated from housing with titanium isolators
  - Housing surface under aperture in shield coated with SiO2 and diamond machined





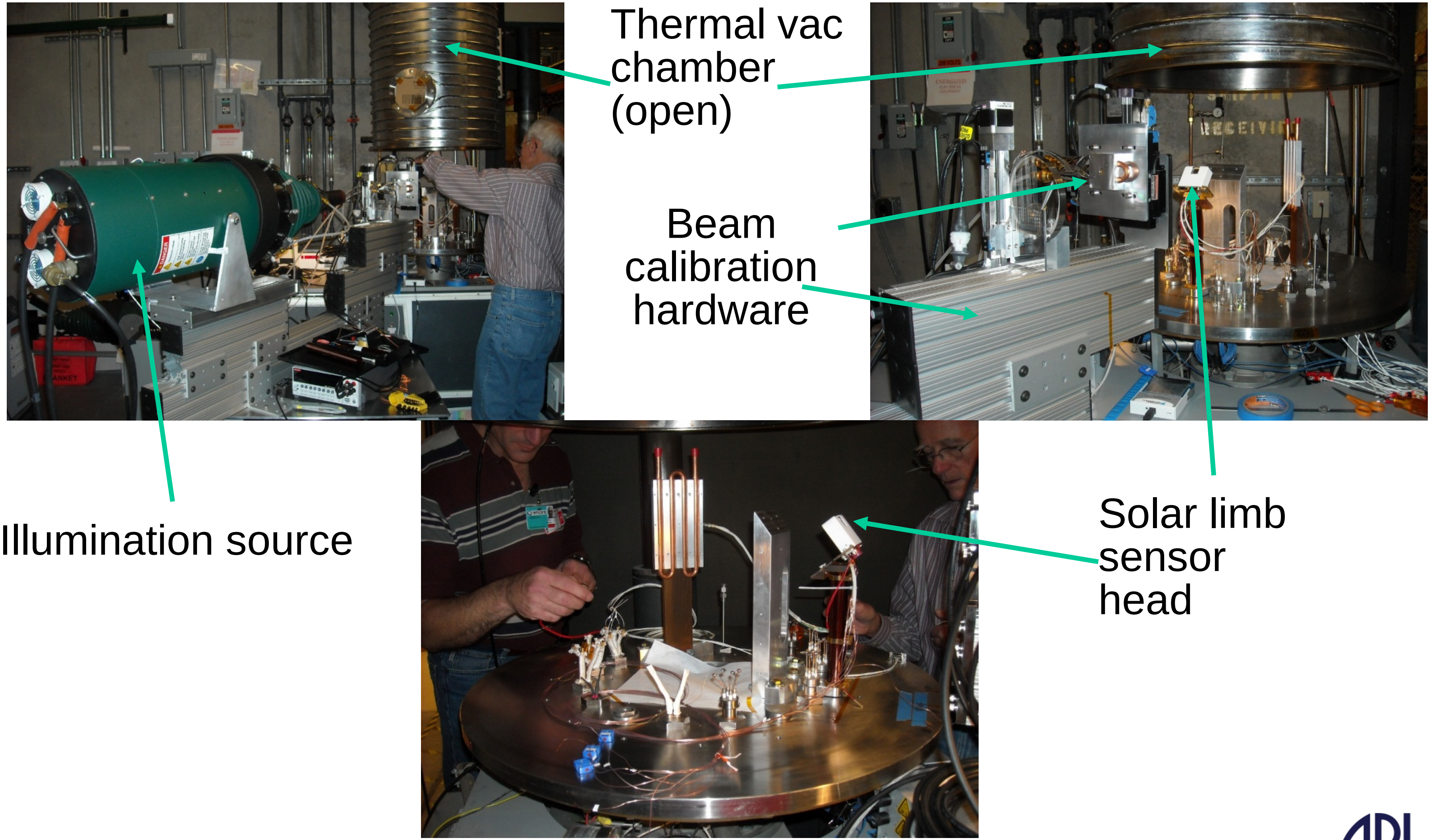
Solar Limb Sensor
TRL 6 Development and Testing

- SLS head design matured and prototype sensor and electronics have been fabricated during phase B
  - Thermal model developed by Adcole with input from APL
- TRL 6 has been demonstrated by testing using combination of Adcole and Emcore test facilities

- Testing at Adcole for workmanship and basic system functions at lower illumination levels (~2.6 sc)
  - Vibration and thermal cycling for head
  - Functional and performance testing using standard solar simulator at Adcole with no illumination gradient
  - System test using solar simulator with a gradient density filter mounted on a translation stage to generate illumination gradient

- Testing at Emcore for operation and survival at worst-case hot temperature and illumination conditions
  - Exposure to high intensity solar illumination with sensor in thermal-vacuum chamber
  - Use of filter to generate illumination gradient and translation stage to simulate spacecraft rotation to test differential intensity signals similar to Adcole system test
    - Steady state exposure at 3 different illumination levels with fixed gradient along sensor head
      - Worst-case: full level 22 – 7.5 solar constants (sc); 2 partial levels ($^{3}/_{4}$ intensity:16 – 6 sc, ½ intensity:11 - 4 sc)
    - Transient exposure – monitor conditions as head taken from low exposure (room conditions) to the different high exposure levels
    - Exposures using translation stage to vary gradient along sensor head from steady-state gradient

Solar Limb Sensor Testing at Emcore



Thermal vac chamber (open)

Beam calibration hardware

Illumination source

Solar limb sensor head

Solar Limb Sensor Thermal Model Validation

- Simulations run with thermal model for SLS head for conditions matching tests in Emcore chamber
  - BOL properties for white paint, radiation to chamber walls instead of "deep space"
- Predicted temperatures are higher than measured temperatures from the tests; temperature differences generally within 10° C
  - Correlation is sufficient to demonstrate TRL 6 and validates use of model for flight unit development

	Full Illumination		**¾ Intensity**		**Half Intensity**	
	Test	**Analysis**	**Test**	**Analysis**	**Test**	**Analysis**
Avg Shield Temp (°C)	230	239	216	222	177	182
Avg Sensor Body Temp (°C)	158	168	144	150	116	129
Reticle Temp (°C)		191		169		143
Box Temp (°C)	91 (box rear)	103 (average)	84 (box rear)	96 (average)	69 (box rear)	78 (average)
Box Bottom Temp (°C)	119	109 (average)	110	102 (average)	90	83 (average)
Power conducted to Spacecraft	0.19 W	0.23 W	0.16 W	0.21 W	0.11 W	0.15 W
Avg Illumination, Shield	14.5 sc → 8.17 W		12.4 sc → 7.00 W		8.4 sc → 4.74 W	
Illumination, Sensor Body	19.4 sc → 0.69 W		15.8 sc → 0.57 W		11.9 sc → 0.43 W	
Illumination, Reticle	19.4 sc → 0.28 W		15.8 sc → 0.23 W		11.9 sc → 0.18 W	

Reference: Thermal Test Report at Emcore Facility for A Solar Limb Sensor for SPP, Adcole 80809, Rev. -, 11/5/2013

G&C Test and Verification Plans

- **G&C system verification includes:**
  - **Stand-alone simulation reviews and testing**
  - **Flight software testing**
  - **Testbed software (“truth model”) testing**
  - **Tests at vendors and interface and bench testing at APL for G&C hardware**
  - **Spacecraft-level testing of G&C hardware**
    - Functional, aliveness, and performance testing, including G&C portion of spacecraft comprehensive performance test (CPT)
    - Phasing (polarity) tests
  - **Spacecraft-level testing of G&C software**
    - G&C portion of spacecraft CPT
    - Mission simulations, autonomy testing, and special systems-level tests
  - **Performance analyses**
  - **Parameter review**

G&C Test and Verification Software

- **Flight software testing**
- **Testbed software (“truth model”) testing**
  - Follows formal software development process as defined in 7434-9042 SPP Software Development Plan
  - Initial development and testing by SPP team members
  - Code “walk throughs” with project and external reviewers
  - Independent testing by software test teams not involved in SPP development
    - Test team includes G&C experts to develop tests and assess results

- **G&C stand-alone simulation reviews and testing similar to software process**
  - Initial development and testing by SPP G&C analysts
  - Reviews to step through model blocks with project and external reviewers
  - Independent testing by G&C analysts not involved in SPP development

G&C Test and Verification Hardware

- **Tests at vendors and interface and bench testing at APL for G&C hardware**
  - **Vendor tests**
    - Environmental testing as defined in SPP EDTRD and EMECP
    - Functional and performance testing tailored to specific component (e.g. night sky test for star trackers)
    - Includes EM testing for Sun sensor system and reaction wheels
      - Flight SLS heads tested at Emcore for high illumination and temperature in vacuum
  - **APL G&C hardware tests**
    - EM interface tests with early version of flight software (EM hardware data interfaces match flight interface)
    - Bench tests with flight units

G&C System Performance Verification & Parameter Review

- **Performance analyses used to verify most G&C functions**
  - G&C stand-alone simulation configured to replicate key mission scenarios
    - Changing attitudes – turns
    - Holding attitude – pointing accuracy, jitter, and windowed stability for science data collection, Earth pointing for communication
    - Executing TCMs
  - Covers all performance requirements for nominal and contingency situations
  - Time domain & Monte Carlo scenario tests
  - Also includes control stability analysis (determination of margins and robustness)

- **Performance review**
  - Will be held near end of development cycle when near-final system parameter values are available
  - Presents the results of the scenario tests and compares with requirements
  - Presents stability analysis results
- **All analyses documented in memo(s) with test cases and results stored in a configuration-controlled directories**

- **Review of all parameters used for G&C functions conducted just prior to launch**
  - Will mostly be flight software parameters, although parameters for ground software tools will be included
  - Independent analyst tasked to check value and source of each parameter
  - Results documented in a memo and any discrepancies corrected prior to launch

G&C Test and Verification
I&T

- **Spacecraft-level testing of G&C hardware**
  - Functional, aliveness, and performance testing (including G&C portion of CPT)
  - Phasing (polarity) tests
    - Will test with both sides of spacecraft avionics
    - Will use stimulators and test ports as needed
    - Performed for:
      - Sun sensor system: solar limb sensors and DSS heads
      - Star trackers
      - IMU – gyros and accelerometers
      - Reaction wheels
      - Propulsion system: thrusters, catbed heaters, latch valves
      - Solar array drives
      - High-gain antenna drive

- **Spacecraft-level testing of G&C software**
  - G&C portion of spacecraft CPT
  - Mission simulations, autonomy testing, and special systems-level tests
    - Hardware-in-the-loop dynamic simulations for routine and special events, contingency scenarios

G&C Conclusions

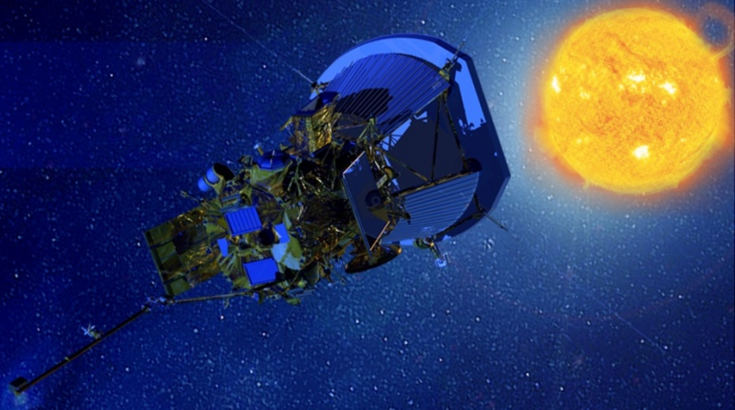
- **Phase B work**
  - G&C requirements development completed
  - Initial performance analyses demonstrated most requirements are met
    - Work in progress to resolve cases where current requirements are not met
  - Potential hardware components and vendors identified
    - Solar limb sensors demonstrated at TRL 6 level

- **Phase C work**
  - Initiate contracts for flight hardware; monitor hardware fabrication and testing at vendors
    - Trade study and further work with vendor to finalize selection of reaction wheels
  - Perform interface tests with EM hardware
  - Add all required capability to G&C simulation and deliver new versions synchronized with flight and testbed software builds
  - Finalize all performance analyses for G&C CDR, including nominal and fault scenarios
  - Generate system test plan covering I&T activities such as phasing tests
  - Hold G&C CDR and support mission CDR

- **G&C subsystem is ready to begin phase C development**

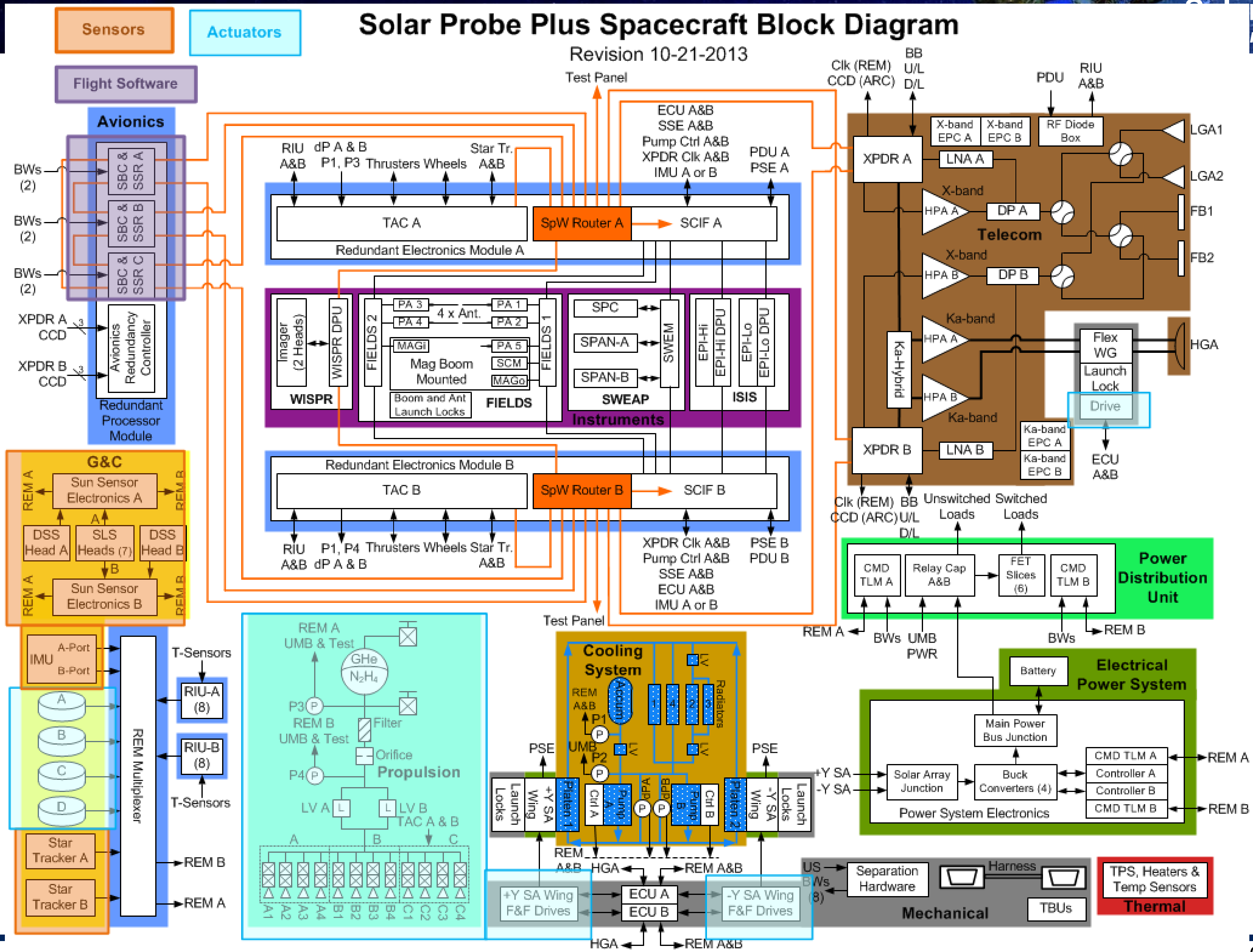
Solar Probe Plus

A NASA Mission to Touch the Sun



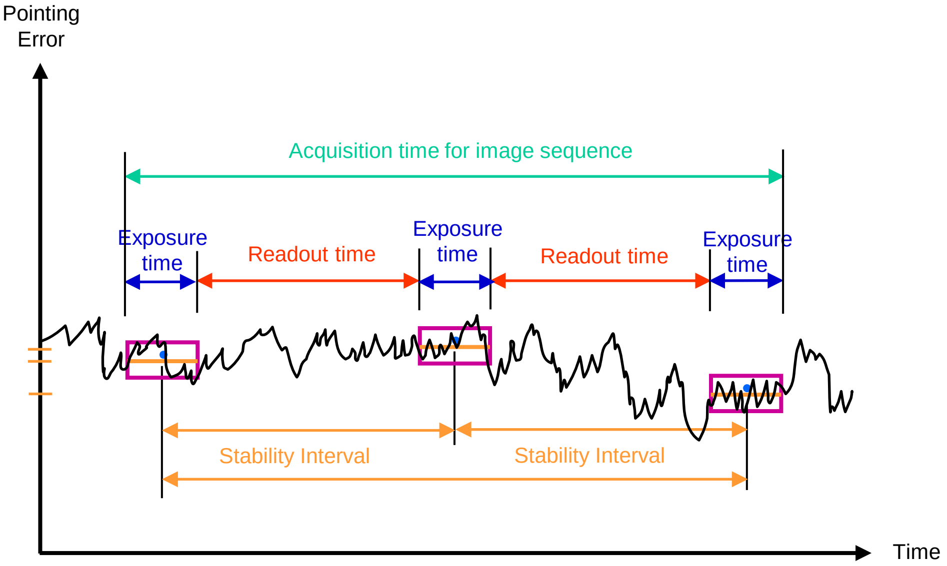
G&C
Backup

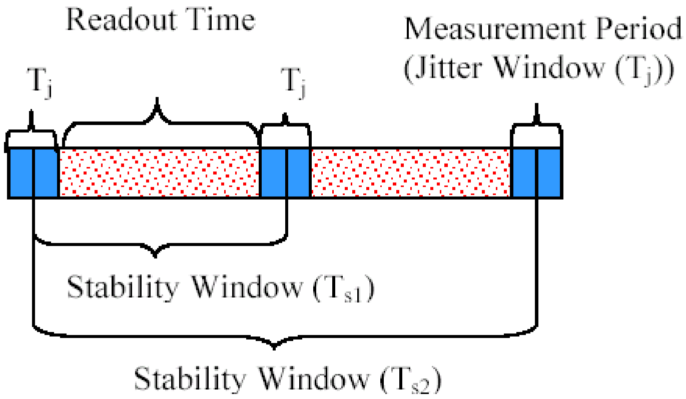
Spacecraft Block Diagram G&C Components Highlighted



Pointing Metric Definitions

- ***Accuracy*** **is the root-mean-square (RMS) pointing error, σ_a, of the line of sight (LOS) over any interval of time (window width $T \rightarrow \infty$).**
- ***Jitter*** **is the RMS pointing error, σ_j, of the LOS *within* an interval of T_j seconds. The jitter window T_j is defined by the integration or measurement time for a single instrument observation.**
- ***Windowed Stability*** **is the RMS change in the LOS from the centroid time of one measurement to the centroid time of another measurement.**





G&C Performance Requirements
Attitude Knowledge & Control
Other Instruments ≤0.25 AU

Requirement Source	Line of Sight	Required Accuracy	
	Pointing Knowledge		
FIELDS, ISIS, SWEAP	Z axis to Sun	60 arcmin (1°) (3-σ)	
	Pointing Control		
FIELDS pointing accuracy	Z axis to Sun	180 arcmin (3°) (3-σ)	
ISIS pointing accuracy	Z axis to Sun	120 arcmin (2°) (3-σ)	
SWEAP pointing jitter	X, Y, Z axes	30 arcmin (0.5°) (3-σ)	Jitter Window Durations 10 s 9.86 Rs - 0.25 AU

G&C Hardware Mass Changes

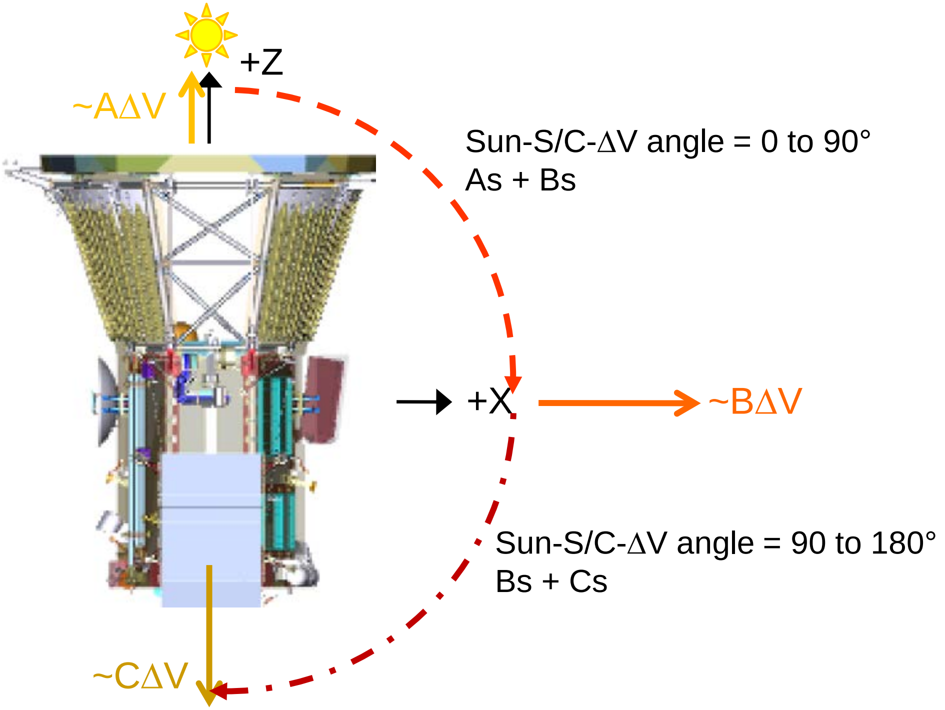
Mass Liens	Mass Opportunities	Mass Uncertainties
Sun sensor system: Possible growth in electronics mass during detailed design with interface for 3 more SLS heads and 2 DSS heads Addition of DSS head(s) on +X side of spacecraft	IMU - eliminate extra shielding for radiation tolerance if radiation analysis indicates it's not needed	Propellant usage for momentum dumps: Decrease possible if Cp-Cg offset controlled to small value Increase possible if Cp-Cg at larger value or environmental torques larger than predicted
Reaction wheels – uncertainty in mass estimate for re-build of small wheels; fall back to using modified larger wheels to reduce risk		Propellant usage for TCMs: decrease possible as control logic matures; Increase possible from unfavorable Cg location as mass properties are updated

G&C Hardware
Power Changes

Power Liens	Power Opportunities	Power Uncertainties
IMU – power increase if temperature not maintained within predicted limits		Sun sensor system: uncertainty in power estimate including interface for 3 more SLS heads and 2 DSS heads
Star trackers – power increase if temperature not maintained within predicted limits		
Reaction wheels – uncertainty in power estimate for re-build of small wheels; fall back to using modified larger wheels to reduce risk	Reaction wheels – restrict maximum operating speed/torque; would have to assess impact on G&C performance	

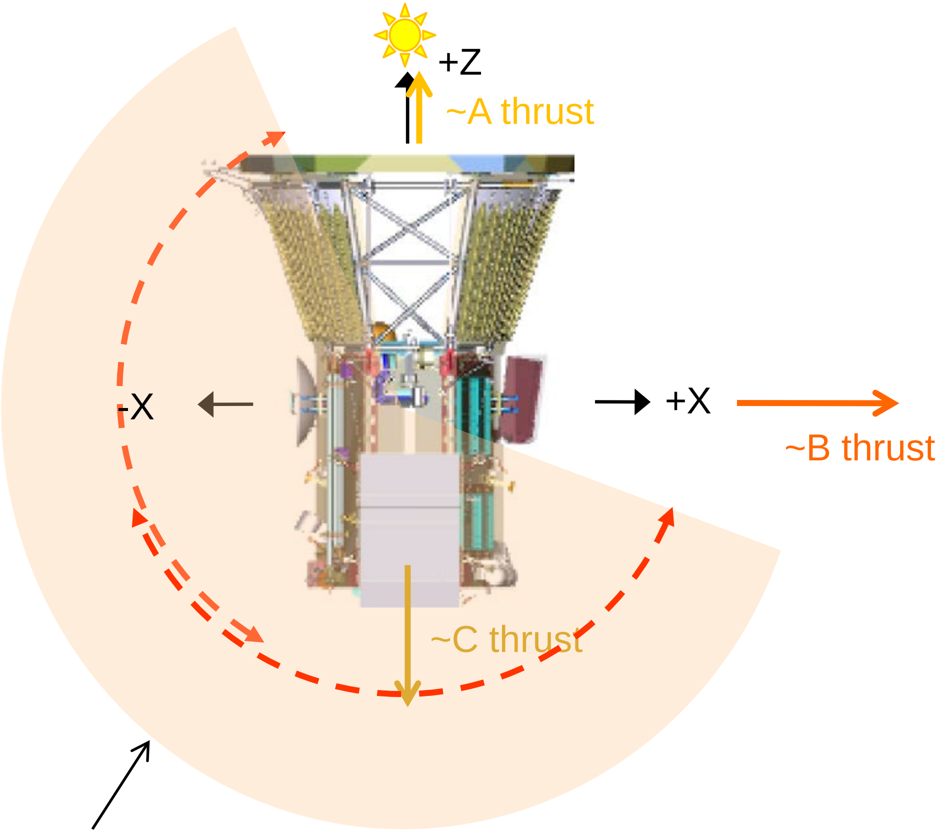
ΔV Thruster Selection
TCMs with +Z to Sun

- <u>Required</u> attitude keeps the Sun line along the +Z axis (TPS to Sun)
- TCMs must be executed as “vectorized” or “component” burn with components in two of the 3 ΔV directions provided by the thruster groups
- The choice of thruster group depends on SPdV = Sun-S/C-ΔV angle
  - For SPdV = 0 to 90°, ΔV has +X and +Z components so use Bs + As
  - For SPdV = 90 to 180°, ΔV has +X and –Z components so use Bs + Cs. These will be less efficient because Cs are canted farther away from the -Z axis than the As are from the +Z axis



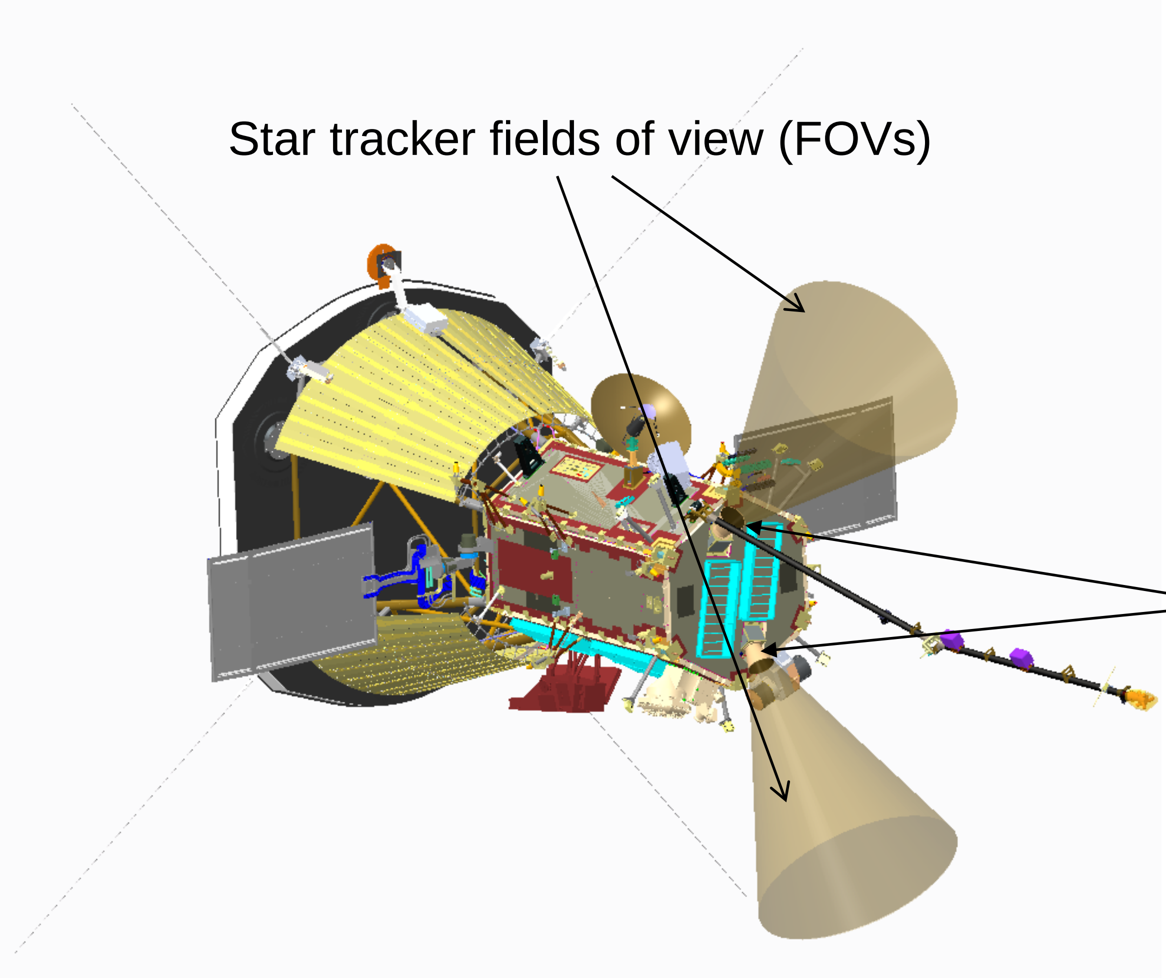
Momentum Dump Thruster Selection
≤ 0.25 AU

- **Required attitude keeps the Sun line along the +Z axis (TPS to Sun)**
- **Science teams prefer no thrust exhaust towards Sun or along direction of travel (ram)**
- **Limits thruster groups for momentum dumps to As and Bs**
  - **C thrusters exhaust towards Sun**
- **Can't use thrusters with thrust directions within 70° of –X or –Z axes**



Thrust direction exclusion zone for momentum dumps

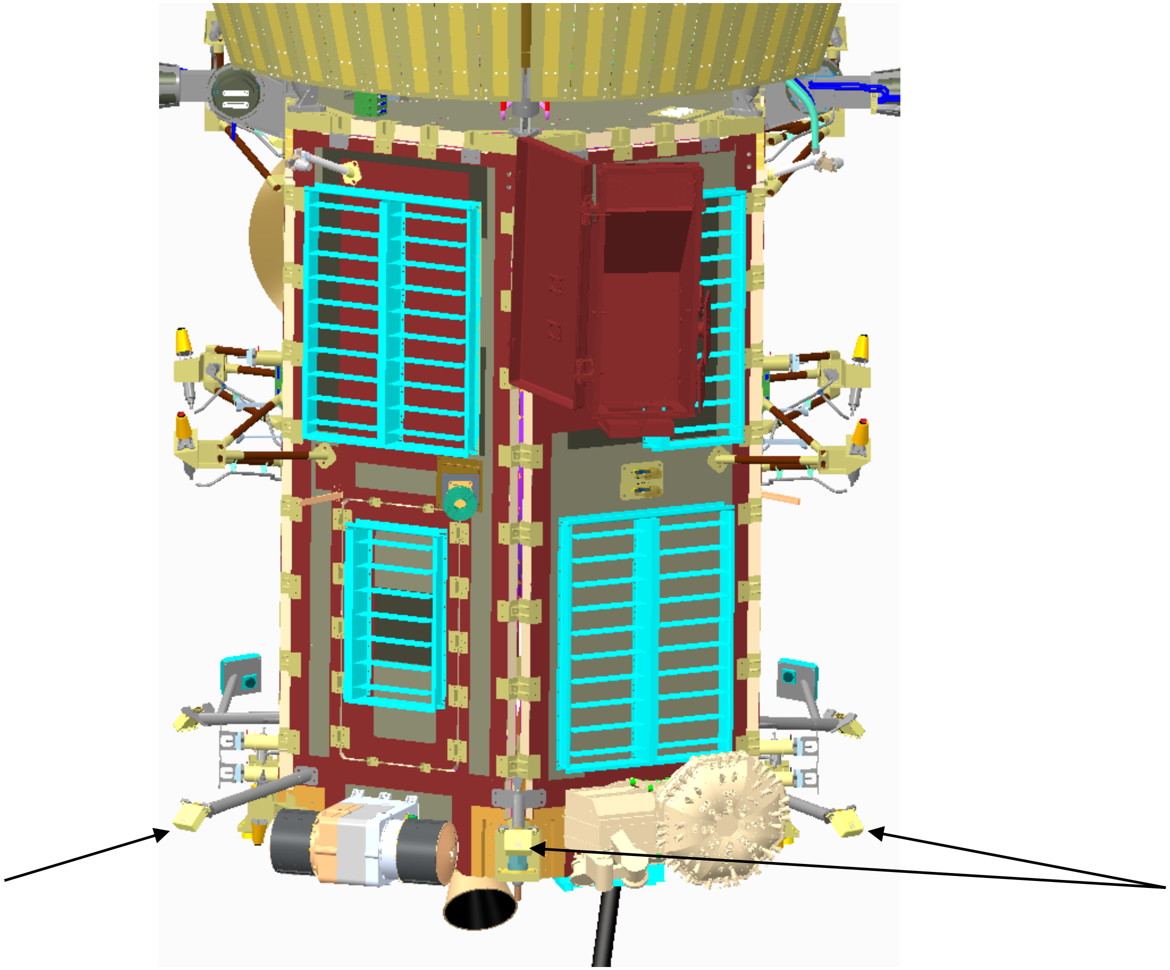
G&C Hardware Placement
Star Trackers



Star tracker fields of view (FOVs)

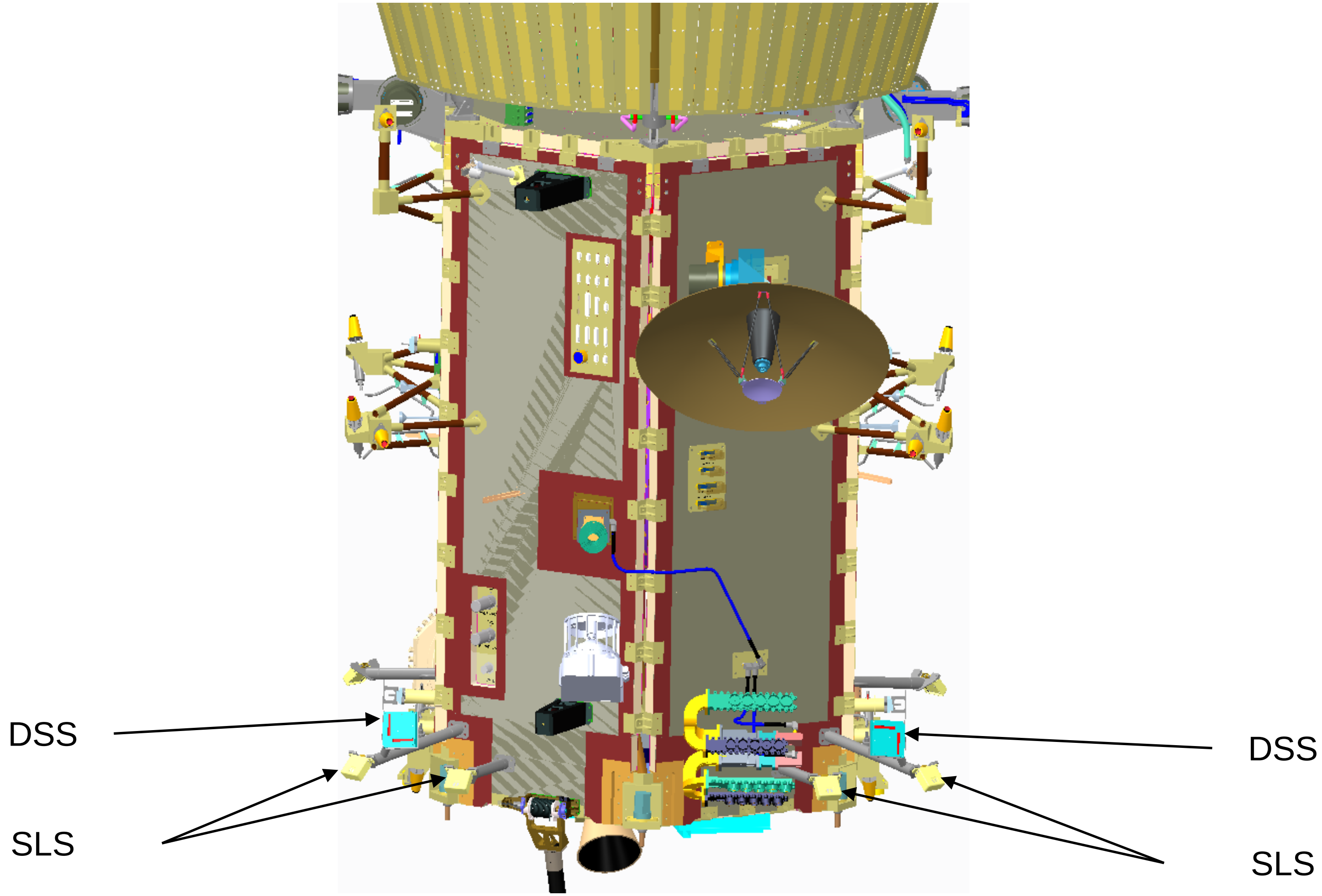
Star Trackers

G&C Hardware Placement
Sun Sensor System - 1



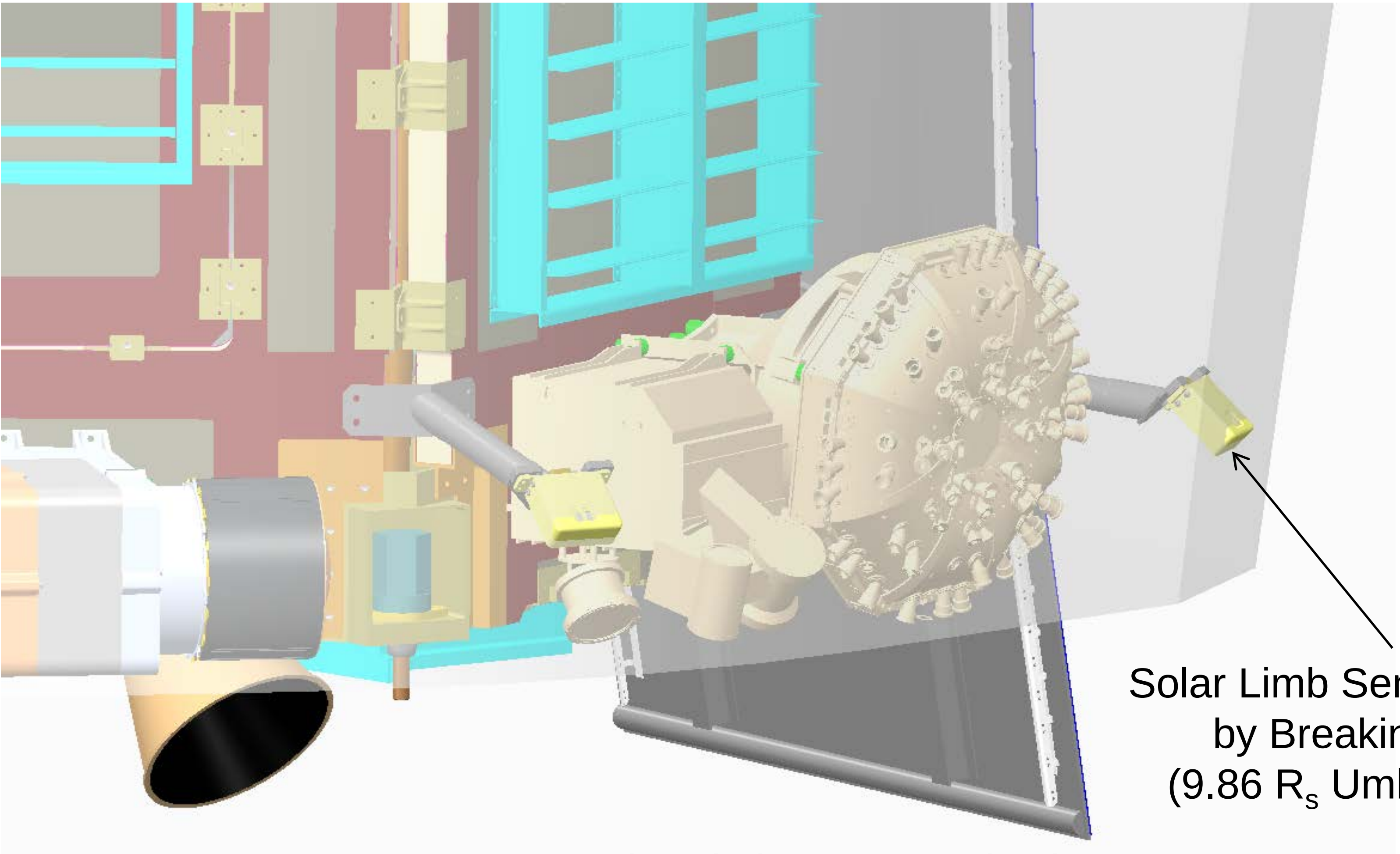
+X (ram) side solar limb sensors (3 of 7)

G&C Hardware Placement
Sun Sensors - 2



-X (anti-ram) side solar limb sensors (4 of 7), digital Sun sensors (2 of 2)

G&C Hardware Placement
Sun Sensors - 3

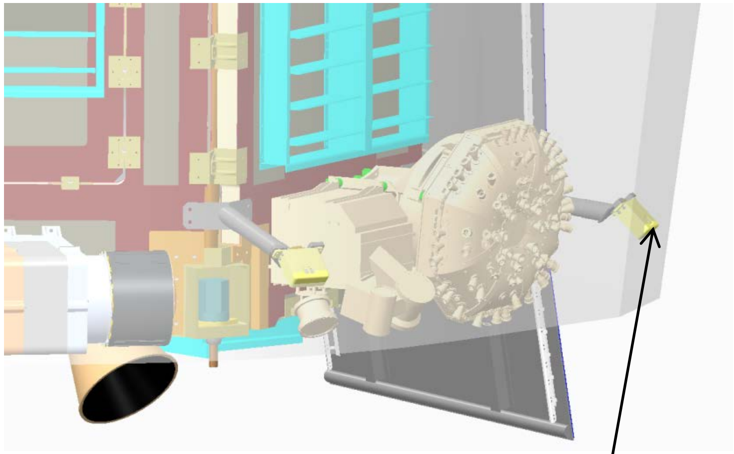


Solar Limb Sensor Activated
by Breaking Umbra
(9.86 R_s Umbra + 1.18°)

Typical limb sensor activation

Solar Limb Sensor Placement

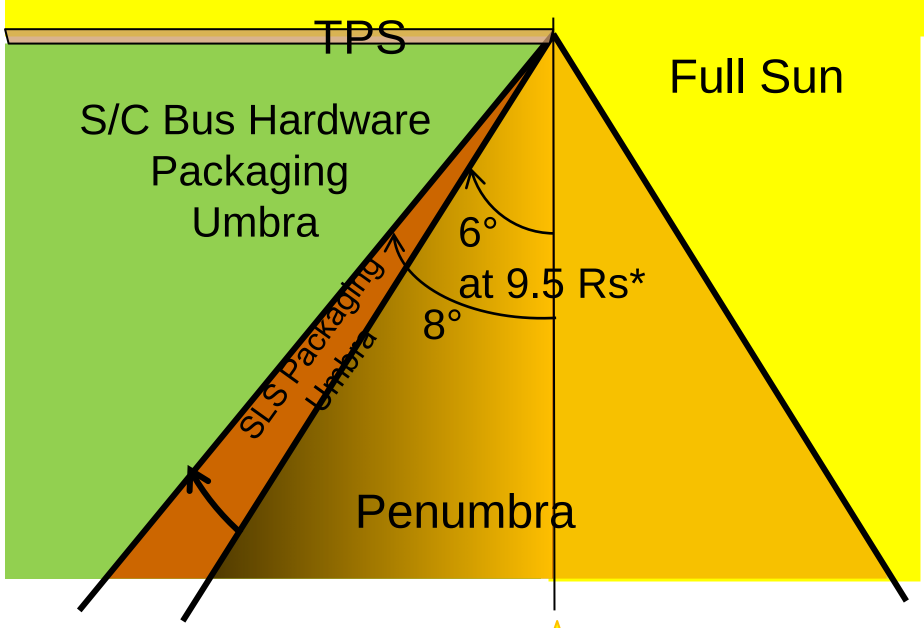
- SLS heads are mounted around the perimeter of the aft end of the spacecraft
  - TPS chamfer corners and other TPS edges serve as one boundary for SLS head fields-of-view



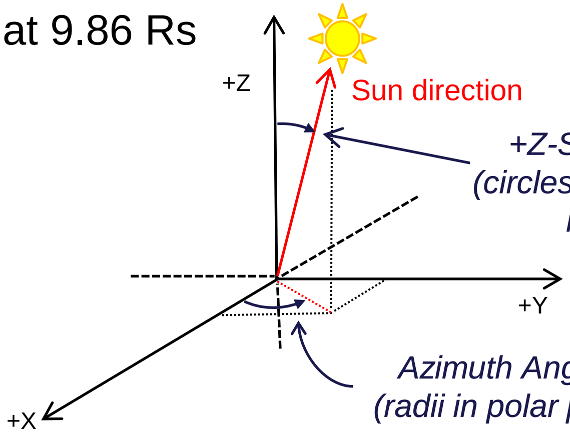
Solar Limb Sensor illuminated at 9.86 R_s Umbra + 1.18°

- 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 of sensor head from spacecraft center line)
  - At least one head must be illuminated by the Sun prior to illumination of any spacecraft bus components for solar distance < 0.7 AU
    - Determines azimuthal placement of heads around perimeter and number of heads
    - Satisfied with just 4 SLS heads at 9.86 Rs, but gaps in coverage with 4 heads at 0.7 AU
    - Added 3 additional heads to close coverage gaps at 0.7 AU

Solar Limb Sensor
Coverage at Perihelion Attitude



* 5.82° at 9.86 Rs



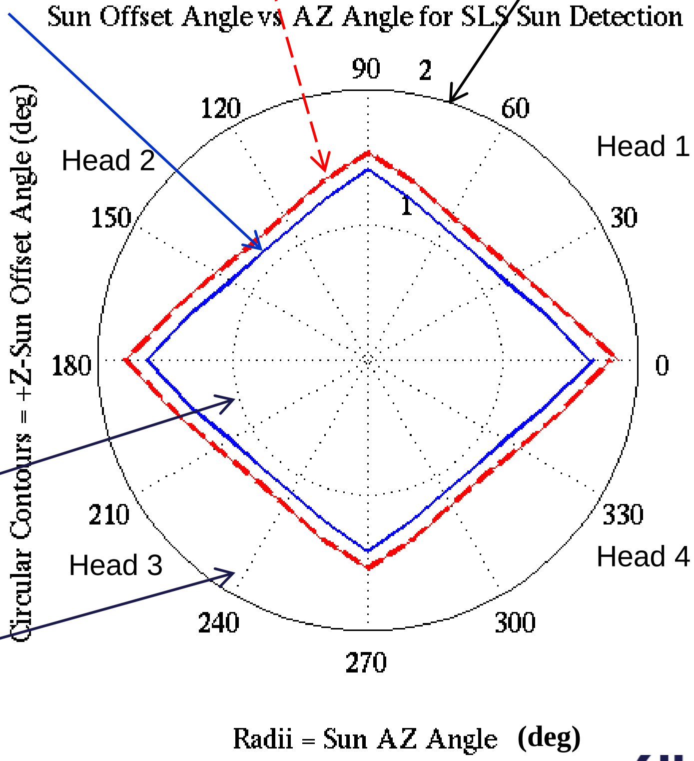
+Z-Sun Offset Angle (circles of constant radius in polar plot)

Azimuth Angle (radii in polar plot)

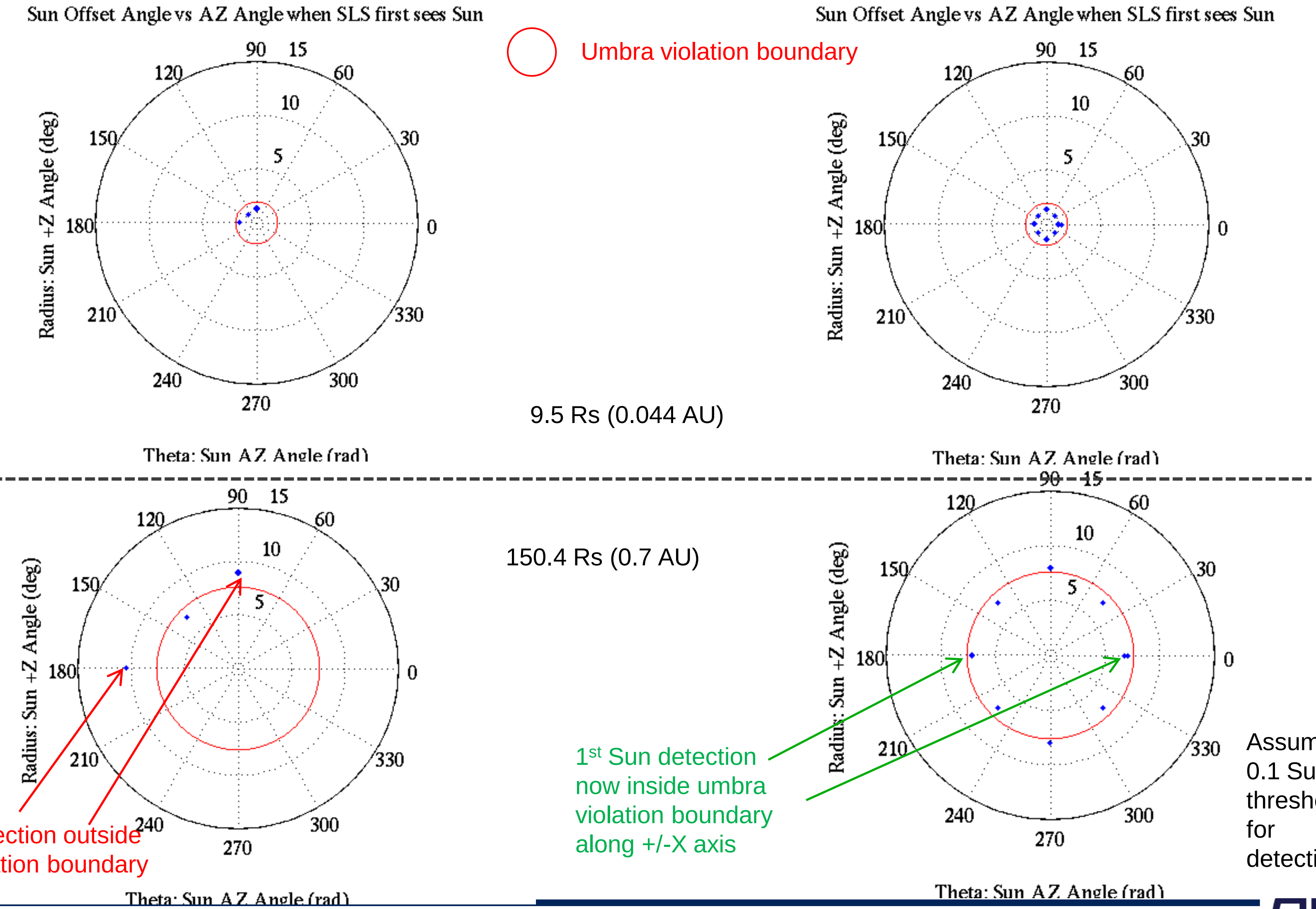
Sun Offset from +Z angle when SLS head first generates offset angle at 9.5 Rs

Sun Offset from +Z angle when SLS head first illuminated at 9.5 Rs

Nominal packaging umbra violation is 2°+Z-Sun offset angle at 9.5 Rs (2.18° at 9.86 Rs)



Solar Limb Sensor Coverage for 9.5 Rs vs 0.7 AU



Umbra violation boundary

Single quadrant shown; geometry repeats for other quadrants

4 SLS Heads

7 SLS Heads

9.5 Rs (0.044 AU)

150.4 Rs (0.7 AU)

1st Sun detection outside umbra violation boundary

1st Sun detection now inside umbra violation boundary along +/-X axis

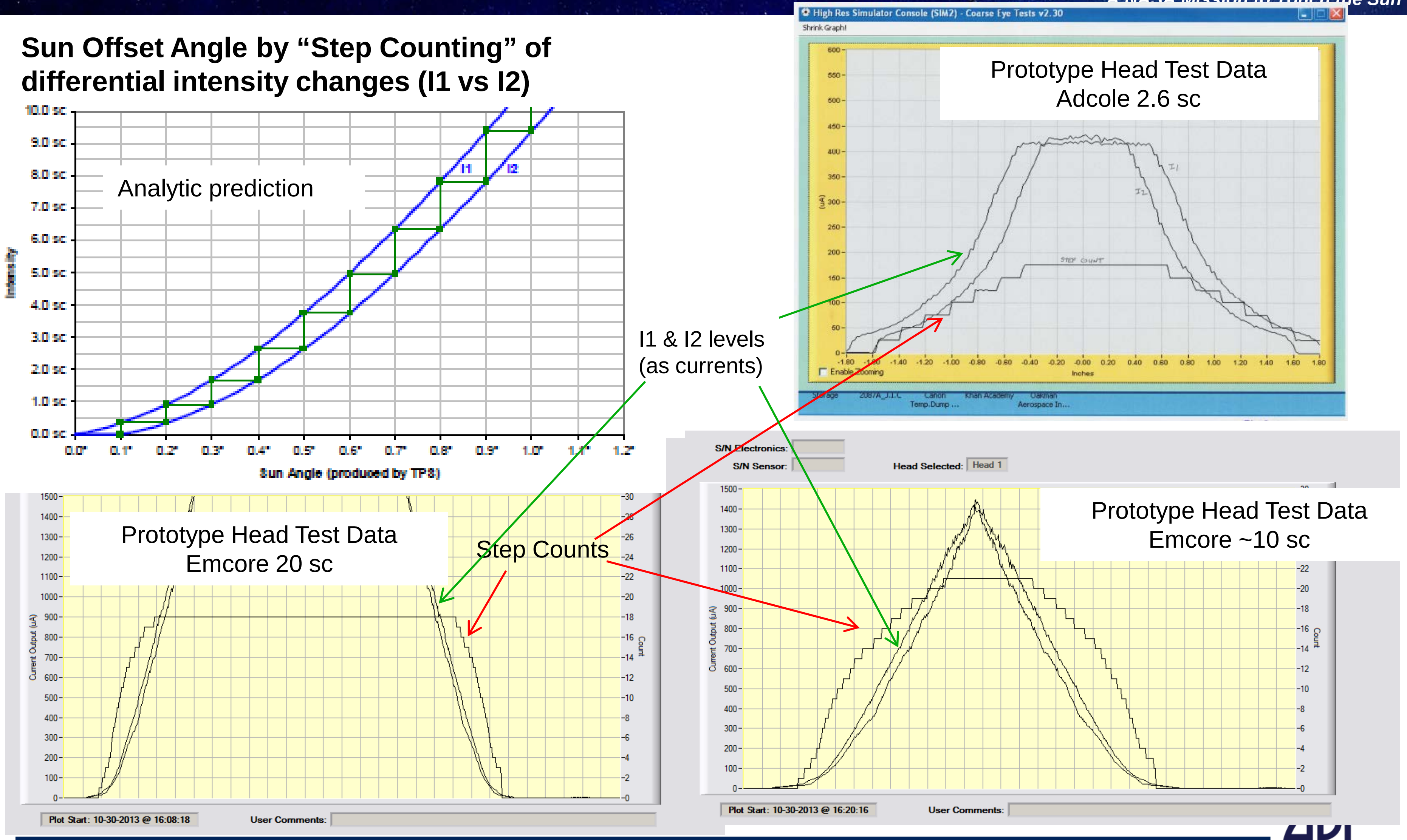
Assumes 0.1 Suns threshold for detection

Solar Limb Sensor
Design Concept and Test Data

Solar Probe Plus

A NASA Mission to Touch the Sun

Sun Offset Angle by "Step Counting" of differential intensity changes (I1 vs I2)



Analytic prediction

Prototype Head Test Data
Adcole 2.6 sc

I1 & I2 levels
(as currents)

Step Counts

Prototype Head Test Data
Emcore 20 sc

Prototype Head Test Data
Emcore ~10 sc

High Res Simulator Console (SIM2) - Coarse Eye Tests v2.30

S/N Electronics:

S/N Sensor:

Head Selected: Head 1

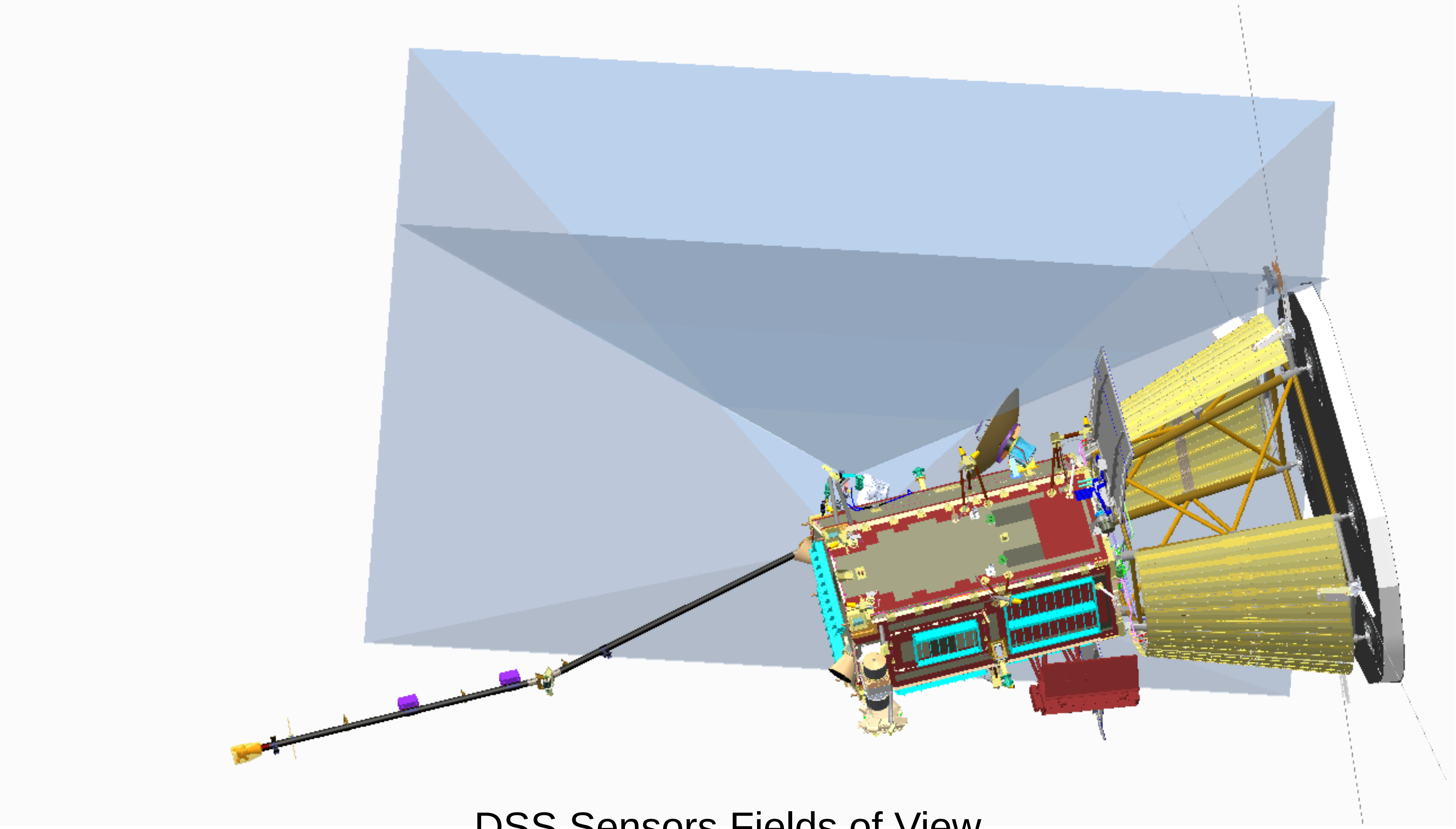
Plot Start: 10-30-2013 @ 16:08:18

User Comments:

Plot Start: 10-30-2013 @ 16:20:16

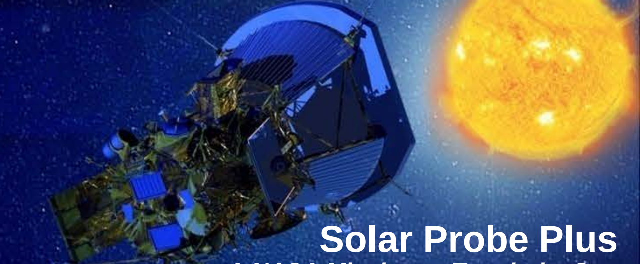
User Comments:

G&C Hardware Placement
Sun Sensor System - 4



DSS Sensors Fields of View

Test Equipment for G&C Hardware (GSE)



Solar Probe Plus

A NASA Mission to Touch the Sun

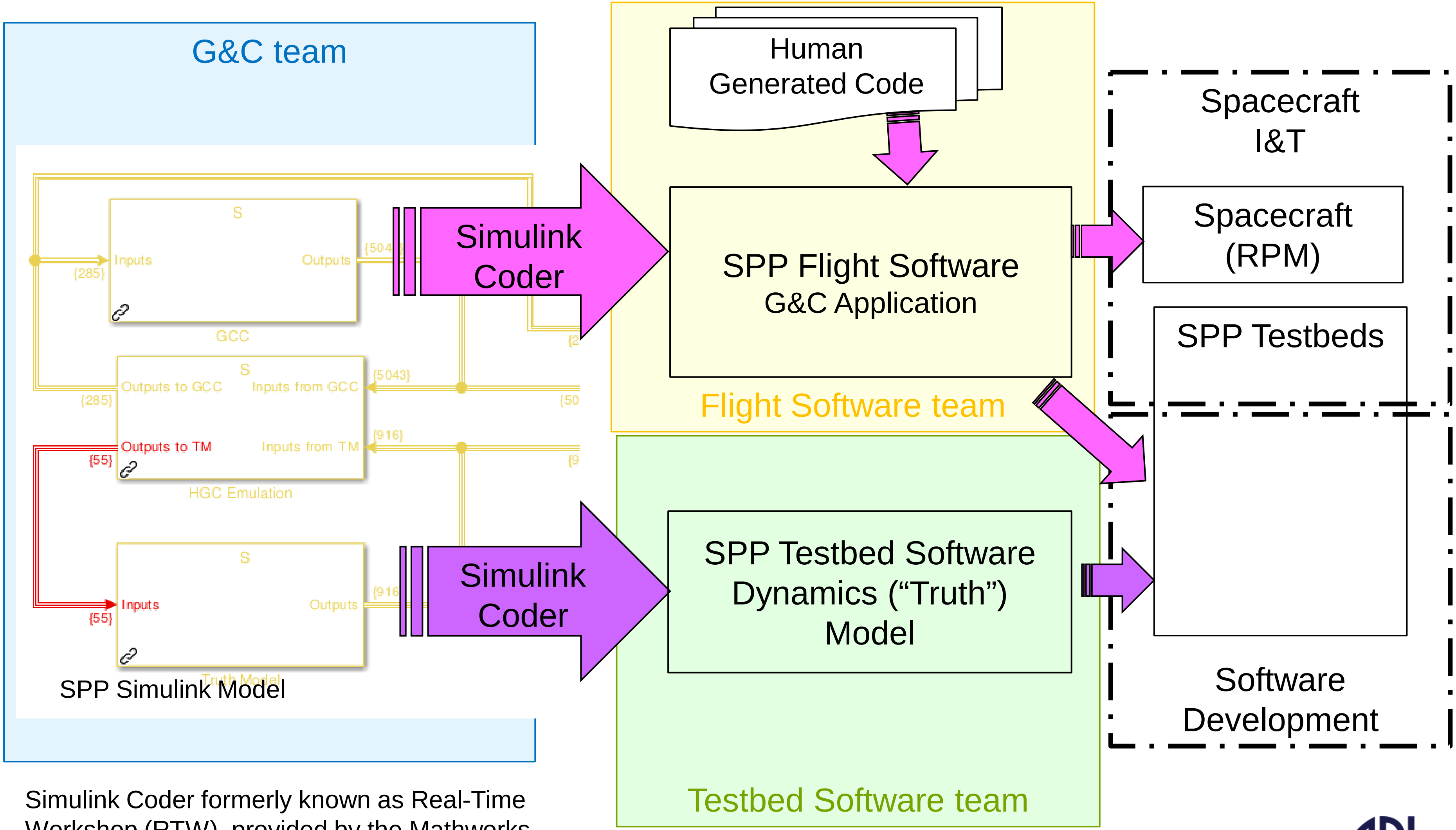
- Star trackers
  - Optical stimulators and test port injestion of simulated star image data
  - Tracking attitude dynamics from testbed only possible with test port
- IMU
  - Test port to set offset values applied to actual gyro and accel measurements (remove Earth gravity and rotation and substitute testbed values for rate and acceleration)
- SLS and DSS
  - Optical stimulators with LEDs to illuminate heads
  - Stimulators can follow attitude and intensity readings from testbed software
  - Will also use lamp to illuminate heads for some tests
- Reaction wheels
  - Feedback of wheel speed measurements into testbed software
- All test equipment or test capabilities included in hardware specification documents
  - Vendors included test equipment in their proposals

G&C In-Flight Calibration Activities

- **WISPR – star tracker alignment calibration**
  - Necessary to meet WISPR attitude knowledge requirement
  - WISPR images of star fields with simultaneous recording of raw star tracker attitude solutions and on-board attitude estimates
    - Ground processing to determine WISPR-tracker alignment during calibration
  - Performed once per orbit as permitted by data downlink constraints
  - May be combined with WISPR dark current imaging sessions
- **IMU – star tracker calibration**
  - Series of rotations within Sun-safe region
    - Full rotation about Sun line, smaller rotations about X and Y axes within umbra limits
    - Performed at larger solar distances to obtain larger rotations within umbra limits
    - Similar to turns used within Sun keep-in constraints for calibration on MESSENGER
  - Simultaneous recording of raw star tracker and gyro measurements
  - Data processed on ground to determine gyro-tracker relative alignment and other parameters
    - Results used to update flight software parameters used for attitude estimation
  - Performed once per orbit or as needed to support TCM execution within data downlink constraints
- **SLS calibration**
  - Rotations from umbra pointing orientation to test offset angle at which SLS heads first detect the Sun
  - Performed in full attitude & rate mode; SLS not in control loop
  - Performed as part of G&C commissioning at farther solar distances in first orbit

G&C Stand-Alone Simulation Evolution to Flight and Testbed Software

Solar Probe Plus
A NASA Mission to Touch the Sun



G&C team

SPP Simulink Model

Simulink Coder

Simulink Coder

Human Generated Code

SPP Flight Software
G&C Application

Flight Software team

SPP Testbed Software Dynamics ("Truth") Model

Testbed Software team

Spacecraft I&T

Spacecraft (RPM)

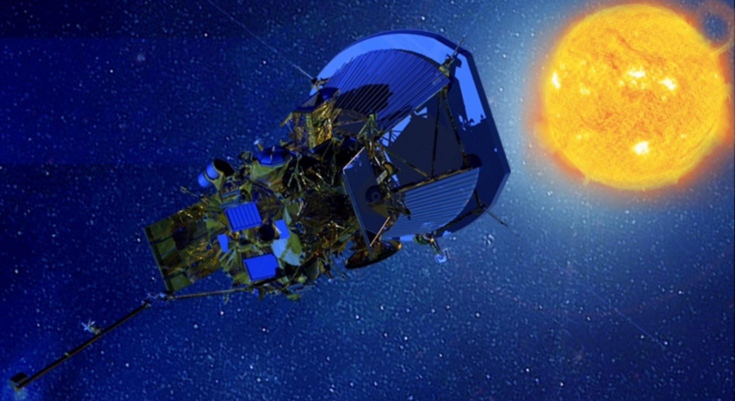
SPP Testbeds

Software Development

Simulink Coder formerly known as Real-Time Workshop (RTW), provided by the Mathworks

Solar Probe Plus

A NASA Mission to Touch the Sun



Propulsion Subsystem

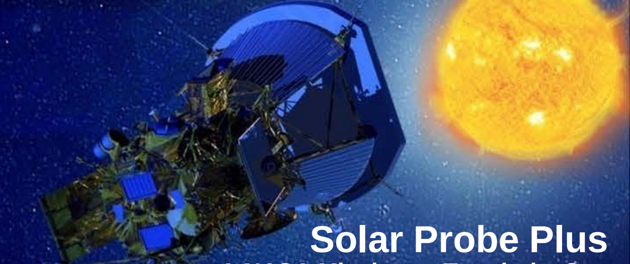
Stewart Bushman
Lead Propulsion Engineer

stewart.bushman@jhuapl.edu

13 – 16 January 2014

APL
The Johns Hopkins University
APPLIED PHYSICS LABORATORY

Propulsion Subsystem Agenda



- **Driving Subsystem Requirements**
- **Subsystem Description**
- **Verification Plans**
- **Backup Slides**

Propulsion Subsystem Driving Requirements

- Propulsion Subsystem Requirements Document 7434-0600 released in PLM 2013.12.02
  - Requirements derived from SPP SCRD 7434-9048
- Operational Lifetime:
  - PROP-1: The Propulsion Subsystem shall be designed to operate through observatory commissioning, science operations, cruise operations and data downlink operations, for a total lifetime in orbit of 7 years.
- Thrusters:
  - PROP-72: The Propulsion Subsystem shall provide thrusters for the expected usage with a minimum steady-state specific impulse of 215 s.
  - PROP-73: The Propulsion Subsystem shall provide thrusters with a nominal thrust level of 4.4 N (1.0 lbf) at beginning of life.
  - PROP-74: The Propulsion Subsystem shall provide 12 thrusters, located per the Mechanical ICD and aligned within 1 degree (TBR) of the nominal direction specified in the Mechanical ICD.
- Propellant:
  - PROP-71: The Propulsion Subsystem shall size the propellant tank such that it provides sufficient capacity for 66.40 (TBR) kg of propellant and sufficient pressurant to ensure an End of Life minimum tank pressure above 80 (TBR) psi.

Propulsion Subsystem Driving Requirements

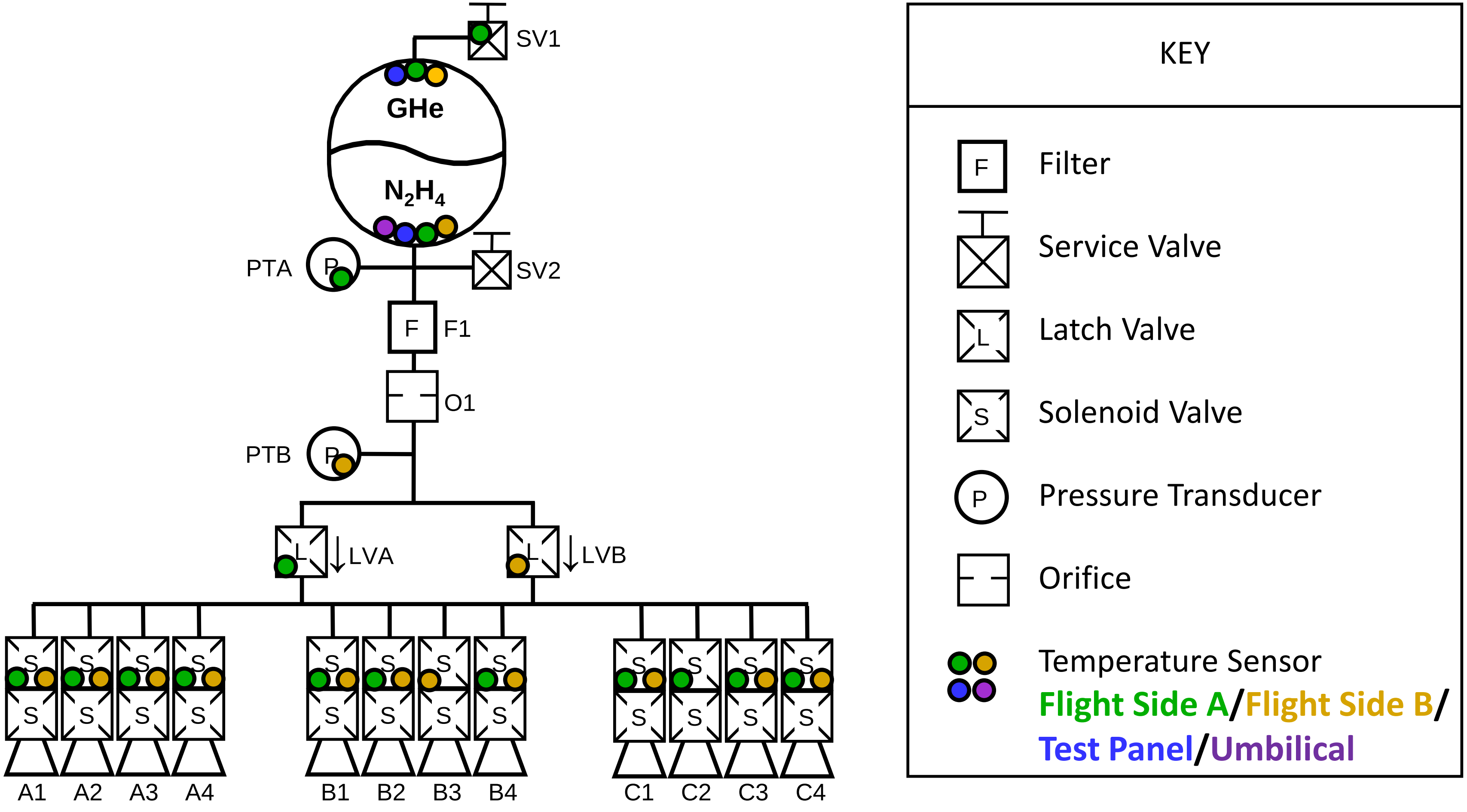
- Mass:
  - PROP-4: The Propulsion Subsystem shall not exceed not exceed **22.2 kg** (TBR) dry mass.
- Power:
  - PROP-21: The Propulsion Subsystem shall not exceed the power load not-to-exceed values (NTEs) of 55.8 W (TBR) during the launch correction phase and 19.4W (TBR) during the science phase over the bus voltage range specified in the SPP Environmental Design and Test Requirements Document. Power NTEs consist solely of thruster valve and catalyst bed heater loads.
- Launch Phase:
  - PROP-78: The Propulsion Subsystem shall load hydrazine to the upstream thruster valve seats during propellant loading.
  - PROP-7: The Propulsion Subsystem shall be capable of turning on catalyst bed heaters during launch phase.
- TCM Execution Error:
  - PROP-19: The Propulsion Subsystem shall baseline thrusters which do not exceed a thrust level of 11N.

Propulsion Subsystem Key Trades

- Thruster Sizing Trade
  - Evaluated commercial-off-the-shelf (COTS) thrusters ranging from 1.0 N (0.2 lbf) to 35 N (8 lbf).
  - Verified that baselined 4.4N (1.0 lbf)-class thrusters on Solar Probe Plus adequate to achieve all mission goals.
    - Eliminated thrusters under 4N due to excessive TCM 1 durations
    - Eliminated thrusters over 11N due to maneuver execution accuracy requirements.
  - Results documented in memorandum SEM-12-6-051.

- Pressurant Trade
  - Compared Nitrogen vs. Helium as candidate SPP propellant tank pressurants.
  - Nitrogen considered superior due to molecular size and specific heat ratio, but only a minor advantage due to negligible leakage over mission and no Prime sequence.
  - Instrument teams verified Helium acceptable.
  - Helium selected due to substantial mass savings of 0.7 kg.
  - Results documented in memorandum SEM-13-6-033.

Subsystem Schematic



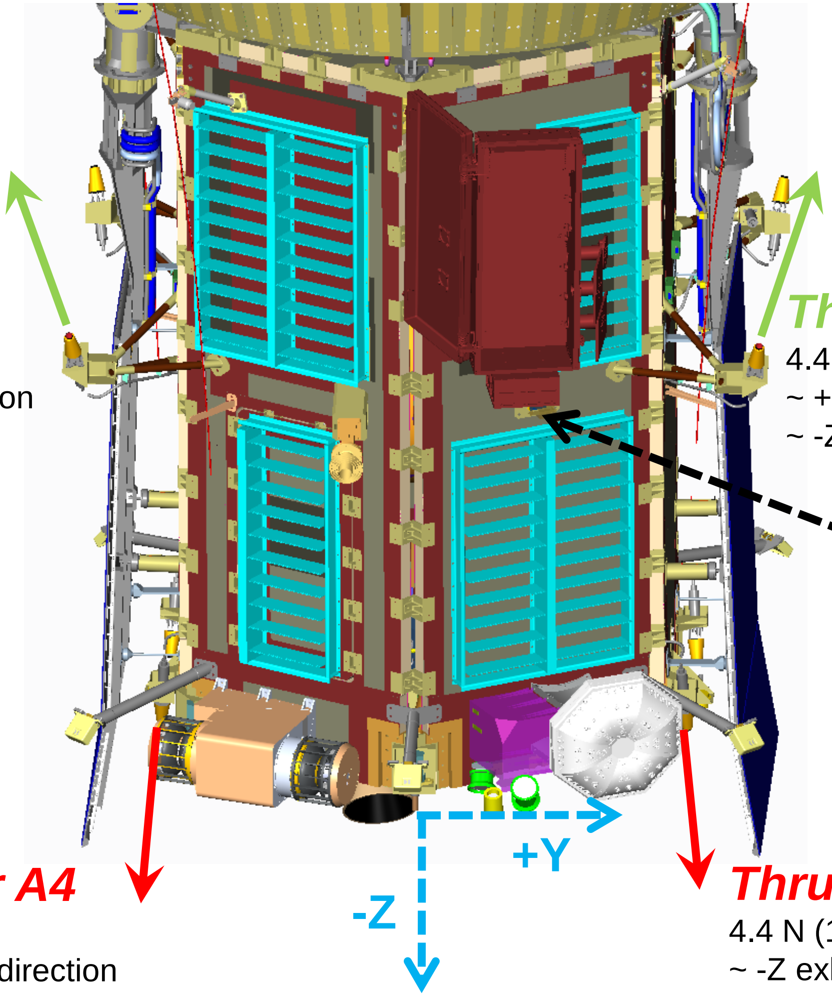
Twelve 4.4 N (1 lbf) Thrusters

- **26 line temp sensors, interior and exterior, not shown.**

Subsystem Configuration

- Subsystem procured from Aerojet-Rocketdyne and installed on an APL-furnished primary structure.
  - Subsystem PDR to be held at Aerojet-Rocketdyne in November 2014.
- Blowdown (4:1) monopropellant hydrazine propulsion system
  - Low-complexity, high-reliability design using mostly flight-heritage hardware
  - Twelve 4.4N (1.0 lbf) monopropellant thrusters
    - Meets mission requirements for propellant throughput, thruster cycles, and deep thermal cycles
    - Provides ΔV maneuvers, attitude adjustments, and reaction wheel desaturation
  - ATK-PSI spherical titanium propellant tank
    - Helium pressurant for mass reasons (Trade documented in APL Memorandum SEM-13-6-033)
    - AF-E-332 diaphragm
    - Modified mounting configuration (three midplane tabs vs. four)
  - All other subsystem components can be sourced from a variety of suppliers.
  - PDB functionality incorporated into Avionics/PDU/Harness.

Thruster Locations
+X (RAM) Side



Thruster C4
4.4 N (1lb_f)
~ +Z exhaust direction
~ -Z Force

Thruster C1
4.4 N (1lb_f)
~ +Z exhaust direction
~ -Z Force

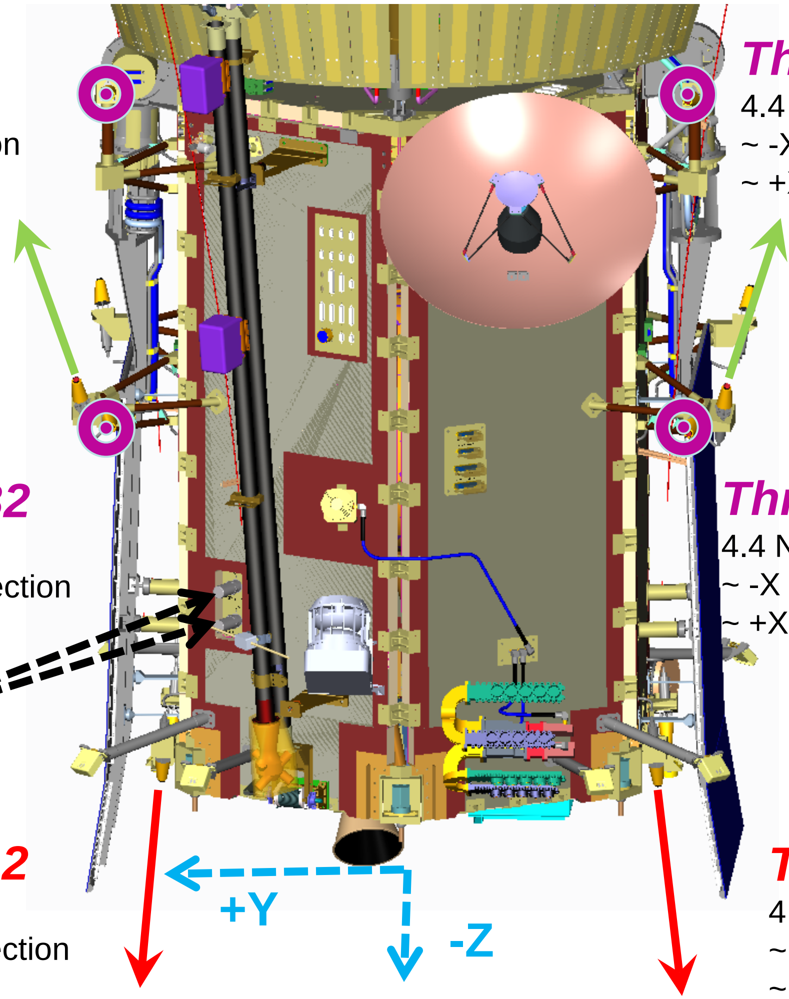
Propulsion arming plugs

Note: Arrows denote exhaust directions.

Thruster A4
4.4 N (1lb_f)
~ -Z exhaust direction
~ +Z Force

Thruster A1
4.4 N (1lb_f)
~ -Z exhaust direction
~ +Z Force

Thruster Locations –X (Anti-RAM) Side



Thruster B1
4.4 N (1lb$_f$)
~ -X exhaust direction
~ +X Force

Thruster B4
4.4 N (1lb$_f$)
~ -X exhaust direction
~ +X Force

Thruster C2
4.4 N (1lb$_f$)
~ +Z exhaust direction
~ -Z Force

Thruster C3
4.4 N (1lb$_f$)
~ +Z exhaust direction
~ -Z Force

Thruster B2
4.4 N (1lb$_f$)
~ -X exhaust direction
~ +X Force

Thruster B3
4.4 N (1lb$_f$)
~ -X exhaust direction
~ +X Force

Service Valves

Note: Arrows denote exhaust directions.

Thruster A2
4.4 N (1lb$_f$)
~ -Z exhaust direction
~ +Z Force

Thruster A3
4.4 N (1lb$_f$)
~ -Z exhaust direction
~ +Z Force

Propulsion Subsystem Notional Components

Component	**Manufacturer**	**Part Number**	**Heritage**
Thruster	Aerojet	MR-111C	MESSENGER, STEREO, New Horizons
Propellant Tank	ATK-PSI	80259-101	DSCS III
Fill/Drain Valve	Vacco	V1E10701-01	Van Allen Probes, STEREO, New Horizons
Latch Valve	Vacco	V1E10747-01	Van Allen Probes, STEREO, New Horizons
Pressure Transducer	Tavis	30001	GRAIL, MAVEN, MSL, Deep Impact
Filter	Vacco	F1D10767-07	Van Allen Probes, STEREO, New Horizons

- Components will be acceptance-tested by the manufacturer
- Subsystem-level leak and functional testing performed by subsystem supplier.

Propellant Budget

- Mission Design's ΔV budget is CBE with "Burn Penalty" using mean results from G&C simulations spanning the range of DV magnitudes and directions with thrusters pulsed for DV and attitude control and mean thruster cant angles as shown below, plus 8% unallocated margin on DV.
  - A thrusters canted 20º off +Z axis
  - B thrusters canted 10º off +X axis
  - C thrusters canted 30º off -Z axis
- Momentum dump propellant requirements provided by G&C based on results of Phase B simulations of momentum build up and dump execution for SPP.
- Propulsion propellant margin captured in maneuver calculation with minimum mission-average thruster I_{sp} = 215s. Residual propellant in tank and manifold = 1% total prop load. No additional propellant margin added by Propulsion.

Propellant Budget:

TCM-1 (Launch Correction)	59.98 m/s	18.65 kg
TCM-1 Burn Penalty	11.57 m/s	3.54 kg
8% Margin on TCM-1	5.72 m/s	1.74 kg
All other TCMs	64.32 m/s	19.26 kg
Burn Penalty on all other TCMs	36.01 m/s	10.53 kg
8% Margin on all other TCMs	8.03 m/s	2.32 kg
Wheel Momentum Dumps		7.00 kg
Residual Propellant		0.63 kg
Total Propellant Mass		63.68 kg
Total GHe Pressurant Mass		0.10 kg

Mass Budget

Item	Unit Mass [kg]	QTY	CBE Mass [kg]	Contingency	Total Mass [kg]
N2H4 Tank (ATK 80259)	6.36	1	6.36	4.3%	6.64
1 lbf Thruster	0.36	12	4.32	4.3%	4.51
Latch Valve	0.34	2	0.68	4.3%	0.71
Filter	0.16	1	0.16	4.3%	0.17
Service Valves	0.21	2	0.42	4.2%	0.43
Pressure Transducer	0.23	2	0.46	4.3%	0.48
Orifice	0.03	1	0.03	4.2%	0.03
Tubing / Fasteners / Tube Clamps / Etc.	3.94		3.94	4.3%	4.11
Thermal (TStats, Heaters, TSensors, Wire)	1.51		1.51	4.3%	1.57
Cabling (Wire, Harness, Supports)	3.40		3.40	4.3%	3.55
Total Component Dry Mass			21.28		22.19
Residual N2H4			0.63		0.63
GHe Pressurant			0.10		0.10
Total Propulsion System Dry Mass			**43.29**		**45.12**
Usable N2H4			**63.05**		**63.05**

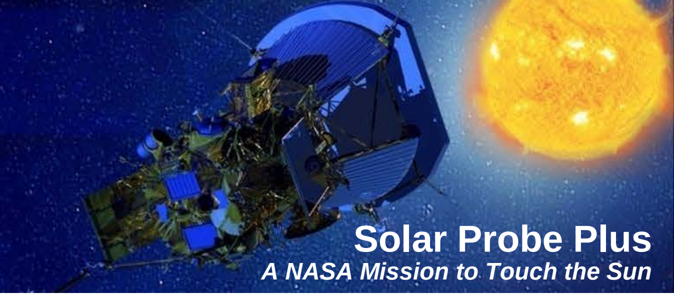
- All COTS component unit masses based on NTE values.
- Tubing/thermal/cabling masses based on Van Allen Probes actuals.
- Does not include tank/thruster brackets, plume shields, or MLI.

Power Budget

Item	Number of Components	Power per Element (W)	Number of Elements per Component	Power per Component (W)
1 lbf Thruster Valve	12	4.13	2	8.26
1 lbf Thruster Valve Heater	12	1.54	1	1.54
1 lbf Thruster Cat Bed Heater	12	1.93	2	3.86
Latch Valve	2			18.00
Pressure Transducer	2			0.90

- Component power at 28 VDC
- Valve heater power notional
- Latch Valve only powered for 100 ms.
- Only 1 catbed heater per thruster powered at a time.
- Does not include line/tank/component/valve heaters.

Propulsion Subsystem Key Analyses



- Blowdown Performance, MR-111C Thrusters
  - Nominal mission (63.05 kg usable N_2H_4, 20ºC)
    - BOL Pressure = 340 psia, Isp = 229.3 s, Thrust = 4.70 N
    - EOL Pressure = 100.4 psia, Isp = 221.2 s, Thrust = 1.76 N
  - Full Tank (66.40 kg usable N_2H_4, 20ºC)
    - BOL Pressure = 340 psia, Isp = 229.3 s, Thrust = 4.70 N
    - EOL Pressure = 87 psia, Isp = 219.5 s, Thrust = 1.57 N
- Plume Impingement
  - Aerojet-Rocketdyne contracted to provide updated plume model for MR-111C engine, updating APL’s STEREO-era model.
  - APL analyses determined spacecraft keep-out zones.
  - Aerojet-Rocketdyne will provide additional plume report, detailed later, as part of subcontract.
- Orifice sizing
  - Despite propellant loading to thruster valves, orifice must be sized to prevent adiabatic decomposition under worst-case conditions – opening latch valve at MEOP – by keeping surge pressure under 1000 psi.
  - For current manifold design, orifice should be no larger than 1.0 mm (0.039”), corresponding to a worst-case surge pressure of 959 psi.
- Filter sizing to ensure that baselined component has sufficient capacity.

Requirements Verification Plan: Sample Compliance Matrix

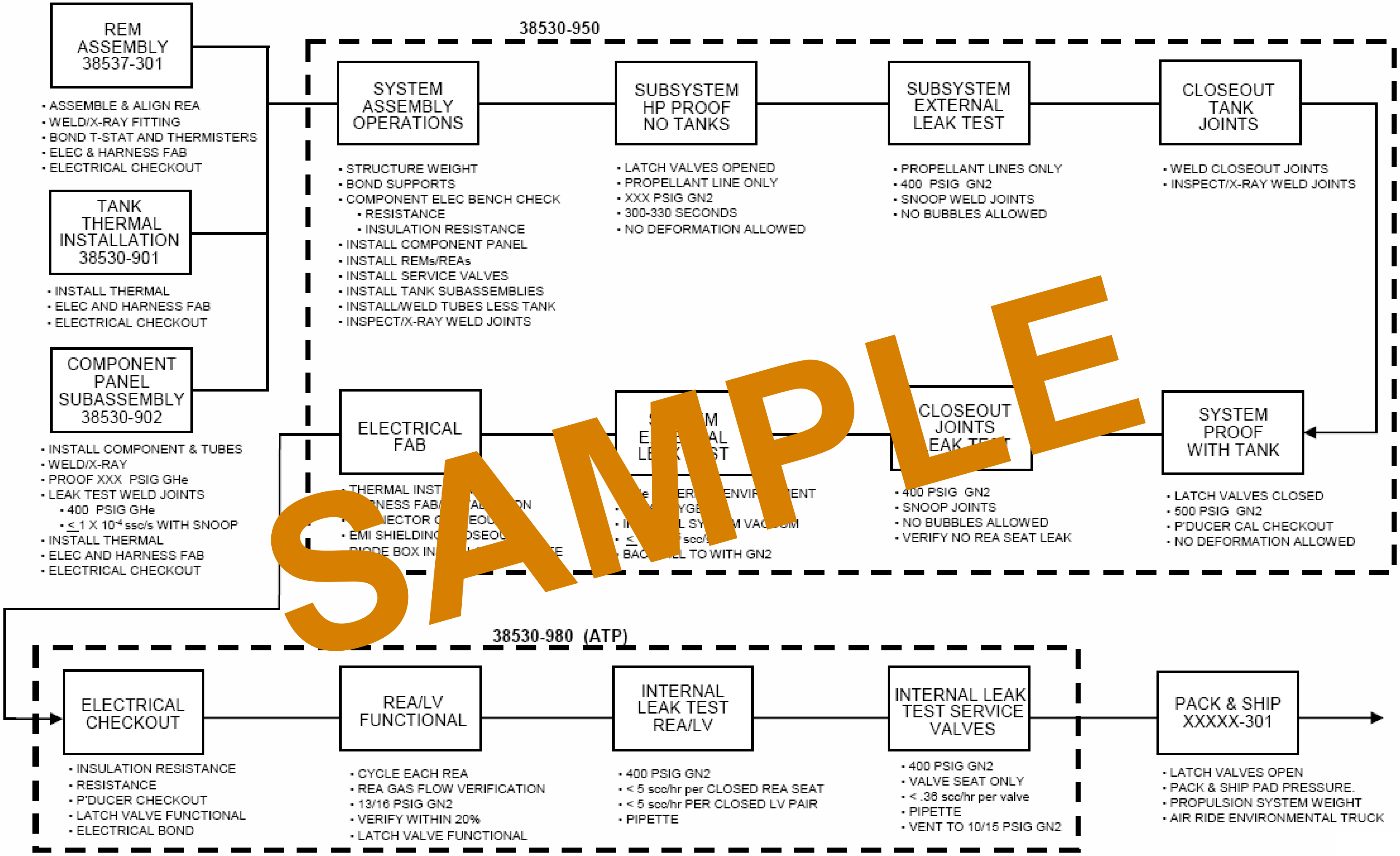
Solar Probe Plus

A NASA Mission to Touch the Sun

- **Matrices will be created for all procurement documents (SOW, Spec., PAIP, EMECP, ETDRD, M&P, etc.)**

Table 2	**RBSP Propulsion Sybsystem Performance Specification Compliance Matrix 7417-9452 Rev 1: 6/25/08**						**Supplier Flow Down Requirements**					
Para.	**Paragraph Title**	**How Verified** **QT = Qualification Testing** **QI = Qualification Inspection** **AT = Acceptance Testing** **AI = Acceptance Inspection**	**Compliance**	**Comments**	**Customer**	**System**	**Diode Box**	**Tank**	**Latch Valve**	**Service Valve**	**PDucer**	**Filter**
3.0	TECHNICAL REQUIREMENTS	N/A	N/A									
3.1	Propulsion Subsystem Functions	N/A	N/A									
3.1.1	Precession Maneuvers	N/A	N/A									
3.1.2	Delta–V Maneuvers	N/A	N/A									
3.1.3	Spin Rate Adjustments	N/A	N/A									
3.2	Design Requirements	N/A	N/A									
3.2.1	System–Level Requirements	Analysis, AI	Yes									
3.2.1.1	Operating Media	N/A	N/A									
3.2.1.1.1	Propellant	Analysis	Yes									
3.2.1.1.2	Pressurant	Analysis	Yes									
3.2.1.1.3	Fluids and Solvents	Analysis	Yes									
3.2.1.2	Nominal Operating Temperature and Pressure	Analysis, QT	Yes									
3.2.1.3	Maximum Expected Operating Pressure	Analysis, QT, AT	Yes									
3.2.1.4	Maximum Expected Operating Temperature	Analysis, QT	[illegible]									
3.2.1.5	Proof Pressure	[illegible]	Yes									
3.2.1.6	Design Burst Pressure	Analysis, [illegible]	Yes									
3.2.1.7	Subsystem Leak Rate	Analysis, QT, AT	Yes									
3.2.1.8	Construction	Analysis	Yes									
3.2.2	Life	[illegible]	Yes									
3.2.3	Propellant/Pressurant Tank	QT, AI	Yes									
3.2.3.1	Capacity	Analysis, QT	Yes									
3.2.3.2	Spacecraft Tubing Interfaces	Analysis	Yes									
3.2.3.3	Negative Pressure	QT, AT	Yes									
3.2.3.4	External Leakage	QT, AT	Yes									
3.2.3.5	Energy Dissipation/Slosh Characteristics	N/A	Yes									
3.2.3.6	Instrumentation	AI	Yes									
3.2.3.7	Tank Pressure and Load Cycles	Analysis	Yes									
3.2.4	Thrusters	AI	Yes									

Requirements Verification: Sample Manufacturing and Test Flow Plan



REM ASSEMBLY 38537-301
- ASSEMBLE & ALIGN REA
- WELD/X-RAY FITTING
- BOND T-STAT AND THERMISTERS
- ELEC & HARNESS FAB
- ELECTRICAL CHECKOUT

TANK THERMAL INSTALLATION 38530-901
- INSTALL THERMAL
- ELEC AND HARNESS FAB
- ELECTRICAL CHECKOUT

COMPONENT PANEL SUBASSEMBLY 38530-902
- INSTALL COMPONENT & TUBES
- WELD/X-RAY
- PROOF XXX PSIG GHe
- LEAK TEST WELD JOINTS
  - 400 PSIG GHe
  - $\leq$ 1 X 10^{-4} ssc/s WITH SNOOP
- INSTALL THERMAL
- ELEC AND HARNESS FAB
- ELECTRICAL CHECKOUT

38530-950

SYSTEM ASSEMBLY OPERATIONS
- STRUCTURE WEIGHT
- BOND SUPPORTS
- COMPONENT ELEC BENCH CHECK
  - RESISTANCE
  - INSULATION RESISTANCE
- INSTALL COMPONENT PANEL
- INSTALL REMs/REAs
- INSTALL SERVICE VALVES
- INSTALL TANK SUBASSEMBLIES
- INSTALL/WELD TUBES LESS TANK
- INSPECT/X-RAY WELD JOINTS

SUBSYSTEM HP PROOF NO TANKS
- LATCH VALVES OPENED
- PROPELLANT LINE ONLY
- XXX PSIG GN2
- 300-330 SECONDS
- NO DEFORMATION ALLOWED

SUBSYSTEM EXTERNAL LEAK TEST
- PROPELLANT LINES ONLY
- 400 PSIG GN2
- SNOOP WELD JOINTS
- NO BUBBLES ALLOWED

CLOSEOUT TANK JOINTS
- WELD CLOSEOUT JOINTS
- INSPECT/X-RAY WELD JOINTS

SYSTEM PROOF WITH TANK
- LATCH VALVES CLOSED
- 500 PSIG GN2
- P'DUCER CAL CHECKOUT
- NO DEFORMATION ALLOWED

CLOSEOUT JOINTS [illegible]EAK TE[illegible]T
- 400 PSIG GN2
- SNOOP JOINTS
- NO BUBBLES ALLOWED
- VERIFY NO REA SEAT LEAK

S[illegible]M E[illegible]AL LE[illegible]ST
- [illegible]e[illegible]ER[illegible]ENVIR[illegible]ENT
- [illegible]YGE[illegible]
- I[illegible]L SY[illegible]M VAC[illegible]UM
- $\leq$ [illegible] scc/[illegible]
- BAC[illegible]LL TO WITH GN2

ELECTRICAL FAB
- THERMAL INST[illegible]
- [illegible]NESS FAB[illegible]AL[illegible]ON
- [illegible]NECTOR C[illegible]EOU[illegible]
- EMI SHIELDIN[illegible]OSEOU[illegible]
- DIODE BOX IN[illegible]E

38530-980 (ATP)

ELECTRICAL CHECKOUT
- INSULATION RESISTANCE
- RESISTANCE
- P'DUCER CHECKOUT
- LATCH VALVE FUNCTIONAL
- ELECTRICAL BOND

REA/LV FUNCTIONAL
- CYCLE EACH REA
- REA GAS FLOW VERIFICATION
- 13/16 PSIG GN2
- VERIFY WITHIN 20%
- LATCH VALVE FUNCTIONAL

INTERNAL LEAK TEST REA/LV
- 400 PSIG GN2
- < 5 scc/hr per CLOSED REA SEAT
- < 5 scc/hr PER CLOSED LV PAIR
- PIPETTE

INTERNAL LEAK TEST SERVICE VALVES
- 400 PSIG GN2
- VALVE SEAT ONLY
- < .36 scc/hr per valve
- PIPETTE
- VENT TO 10/15 PSIG GN2

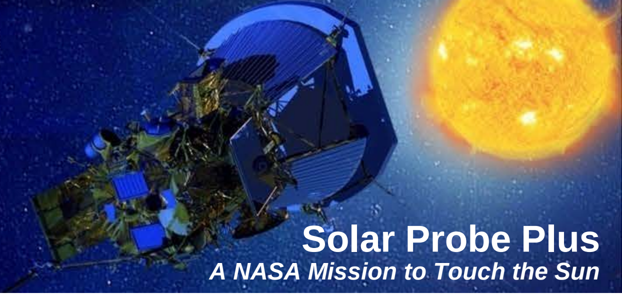
PACK & SHIP XXXXX-301
- LATCH VALVES OPEN
- PACK & SHIP PAD PRESSURE.
- PROPULSION SYSTEM WEIGHT
- AIR RIDE ENVIRONMENTAL TRUCK

Propulsion Subsystem Phase B Reviews Held

- Pre-PDR Requirements Peer Review
    - Held 27 September 2013
    - APL Reviewers: C. Engelbrecht, D. Eng
    - GSFC Reviewer: E. Cardiff (Chair)
    - 9 Action Items generated, all closed.
    - Action Items Closed Memo SEM-13-6-062 released 13 Nov 2013.

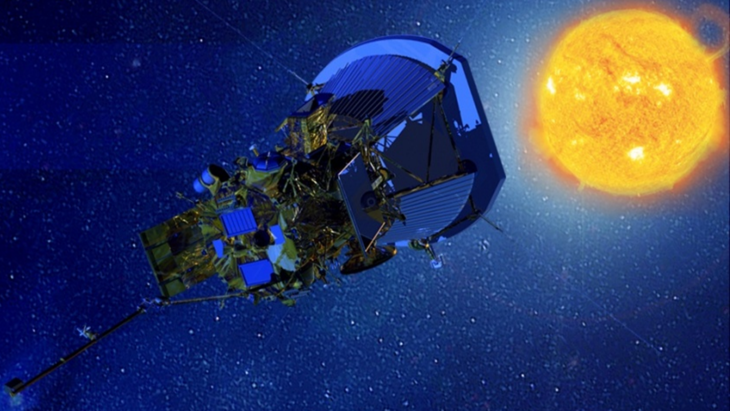
Propulsion Subsystem Phase C Work

- Get subsystem supplier (Aerojet-Rocketdyne) on contract.
- Supplier reviews: Kick-off, Peer, PDR, CDR, Consent-to-Ship
- Refine mechanical layout
  - Tubing runs
  - Manifold and harness standoff design and placement
  - Alignment tolerance stack-up
- Structural, thermal, plume, and flow Analyses
  - Subsystem-level models
  - Negotiation of thermal zones, locations of thermostats and temperature sensors
  - Design of magnetically-cancelling patch heaters
  - Plume: Composition, number density, heat flux, impingement force
  - Flow: Water hammer, surge pressure, component pressure drop
- Tank delta-qualification for new mounting configuration
- Component evaluation, selection, procurement, and acceptance testing
- Build up subsystem (manifold, components, harness, thermal) on APL-supplied bus
- Subsystem-level acceptance testing
- Primary deliverables from supplier:
  - Propulsion-populated spacecraft bus for thermal balance testing prior to I&T start
  - End-Item Data Package



Propulsion Subsystem Conclusions

- The Propulsion Subsystem has defined requirements, developed a detailed design, and selected a subsystem supplier (Aerojet-Rocketdyne) in a competitive procurement.
- Propulsion is ready to get the supplier on contract and proceed into Phase C.

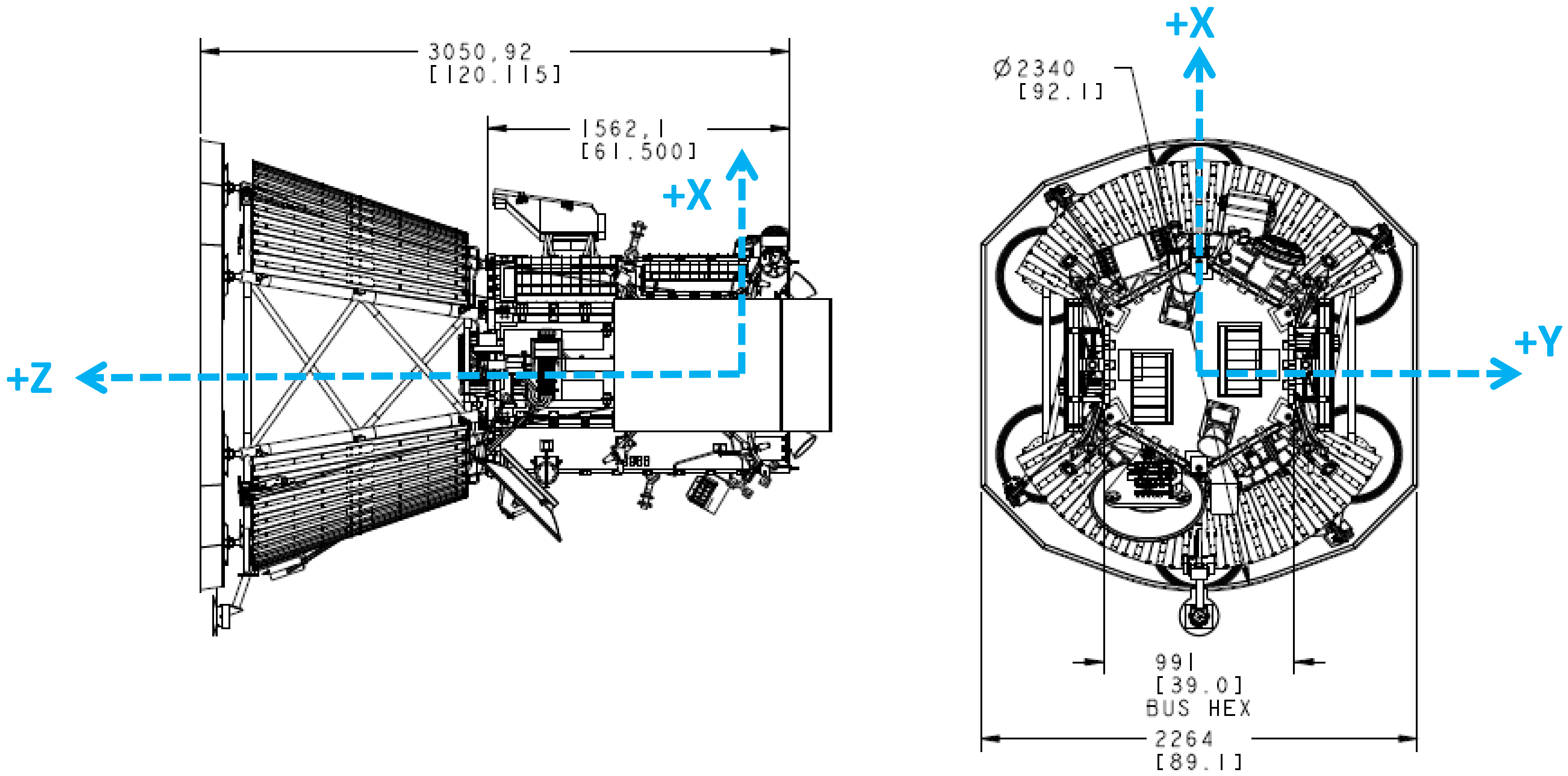


Backup Slides

Documentation Status

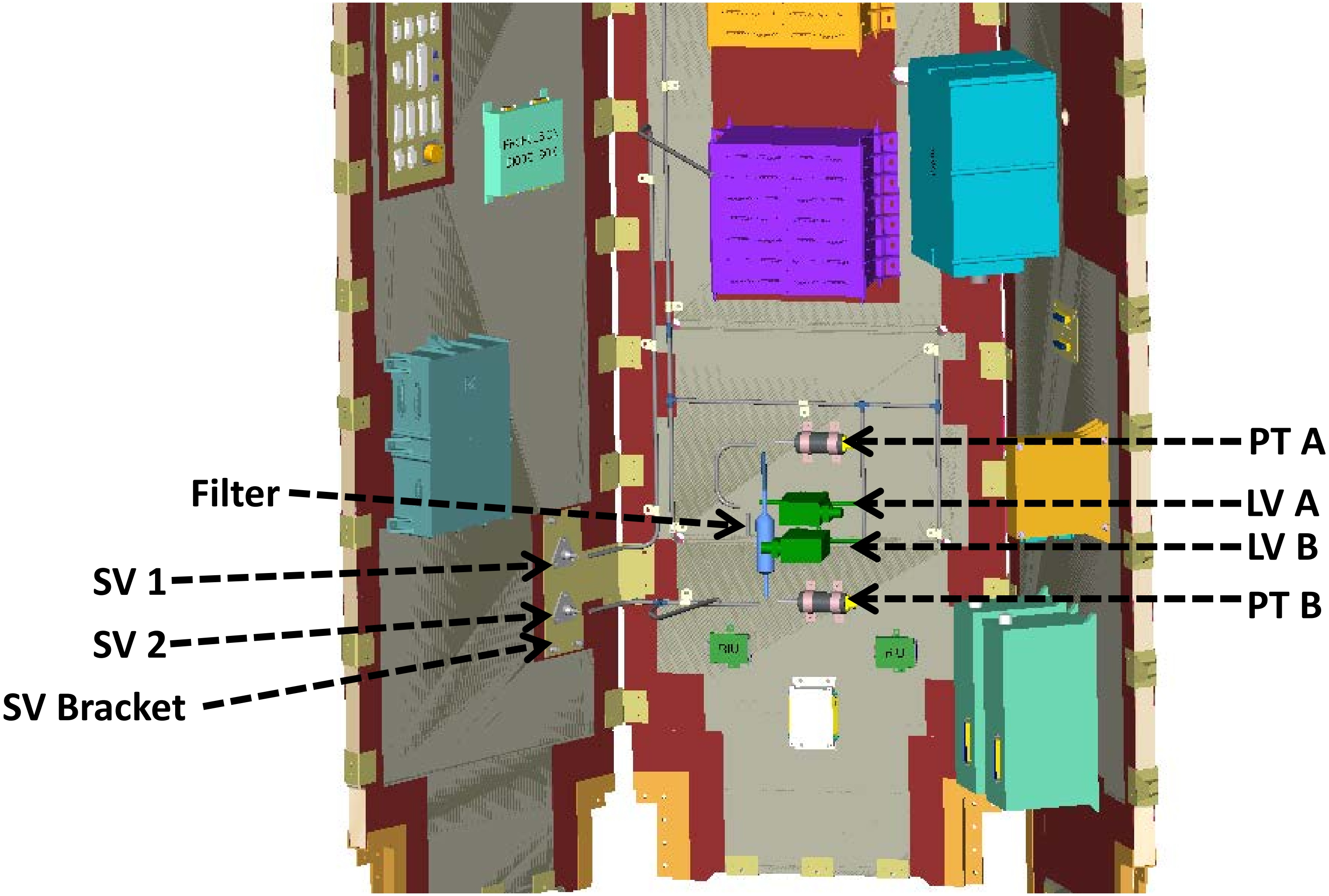
- PLM Documentation
  - Released:
    - 7434-0600 – SPP Propulsion Subsystem Requirements Document
    - 7434-0601 – SPP Propulsion Subsystem Performance Specification
    - 7434-0602 – SPP Propulsion Subsystem Statement of Work
  - TBR:
    - 7434-0603 – SPP Propulsion Subsystem to Observatory ICD
      - Released after delivery of final ICDs from subsystem supplier in Phase C
    - 7434-0604 – SPP Propulsion Subsystem Electrical ICD
      - To be released prior to Propulsion Subsystem Kickoff Meeting at Aerojet-Rocketdyne
    - SPP Propulsion Subsystem Users Manual
      - Will be released during Phase C/D
- Relevant Documents
  - Released:
    - SEM-11-6-046 – SPP Propulsion Subsystem Concept Peer Review Memorandum
    - SEM-12-6-051 – SPP Thruster Sizing Memorandum
    - SEM-13-6-033 – SPP Propulsion Subsystem Pressurant Selection Memorandum
    - SEM-13-6-057 – SPP Propulsion Subsystem Procurement Evaluation Criteria Memorandum
    - SEM-13-6-058 – SPP Propulsion Subsystem Supplier Selection Memorandum
    - SEM-13-6-060 – SPP Propulsion Pre-PDR Requirements Peer Review Minutes Memo
    - SEM-13-6-062 – SPP Propulsion Pre-PDR Requirements Peer Review Action Items Closed Memo
  - Presented:
    - 2013.01.03 – SPP Pressure Transducer Trade Study (block redundant vs. cross-strapped)

Spacecraft Dimensions

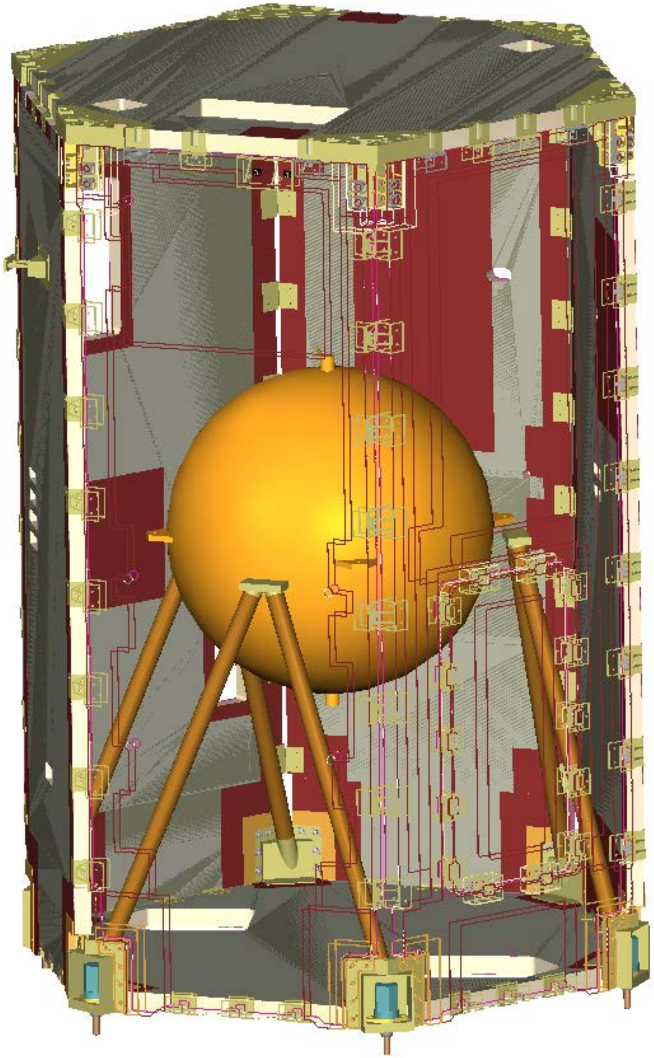


- **Propulsion-populated structure envelope: 61.5”x39.0”x39.0”**

Component Locations
+Y Interior (Fixed Panel)



Propellant Tank and Support Bracketry



SPP Propulsion Electrical Interfaces

Solar Probe Plus

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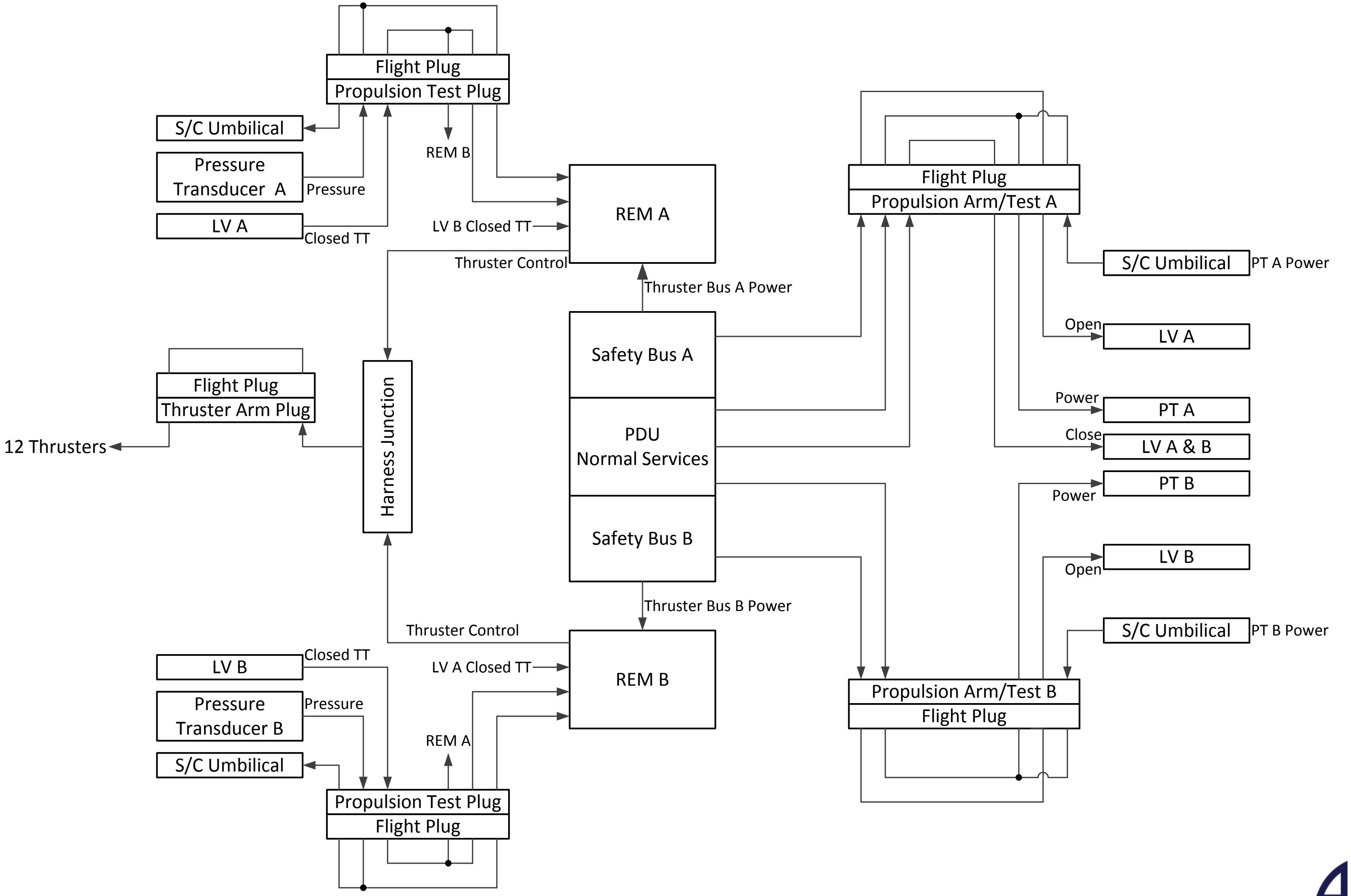
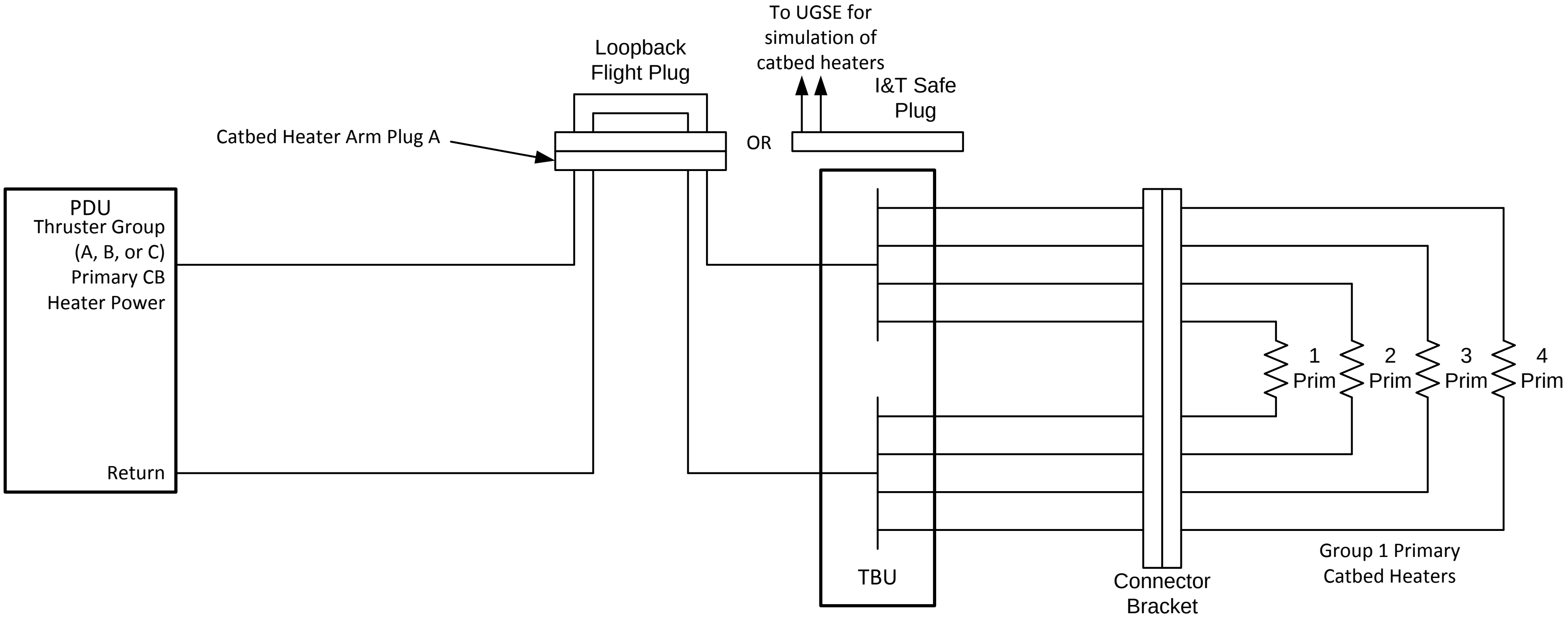


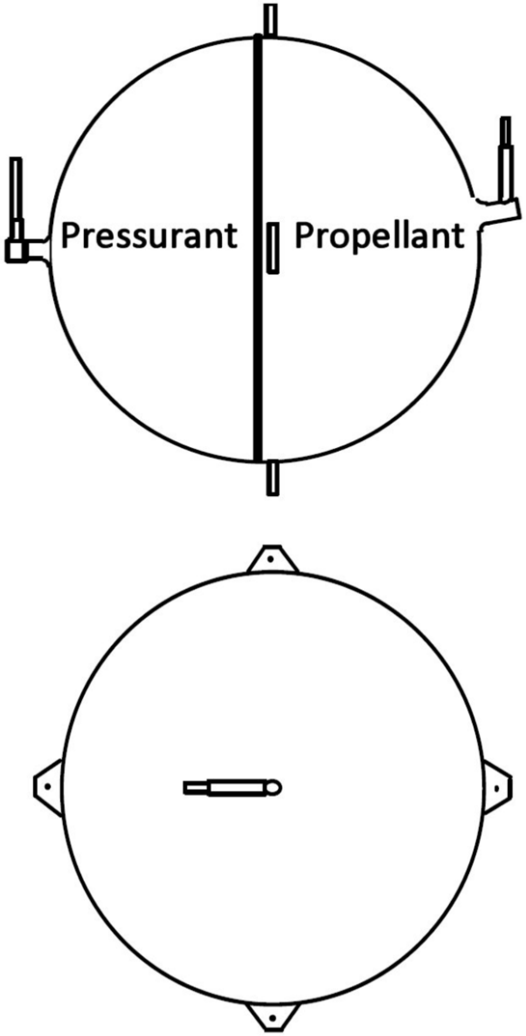
SPP Propulsion Catalyst Bed Heater Electrical Interface



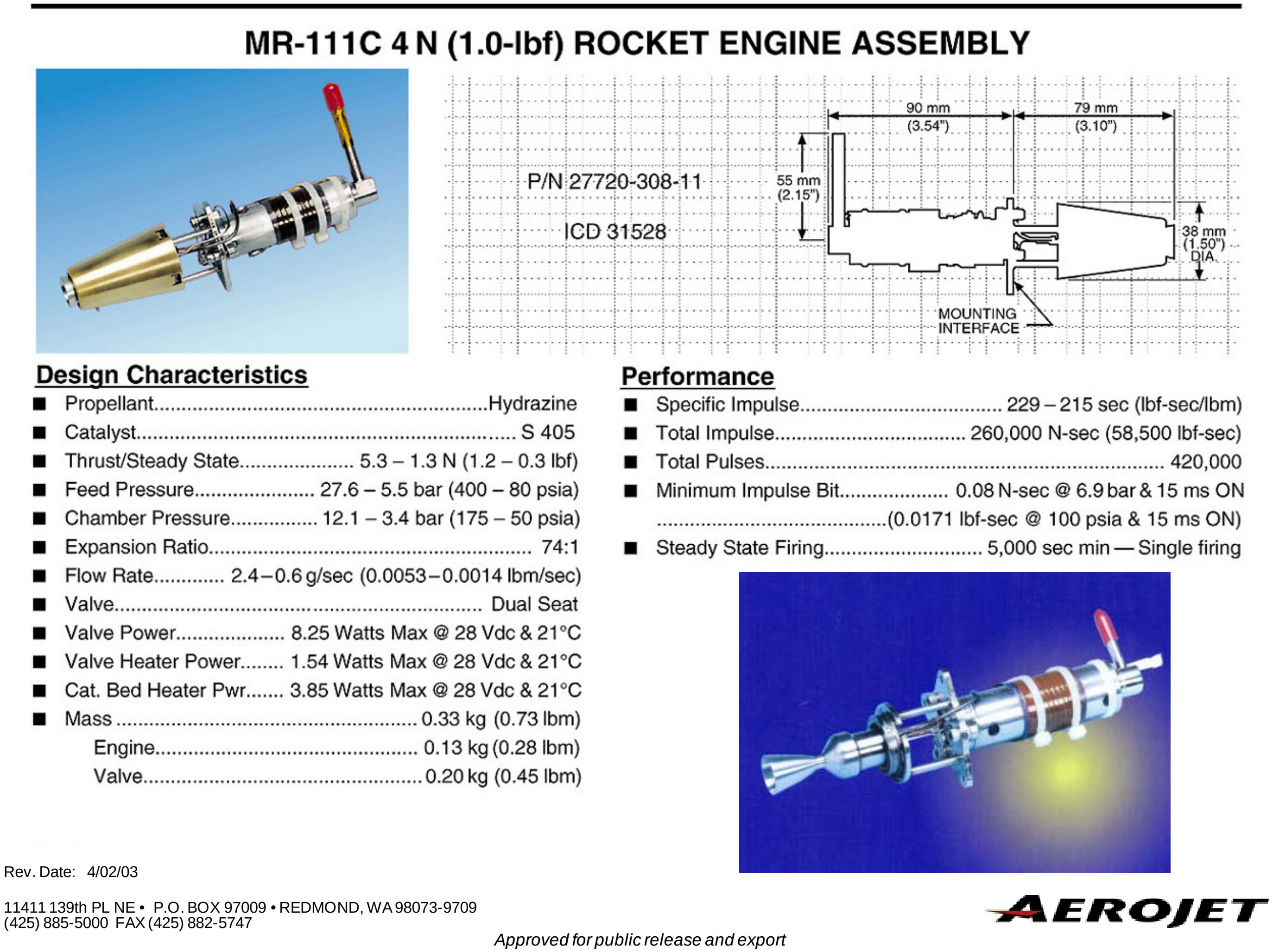
- CB heaters wired in parallel in six groups of four thrusters each (three primary, three redundant). Each group has dedicated service.
- Additional thermal electrical interfaces (temperature telemetry and tank/line/valve heaters schematic TBD.

Propellant Tank

- Baseline is a 22.14” ID spherical COTS titanium tank with an AF-E-332 diaphragm.
  - ATK-PSI P/N 80259-101
  - DSCS III Heritage
  - Modified mounting configuration (three midplane tabs vs. four)
  - Silica contamination of thruster plume due to diaphragm not a concern for SPP instruments (per Rob Decker 2011.09.02 email)
- Tank Volume = 91 liters (5555 in^3)
- Propellant Capacity = 68 liters (4167 in^3)
- Tank Mass = 6.36 kg
- MEOP = 375 psig
- Proof = 650 psig
- Burst = 750 psig
- Vacuum rated



4.4N (1.0 lbf) Thruster: Aerojet-Rocketdyne MR-111C



MR-111C 4 N (1.0-lbf) ROCKET ENGINE ASSEMBLY

P/N 27720-308-11

ICD 31528

Design Characteristics

- Propellant.......................Hydrazine
- Catalyst.......................S 405
- Thrust/Steady State.................... 5.3 – 1.3 N (1.2 – 0.3 lbf)
- Feed Pressure..................... 27.6 – 5.5 bar (400 – 80 psia)
- Chamber Pressure............... 12.1 – 3.4 bar (175 – 50 psia)
- Expansion Ratio....................... 74:1
- Flow Rate............. 2.4–0.6 g/sec (0.0053–0.0014 lbm/sec)
- Valve....................... Dual Seat
- Valve Power.................... 8.25 Watts Max @ 28 Vdc & 21°C
- Valve Heater Power........ 1.54 Watts Max @ 28 Vdc & 21°C
- Cat. Bed Heater Pwr....... 3.85 Watts Max @ 28 Vdc & 21°C
- Mass .... 0.33 kg (0.73 lbm)
  - Engine....................... 0.13 kg (0.28 lbm)
  - Valve....................... 0.20 kg (0.45 lbm)

Performance

- Specific Impulse.................... 229 – 215 sec (lbf-sec/lbm)
- Total Impulse.................... 260,000 N-sec (58,500 lbf-sec)
- Total Pulses....................... 420,000
- Minimum Impulse Bit.................... 0.08 N-sec @ 6.9 bar & 15 ms ON
  ....(0.0171 lbf-sec @ 100 psia & 15 ms ON)
- Steady State Firing.................... 5,000 sec min — Single firing

Rev. Date: 4/02/03

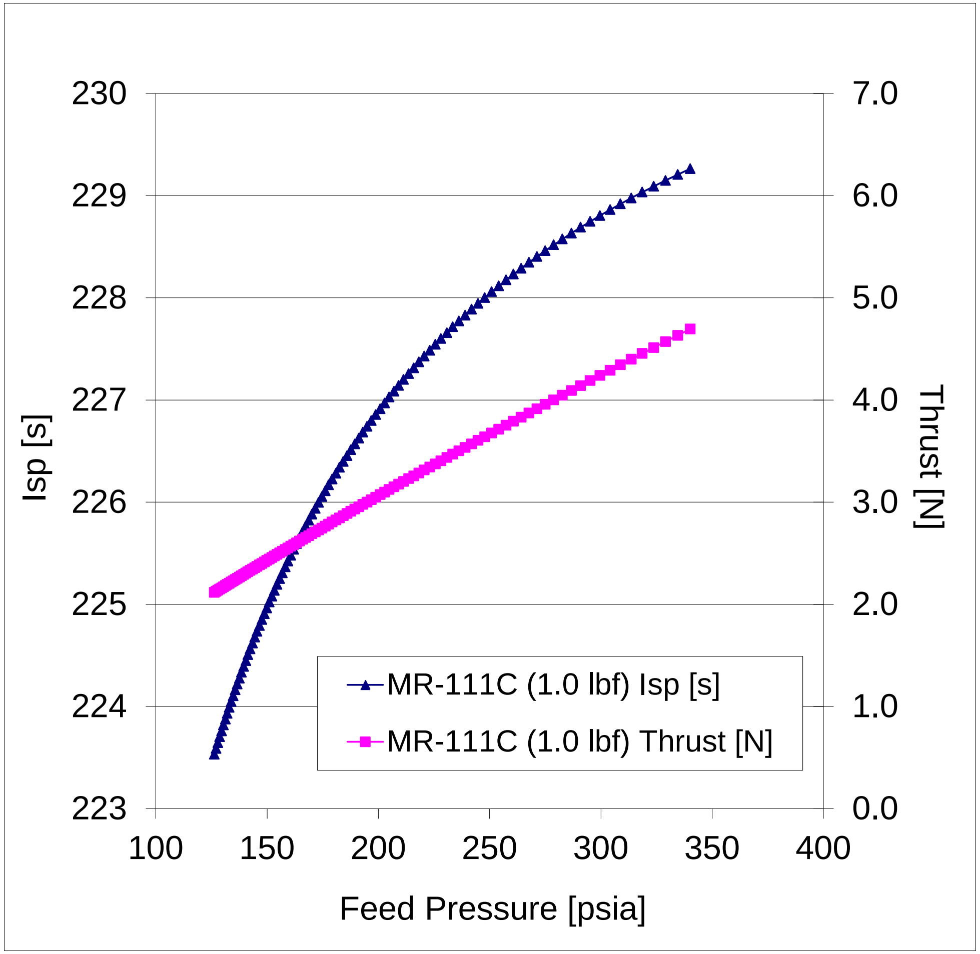
11411 139th PL NE • P.O. BOX 97009 • REDMOND, WA 98073-9709
(425) 885-5000 FAX (425) 882-5747

Approved for public release and export

- **APL Heritage: MESSENGER, STEREO, New Horizons**

MR-111C Blowdown Profile

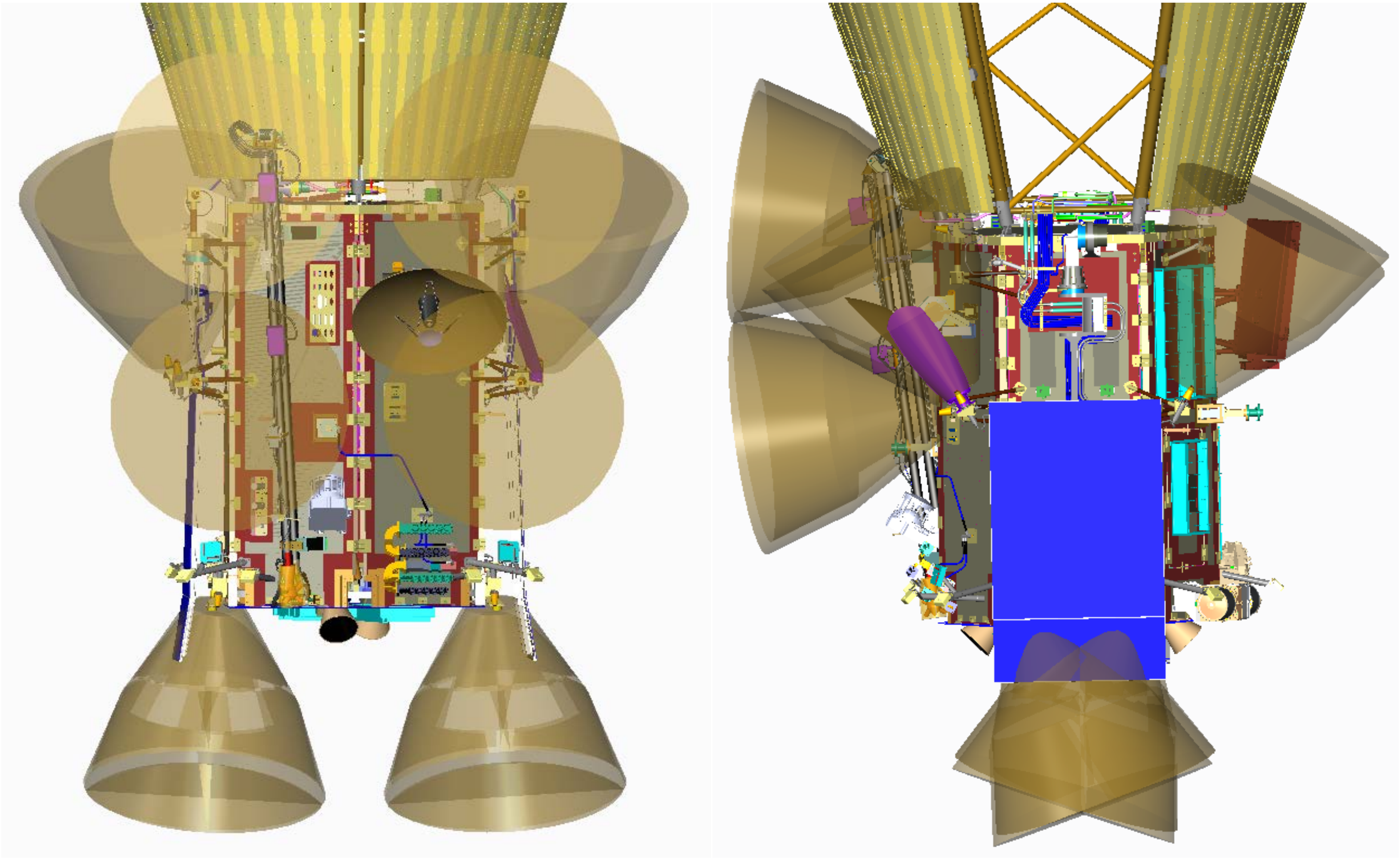
- **Blowdown profile over mission**
- **T = 20ºC**
- **BOL**
  - **Pressure = 340 psia**
  - **Isp = 229.3 s**
  - **Thrust = 4.70 N**
- **EOL**
  - **Pressure = 100.4 psia**
  - **Isp = 221.2 s**
  - **Thrust = 1.76 N**
- **Mission-Average Isp = 225.2 s**
- **MR-111C Minimum Mission-Average Isp = 216.9 s**



MR-111C Plume Analysis

- **Plume Analysis will be performed by supplier as part of Propulsion Subsystem procurement.**
- **Additional plume studies will be done by APL analysts.**
- **Analysis will include at spacecraft surfaces of interest:**
  - **Number Density**
  - **Density**
  - **Temperature**
  - **Pressure**
  - **Velocity Field**
  - **Species Concentrations**
  - **Impingement Force**
  - **Heat Flux**

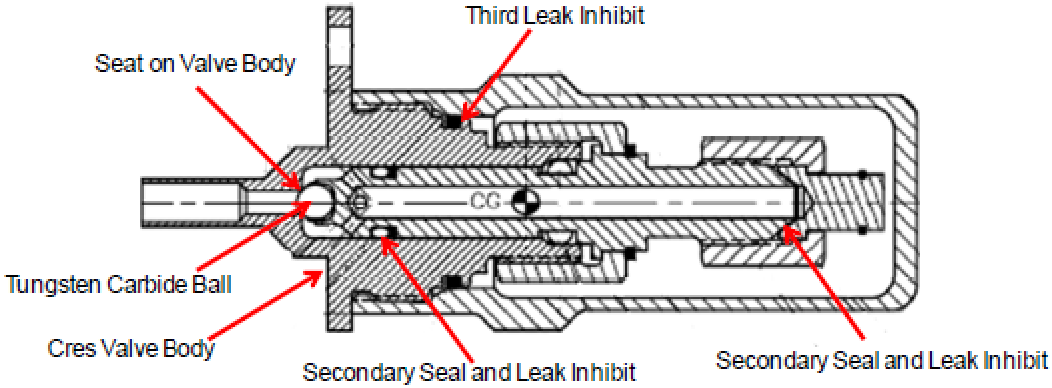
Thruster Plumes



- Effect of plume impact on HGA to be evaluated in design of protective shield.

Candidate Service Valve

- Vacco P/N V1E10701-01
  - **STEREO, New Horizons, Van Allen Probes Heritage**
  - No additional qual testing required
  - 1/4” Diameter CRES Tube For Integration
  - 1/4” Threaded Connection On Liquid Side, P/N V1E10701-01
  - 3-Seat Seal Design Configuration
  - Performance Characteristics
    - MEOP 500 PSI All Three Seats
    - Proof 1750 PSI On Primary & Secondary Seats
    - Proof 750 PSI On Third Seat (Cap)
    - Burst Pressure 2000 PSI All Three Seats
    - Weight < 0.46 Lb
    - 0.15 Lb/sec Water @ 400 PSIG Inlet, < 16 PSID



Candidate Latch Valve

- Manufacturer: VACCO (South El Monte, CA)
- Part Number: V1E10747-01
- Material: All-welded titanium construction and incorporates a Teflon seal
- **New Horizons, STEREO, Van Allen Probes Heritage**
- No additional qualification testing required.

PORTS:	0.250/0.254 IN. DIA X 0.022/0.025 IN. WALL	RELIEF PRESSURE:	50 MIN TO 200 MAX PSID
OPERATING PRESSURE:	25 – 450 PSIG	WEIGHT:	0.75 LBM (MAX)
DESIGN PRESSURE:	600 PSIG	CYCLE LIFE:	20,000 CYCLES (MIN)
PROOF PRESSURE	1000 PSIG	RESPONSE:	
BURST PRESSURE:	2400 PSIG (MIN)	OPENING:	50 ms (MAX) @ 450 PSID & 20 VDC (MIN)
MEDIA:	GHe, ANHYDROUS HYDRAZINE	OPENING:	50 ms (MAX) @ 600 PSID & 24 VDC (MIN)
FLOW RATE:	0.025 LB/SEC H2O	CLOSING:	50 ms (MAX) @ 0 PSID & 20 VDC (MIN)
PRESSURE DROP:	5.0 PSID MAX @ RATED FLOW	PULSE DURATION:	1 SEC (MAX)
LEAKAGE:		PULL-IN VOLTAGE	20 – 50 VDC
EXTERNAL	1.0E-06 SCC/SEC GHe @ 900 PSIG INLET (MAX)	DIELECTRIC STRENGTH:	500 VAC RMS @ 60 HZ FOR 60 SEC @ 0.5 mA
INTERNAL:	5.0 SCC/HR GHe @ 25-450 PSID (MAX)	INSULATION RESISTANCE:	1000 MΩ @ 500 ± 25 VDC FOR 60 SEC
INLET FILTER RATING:	40 MICRONS ABS	COIL RESISTANCE:	62 Ω – 66.8 Ω @ +68°F
TEMPERATURE:		INDUCTANCE:	300 mH (MAX) @ 1000 Hz
OPERATING	+30°F TO +160°F	MINIMUM OPERATING MARGIN:	15% AT 20 VDC, 450 PSID, AMBIENT TEMP
NON-OPERATING:	-65°F TO +160°F	CLEANLINESS	MIL-STD-1246, LEVEL 100

Candidate Filter

- Manufacturer: VACCO (South El Monte, CA)
- Part Number: F0D10635
- **STEREO, New Horizons, Van Allen Probes Heritage**
- We will waive the acceptance vibration test requirement. (This is standard.)
- Basic Design and Operation:
  - The filter consists of chemically etched titanium discs that are stacked, compressed, and retained by an element tube and welded retaining nut
  - This construction forms a semi-rigid cylinder
  - Material: Stainless Steel and Titanium

END CONNECTIONS:	0.25 IN. TUBE X 0.018/0.022 IN. WALL	**FLOW RATE**	0.005 LB/SEC HYDRAZINE (0.036 GPM WATER)
MEOP:	420 PSIG	**PRESSURE DIFFERENTIAL, CLEAN:**	1.0 PSID (MAX) @ RATED FLOW
PROOF PRESSURE:	1000 PSIG	**EXTERNAL LEAKAGE:**	1.0E-07 SCC/SEC GHe @ 420 PSIG
BURST PRESSURE:	1680 PSIG	**FILTRATION RATING:**	10 MICRON ABS
WORKING TEMPERATURE:	+10°F TO +170°F	**DIRT LOAD CAPACITY**	325 mg AC COARSE DUST
MEDIA:	HYDRAZINE		

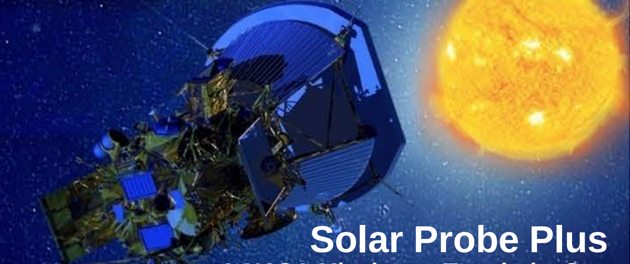
Candidate Pressure Transducer

- Tavis P/N 30001
  - **GRAIL, MAVEN, MSL heritage**
  - Aerojet-Rocketdyne P/N 40293
  - No additional qual testing required

General	
Pressure Range	30 psia to 6000 psia
Proof Pressure	>150% FSO
Burst Pressure	>>200% FSO
Sensor Type	Variable Reluctance
Weight	255 gm Max
Wetted Materials	304L/321 CRES
	Inconel 718
Construction	Electron Beam Welded Gage
	Secondary Barrier
Fittings / Ports	1/4 Tube Stub
	0.035 Wall
Electrical	
Input Voltage	24 - 32 VDC
Output Signal	0.0 - 5.0 VDC
Power	7 mA Nominal
Electrical Interface	MSFC 40M39569 (10-6)Connector
Reverse Polarity Protection	Yes
Isolation	>100 MΩ @ 50 VDC
Output Impedance	<1000 Ω

Environmental	
EMI	MIL-STD-461C & MIL-STD-462:CE01, CE02, CE03, CE04, RE02, CS01, CS02, CS06, RS02, RS03, Transients, Ripple
Compensated Temps	-65 ºF to 200 ºF
Vibration	15 grms
App Media	MON-3
	N_2H_4
	N_2O_4
Performance	
Static Error Band	±0.5% FSO
Thermal Error	±0.01%/ºF Max Average
Total Error Band (TEB)	±0.5" H_2O @ 10" H_2O
	±1.0" H_2O @ 30" H_2O
Frequency Response	<100 ms

Compliance Documents



- **Propulsion subsystem must be compliant with:**
  - 7434-9001 - SPP Parts Control Plan
  - 7434-9009 - SPP Materials and Processes Control Plan
  - 7434-9006 - SPP Configuration Management Plan
  - 7434-9013 - SPP System Safety Program Plan
  - 7434-9011 - SPP Contamination Control Plan
  - 7434-9039 - SPP Environmental Design & Test Requirements Document
  - 7434-9040 - SPP Electromagnetic Environment Control Plan
  - 7434-9095-02 - SPP Propulsion Subsystem Performance Assurance Matrix
  - 7434-8902 - SPP Harness Fabrication Specification
  - AFSPCMAN 91-710 - Range Safety User Requirements Manual
  - MSFC-STD-3029 - Guidelines for Selection of Metallic Materials for Stress Corrosion Cracking Resistance in Sodium Chloride Environments
  - ASTM A967/A967M - Chemical Passivation Treatments for Stainless Steel Parts (formerly QQ-P-35)
  - DOT/FAA/AR-MMPDS-01-Metallic Materials Properties Development and Standardization (formerly MIL-HDBK-5J)
  - MIL-STD-1547B - Electronic Parts, Materials & Processes for Space and Launch Vehicles

Compliance Documents

- **Propulsion subsystem must be compliant with:**
    - NASA-RP-1124 - Outgassing Data for Selecting Spacecraft Materials
    - IEST-STD-CC1246E - Product Cleanliness Levels - Applications, Requirements, and Determination (formerly MIL-STD-1246)
    - NASA-STD-8739.4 - Crimping, Interconnecting Cables, Harnesses, and Wiring
    - ANSI/ESD-S20.20-2007 - Protection of Electrical and Electronic Parts, Assemblies and Equipment (excluding electrically initiated explosives devices)
    - ISO-14644 - Clean Rooms and Associated Controlled Environments
    - JSC SPEC-C-20C, Grade A - Water, High Purity
    - GSFC 541-PG-8072.1.2A - Goddard Space Flight Center Fastener Integrity Requirements
    - ANSI/AIAA-S-080-1998 - AIAA Standard for Space Systems - Metallic Pressure Vessels, Pressurized Structures, and Pressure Components
    - MIL-P-26536F - Amendment II Propellant, Hydrazine (high purity), 1 April 2011
    - MIL-PRF-27401F- Propellant Pressurizing Agent, Nitrogen, 10 January 2008
    - MIL-PRF-27407C - Propellant Pressurizing Agent, Helium, 29 November 2006
    - TT-I-735A - Isopropyl Alcohol

Propulsion Subsystem GSE

- The procurement plan includes funds for a new propulsion pressurization/test cart which will be designed and fabricated by the propulsion subsystem supplier.
- SEI will be providing a thruster valve/latch valve actuation box which will interface with the test ports.
- SEI will be providing a box which will power the pressure transducers and display the manifold pressure and tank temperatures.
    - The box will allow reading pressures and temperatures also during propellant loading and in a hazardous environment.