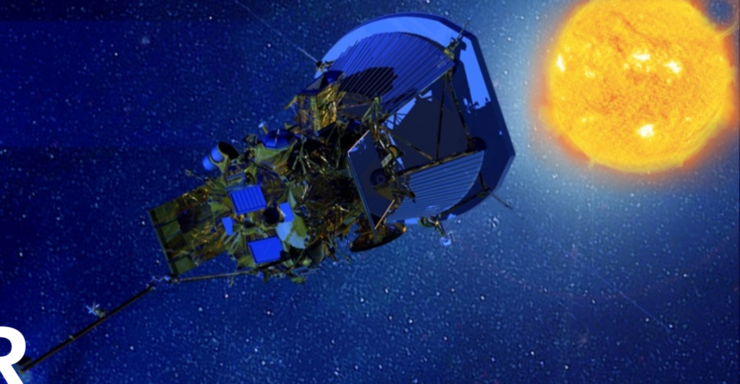
Solar Probe Plus

A NASA Mission to Touch the Sun



Solar Probe Plus PDR
1.0 Logistics, Agenda and Welcome

Andrew Driesman
SPP Program Manager

13 – 16 January 2014

The Johns Hopkins University
APPLIED PHYSICS LABORATORY

Logistics

- **Welcome**
- **Sign-in**
- **APL Parsons Auditorium Reserved 13-17 January 2014**
- **All presented materials are posted on SPP Sharepoint and NS-CKN**
- **CDs are available**
- **Wireless Network Access to internet on information provided as a separate hand-out**
- **Auditorium will be locked or guarded during lunch period**
- **All valuables should be removed overnight**
- **No food in Parsons**
- **Maps for local restaurants are at the desk**
- **Restrooms**
- **Security Perimeter**
- **Room available for splinter sessions and review team caucus**

ITAR Sensitive Material

- **The SPP PDR does not contain any ITAR Sensitive material.**
- **ITAR sensitive material is being handled through splinters.**

- **ITAR sensitive written material**
  - **ITAR sensitive presentations are distributed in a separate volume and CD. Distribution is controlled.**

PDR Agenda Day 1
(rev F)

Time	Topic	Presenter	Time
8:30 AM	01-Welcome	Ryschkewitsch /Driesman	15
8:45 AM	SRB Chair Remarks	Jones	15
9:00 AM	02-Project Overview	Driesman	30
9:30 AM	03-Science implementation	Fox	30
10:00 AM	04-System Engineering Overview	Kinnison	30
10:30 AM	Break		15
10:45 AM	05-System Software Engineering	Furrow	20
11:05 AM	06-Requirements	Kelly	30
11:35 AM	07-Mission Design	Guo	30
12:05 PM	Lunch		55
1:00 PM	08-Solar Illumination	Decker	20
1:20 PM	09-Radiation	Roth	20
1:40 PM	10-Spacecraft Charging	Donegan	20
2:00 PM	11-Dust	Mehoke	20
2:20 PM	Break		10
2:30 PM	13-EMI/EMC	Herrmann	20
2:50 PM	14-FIELDS	Bale	45
3:35 PM	15-SWEAP	Kasper	45
4:20 PM	16-ISIS	McComas	45
5:05 PM	End of Day 1		
			8.58

PDR Agenda Day 2

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/Hartka	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		
			8

PDR Agenda Day 3

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		
			8.25

PDR Agenda Day 4

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Time	Topic	Presenter	Time
8:30	42-Launch System	Englebrecht	45
9:15	43-Integration & Test	Dolbow	30
9:45	44-Mission Assurance	Becker	30
10:15	45-Software IV&V	Stanton (IV&V)	15
10:30	46-Safety	Ndu	15
10:45	47-Contamination Control	Nichols	30
11:15	48-Parts Control	Bonner	15
11:30	49-Materials Control	Langley	15
11:45	Lunch		45
12:30	**50-Programmatics**	**Driesman**	**90**
14:00	SRB Caucus		
			5.50

- Programmatic Session will be closed session between NASA, the Project Office and the SRB
- STAR48GXV Splinter planned for 9:45 – 10:45
- Splinter will contain ITAR controlled information. Splinter is only open to US Persons.

APL

PDR Entrance Criteria (ref: 7123.1A)

NPR 7123.1A Entrance Criteria	Comply
1. Successful completion of the SDR or SRR and/or MDR and responses made to all SDR or SRR and/or MDR RFAs and RIDs, or a timely closure plan exists for those remaining open.	✓
2. A preliminary PDR agenda, success criteria, and charge to the board have been agreed to by the technical team, project manager, and review chair prior to the PDR.	✓
3. PDR technical products listed below for both hardware and software system elements have been made available to the cognizant participants prior to the review.	✓

PDR Entrance Criteria (ref: 7123.1A)

NPR 7123.1A Entrance Criteria	Comply
3a. Updated baselined documentation, as required.	✓
3b. Preliminary subsystem design specifications for each configuration item (hardware and software), with supporting trade-off analyses and data, as required. The preliminary software design specification should include a completed definition of the software architecture and a preliminary database design description, as applicable.	✓
3c. Updated technology development maturity assessment plan.	✓
3d. Updated risk assessment and mitigation.	✓
3e. Updated cost and schedule data.	✓
3f. Updated logistics documentation, as required.	✓
3g. Applicable technical plans	✓
3h. Applicable standards.	✓
3i. Safety analyses and plans.	✓
3j. Engineering drawing tree.	✓

PDR Entrance Criteria (ref: 7123.1A)

NPR 7123.1A Entrance Criteria	Comply
3k. Interface control documents.	✓
3l. Verification/validation plan.	✓
3m. Plans to respond to regulatory requirements (e.g., Environmental Impact Statement), as required.	✓
3n. Disposal plan.	✓
3o. Technical resource utilization estimates and margins.	✓
3p. System-level safety analysis.	✓
3q. Preliminary limited life items list (LLIL).	✓

The SPP Project successfully completed its PDR Readiness Assessment on 9 Dec 2013.

PDR Success Criteria (ref: 7123.1A)

NPR 7123.1A Success Critere	Comply
1. The top-level requirements including mission success criteria, TPMs, and any sponsor-imposed constraints are agreed upon, finalized, stated clearly, and consistent with the preliminary design.	
2. The flow down of verifiable requirements is complete and proper or, if not, an adequate plan exists for timely resolution of open items. Requirements are traceable to mission goals and objectives.	
3. The preliminary design is expected to meet the requirements at an acceptable level of risk.	
4. Definition of the technical interfaces is consistent with the overall technical maturity and provides an acceptable level of risk.	
5. Adequate technical interfaces are consistent with the overall technical maturity and provide an acceptable level of risk.	
6. Adequate technical margins exist with respect to TPMs.	

PDR Success Criteria (ref: 7123.1A)

NPR 7123.1A Success Criteria	Comply
7. Any required new technology has been developed to an adequate state of readiness, or back-up options exist and are supported to make them a viable alternative.	
8. The project risks are understood and have been credibly assessed, and plans, a process, and resources exist to effectively manage them.	
9. Safety and mission assurance (e.g., safety, reliability, maintainability, quality, and EEE parts) have been adequately addressed in preliminary designs and any applicable S&MA products (e.g., PRA, system safety analysis, and failure modes and effects analysis) have been approved.	
10. The operational concept is technically sound, includes (where appropriate) human factors, and includes the flow down of requirements for its execution.	

Back Up

Solar Probe Plus
Preliminary Design Review
SRB Introduction

Chris Jones, SRB Chair

SPP Standing Review Board

(Non-Consensus Board)

Last	First	Affiliation	Expertise
Jones	Chris	JPL	SRB Chair / Programmatic
Land	Robin	HQ	Review Manager / Programmatic
Battel	Steve	CTS	Avionics
Borchardt	Heidemarie	HQ	Schedule Analyst / Programmatic Lead
Bowman	Keith	USAF/AFRL	Thermal
Byrnes	Dennis	CTS	Mission Design
Kerslake	Tom	GRC	Power
Amador	Arthur	JPL	MOS/GDS
Murphy	Neil	JPL	Instruments/Science
Petro	Susanna	GSFC	Systems Engineering/Instruments
Scott	Steve	GSFC	Systems Engineering
Steinfeld	David	GSFC	Thermal
Stevens	Chris	JPL	Programmatic
Consultant-to-the-Board			
Chodas	Jan	JPL	Programmatic / Flight Software
Clark	Kim	TMG	Cost Analyst
Drexler	Jonathan	GRC	Schedule Analyst
Glubke	Scott	GSFC	Sys Engineering
Harvison	Steve	MSFC	LV-Upper Stg
Hinkle	Ken	CTS	Mechanical Systems
Iamsakuldacha	Nopachai	SAIC	Cost Analyst
Kinsella	Gary	JPL	Thermal
Prince	Andrew	MSFC	LV-Upper Stage

SRB Information

- SRB is a Non-Consensus Board
  - Each member submits their findings as part of the review package
    - Chair will develop the Final Report and brief through APMC
    - Members can submit an Alternate Opinion
- Individual Member Independent Report (IMIR)
  - Issues should be documented in an RFA
  - Record document review feedback in “Special Assignments”
  - Email to Chris/Robin on the last review day (Thu, Jan 16th)
- Request For Action (RFA)
  - RFAs from other than SRB members must have an SRB sponsor
  - Will be discussed in caucus
  - Only closed with the agreement of the submitter and the Chair
  - Email to Chris/Robin as the review goes on
- Programmatics
  - Additional opportunity to update risks at the end of each review day (in SRB caucus)
  - SRB programmatic members will continue analysis in site review and update after site review close
  - Briefing to the SRB on Jan 30, 2014 (everyone should have on their calendar)

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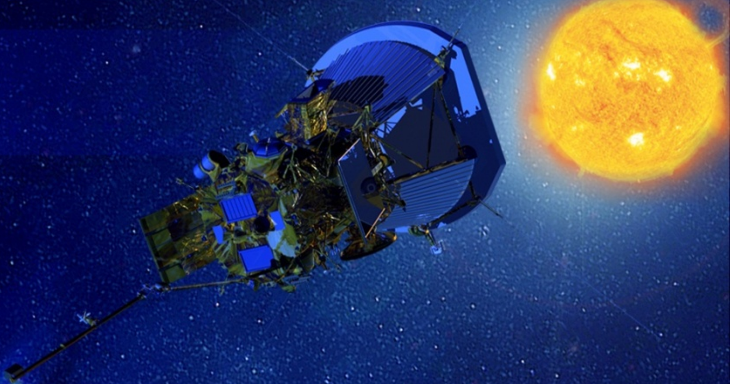

Solar Probe Plus
Programmatic Overview

Andrew Driesman
SPP Project Manager

13 – 16 January 2014

NASA

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APPLIED PHYSICS LABORATORY

Topics

- **Governance**
- **Project Management Structures**
- **Schedule Overview**
- **SRR/MDR Actions**
- **Changes since Systems Requirement Review/Mission Design Review**

Governing Documents

Solar Probe Plus
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- The SPP Project Plan, 7434-9000 is written and is responsive to:
  - NPR 7120.5E NASA Program and Project Management Processes and Requirements
  - NPR 7123.1A, NASA System Engineering Processes and Requirements
  - Level 1 Requirements for the Solar Probe Plus Mission. Appendix to the LWS Program Plan 462-PLAN-0005
  - JHU/APL Space Department Quality Management System
- The SPP Project Plan is in review and signature cycle

7120.5E Waived and Tailored Requirements

- **Compliance matrix against 7120.5E has been completed as an appendix to the SPP Project Plan. The following waiver and tailored items exist:**
- **Waiver:**
  - **Project Protection Plan – Agency wide waiver for projects with KDP prior to 15 Apr 2014.**
    - **SPP has submitted its implementation of "Candidate Project Protection Strategies".**
- **Requested Tailoring**
  1. **Schedule BOEs – schedule BOEs were not required by NID81 (SPP Contractual Requirement).**
     - **The SPP Project has been actively supporting IPAO schedule analysis.**
  2. **Provide a range of cost and a range for schedule at KDP B, each range (with confidence levels identified for the low and high values of the range) established by a probabilistic analysis and based on identified resources and associated uncertainties by fiscal year.**
     - **7120.5E was not active at MDR/KDP-B. SPP was under NID81 for Phase A.**
     - **SPP completed a probabilistic assessment of Cost.**
     - **SPP only completed a Monte-Carlo assessment of SPP's LRD.**

General PDR Guidance and Assumptions

- **Required review defined in NPR 7120.5E (*NASA Procedural Requirements*)**
  - **Review guidance provided in NPR 7123.1A (*Systems Engineering Procedural Requirements*)**
- **Per 7120.5E, Table 2-2, Authorities are:**
  - **Decision Authority: Robert Lightfoot, NASA AA**
  - **Decision Authority: John Grunsfeld, NASA MDAA**
  - **Technical Authority: Arthur Obenschain, GSFC Dep Center Director**
  - **Office of Evaluation: Janet Petro, Director, Office of Evaluation**

SPP Mission Definition

- **Per NPR 7120.5E:**
  - **SPP is classified as:**
    - **Category 1 (high priority level) [ref. Table 2-1 Project Categorization Guidelines]**
    - **Part of a Loosely Coupled Program [ref. section 2.3]**

- **Per NPR 8705.4:**
  - **SPP has a Mission Risk Classification of Class B [ref. Appendices A and B]**

SPP Organizational Chart

NASA
Science Mission Directorate
Heliophysics Division
Director: D. Chenette
Program Scientist: M. Guhathakurta
Program Executive: J. Lee

GSFC LWS Program Office
Program Manager: N. Chrissotimos
PM for APL Projects: M. Goans
Mission Scientist: A. Szabo

SD Management

Project SAM: L. Becker

EPO
Alexandra Novak

Solar Probe Plus Project Office
Project Manager: A. Driesman
Deputy Project Manager: E. Reynolds
Deputy PM for Instruments: P. Hill

EV Manager: H. Hunter
Planning Manager: C. Battista
Financial Manager: J. Rodgers

HELIOSPP – JPL*
M. Velli, Obs Sci

WISPR – NRL*
PI: R. Howard
PM: S. Plunkett

SWEAP – SAO
PI: J. Kasper
PM: J. Bookbinder

ISIS – SwRI
PI: D. McComas
PM: S. Weidner

FIELDS – UCB
PI: S. Bale
PM: P. Harvey

Mission System Engineer
MSE: J. Kinnison
DMSE: M. Lockwood

Project Scientist
N. Fox

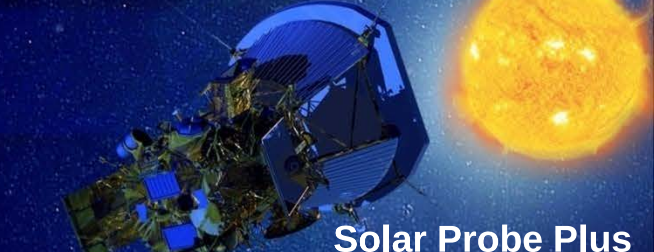
Upper Stage Project
PjM: C. Engelbrecht

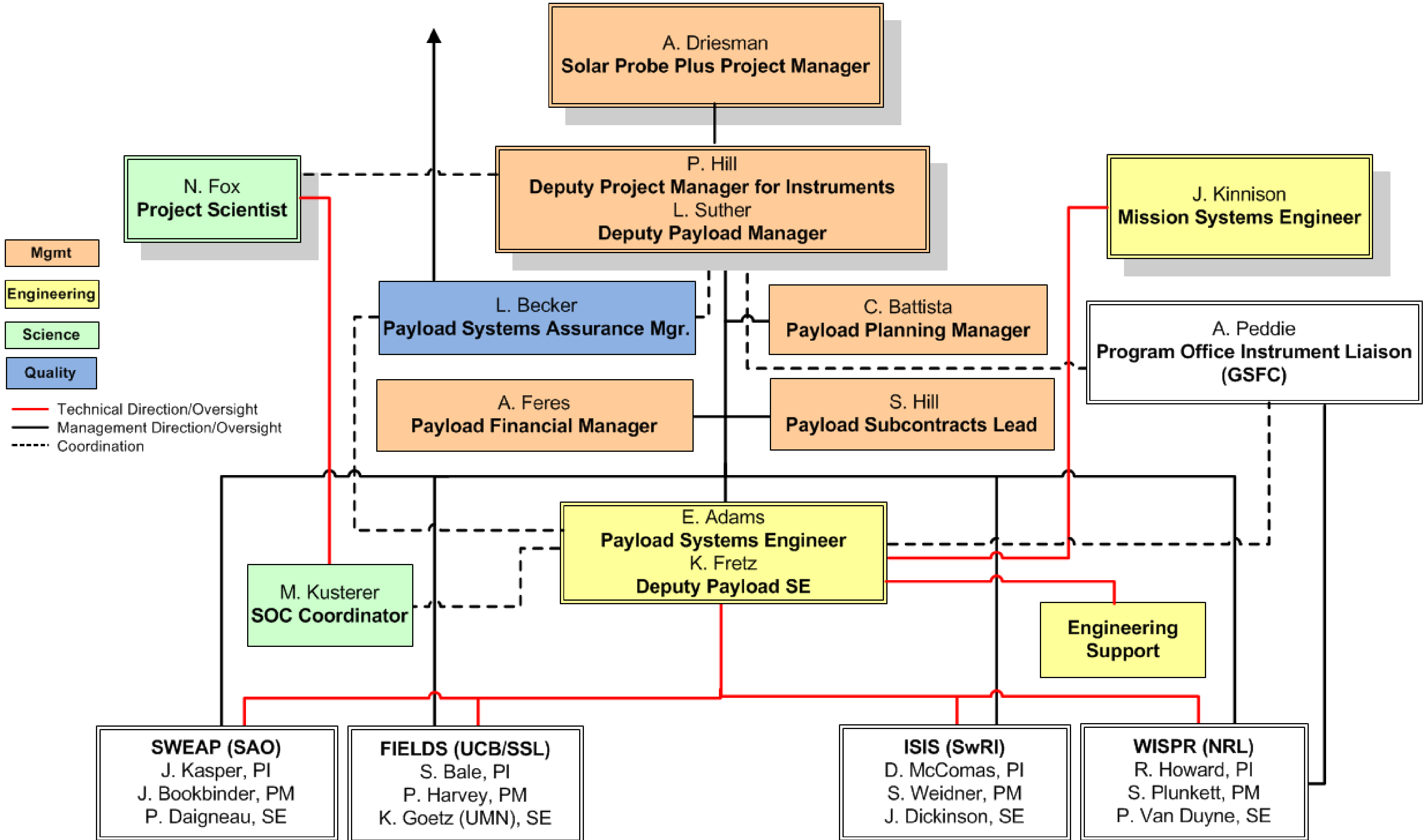
* Funded directly by NASA

SPP Science Investigations

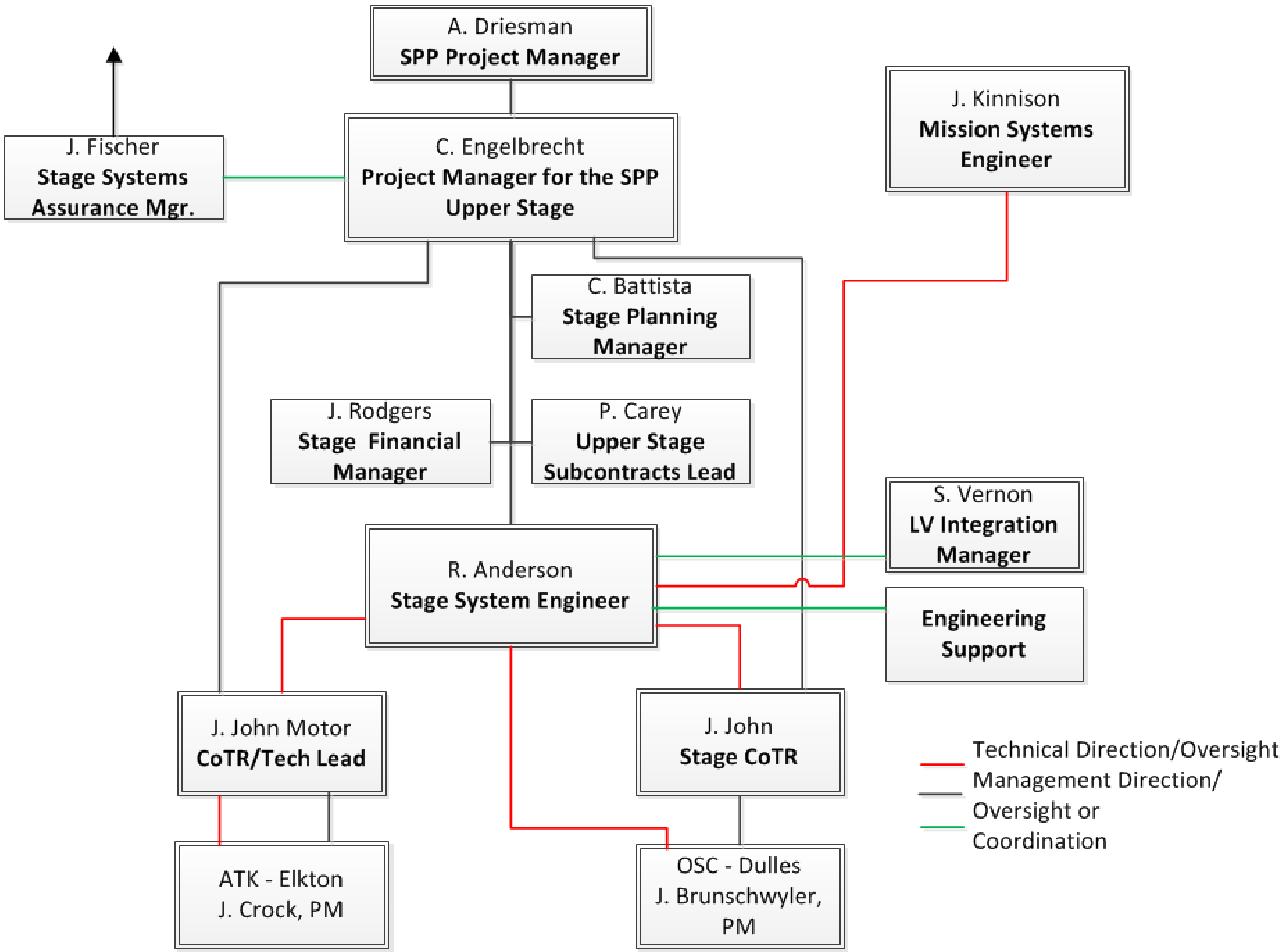
- **Chosen by AO in Phase A.**
- **Five investigations were selected:**
  - **Solar Wind Electron Alphas and Protons (SWEAP) Suite**
    - PI: Justin Kasper, Smithsonian Astrophysical Observatory and the University of Michigan
    - Key Partners: NASA/MSFC
  - **Integrated Science Investigation of the Sun (ISIS) Suite**
    - PI: David McComas, Southwest Research Institute
    - Key Partners: JHU/APL, Caltech, NASA/GSFC, LBNL
  - **Fields Suite**
    - PI: Stuart Bale, University of California, Berkeley
    - Key Partners: NASA/GSFC, LPC2E/CNRS (France)
  - **Wide-Field Imager for Solar Probe Plus (WISPR)**
    - PI: Russ Howard, Naval Research Laboratory
    - Key Partners: JPL
  - **HELIOSPP**
    - PI: Marco Velli, Jet Propulsion Laboratory
- **Government providers are funded through GSFC or NASA/HQ but are managed through the SPP Project Organizational Structure.**
- **SPP Investigations that provide HW are the only subcontracted organizations that have allocated Management Reserve.**

Investigation Management Organization





SPP Stage Project Management Organization



SPP Project Schedule Overview

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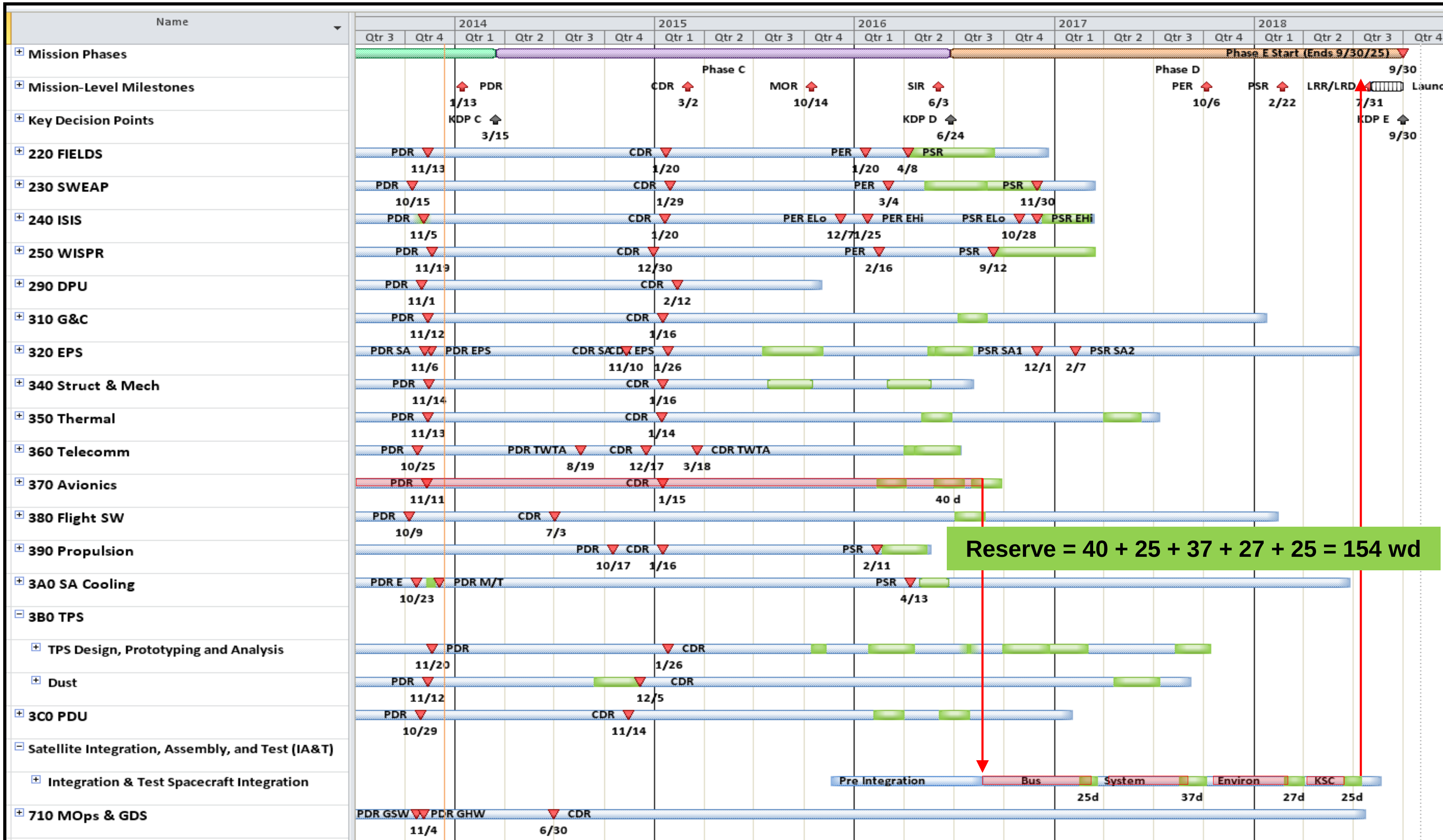

Reserve does not include weekends, holidays or nights except during TV.

Significant Changes since MDR

Key Changes associated with meeting L1RD or Programmatic Requirements

MDR Reference Mission	PDR Baseline	Comment
Perihelion = 9.5 Rs	Perihelion = 9.86 Rs	Coupled with Launch Vehicle enhancements, increased launch mass from 610 Kg to 665 Kg. Minor change to L1RD. Negligible impact on Science.
WISPR single telescope	WISPR two telescope	Mitigates stray light from FIELDS V1-V4. Satisfies red issue from MDR
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.

Summary

- **SPP Management Structures are in place.**
- **Driving documents have been identified and SPP is in compliance with two exceptions.**
  - **The SPP Project is requesting that two items in 7120.5E be tailored.**
- **A Readiness Assessment has been successfully completed.**
- **SPP is operating in a manner consistent with NASA Requirements and has agreement from the Convening Authorities to conduct PDR.**

Backup

Solar Probe Plus

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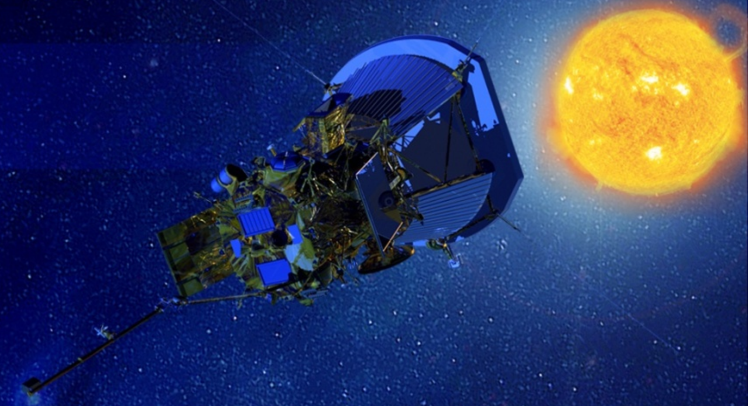

Project Science Overview

Nicola J. Fox
Project Scientist

nicky.fox@jhuapl.edu

Rob Decker, Marco Velli, Adam Szabo
& the SPP Project Science Team

13 – 16 January 2014

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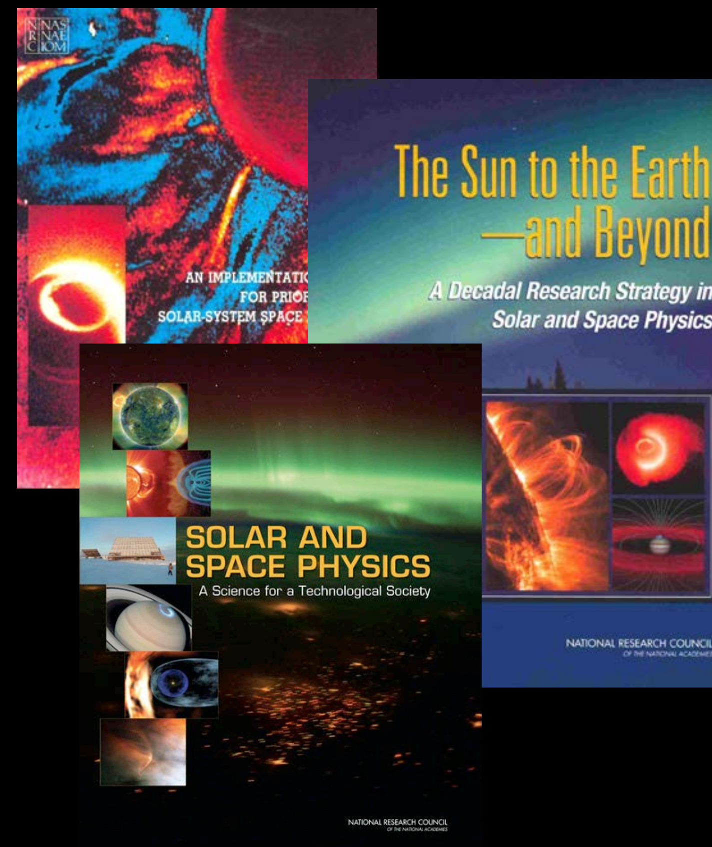
Outline

- Introduction to the Science of SPP
- Understanding and capturing science/measurement requirements
- Science Working Group activities
- Changes to Project Level (Level-1) Requirements
  - Baseline, Threshold & Mission Success Requirements
- Required measurement parameters against instrument capabilities
- Observatory Robustness
- Science Environment Studies
- Science Data Management Plan
- Telemetry Allocation
- Burst mode requirements
- Science Planning
- Summary

Solar Probe History (1958 - present)

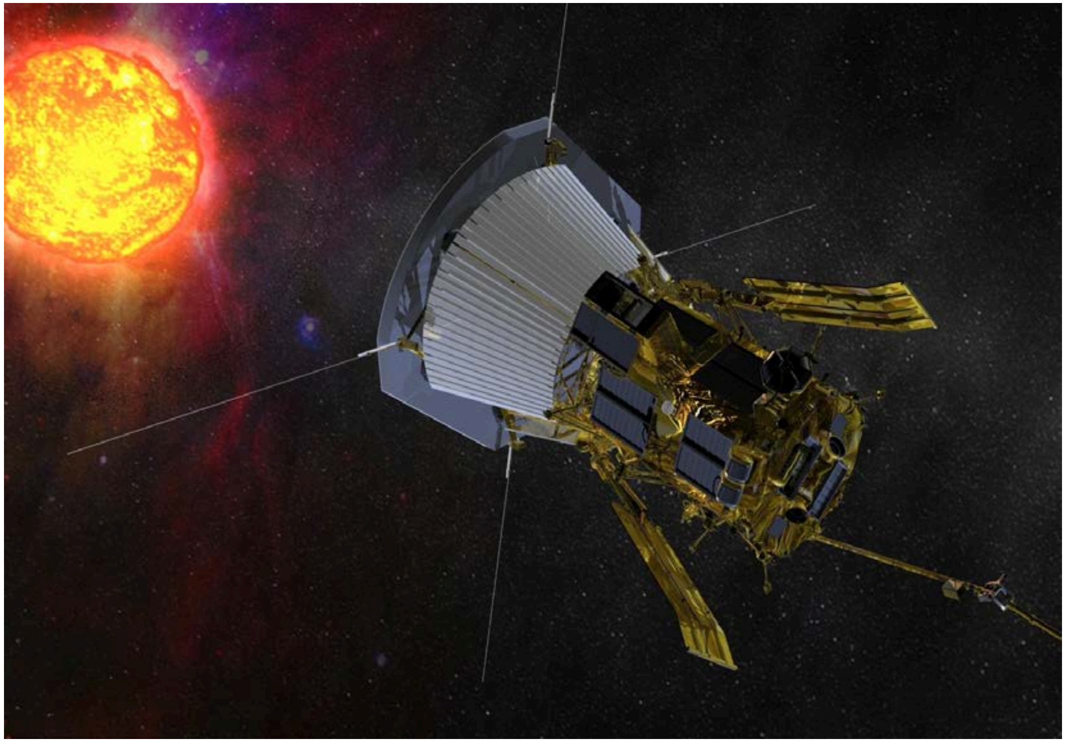
New STDT in line of studies dating back to "Simpson's Committee" of the Space Science Board (National Academy of Sciences) (24 October 1958)



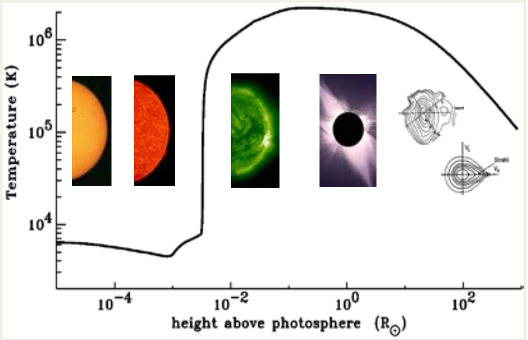
Solar Probe studies, reports; NAS: 1962, 1985, 1995, 2003; 2013

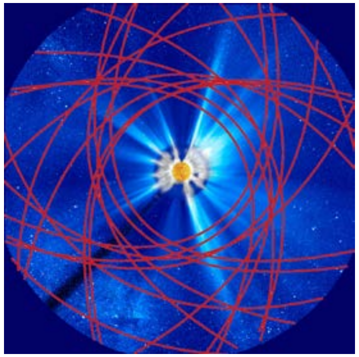
SPP Over-arching Science Objective

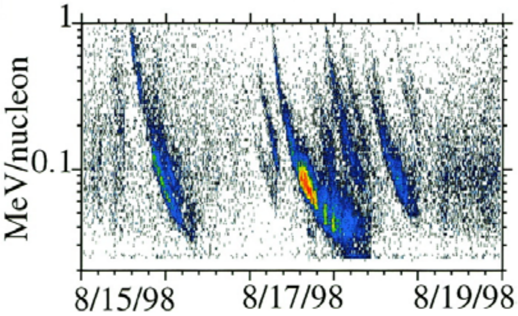
- **To determine the structure and dynamics of the Sun's coronal magnetic field, understand how the solar corona and wind are heated and accelerated, and determine what mechanisms accelerate and transport energetic particles.**



SPP Science Objectives







- Trace the flow of energy that heats the corona and accelerates the solar wind
- Determine the structure and dynamics of the magnetic fields at the sources of the fast and slow solar wind
- Determine what mechanisms accelerate and transport energetic particles
  - Level 1 Mission and Measurement Requirements have been derived in order to achieve these science objectives.
  - There are three detailed science sub-questions stemming from these objectives (included in the back-up).

Observations from 10-20 R_s are required to achieve the SPP Science Objectives

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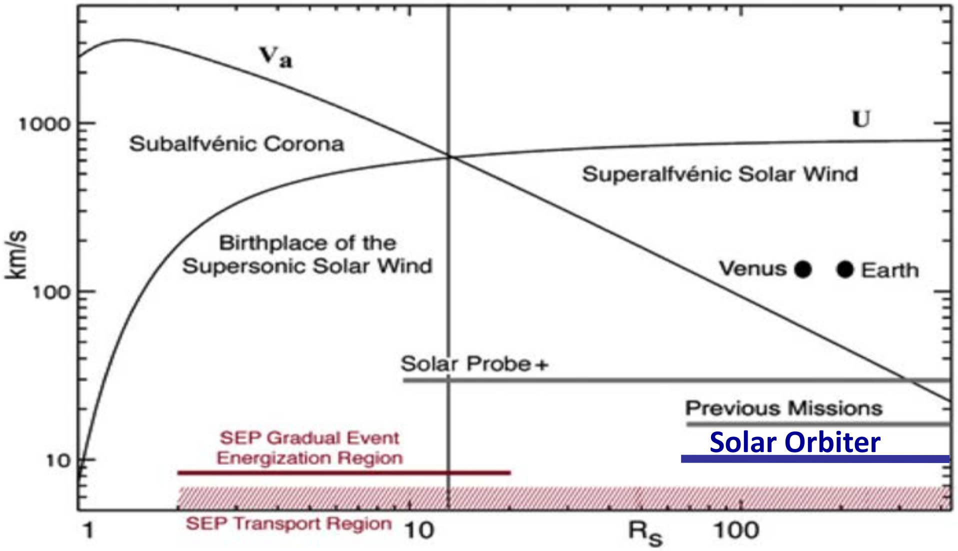
- Coronal magnetic structure still channels the flow and determines angular momentum loss
- Waves, turbulence strongest
- Temperature maximum
- Collisional-Collisionless Transition
- Magnetic–Kinetic Pressure Transition



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SPP Rapidly Explores the Inner Heliosphere

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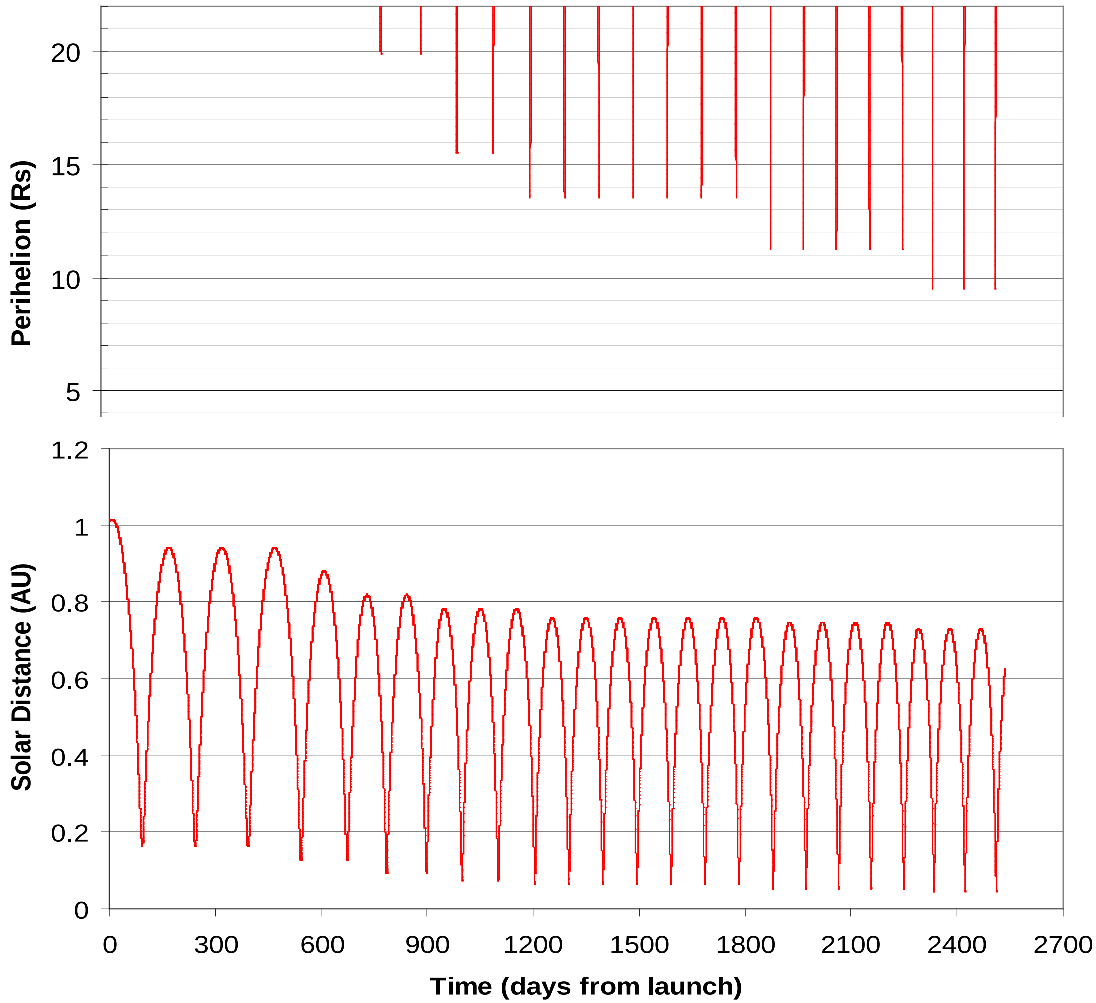

- **1st perihelion (0.16 AU) 3 months after launch**
- **24 passes below 43 R_s**
- **17 passes below 20 R_s**

APL

Level 1 Objectives & Processes require high quality, integrated measurements

L1 Science Objectives	Sample Processes	Needed Measurements	Instruments
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. 3. Explore mechanisms that accelerate and transport energetic particles.	- Heating mechanisms of the corona and the solar wind; - Environmental control of plasma and fields; - Connection of the solar corona to the inner heliosphere. - Particle energization and transport across the corona	- Electric & magnetic fields and waves, Poynting flux, absolute plasma density & electron temperature, spacecraft floating potential & density fluctuations, & radio emissions - Energetic electrons, protons and heavy ions - Velocity, density, and temperature of solar wind e-, H+, He++ - Solar wind structures and shocks	FIELDS - Magnetic Field - Electric Field - Electric/Mag Wave ISIS - Energetic electrons - Energetic protons and heavy ions - (10s of keV to ~100 MeV) SWEAP - Plasma e-, H+, He++ - SW velocity & temperature WISPR - White light measurements of solar wind structures

SPP Investigations to Answer the Science Questions

Investigation	Instruments	Principle Investigator
Fields Experiment (FIELDS)	4 x Electric Antennas 2 x Fluxgate Magnetometer (MAG) 1 x Search Coil Magnetometer (SCM)	Prof. Stuart D. Bale, University of California Space Sciences Laboratory, Berkeley, CA
Integrated Science Investigation of the Sun (ISIS)	High energy Energetic Particle Instrument (EPI-Hi) Low energy Energetic Particle Instrument (EPI-Lo)	Dr. David J. McComas, Southwest Research Institute, San Antonio, TX
Solar Wind Electrons Alphas and Protons (SWEAP)	Solar Probe Cup (SPC) 2 Solar Probe ANalyzers (SPAN)	Dr. Justin Kasper, University of Michigan, Ann Arbor, MI & Smithsonian Astrophysical Observatory, Cambridge, MA
Wide-field Imager for Solar PRobe (WISPR)	White light imager	Dr. Russ Howard, Naval Research Laboratory, Washington, DC
Heliospheric Origins with Solar Probe Plus (HeliOSPP)	Observatory Scientist - addresses SPP science objectives via multi-instrument data analysis to optimize the scientific productivity of the mission	Dr. Marco Velli, Jet Propulsion Laboratory, Pasadena, CA

SPP spacecraft must target key solar wind acceleration regions to answer mission questions

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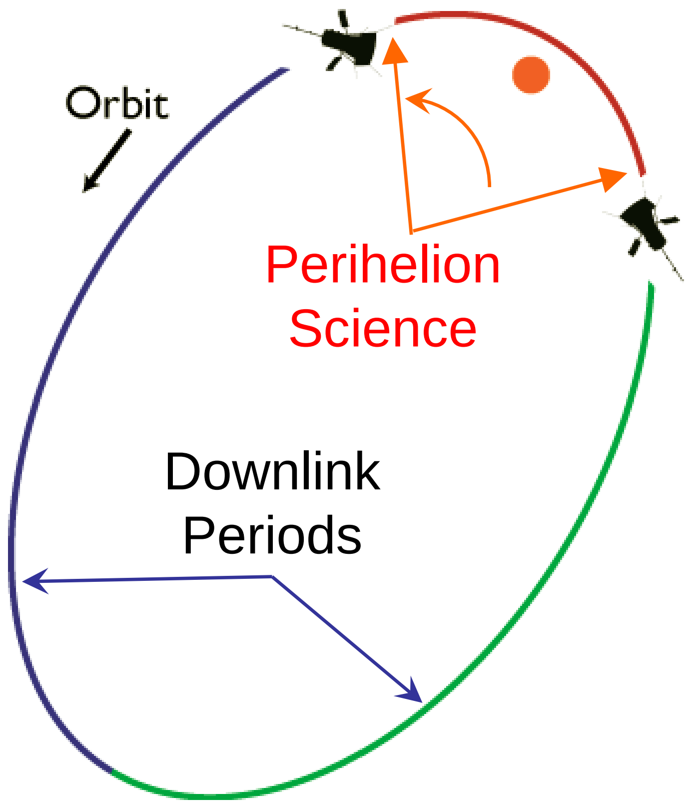
A NASA Mission to Touch the Sun

▪ The SSP Mission design is optimized to achieve mission objective

- Solar Probe Plus periapsis from 35 - < 10 solar radii (R_s) of the Sun
- 24 orbits allow periapsis to be lowered using Venus fly-bys
- Spacecraft nadir direction always pointing sunward during perihelion science to allow heat-shield to protect sensitive instruments
- Highly comprehensive particle & fields instrument measurement capabilities
- Prime science gathering inside 53.5 R_S



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SPP Science Working Group Activities

- Science Working Group (SWG) is chartered by HQ Program Scientist, chaired by the SPP Project Scientist, and advises the Program and Project.
- The SWG is comprised of the Principal Investigators and PI-designated sensor representatives from all of the investigations on the SPP spacecraft, and the Mission & Project Scientist.
- SWG communicates regularly - four in-person SWG meetings (2 per year), and monthly telecons during Phase B
- During Phase B, the SWG has dealt with a number of issues:
  - Refinements to science objectives and measurement requirements
  - Review of SPP Project Science Environment Trades
  - Burst mode (management for clustered bursting and trigger management), shared data, science campaign planning
  - Descope plan

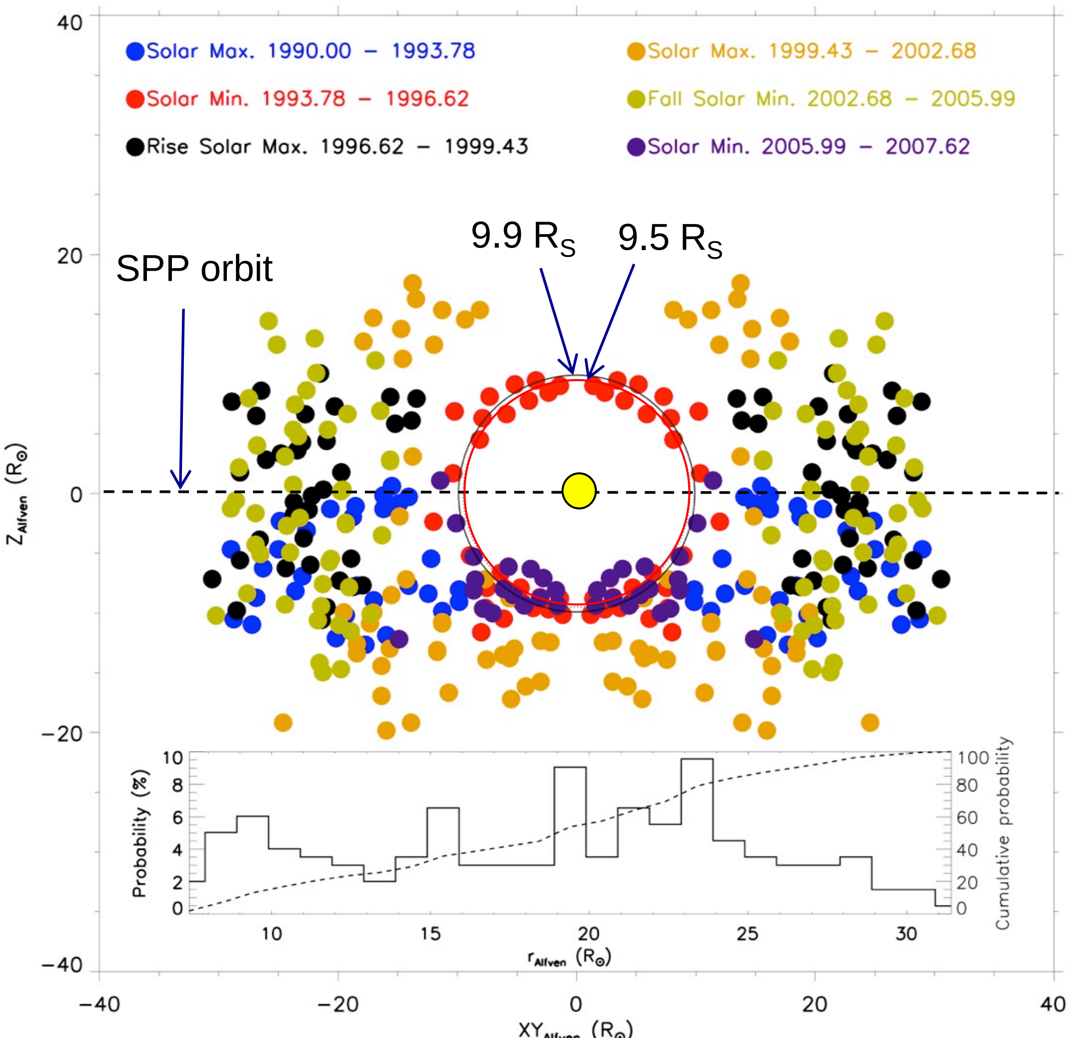
Changes to Level 1 Science Requirements Document

- Time below 10 Rs – affects Baseline and Threshold sections but not the measurements themselves
- Science Data Management Section – reorganized to make requirements flow possible down to lower levels (and corrected grammar)
    - No change in actual requirement

Raising SPP Minimum Perihelion from 9.5 to 9.86 R_S has Insignificant Impact on Science

- The impact of increasing the perihelion to 9.86 R_S has been considered thoroughly by the project science team and discussed with the SWG
  - Raising closest perihelion from 9.5 to 9.86 R_S will not significantly change the probability of encountering the Alfvén point
    - The following slide illustrates worst-case analysis using data from Ulysses – clearly showing that the resulting change in the probability of detecting the Alfven Critical point is very small. MHD code runs show similar results
  - The change in perihelion has a 2% reduction in the maximum perihelion speed but this does not significantly impact the ability to:
    - measure orthogonal power spectra, based on “flow-to-field” considerations.
    - make “corotation radial scans” where SPP explores the wind coming from the same regions of the sun over radii from 15 to 40 solar radii.

The location of the Alfvén critical surface varies in space and time over the solar activity cycle



- Symbols show estimated locations of Alfvén radius $r_{Alfvén}$ as a function of cylindrical radius (from sun center) and height above the heliographic equator
- Color code (legend) denotes the period during solar activity cycles 22 and 23 when Ulysses data were used for these estimates
- Except under some solar minimum conditions (red, purple), SPP's near-equatorial orbit will enable multiple crossings of $r_{Alfvén}$ between ≈10-30 R_S
- ***Raising closest perihelion from 9.5 to 9.86 R_S will not significantly change the probability of encountering the Alfvén point***

Source: Katsikas et al., **ASR**, **46**, 382, 2010.

Project Definition and Mission Performance

- *1.2 Project Definition (paragraph 2)*
- The SPP spacecraft will make in-situ measurements and remote observations between a minimum perihelion of ~~9.5~~ less than 10 solar radii (Rs) and at least out through (~~55)~~ 53.5 Rs. ~~The perihelion, over the solar equator, must be within the corona.~~

- *4.2.1 Mission and Spacecraft Performance*
- Solar Probe Plus shall complete at least three orbits with a minimum perihelion distance of (~~9.5~~) less than 10 Rs from the center of the Sun.

Baseline Requirements

- *4.1.1 Baseline Science Requirements*
- ~~*To meet the baseline science objectives the mission shall spend 950 hours below 20 Rs, with no less than 25 hours below 10 Rs. The mission shall make the detailed measurements contained in tables 4.1, 4.2, 4.3, and 4.4 at least between 9.5 Rs and 55 Rs from the Sun.*~~
  - 4.1.1.1 To meet the baseline science objectives the mission shall spend 920 hours below 20 Rs, with no less than14 hours below 10 Rs.
  - 4.1.1.2 The mission shall make the detailed measurements contained in tables 4.1, 4.2, 4.3, and 4.4 at least between a minimum perihelion of less than 10 Rs and 53.5 Rs from the Sun
    - *55 Rs changed to 53.5 Rs due to inconsistency in requirements – previously defined as 0.25 AU, error in conversion to Rs*
    - *Change requirement numbers from 4.1.1.1-4.1.1.9 to 4.1.1.3-4.1.1.11 in tables 4.1-4.4*

Req	Measurement	Dynamic Range	Cadence	Bandwidth
4.1.1.~~1.~~3	Magnetic Field	140 dB	100k vectors/s	DC - 50 kHz
4.1.1.~~2.~~4	Electric Field	140 dB	2M vectors/s	DC - 1 MHz

Threshold and Mission Success Requirements

- *4.1.2 Threshold Science Requirements*
  - 4.1.2.1 The SPP mission threshold shall be satisfied by making minimum measurements for (~~9~~) 8 hours below 10 Rs and at least (~~500~~) 400 hours below 20 Rs.
- *4.6 Mission Success Criterion*
  - No change required

4.5. MISSION DATA REQUIREMENTS (1/2)

- ~~4.5.1 Science Data Management~~
  - ~~*The SPP Principal Investigators shall be responsible for initial analysis of their data, its subsequent delivery to an appropriate data repository, the publication of scientific findings, and communication of results to the public. Additionally, the SPP Principal Investigators shall be responsible for collecting engineering and ancillary information necessary to validate and calibrate the scientific data prior to depositing them in a NASA approved data repository. The time required to complete this process shall be no more than 6 months. The SPP science database shall be made available to the science community without restrictions or proprietary data rights of any kind.*~~
- 4.5.1 Science Data Delivery
  - The SPP Principal Investigators shall be responsible for initial analysis of their data, its subsequent delivery to an appropriate data repository, and collecting engineering and ancillary information necessary to validate and calibrate the scientific data prior to depositing them in a NASA approved data repository, all within 6 months of downlink of all data from a given encounter.
- 4.5.2 Science Data Availability
  - The SPP science data shall be made available to the science community without restrictions or proprietary data rights of any kind.
- 4.5.3 Data Archiving
  - Each SPP science investigation team shall deliver their respective data archive from the prime mission to a NASA-designated location for a deep data archive within one year of the completion of the prime mission operations. This location will be described in the Mission Archive Plan (MAP) produced by the SPP Project during Phase E.
- 4.5.4 Science Data Publication
  - The SPP Principal Investigators shall be responsible for the publication of scientific findings and communication of results to the public.

4.5. MISSION DATA REQUIREMENTS (2/2)

- ~~4.5.2 Data Management Plan~~
  - ~~*The SPP Project shall develop a data management plan to address the total activity associated with the flow of science data, from acquisition, through processing, data product generation and validation, to archiving and preservation. The data management plan shall be formally approved as a Level 2 requirement no later than the Project's Critical Design Review. Science analysis software development, utilization, and ownership shall be covered in the Data Management Plan*~~*.*

- 4.5.5 Science Data Management Plan
  - The SPP Project shall develop a Science Data Management Plan (SDMP) to address the total activity associated with the flow of science data, from acquisition, through processing, data product generation and validation, to archiving and preservation. The SDMP will be formally approved as a Level 2 requirement no later than the Project's Critical Design Review. The SDMP will include information on:
    - Science analysis software development, utilization, and ownership,
    - Initial data analysis,
    - Delivery to an appropriate data repository,
    - Collection of engineering and ancillary information for scientific data validation and calibration,
    - Time taken to complete these processes,
    - Availability and access by the science community

No change to Baseline or Threshold Measurement Requirements

- The Level 1 document contains 8 detailed tables (4 for Baseline and 4 for Threshold) which define the required measurements for the mission (in back-up).
  - One small change to the footnote #3 for Tables 4.2 and 4.6
  - 3: Mass resolution ~~not~~ only required in ~~all directions~~ ram direction
- **Example layout for Baseline**

REQ#	Measurement	Range	Cadence	Resolution	etc.
4.1.1.x	Science Measurement	A-C	D / sec	E%	

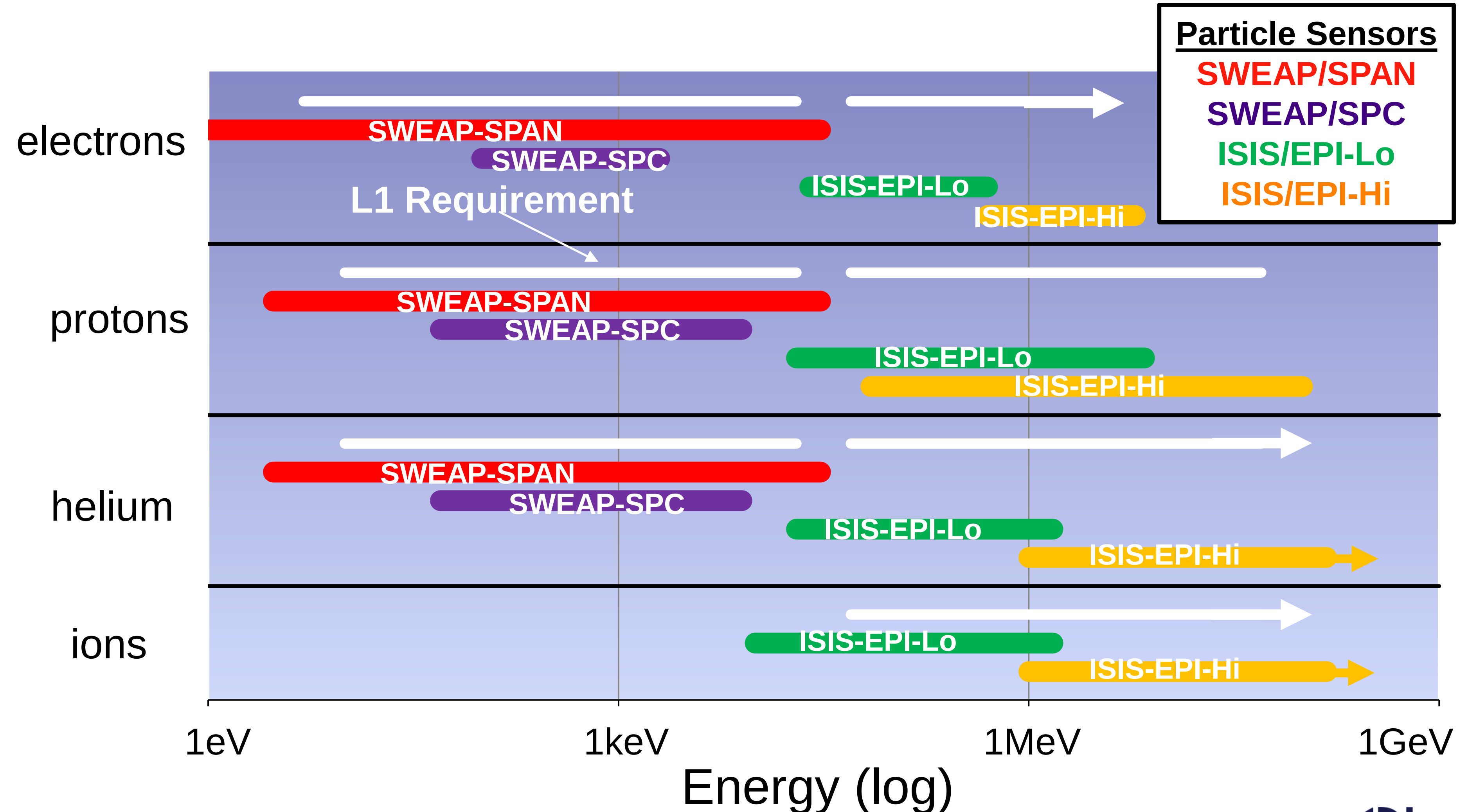
- **Example layout for Threshold**

REQ#	Measurement	Range	Cadence	Resolution	etc.
4.1.2.x	Science Measurement	a-c	d / sec	e%	

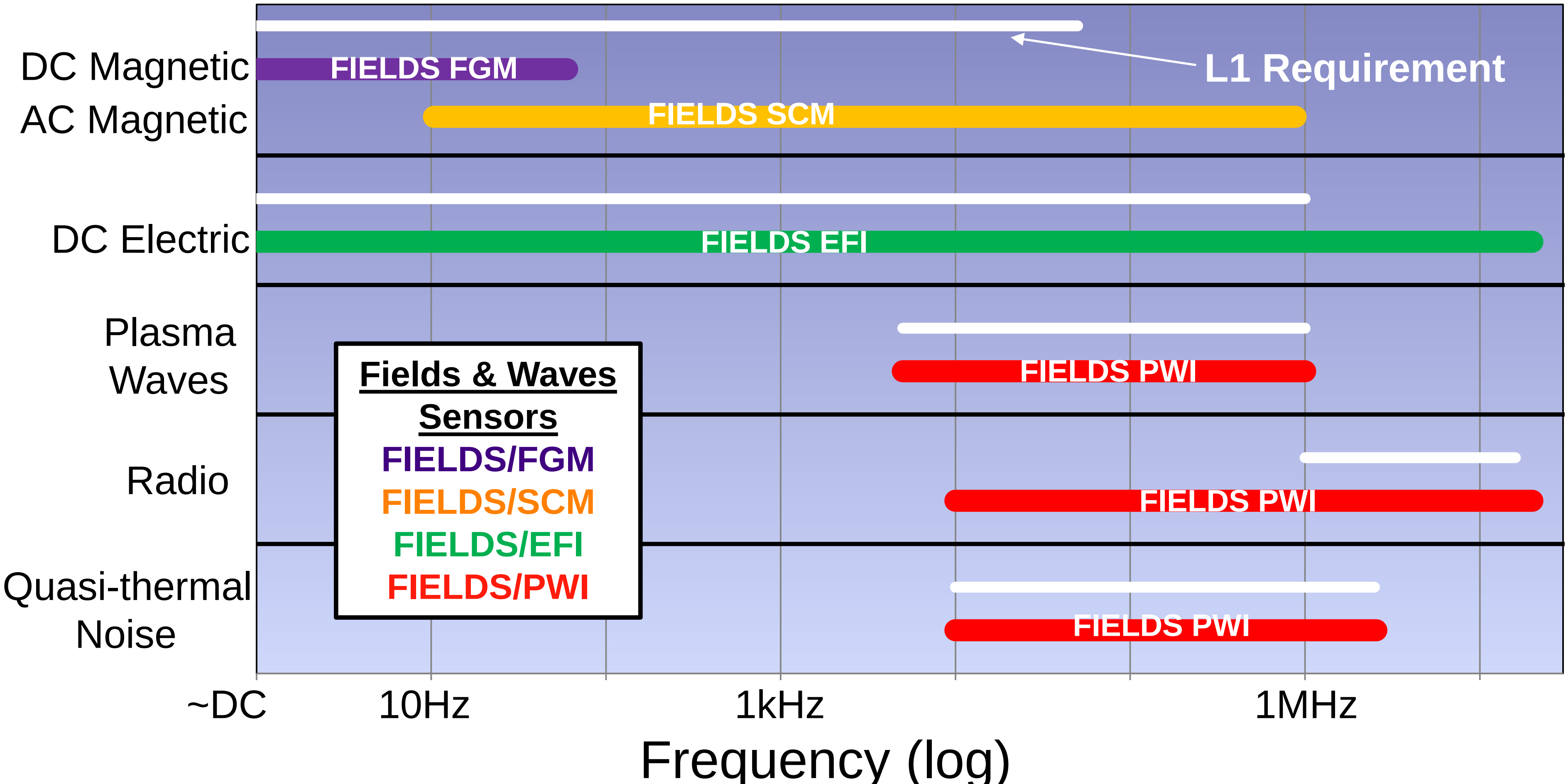
Mission Success Requirements

- The criteria that must be met after launch to declare mission success.
  - Sufficient flexibility to allow for degradation of the spacecraft and instruments.
- In order for Solar Probe Plus to achieve mission success at the end of prime mission, progress on at least two of the three science objectives must be made.
  - The science can be addressed with different combinations of measurements and, furthermore, there are multiple methods of obtaining the measurements using different instrumentation.
  - Thus, the mission is robust against the failure of any instrument and the loss of any given measurement after launch.
- *Therefore, Solar Probe Plus will achieve mission success at the end of prime mission by returning no less than 64 Gb of science data composed of at least 7 out of 9 of the required (threshold) measurements collected during 150 hours below 20 R_S, including no less than 5 hours below 10 R_S.*

Particle Instrument capabilities meet Level 1 requirements with margin



Fields & Waves Instrument capabilities meet Level 1 requirements with margin



SPP is Highly Robust: multiple paths lead to mission success

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Science Objective	Objective Questions	Solar Wind Plasma	Solar Wind Mag. Field	Plasma Waves	Energetic Particles	Large-scale Structures
Trace the flow of energy that heats and accelerates the solar corona and solar wind.	How is energy from the lower solar atmosphere transferred to, and dissipated in, the corona and solar wind?	X	X	X		
	What processes shape the non-equilibrium velocity distribution observed throughout the heliosphere?	X†	X	X		
	How do the processes in the corona affect the properties of the solar wind in the heliosphere?	X	X	X		
Determine the structure and dynamics of the plasma and magnetic fields at the sources of the solar wind.	How does the magnetic field in the solar wind source regions connect to the photosphere and the heliosphere?	X	X		X	X
	Are the sources of the solar wind steady or intermittent?	X		X		
	How do the observed structures in the corona evolve into the solar wind?	X†	X		X	X
Explore mechanisms that accelerate and transport energetic particles.	What are the roles of shocks, reconnection, waves, and turbulence in the acceleration of energetic particles?		X	X	X	
	What are the source populations and physical conditions necessary for energetic particle acceleration?	X‡		X	X	
	How are energetic particles transported in the corona and heliosphere?		X		X	X

† Full particle distribution functions are required. ‡ Requires measurement of suprathermal tail.

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Multiple Instruments can return the required science measurements

Measurement Type	Instruments Providing Measurement
Solar Wind Plasma	SPAN (electrostatic analyzer) SPC (Faraday Cup) FIELDS (electron plasma frequency -> density; s/c potential -> temperature) EPI-Lo (velocity) WISPR (White Light Imager -> density, velocity)
Vector Magnetic Field	FIELDS (dual fluxgate magnetometers) SPAN (electron pitch angles -> mag direction) FIELDS (electric fields -> B vector) EPI-Lo (pitch angle -> mag direction)
Plasma Waves	FIELDS (PWI, search coil, fluxgate mags) SPAN (electrostatic analyzer) SPC (Faraday Cup) WISPR (low frequencies)
Energetic Particles	ISIS (EPI-Hi) ISIS (EPI-Lo)
Large-scale structures	WISPR FIELDS

SPP Science Environment studies have optimized and validated implementation plans

1. Solar energetic proton fluences & peak intensities
2. Solar energetic electron fluences & peak intensities
3. Distributions of time durations when $j_{SEP} > j_{critical}$
4. Solar electrons & Deep Dielectric Discharge
5. ***Radiant energy and momentum fluxes on solar arrays***
6. ***Dust environment & star trackers***
7. ***Solar activity & solar limb sensors***
8. ***Coronal brightness***
9. Key Solar Wind Parameters and Their Radial Variations for Use in Modeling Environmental Effects
10. Spacecraft surface charging
11. Observability of Z+ and Z- fluctuations
12. Magnetic fields from induced currents in TSA
13. Solar wind fluxes on SPP
14. Thruster plume gas expansion
15. Thruster plume neutral constituents & science impacts
16. Estimation of the Solar Flare Neutron Worst-case Fluxes and Fluences
17. Estimation of the Solar Flare Gamma-ray Fluence at Solar Probe Plus
18. Estimation of the Solar Flare Soft X-ray Fluence at Solar Probe Plus

Science Data Management Plan

- During Phase B, a draft version of the SPP SDMP has been generated
- Compliant with "Heliophysics Science Data Management Policy" and relevant NASA documents (NPD 2200.1; NPR 2200.2B; NPR 1441.1)
- Presents strategy for generation, validation, documentation, delivery & sharing of science data products by each instrument Science Operation Centers (SOCs).
- The document includes:
  - <u>Mission Level Science and Data Operations</u>
    - Coordination of science/data activities between teams, sharing data for cross-calibration, sharing burst data
    - Coordination of science/data activities with other assets, missions and the broader heliophysics community
  - <u>Data Processing at the Science Operation Centers</u>
    - Commanding and Health and Safety
    - Telemetry and Data Processing
    - Data Products
      - Definition of data products and levels, Documentation including meta-data, Science Algorithms and supporting tools
    - Data Distribution and Archiving
      - Data Access Policy, Latency and Release Schedule, Catalogs and VxO interfaces

No Change to Telemetry Allocation

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- Telemetry allocations, based on the PI team science justifications and mission capability of 85 Gb orbit average (not including reserves):
    - Allocations include instrument housekeeping, health/safety, collected shared data, compression, and packet overheads.
    - Burst data managed within participating instruments and telemetered to spacecraft at a rate not to exceed 80 kbps (during encounter)
- Per discussions with the PI's, an agreement that part of the allocation will be held for coordinated campaigns on an orbit by orbit basis determined by the SWG

Instrument	Gb/orbit
WISPR	23
FIELDS	20
SWEAP	20
ISIS	12
Science campaign "data bank"	10

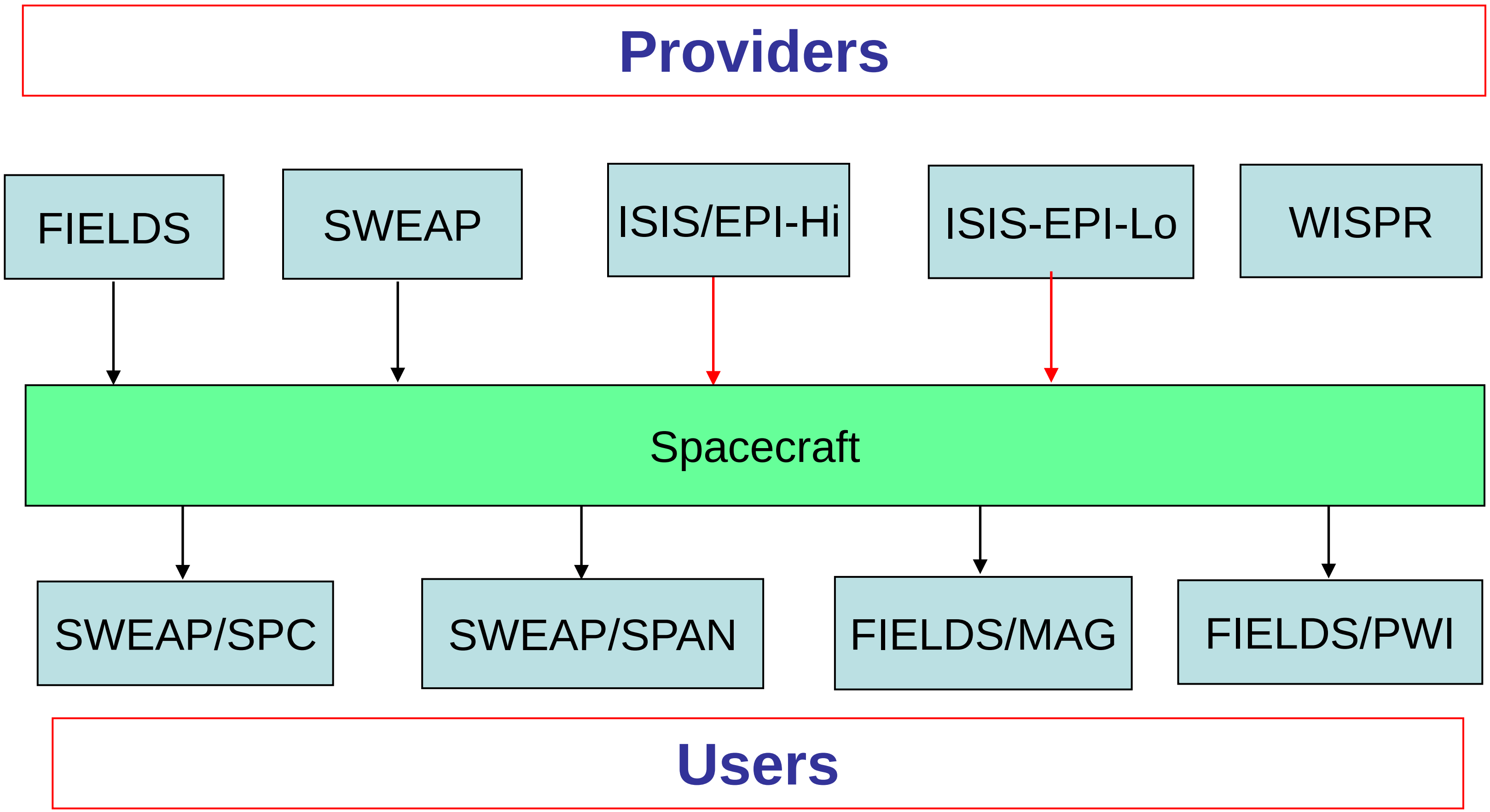
Additional telemetry will be allocated to instruments as the design matures and the margin is released

SPP Burst Flag Plans: Information to be communicated

- Information to be communicated. Once per second, participating instrument provides:
  - Burst mode status once per second (Is the sensor capturing high rate burst data?)
  - “State of the system” information: What is the natural environment doing? e.g.:
    - Sample channel particle Intensity
    - Sample wave channel intensity
    - Magnetic RMS variability
    - Electric field magnitude
- Flags may be simple data extractions or complicated algorithms
  - Intensity of one selected channel.
  - Summation of many channels
  - Variability of a channel (e. g. $\Sigma(B_i\text{-}B_o)^2$)
  - Channel ratios (spectral hardness)
- Effective use of Burst Flags depend critically on SWG coordination.
  - SWG recommends when and where it would like all instruments to burst together based on “burst mode status” bits.
  - Coordination of responses to “state of the system” states is performed by the SWG or a designated subcommittee

SPP Burst Flag Plans: Who is participating?

Not all teams have indicated their desired level of participation



Science Planning on Solar Probe Plus

- Challenges
  - Managing the data on the instrument SSR and instrument part of the spacecraft SSR
  - Limited uplink and downlink opportunities on some orbits
  - Limited time to react to survey data and create commands to transfer data from the instrument SSR to the spacecraft SSR
- Solution
  - Create interactive display and analysis tool to integrate orbit operations template information with instrument specific information as an aid to planning
  - Use a file priority scheme optimized for orbit type, to downlink high priority survey data quickly
  - This will maximize the reaction time that the instrument teams have to analyze data and create commands to transfer over the data from the instrument SSR to the spacecraft SSR

Summary

- Top-priority science goals for over five decades will be answered by SPP
  - How the corona is heated and the solar wind accelerated
- SPP will return the key, lacking, local and in-situ diagnostics and integrated measurements to make transformational advances in understanding.
  - Ionized particle distributions from plasma through the most energetic particles
  - Electromagnetic and electrostatic plasma waves can buffer and enable energy and momentum flow
  - Coronal imaging “from the inside out” bridges local to global scales by providing the context
- The science drivers are well understood
- The science objectives of the mission flow to specific mission, measurement, and instrument requirements.
- The SPP mission meets Level 1 traceability requirements for full and threshold success.


It has been 50+ years since the Solar Probe Concept was introduced. . .
We are on our way!

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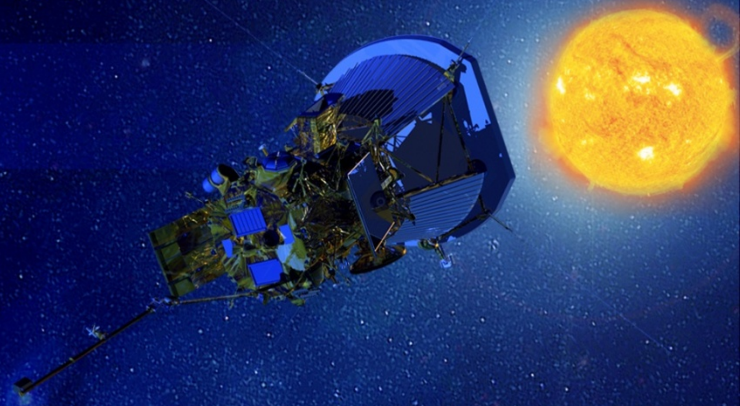

Project Science Overview

Back-up slides

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Project Science Team Org Chart

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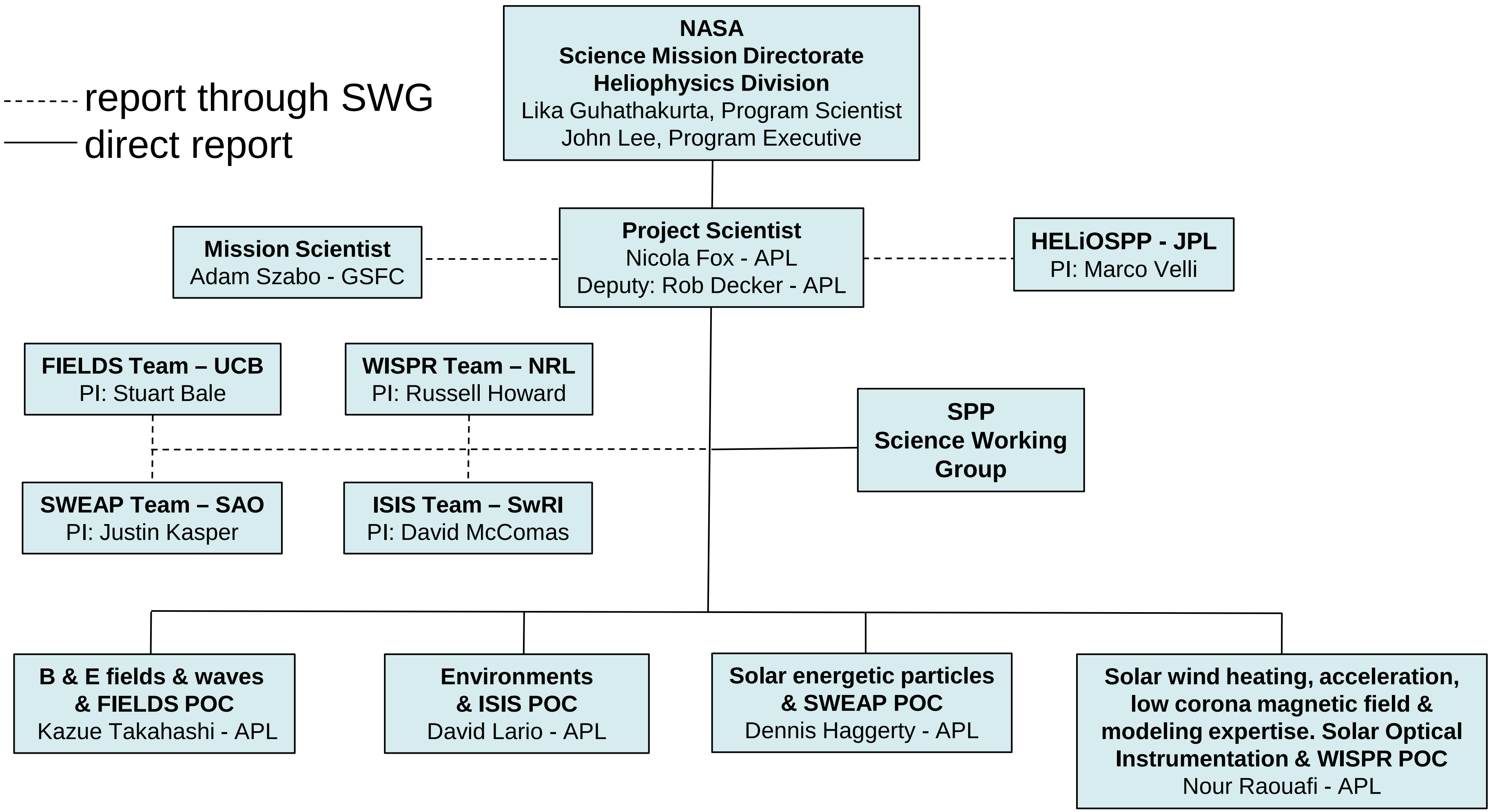

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SPP Maps Directly to NASA's Strategic Plan and Heliophysics Science Goals

- **The SPP mission is a major contributor to the heliophysics research objectives in the 2010 *Science Plan for NASA's Science Mission Directorate* that flow from Outcome 2.2 in the *2011 NASA Strategic Plan* and down to the heliophysics roadmap**

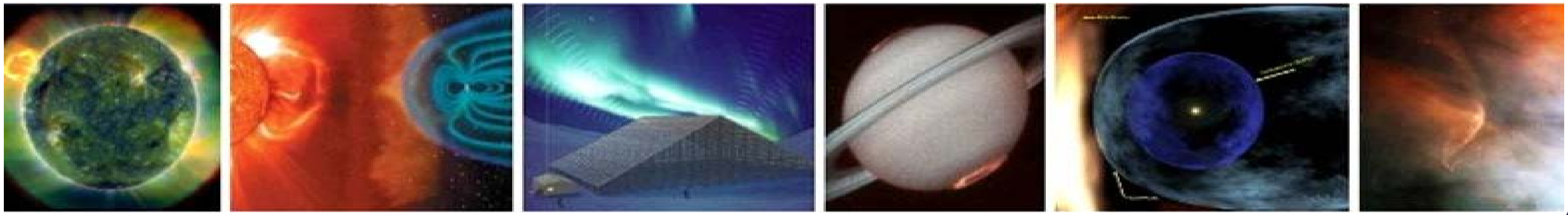
Strategic Goal 2: Expand scientific understanding of the Earth and the universe in which we live.		
NASA Outcome 2.2: Understand the Sun and its interactions with Earth and the solar system.		
Heliophysics Research Objectives		Applicability of Solar Probe Plus
2.2.1	Improve understanding of the fundamental physical processes of the space environment from the Sun to Earth, to other planets, and beyond to the interstellar medium	Major
2.2.2	Improve understanding of how human society, technological systems, and the habitability of planets are affected by solar variability interacting with planetary magnetic fields and atmospheres	Supporting
2.2.3	Maximize the safety and productivity of human and robotic explorers by developing the capability to predict extreme and dynamic conditions in space.	Supporting

Solar Probe Plus and the 2013-2022 Decadal Survey in Solar and Space Physics (Heliophysics)

- Solar Probe was the top priority mission in the 2003 NRC Decadal Survey in Heliophysics and this support was renewed in the 2009 mid-decade review
- The new 2013-2022 Decadal Survey in Solar and Space Physics (Heliophysics) released last year was the first opportunity for an NRC review of Solar Probe Plus and the selected science payload.
  - The steering committee was asked to comment on the scientific rational for the mission in the context of scientific developments since the publication of the 2003 survey
- Highest priority recommendation of the survey was to complete implementation of the selected missions, including SPP
  - "Solar Probe Plus will make mankind's first visit to the solar corona to discover how the corona is heated, how the solar wind is accelerated, and how the Sun accelerates particles to high energy."
  - Makes fundamental progress on two of the overarching goals of the Decadal Survey
    - Goal 1. Determine the origins of the Sun's activity and predict the variations in the space environment.
    - Goal 4. Discover and characterize fundamental processes that occur both within the heliosphere and throughout the universe.

Selected Decadal Survey Steering Committee statements on SPP

- **“The 2002 Decadal Survey recommended a solar probe intended to, ‘determine the mechanisms by which the solar corona is heated and the solar wind is accelerated and to understand how the solar wind evolves in the innermost heliosphere.’ Our survey finds that the scientific rationale for a solar probe remains compelling and concludes that SPP meets that challenge.”**
- **“During the past decade remote observations have revealed much about particle acceleration, heating, plasma turbulence, waves, and the flows of mass and energy in the corona. In the survey committee’s view, these observations only increase the need for measurements from this critical region.”**
- **“The closest approach for SPP is 9.5 solar radii instead of 4 solar radii. The loss in proximity is significant, but more than compensated for by the opportunity to spend far more time close to the Sun and gather observations spanning half a solar cycle. This latter feature in particular makes the timing of the mission with respect to the solar activity cycle a less significant issue.”**
- **“… SPP offers the prospect of a substantially enhanced scientific return compared to the earlier solar probe concept.”**



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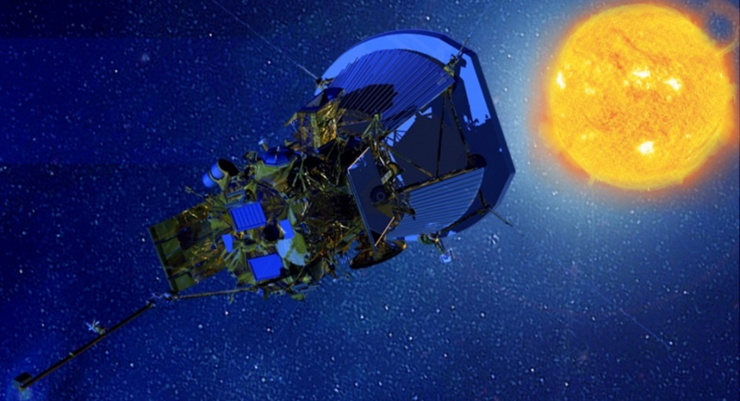

Level 1 Science Requirements Document Details

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Detailed Science Sub-Questions

1. **Trace the flow of energy that heats and accelerates the solar corona and solar wind.**
   a. **How is energy from the lower solar atmosphere transferred to, and dissipated in, the corona and solar wind?**
   b. **What processes shape the non-equilibrium velocity distribution observed throughout the heliosphere?**
   c. **How do the processes in the corona affect the properties of the solar wind in the heliosphere?**
2. **Determine the structure and dynamics of the plasma and magnetic fields at the sources of the solar wind.**
   a. **How does the magnetic field in the solar wind source regions connect to the photosphere and the heliosphere?**
   b. **Are the sources of the solar wind steady or intermittent?**
   c. **How do the observed structures in the corona evolve into the solar wind?**
3. **Explore mechanisms that accelerate and transport energetic particles.**
   a. **What are the roles of shocks, reconnection, waves, and turbulence in the acceleration of energetic particles?**
   b. **What are the source populations and physical conditions necessary for energetic particle acceleration?**
   c. **How are energetic particles transported in the corona and heliosphere?**

Fields and Waves Measurement Tables

- **Baseline**

REQ#	Measurement	Dynamic Range	Cadence	Bandwidth
4.1.1.1	Magnetic Field	140 dB	100k vectors/s	DC - 50 kHz
4.1.1.2	Electric Field	140 dB	2M vectors/s	DC - 1 MHz
4.1.1.3	Plasma Waves	140 dB	1 spectrum/s	~ 5 Hz - 1 MHz
4.1.1.4	Quasi-Thermal Noise/Radio	100 dB for QTN 80 dB for radio	1 spectrum/4 s QTN 1 spectrum/16 s radio	10-2500 kHz QTN 1-16 MHz radio

- **Threshold**

REQ#	Measurement	Dynamic Range	Cadence	Bandwidth
4.1.2.3	Magnetic Field	125 dB	256 vectors/s	DC - 128 Hz
4.1.2.4	Electric Field	125 dB	256 vectors/s	DC - 128 Hz
4.1.2.5	Plasma Waves	90 dB	1 spectrum/10 s	~ 5 Hz - 50 kHz
4.1.2.6	Quasi-Thermal Noise/Radio	70 dB for QTN 70 dB for radio	1 spectrum/32 s QTN 1 spectrum/32 s radio	10-2500 kHz QTN 1-16 MHz radio

*plasma density to better than 1% accuracy over the whole orbit & temperature to better than 5%

Thermal Particle Measurement Requirements Tables

- **Baseline**

REQ#	Meas.	Energy range(1)	Energy Res.	FOV	Ang. Res.(2)	VDF cadence	Mass Res.(3)
4.1.1.5	Thermal Ions	10 eV – 20 keV	< 20%	nadir and ram directions	$10^{o}x25^{o}$	1 Hz	d(m/q)/(m/q) < 25%
4.1.1.6	Thermal Electrons	5 eV – 20 keV	< 20%	> 75% of the sky	$10^{o}x10^{o}$	1 Hz	n/a

- **Threshold**

REQ#	Meas.	Energy range(1)	Energy Res.	FOV	Ang. Res.(2)	VDF cadence	Mass Res.(3)
4.1.2.7	Thermal Ions	100 eV – 10 keV	< 30%	nadir and ram directions	$20^{o}x25^{o}$	1 Hz	None
4.1.2.8	Thermal Electrons	5 eV – 2 keV	< 30%	> 65% of the sky	$20^{o}x20^{o}$	1 Hz	n/a

1: Energy range not required in all directions
2: Angular resolution not required in all directions
3: Mass resolution not required in all directions

White Light Baseline Measurement Requirements Tables

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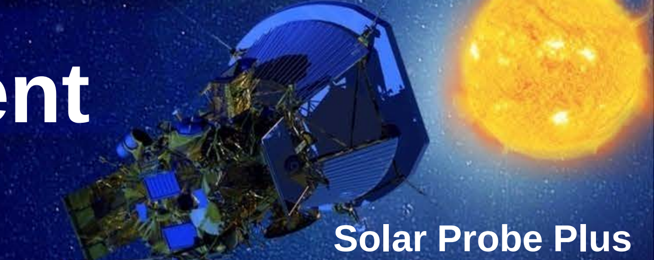
- **Baseline**

REQ#	Meas.	Cadence	FOV	Inner FOV bound.	Spatial res.	Photometric sensitivity (SNR/pixel)
4.1.1.7	Visible Broadband	≤16.5 min	≥76° radial x ≥20° transverse at 14° elongation to ≥44° transverse at 90° elongation	≤ 14°	≤ 6.4 arcmin	≥ 20

- **Threshold**

REQ#	Meas.	Cadence	FOV	Inner FOV bound.	Spatial res.	Photometric sensitivity (SNR/pixel)
4.1.2.9	Visible Broadband	≤22.5 min	≥ 74.75° radial x ≥ 20° transverse at 15.25° elongation to ≥ 44° transverse at 90° elongation	≤ 15.25°	≤ 7.5 arcmin	≥ 8

Energetic Particle Measurement Requirements Tables



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- **Baseline**

REQ#	Meas.	Energy range (1)	Highest cadence (2)	FOV (3)	Angular sector	Composition (4)
4.1.1.8	Energetic electrons	≤0.05 to ≥3 MeV	≤1 sec (select rates)	≥π/2 sr in sunward & anti-sunward hemispheres	≤45° sectors	n/a
4.1.1.9	Energetic protons and heavy ions	≤0.05 to ≥50 MeV/nuc	≤5 sec (selected rates)	≥π/2 sr in sunward & anti-sunward hemispheres	≤30° sectors	at least H, He, ^{3}He, C, O, Ne, Mg, Si, Fe

- **Threshold**

REQ#	Meas.	Energy range (1)	Highest cadence (2)	FOV (3)	Angular sector	Composition (4)
4.1.2.10	Energetic electrons	≥1.5 decade in the range from 0.02 - 6 MeV	≤10 sec	≥π/4 sr in sunward & anti-sunward hemispheres	sunward vs anti-sunward	n/a
4.1.2.11	Energetic protons and heavy ions	≥2 decades in the range from 0.02 to 100 MeV/nuc	≤10s, protons; 1 min, ion rates	≥π/4 sr in sunward & anti-sunward hemispheres	sunward vs anti-sunward	protons, heavy ion groups (He, CNO, NeMgSi, Fe)

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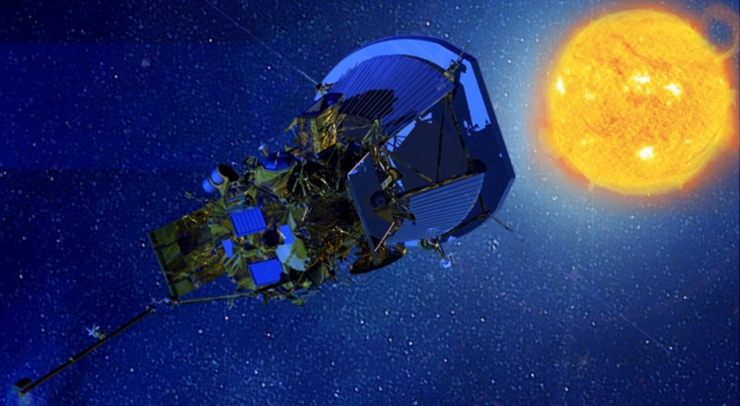

SPP Project Science Environment Trades

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1. Solar energetic proton fluences & peak intensities

- Title: "*Estimation of Solar Energetic Proton Mission-integrated Fluences and Peak Intensities at Solar Probe Plus*"
- Purpose: Estimate mission-integrated solar energetic proton (>5 MeV) fluences and peak intensities that SPP may observe throughout its orbit
- Method: (1) Use solar energetic proton data measured at 1 AU during solar cycles 20-23 (1973/303-2008/182)*; (2) assume 1 AU proton intensities are representative of those that SPP will see; (3) use Monte Carlo code to perform successive SPP launches during time covered by proton data; (4) adopt radial (*r*) intensity dependence $j(r) \sim r^{-a}$ of protons to extrapolate 1 AU peak intensities and fluences to SPP; (5) generate statistical dists. using set of virtual launches from step (3); (6) estimate mission-integrated fluences and maximum peak intensities at given confidence levels from dists. generated in step (5).
- Product: Plots and tables of proton fluences and peak intensities in multiple integral and differential proton channels >5 MeV; [recent update to includes >300 keV protons]. *Space Weather*, *9*, S11003, doi:10.1029/2011SW000708, 2011.
- SharePoint Folder/Relevant Documents/POC: Shared_Documents/Science Trade Documentation/High-energy_solar_protons/"2011SW000708"/POC: D. Lario (david.lario@jhuapl.edu), R. Decker (robert.decker@jhuapl.edu)
- Misc.: Supporting material [code, data files, presentations, earlier work ("SPP Radiation Environments_Jan-27-09, related results"), etc.] are included for reference.

*Extending data set to include solar cycle 24.

2. Solar energetic electron fluences & peak intensities

- Title: "*Estimate Mission-integrated Fluences and Peak Intensity Distributions of Electrons 0.05-6.2 MeV at Solar Probe Plus*"
- Purpose: Purpose: Estimate mission-integrated solar energetic electron fluences and peak intensities that SPP may observe throughout its orbit
- Method: Method: (1) Use ACE and SOHO electron data measured at 1 AU for solar cycles 23 & 24 (1997/242-2012/197); (2) assume 1AU electron intensities are representative of those that SPP will encounter; (3) use Monte Carlo code to perform successive SPP launches during period covered by electron data set; (4) adopt radial (r) intensity dependence $j(r) \sim r^{-a}$ to extrapolate 1AU peak intensities and fluences to SPP; (5) generate statistical dists. using set of virtual launches from step (3); (6) estimate mission-integrated fluences and maximum peak intensities for given confidence levels from dists. generated in step (5).
- Product: Integral and differential fluence and peak intensity energy spectra of electrons 0.05-6.2 MeV on several time scales (mission-integrated, yearly, daily, and hourly)
- SharePoint Folder/Relevant Document/POC: Shared_Documents/Science Trade Documentation/High-energy_solar_electrons/"*SPP Radiation Environments Jan-27-09*," (fluences), "*SPP_Electron_DDD_Dists_11feb13*" (peak intensities) / POC: R. Decker, D. Lario

3. Distributions of time durations when $j_{SEP} > j_{critical}$

- Title: "*SEP Events at distances <1 AU: Particle Intensities above Threshold Values*"
- Motivation: Protons > few 10s of MeV with intensity $j > j_c$ (c = critical) can produce transient ionization tracks intense enough white-out star tracker CCD array images. Purpose is to estimate probability distribution of time durations for which $j > j_c$ as a function of SPP helioradius for proton energies > *E.*
- Method: (1) Step hour-by-hour along SPP orbit, sample Earth-based time-series of data, varying 1AU SEP intensity (j_E) with helioradius (r) as $j(r)=j_E(r_E/r)^a$; (2) For each virtual mission, identify and record all time periods when $j(r) > j_c$. (3) Repeat N >>1 virtual missions by sliding "launch date" by one day, thereby exposing SPP to different intensity profiles as function or *r*. (4) Extract statistical info. from dists.
- Product: Probability dists. in several radial bins within 9.5-230 R_S from which one can calculate when *j* will exceed j_c for specified time duration and specified value of j_c for solar energetic protons > 30 MeV.
- SharePoint Folder/Relevant Documents/POC: Shared_Documents/Science Trade Documentation/Star_trackers_SEPS/"*AGUF11_SH44B-05_decker.pptx," and earlier report "SEP_Protons_and _Star_Trackers_30aug10*"/ POC: R. Decker, D. Lario
- Misc.: Method has also been used for other proton energies and for electrons

4. Solar electrons & DDD

- Title: "*Solar Energetic Electrons (0.05-6.2 MeV): Estimates of Peak Intensities and Long-term Averages for use in SPP Deep Dielectric Discharge Analyses*"
- Motivation: Solar energetic electrons can bury themselves inside dielectric materials of SPP. If the deeply-penetrating electrons build up faster than charges are able to leak out of the material, the charge inside the dielectric can create potentials that exceed the breakdown potential for the material. The purpose is to characterize the high-energy electron environment with regard to peak electron intensities and their durations and the long-term intensities over the SPP mission
- Method: Monte Carlo simulation code uses hourly electron intensities $j(E)$ and SPP mission profile to: (1) perform multiple, daily-spaced, successive virtual launches of SPP into electron intensity versus time profiles, which are assumed to vary with helioradius r as $j(E, \mathrm{r}) = j(E, r_E)(r_E/r)^{-a}$; (2) record peak one-hour intensity for each mission; and, (3) construct probability distributions versus peak intensity for five electron channels. Also construct distributions of time durations when $j(E) > j_c(E)$.
- Product: Tables and plots of peak electron intensities at 1- and 2-sigma confidence levels, mission-averaged electron intensities in multiple radial bins 9.5-230 R_S, and probability dists. that $j > j_c$ for given time duration, energy channel, critical intensity j_c
- SharePoint Folder/Relevant Document/POC: Shared_Documents/Science Trade Documentation/Deep_dielectric_charging/"SPP_Electron_DDD_Dists_15JUL13" & "spp_electons_decker_01mar13.ppsx"/ POC: R. Decker, D. Lario

5. Radiant energy and momentum fluxes on solar arrays

- Title: “*Energy and Momentum Fluxes from a Spherical Segment of the Sun: Application to Solar Probe Plus*”
- Purpose: Calculate the wavelength-integrated and wavelength-dependent radiant energy flux and wavelength-integrated momentum flux incident on a tilted area element that views a spherical segment of the limb-darkened sun when the area element is at a given radial distance from sun-center.
- Method: Constancy of specific intensity (I) along ray paths from sun to spacecraft element and the geometry are used to evaluate energy and momentum fluxes (1^{st} & 2^{nd} moments of I w.r.t cosθ) by integrating over solid angle subtended by solar segment as viewed by array area element at SPP
- Product: Expressions for energy and momentum fluxes both as definite integrals that can be evaluated numerically and as analytic approximations based on expansions in smallness parameter (solar radius)/(SPP radius), which allows quick and relatively accurate evaluations
- SharePoint Folder/Relevant Documents/POC: Shared_Documents/Science Trade Documentation/Solar_array_energy_and_momentum_flux/ ”Radiant_Energy_and_Momentum_Flux_25Jul12”/ POC: R. Decker

6. Dust environment & star trackers

- Title: "Modeling the solar dust environment at 9.5 R_{SUN}: Revealing radiance trends with MESSENGER star tracker data"
- Motivation: MESSENGER star tracker background irradiances (2007-2010; 0.3 to 1 AU) show strong spatial (heliocentric latitude and longitude) trends in dust irradiance, the positional changes of which suggest that the background trends are not due to inherent instrument effects. A model was developed to simulate scattered light incident on a sensor due to the F- and K-coronae as a function of radial distance from the Sun.
- Method: Use best interplanetary dust model (e.g., Grün-Mann) to model irradiance at virtual star tracker as functions view direction (lat., long.) & helioradius.
- Results: Scattering model replicated the observed helioecliptic latitudinal trends in the MESSENGER star tracker data. The error associated with the star tracker measurements does not help to validate the dust collision models proposed by Ishimoto (2000). The star tracker data does provide the clearest insight into observations of latitudinal radiance variations to date.
- SharePoint Folder/Relevant Document/POC: Shared_Documents/Science Trade Documentation/Interplanetary_dust/"*space_weather_v3*"/S. Strong et al. (2010)/ POC: R. Decker
- Misc.: Dust models reviewed in "*dust_models_4mar09_appen_2mar10*" (D. Lario)

7. Solar activity & solar limb sensors

- Title: "*Effects of transient solar activity on Solar Probe Plus solar limb sensors*"
- Purpose: (1) Estimate how much the wavelength-integrated solar brightness (total solar irradiance) decreases or increases due to the presence on the solar disk of sunspots and facular fields; and, (2) Provide quantitative evaluations of how such localized brightness variations will affect the performance of solar limb sensors on SPP near closest perihelia passes.
- Method: Developed a model to simulate sun's appearance in integrated light from 350 nm to 2600 nm (> 98% of total solar energy output). Used model to estimate the deviation of radiant intensity and power from nominal conditions (blank sun) when active regions were present within the field of view of the SLSs.
- Results: SLSs are only marginally affected by transient solar activity. Effect at low penetrations into penumbra: (a) < 0.1" → ~1% probability of 10-20% incident power increase, (b) 0.1"- 0.2" → ~1.5% probability of 7-10% incident power increase. Main effect is to trigger SLS earlier → overestimate spacecraft tilt using SLS system.
- SharePoint Folder/Relevant Documents/POC: Shared_Documents/Science Trade Documentation/Solar_limb_sensors/*SPP_SLS_solar_activity_20Jul11_draft*/POC: P. Bernasconi (Pietro.Bernasconi@jhuapl.edu), Nour-Eddine Raouafi (NourEddine.Raouafi@jhuapl.edu)

8. Coronal brightness

- Title: "Radiation scattering in the solar corona: Thomson scattering (K-corona) and Mie scattering (F-corona)"
- Motivation: The SPP project and investigation teams require estimates of radiation flux resulting from the coronal scattering.
- Method: A single numerical package was written to simulate the scattering of solar radiation by coronal free electrons (Thomson scattering) and heliospheric dust, assuming the Mie solution of homogeneous spherical dust grains.
- Product: Computer code that calculates the contributions of both Thomson and Mie scattering using the same numerical code with options for calculating these contributions separately or combined and also returning spectral or wavelength-integrated intensities. The code is written in Fortran 95 with an IDL wrapper whose purpose is to run the Fortran code and use the output data to create plots and estimate different quantities depending on user objectives.
- SharePoint Folder/Relevant Document/POC: *Shared_Documents/Science Trade Documentation/"Radiation_Scattering_Solar_Corona"*/ POC: N-E. Raouafi, R. Decker
- Misc.: Code in *Supporting_Material* folder. Trade "*Corornal_Brghtness_01Aug11*" examined effects of enhanced K-corona brightness on star trackers.

9. Key solar wind parameters

- Title: “*Key Solar Wind Parameters and Their Radial Variations for Use in Modeling Environmental Effects at Solar Probe Plus: Nominal values*”
- Purpose: Provide nominal values for key fast and slow solar wind parameters ($\mathbf{V}$,n_s,T_s) and reasonable upper and lower limits on these parameters as functions of heliocentric radial distance R in the range 9.5-230 R_S (0.0442-1.070 AU) that will be sampled by SPP. Initial work & report performed to support spacecraft surface charging modeling.
- Method: Performed literature searches, extracted functions and data (plots, tables, digitized curves) from several published reports, and constructed fit functions to reproduce radial variation of SW parameters ($\mathbf{V}$,n_e,n_p,T_e,T_p,$\mathbf{B}$).
- Product: Produced technical report describing methodology and results, constructed a variety of tables containing combinations of key solar wind parameters (i.e., avg., upper- & lower-limits), in the SPP frame, for a range of helioradii, in format suitable for input to NASCAP-2K
- SharePoint Folder/Relevant Documents/POC: Shared_Documents/Science Trade Documentation/Solar_Wind_for_charging/ ”SPP_Key_SW_Parms_Nominal_29aug11"/ POC: R. Decker, N-E. Raouafi, D. Lario

10. Spacecraft surface charging

- Trade: "*Spacecraft Surface Charging Modeling for Solar Probe Plus: Results and Recommendations for a Mission to the Near-Sun Environment*"
- Purpose: Extended SPP surface charging analyses to cover a range of trajectory points, from perihelion out to 0.3 AU, using updated solar wind plasma parameters and including various material configurations to predict how self-consistent charging potential varies along SPP orbit.
- Method: NASCAP-2K surface charging code (written, maintained, & owned by SAIC)
- Results: Worked with M. Donegan, who performed runs to determine dependence of differential and charging on solar wind parameters as a function of radial distance. Worked with SAIC to include convected maxwellian distributions for both electrons and ions for arbitrary direction of convection direction in order to include aberrated solar wind flow during closest perihelion passes.
- SharePoint Folder/Relevant Documents/POC: Shared_Documents/Science Trade Documentation/Spacecraft_surface_charging/"SPP_charging_-_Space_Weather", memo "RPM-09-XXX SPP Charging 2009-06-24"/POC: M. Donegan (Michelle.Donegan@jhuapl.edu)
- Misc.: Results included in EDTRD.

11. Observability of Z+ and Z- fluctuations

- Title: "*Z+ and Z- Observability Considerations for FIELDS & SWEAP*"
- Motivation: Z+ is the sum the velocity and magnetic fluctuations ($Z+ = \delta u + \delta b$), while Z- is the difference ($Z- = \delta u - \delta b$). Observing these fluctuations and relating them to temperature measurements may contribute significantly to understanding solar wind heating. Concerns of FIELDS sensitivity and SWEAP Level 1 cadence requirements necessary to observe Z+ fluctuations motivated investigations of the issue via simulation.
- Method: Used a 2.5D compressible MHD simulation code to study observability of Z+ and Z- fluctuations. Scales adjacent the ion-cyclotron resonance were modeled by introducing standard Hall and Finite-Larmor-Radius (FLR) corrections to the MHD code.
- Results: (1) Pure Z- fluctuations are not necessarily emanating from the Alfvén critical point. Depending on the presence of velocity shears or magnetic flux tubes, a broad range of Z- to Z+ ratios is possible. (2) When a Z- population of fluctuations does dominate, the "minority species" of Z+ fluctuations appear in k-space along directions orthogonal to mean magnetic field. (3) Observing the Z+ "minority species", especially at perihelion, requires a high spacecraft transverse speed relative to outward propagating solar wind.
- SharePoint Folder/Relevant Document/POC:Shared_Documents/Science Trade Documentation/Z+_Z-_Observability/ "*SPP_SWG_Telecon_ZplusZminus_20120427_Ghosh*"/POC: R. Ghosh (ron.ghosh@jhuapl.edu)

12. Magnetic fields from induced currents in TSA

- Title: "*Assessment of Contamination Magnetic Fields Generated by Induction Effects in the Solar Probe Plus TSA*"
- Motivation: The transition support assembly (TSA) is a titanium structure forming several electrically closed loops. Variable solar wind magnetic fields will induce electric currents in these loops, which will generate magnetic fields that contribute to the measured external magnetic field. The purpose was to assess the relative magnitude of the contamination field to guide the mechanical design of the TSA.
- Method: Performed calculations to estimate amplitudes of magnetic fields created by loop currents induced in SPP TSA structure by a time-varying solar wind magnetic field to provide worst-case estimate of induced field ~3 meters behind the TSA along the boom where the magnetometers will be located.
- Results: It was concluded from calculation that induced magnetic field will be negligible compared to the applied field for frequencies well below the self-induction frequency, and will increase and flatten off to < 1% of the applied field when the wave frequency ≥ few kHz
- SharePoint Folder/Relevant Document/POC: Shared_Documents/Science Trade Documentation/"*TSA Contamination Magnetic Fields 20120127 with Appendix*"/ POC: H. Korth (haje.korth@jhuapl.edu), R. Decker

13. Solar wind fluxes on SPP

- Trade: "*Estimates of Solar Wind Fluxes near SPP Closest Perihelion Passes*"
- Purpose: Provide estimates of solar wind number, momentum, and energy fluxes nominal for nominal ranges of solar wind parameters along SPP closest perihelion orbit.
- Method: Use nominal solar wind parameters and estimated upper/lower limits to integrate model velocity distributions (convected maxwellian, bi-maxwellian, kappa, bi-kappa, and three-component electron VDF) over surfaces of a reference cube moving along SPP orbit with surfaces oriented normal to spacecraft (x,y,z) axes.
- Product: Predicted fluxes ± 5 days of closest perihelion. Numbers fluxes useful for calculating thruster plume neutral ionization rates. Momentum fluxes useful for calculating small contribution of solar wind to radiation pressure under nominal conditions. Energy fluxes useful for calculating heat fluxes on oriented surfaces under nominal (<~ 1 W/m^2) and transient disturbed <~ few 10s W/m^2 near 9.5 R_S. Disturbed conditions estimated from R-H relations applied to simple model of CME.
- SharePoint Folder/Relevant Document/POC: Shared_Documents/Science Trade Documentation/"spp_sw_fluxes_05jun12"/ POC: R. Decker
- Misc.: Better estimates of fluxes under disturbed conditions will be provided.

14. Thruster plume gas expansion

- Title: “*Simulation of Thruster Plume Neutral Gas Expansion*”
- Purpose: Develop code to simulate expansion of thruster plume neutral constituents H_2, N_2, and NH_3. Use to investigate plume impingement on spacecraft components and science instruments.
- Method: Write DSMC code to include neutral expansion from steady-state thruster firings and interactions with simplified model of SPP spacecraft.
- Results: Developed 3D solar-wind/thruster-plume interaction code. Performed initial tests using flow of solar wind through the simulation domain. Included results provided from AeroJet into the 3D DSMC code. Both identification of the main plume parameters (densities, velocities, temperatures, etc.) at the Bird Breakdown Boundary and adaption between the grid used by Aerojet and the grid of the DSMC are required to start doing the 3D DSMC simulations of the thruster plume evolution.
- SharePoint Folder/Relevant Document/POC: Shared_Documents/Science Trade Documentation/Thruster_plume_expansion/”SPP_Plume_Modeling_07Jan11”/ POC: R. Decker, N.-E. Raouafi
- Misc.:

15. Thruster plume neutral constituents & science impacts

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- Title: "*Solar Probe Thruster Plume Ionization and Propagation*"
- Motivation (2010-11): Firings of 0.8N thrusters at an estimated rate of once every 30 seconds near closest perihelia passes could contaminate science measurements because expanding neutrals will undergo ionization, be picked up by solar wind, and return to spacecraft vicinity and possibly generate e-m fluctuations via instabilities. Purpose was to estimate ionization rate and evolution of various ions species.
- Method: Collected info. on molecular dissociation and ionization parameters of major neutral constituents from thruster firings. A time-dependent collisionless test-particle model of both thruster plume neutral constituents (H_2, N_2, NH_3) and ensuing ionization and spatial distribution of electrons and ions was developed.
- Results: Key finding is that peak electron and ion thruster-sourced densities within 1 km of the spacecraft range between 10^{-3} and 10^{-5} as a fraction of background solar wind densities and persist beyond 20 sec from a single 0.15 sec thruster pulse. Strong possibility that solar wind near spacecraft will be contaminated and not return to nominal state between thruster firings. Results detailed in report.
- SharePoint Folder/Relevant Document/POC: Shared_Documents/Science Trade Documentation/Thruster_plume_contamination/"Solar Probe Thruster Plume Ionization and Propagation"/POC: J. Emhoff (Jerold.Emhoff@jhuapl.edu), R. Ghosh, R. Decker
- Misc.: Ionization rates are in report "spp_plumes_rbd_01Jun11"

16. Solar Neutrons

- Title: “*Estimation of the Solar Flare Neutron Worst-case Fluxes and Fluences for Missions Traveling Close to the Sun*”
- Purpose: Estimate the fluence of solar flare neutrons throughout the nominal mission of SPP to assess probability of radiation damage.
- Method: Account for the survival probability of a neutron to reach a given helioradius and calculate the “observed” time-integrated spectrum of solar neutrons as a function of the observer’s helioradius. Use (1) a working relationship between the soft X-ray class of a flare and the flare’s production of solar neutrons, and (2) the number and size of soft X-ray flares that may occur during the SPP mission. Use method of successive launches of SPP to sample the predicted neutron fluxes.
- Results: Upper limit for the total fluence of solar neutrons at energies >1 MeV, >10 MeV, >100 MeV and >1000 MeV to which SPP may be exposed. Although method gives a conservative estimate of neutron fluxes, the predicted mission-integrated fluence of solar neutrons at SPP is orders of magnitude below that of solar energetic protons.
- SharePoint Folder/Relevant Document/POC: Shared_Documents/Science Trade Documentation/Solar_neutrons/”2011SW000732 (D. Lario, *Space Weather*,*10*, S03002, doi:10.1029/2011SW000732, 2012)”/ POC: D. Lario

17. Solar gamma rays

- Title: "*Estimation of the Solar Flare Gamma-ray Fluence at Solar Probe Plus*"
- Motivation: X-rays, both soft (from about ~1 to ~20 keV) and hard (from about ~20 to ~300 keV), and gamma-rays (from about ~300 keV to ~20 MeV) constitute the high-energy portion of the photon energy spectrum observed during solar flares. Our goal was to estimate the level of gamma radiation that SPP will receive during its mission.
- Method: We separate the energy spectrum into three sections, the first being gamma-rays (hard and soft X-ray fluences are described in another document). We used gamma-ray observations from SMM and RHESSI to estimate the gamma-ray total fluence and worst-case fluxes that SPP will receive during intense solar flares. Correlations between soft X-ray GOES observations and gamma-ray fluence, either observed during selected flares by RHESSI or catalogued using SMM data, were used.
- Product: Estimates of the fluence of gamma-rays that SPP will receive during its nominal mission.
- SharePoint Folder/Relevant Document/POC: Shared_Documents/"Science Trade Documentation/Solar_gamma_rays/"gamma_ray_fluence3"/ POC: D. Lario
- Misc.: Summary of X- and gamma-ray results are in "worst_case_fluence_flux"

18. Solar x-rays

- Title: "*Estimation of the Solar Flare Soft X-ray Fluence at Solar Probe Plus*"
- Motivation: X-rays, both soft (from about ~1 to ~20 keV) and hard (from about ~20 to ~300 keV), and gamma-rays (from about ~300 keV to ~20 MeV) constitute the high-energy portion of the photon energy spectrum observed during solar flares. Our goal was to estimate the level of x-rays that SPP will receive during its mission.
- Method: Estimated the solar flare hard X-ray (~20 to ~300 keV) photon fluence over the SPP nominal mission based on statistical analyses using SMM, ISEE-3, and RHESSI hard X-ray observations and their possible correlations between soft X-ray flare and microwave burst observations.
- Product: Characteristics of the soft and hard X-ray fluence distributions generated by using successive virtual launches of SPP throughout solar cycles 21-23, including the 95% confidence level obtained from these distributions.
- SharePoint Folder/Relevant Document/POC: Shared_Documents/"Science Trade Documentation/Solar_X_Rays/ "soft_Xray_fluence" & "hard_Xray_fluence2"/ POC: D. Lario
- Misc.: Summary of X- and gamma-ray results are in "worst_case_fluence_flux"

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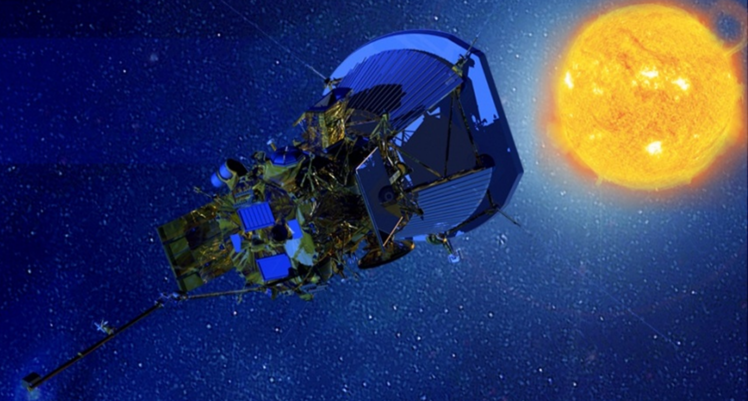

Science Data Management Plan

Selected example sections

APL
The Johns Hopkins University
APPLIED PHYSICS LABORATORY

Science Data Management Plan

- During Phase B, a draft version of the SPP SDMP has been generated
  - Prepared by the Project Scientist with inputs from the science teams, but "owned" and approved by HQ SPP Program Scientist.
- Compliant with "Heliophysics Science Data Management Policy" and relevant NASA documents (NPD 2200.1; NPR 2200.2B; NPR 1441.1)
- Presents strategy for generation, validation, documentation, delivery & sharing of science data products by each instrument Science Operation Centers (SOCs).
- Specifies policies & procedures for distributing data to co-investigators, wider science community, and general public.
- Specifies "Rules of the Road" for data usage, coordination with other Heliophysics missions, archive strategy, access policy and release schedules.
- Describes the high-level plan for coordination with NASA Virtual Observatories, including the creation of meta-data products.

SPP SDMP Table of Contents

Mission-Level Science and Data Operations

- The SPP Mission will fully support the broader goals of the Heliophysics Data Environment by providing full and open access to various levels of the SPP science data products. During Phase C/D, the Science Working Group (SWG) will discuss coordination, cross calibration, and collaboration with other assets and missions and developed a framework for sharing data. The instrument teams will create meta-data products to help integrate SPP data into the appropriate NASA Virtual Observatories.

2.2.1 Coordination of Science/data Activities

- The SPP project will support the broader Heliophysics goals as laid out in the NASA Heliophysics Science Data Management Policy, which is a step forward in the evolution of the Heliophysics Data Environment. The goal of the Heliophysics Data Environment is to enable science discovery where data are efficiently served through active and (longer-term) resident archives. The SPP mission will provide a Science Data Portal – a web-based interface providing a common point of entry of specific interest to SPP scientists as well as the general public. The SPP Science Data Portal will provide ancillary services, tools, data and links that benefit the SPP project itself and allow users from the wider heliophysics community to access all SPP data and related products.
- The SPP instrument teams will also work with the appropriate VOs to promote the distribution of their data. The VOs provide a searchable data catalog of distributed space physics data products within a single user interface and allow scientists to access data from many missions from a single “data portal” or even directly from their own software applications

2.2.2 SPP Mission Rules of the Road for Data Usage

- As part of the development of collaboration with the broader Heliophysics community, the mission has drafted a “Rules of the Road” to govern how SPP instrument data is used.

1. The PI shall make all scientific data products available to the public, as stated in the SPP Science Data Management Plan.
2. Users should consult with the PI to discuss the appropriate use of instrument data or model results and to ensure that the Users are accessing the most recent available versions of the data and analysis routines. Instrument team SOCs and/or VOs should facilitate this process, serving as the contact point between PI and users in most cases.
3. Users should heed the caveats of investigators to the interpretation and limitations of data or model results. Investigators supplying data or models may insist that such caveats be published. Data and model version numbers should also be specified.
4. Browse products are not intended for science analysis or publication and should not be used for those purposes without consent of the PI.
5. Users should acknowledge the sources of data used in all publications, presentations, and reports.

- *" We acknowledge the NASA Solar Probe Plus Mission and [PI name] for use of data.”(list of PIs)*

6. Users are encouraged to provide the PI a copy of each manuscript that uses the PI’s data prior to submission of that manuscript for consideration of publication. On publication the citation should be transmitted to the PI and any other providers of data.

2.2.3 Coordination of science/data activities between SPP teams and other Heliophysics missions

- Through discussions of the SWG, the SPP Mission will develop methods of collaboration between the instrument teams. Initial coordination between SPP instrument teams include but are not limited to onboard data sharing and onboard event trigger signaling. This coordination will continue to be detailed through Phase C/D.
- 2.2.3.1 Data Sharing
- In order to optimize the science return from the SPP mission, the SPP instruments will coordinate data sharing of their Level 1 through 4 products.
- On the ground, there are 3 instances of exchange of data between teams. The first is quicklook data. These data are for planning purposes not for scientific analysis. The second data exchange is for selection of full resolution data periods of interest. The third exchange will occur in order to produce higher level data products.

2.2.3 Coordination of science/data activities between SPP teams and other Heliophysics missions (cont.)

- 2.2.3.2 Operations Planning
- Detailed orbit activity planning is required in advance for each SPP orbit. Since SPP is using a decoupled payload operations approach, tight coordination between the mission operations and instrument teams will be required. A SPP planning process is under development that will facilitate the coordination of spacecraft activities with the various instrument teams. Due to the limited downlink opportunities, a orbit planning tool is required to visualize detailed orbit availability of downlinks, power on opportunities, command uplink opportunities, data transfer from instrument memory to the spacecraft SSR, power constraints and the instrument data content in the spacecraft SSR.

4.1 SPP mission defined data product levels

Data Level	Brief Description	Latency Goal
L0	Reconstructed, unprocessed instrument data at full resolution; any and all communications artifacts, e.g., synchronization frames, communications headers, duplicate data removed.	N/A
L1	Instrument count rates at full resolution with supporting ancillary data (such as spacecraft ephemeris) needed for further processing. L1 data can be further split into L1A and L1B; L1B data would be calibrated L1 data needed to support L2 processing	14 Days (TBR)
L2	Calibrated data presented in the appropriate scientific units and transformed into relevant geophysical coordinate systems.	30 Days (TBR)
L3	Calibrated, re-sampled, averaged data that has been irreversible transformed to the point that lower level data cannot be reconstructed.	90 Days (TBR)
L4	Higher level data products that require significant effort in processing and involve the use of models and additional external data sets. These products may be produced for a subset of the complete dataset only	1 Year (TBR)

Mission Level Data Products (1/3)

Level	FIELDS	SWEAP	ISIS	WISPR
L0	Raw telemetry produced by SPP MOC Possibly 24-hour, APID-separated cleaned, sorted. PTP and SSR binary files	Raw Telemetry (Raw de-commutated telemetry received from MOC)	Raw telemetry packets, including HK, CMD-response rates, and event packets	Raw telemetry (CCSDS data packets)
L1	Uncompressed and decommutated L0 + time tagged waveform and spectral data in telemetry and engineering units [V, dBs, nT] in spacecraft coordinate systems. Data affinity groups. CDFs (one per subsystem per day). Quick look and daily/orbital summary plots	Instrument Count Rates (SPANs) Instrument Currents (SPC)	Time series of uncalibrated instrument science and engineering rates at highest resolution. Unpacked particle event data.	FITS files with uncompressed images. Image values are in raw counts (DN).

Mission Level Data Products (2/3)

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Level	FIELDS	SWEAP	ISIS	WISPR
L2	L1 + Time-tagged waveform and spectral data in fully calibrated physical units [V, mV/m, nT, $(V/m)^2/Hz$, nT^2/Hz] in spacecraft and heliophysical coordinate systems. CDFs. Quick Look and daily/ orbital summary plots.	Calibrated Particle flux (in physical coordinates & units) Solar Wind moments and energy spectra (Calculated onboard, calibrated, in physical coordinates & units)	Time series of calibrated particle intensities at highest time, energy, and look-direction resolution, in physical units.	FITS files with calibrations applied. Image values are in units of brightness.
L3	L2 + VxB removal for DC E-field measurement, offsets and corrections with data quality flags. Plasma density. Spacecraft potential. Merged B. Merged density and temperature (FIELDS-SWEAP) CDFs, Science data plots	Solar wind bulk parameters, energy spectra, and electron pitch angle distribution (Calibrated and calculated on the ground)	Time series of calibrated particle intensities, averaged into (TBD) appropriate sets of larger time, energy and look-direction bins. Time-series plots of the above items.	Data products are the result of combining two or more images (movies, Carrington maps, etc). May or may not be calibrated in physical units.

Mission Level Data Products (3/3)

Level	FIELDS	SWEAP	ISIS	WISPR
L4	Event (shocks, current sheets, radio bursts, stream interaction regions) time tags and parameters. Ad hoc.	Derived power spectra, source location, and event lists	Particle spectra and fluences for specific events and/or periods. Particle anisotropy parameters/plots. Others TBR.	Derived quantities (electron densities, CME masses etc).

4.1.1 Definitions of Planning, Quick-look and Final data products

- Planning Data
  - Planning products are data products that are quickly produced to aid in the operations planning process in-between instrument teams. The data are only to be distributed among the instrument teams and not to the public.
- Quick Look Data
  - The intention of quick look data is to provide a scientifically useful data product within a few days of acquiring data. The data are considered preliminary and cannot be cited, published or presented without the permission of the Principal Investigator.
  - Quick look data can be deleted or replaced once final calibrated data is available
- Final Data
  - Final data is defined as final calibrated data delivered to the public, but is subject to revision and recalibration as described in section 4.2.

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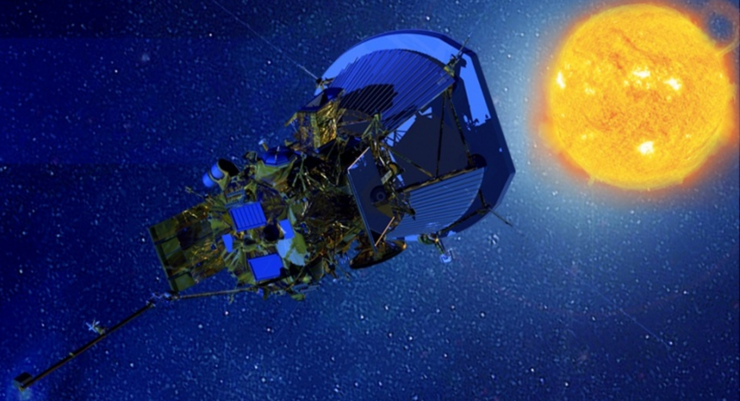

Mission System Engineering

Jim Kinnison
SPP Mission System Engineer

Jim.Kinnison@jhuapl.edu

13 – 16 January 2014

The Johns Hopkins University
APPLIED PHYSICS LABORATORY

Outline

- **System Engineering Organization**
- **Review Status**
- **Top-Level Requirements**
- **Mission Concept**
  - Critical Events
  - Single Point Failures
  - Test As You Fly Exceptions
- **Phase B Trades**
- **Technology Development**
- **Summary**

System Engineering Organization

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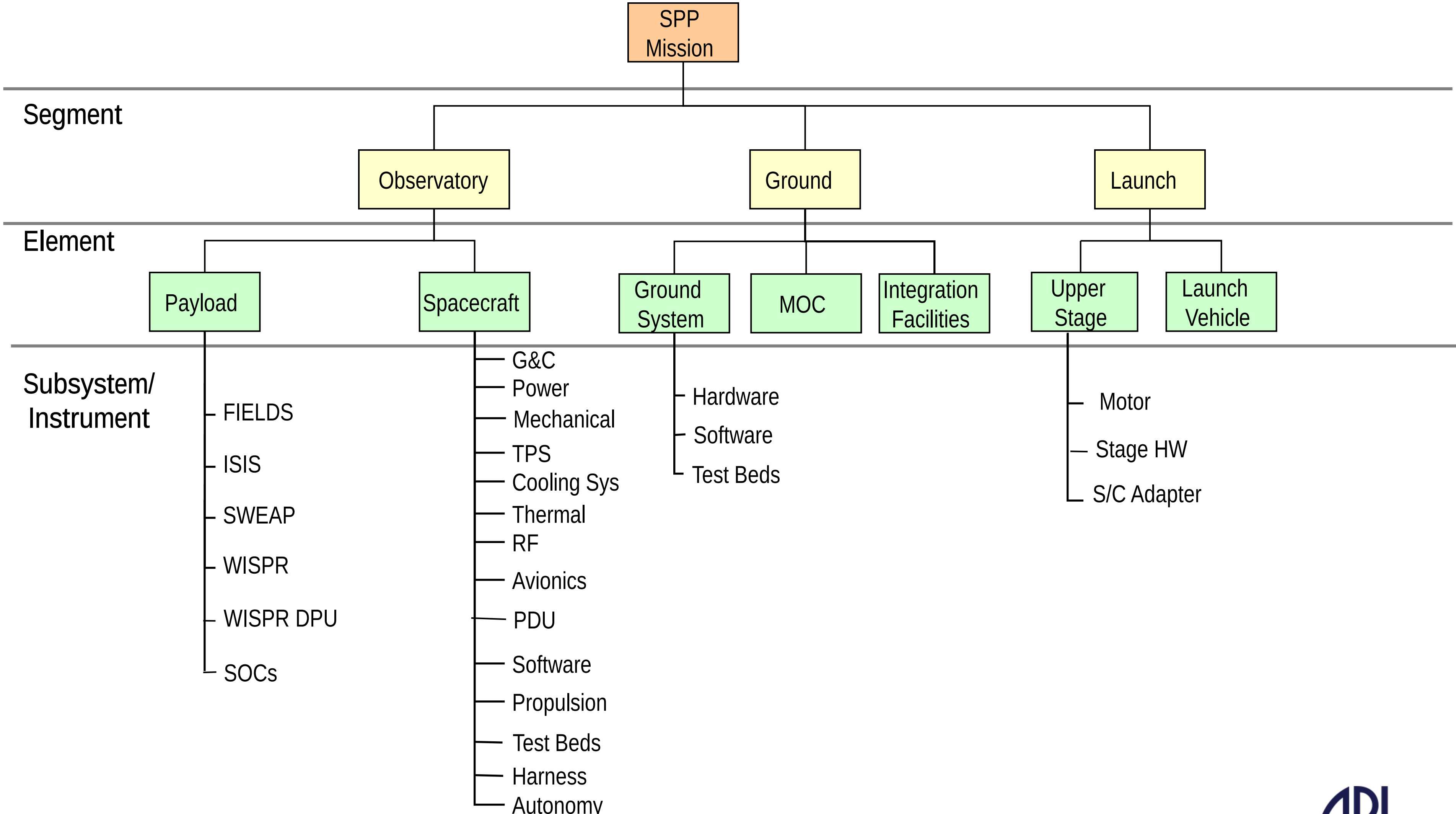
- LWS Program Office, Dennis Dillman, GSFC → Mission System Engineer

- **Mission System Engineer**
  Jim Kinnison
  Mary Kae Lockwood (Deputy)
  - Fault Management – Sanae Kubota
  - EMI/EMC – Carl Herrmann
  - Parts – David Bonner
  - Requirements – Dan Kelly
  - Contamination Control – John Nichols
  - Materials and Processes – Tyler Langley
  - Reliability – Clay Smith
  - Radiation – David Roth
  - Data System Engineer – Alan Mick
  - Charging – Michelle Donegan
  - Mission Design/Navigation – Yanping Guo
  - Integration & Test – Annette Dolbow
  - Spacecraft SE – Mary Kae Lockwood, Rich Conde (Deputy)
  - Payload SE – Elena Adams, Kris Fretz (Deputy)
  - Mission Operations – Nick Pinkine
  - Ground System HW – Walter Mitnick
  - Launch Vehicle Integration Manager – Steve Vernon
  - Upper Stage SE – Rich Anderson
  - Mission Software SE – Mike Furrow

Product Breakdown Structure



MDR Action Item Summary

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SRR/MDR 01	Internal Review of Cooling System Test Results	Completed/Concurred
SRR/MDR 02	Upper Stage System	Completed/Concurred
SRR/MDR 03	Need for a mission perspective on instrument elements	Completed/Concurred
SRR/MDR 04	Programmatic Data Request	Completed/Concurred
SRR/MDR 05	Star 48GXV Development and Qualification	Completed/Concurred
SRR/MDR 06	Star 48GXV Combustion Instability Testing and Analysis	**Completed**
SRR/MDR 07	Upper Stage (US) Coupled Loads Analysis (CLA)	Completed/Concurred
SRR/MDR 08	Basis of Estimation for Cost	Completed/Concurred
SRR/MDR 09	Staffing Profiles for Phase A & Phase B	Completed/Concurred
SRR/MDR 10	Upper Stage Materials Obsolescence	Completed/Concurred
SRR/MDR 11	Upper Stage Controlling Requirements	Completed/Concurred
SRR/MDR 12	Utilize TVC in proof of concept	Completed/Concurred
SRR/MDR 13	Negotiate Realistic IV&V Approach with NASA WVA IV&V	Completed/Concurred
SRR/MDR 14	Need Integrated, Systematic Approach to Fault Management	Completed/Concurred
SRR/MDR 15	Dust model errors & dust impact damage validation	Completed/Concurred
SRR/MDR 16	Solar irradiance modeling	Completed/Concurred
SRR/MDR 17	Fidelity of models used for SEE prediction	Completed/Concurred
SRR/MDR 18	Mission Design	Completed/Concurred

Phase B Reviews

- **Three Types of Reviews**
  - Life Cycle Reviews – mission PDR, currently
  - Subsystem/Discipline/Instrument Review – reviews that feed directly into life cycle review. Independent assessment of technology development.
  - Peer Reviews – less formal reviews (often tabletop) that are held to do a deep dive on specific topics within a subsystem or instrument.

- **Specific requirements for each type of review defined in memo for consistency across SPP.**
  - Format
  - Chair and Review Board
  - Action Item Tracking
  - Project Participation
  - Review Record
  - Entrance/Exit Criteria
  - Material Availability

- **At least one SRB Member invited to each Subsystem/Instrument review.**

Summary of Pre-PDR Instrument and Spacecraft PDRs

Subject	Type	Date(s)	# of RFAs	# of Rec.	Result
POC Motor	PDR	3-Mar-13	14	3	Pass
Fault Management	PDR	21/22-May-13	8	26	Pass
Liquid Propulsion	Peer	17-Sep-13	9	4	Pass
CONOPS	Peer	3-Oct-13	7	9	Pass
Flight Software	PDR	9/10-Oct-13	26	16	Pass
Harness	PDR	14-Oct-13	8	4	Pass
SWEAP	PDR	15/16-Oct-13	16	18	Pass
Ground Hardware	PDR	22-Oct-13	7	18	Pass
Cooling Sys Electrical	PDR	23-Oct-13	21	7	Pass
Telecomm	PDR	25-Oct-13	20	19	Pass
PDU	PDR	29-Oct-13	23	13	Pass
Launch System	Peer	30-Oct-13	0	4	Pass
Ground SW	PDR	4-Nov-13	10	33	Pass
ISIS	PDR	5/6-Nov-13	20	14	Pass
Solar Array	PDR	6-Nov-13	10	0	Pass
Avionics	PDR	11-Nov-13	11	8	Pass
Guidance and Control	PDR	12-Nov-13	8	14	Pass
FIELDS	PDR	13/14-Nov-13	20	26	Pass
Thermal	PDR	13-Nov-13	5	22	Pass

Subject	Type	Date(s)	# of RFAs	# of Rec.	Result
Structures/Mech	PDR	14-Nov-13	14	12	Pass
Mission Design/Nav	PDR	15-Nov-13	8	4	Pass
Electrical Power Sys	PDR	18/19-Nov-13	16	10	Pass
WISPR	PDR	19/20-Nov-13	16	5	Pass
Thermal Protection Sys	PDR	20/21-Nov-13	41	14	Pass
Cooling Sys Mech/Therm	PDR	3/4-Dec-13	21	21	Pass

- **Reviews highlighted in yellow also served as independent TRL-6 Assessments.**
- **All subsystems and technology items passed their pre-PDR assessments.**

Design Philosophy

- **Balance mission performance with resources and risk**
  - Early identification of risks and mitigations
  - Identify options that provide the best performance in priority areas compared to resources
  - High consideration to margin management and preservation
- **Try to maintain a simple design concept that minimizes risk and cost**
  - Maintain flexible mission design allowing step-by-step approach to minimum perihelion
  - Simplify spacecraft systems as possible
  - Maintain simple operating modes
    - STEREO and TIMED heritage operational approach
  - Minimize new technology developments and apply resources early
- **Maintain simple and clean interfaces**
  - Instruments perform de-coupled operations through SOCs

Driving Level 1/Level 2 Requirements

- **SPP shall**
  - Perform the measurements presented in Science Overview
  - Complete at least three orbits with a perihelion distance of <10 Rs from the center of the Sun
  - Develop a perihelion encounter geometry such that there are perihelion passes visible from Earth to allow for simultaneous Earth-based observations of the Sun to support SPP observations
  - Achieve minimum perihelion passes within 10 years of launch
  - Be categorized as Mission Classification 1, Risk Category B
  - Launch on a Risk Level 3 expendable launch vehicle
  - Develop a mission with launch readiness date in July, 2018
  - Develop a ground system to meet performance and data processing requirements
  - Develop a data management plan to address total activity associated with flow of science data.

Levels 1 & 2 Documents

- ✓ Level 1 Document (NASA) in signature cycle

- ✓ Mission Requirements Peer Review – 1 Aug 2012
- ✓ Update of Mission draft requirements following peer review
- ✓ Review draft of Mission requirements published
- ✓ MRD Rev B approved in PLM – Mar 2013
- ✓ Updates to MRD throughout Phase B
- ✓ MRD Rev C approved in PLM – Sept 2013
- ✓ MRD Rev C delivered to GSFC – Sept 2013

Reference Mission: Launch and Mission Design Overview

Launch

- Dates: Jul 31 – Aug 19, 2018 (20 days)
- Max. Launch C3: 154 km^2/s^2
- Requires Atlas V 551/Delta IVH class with project-provided Upper Stage

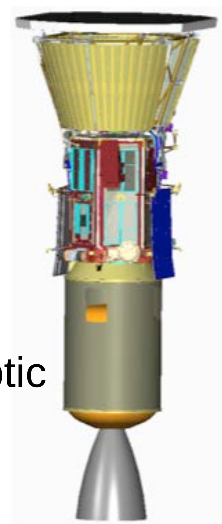
Trajectory Design

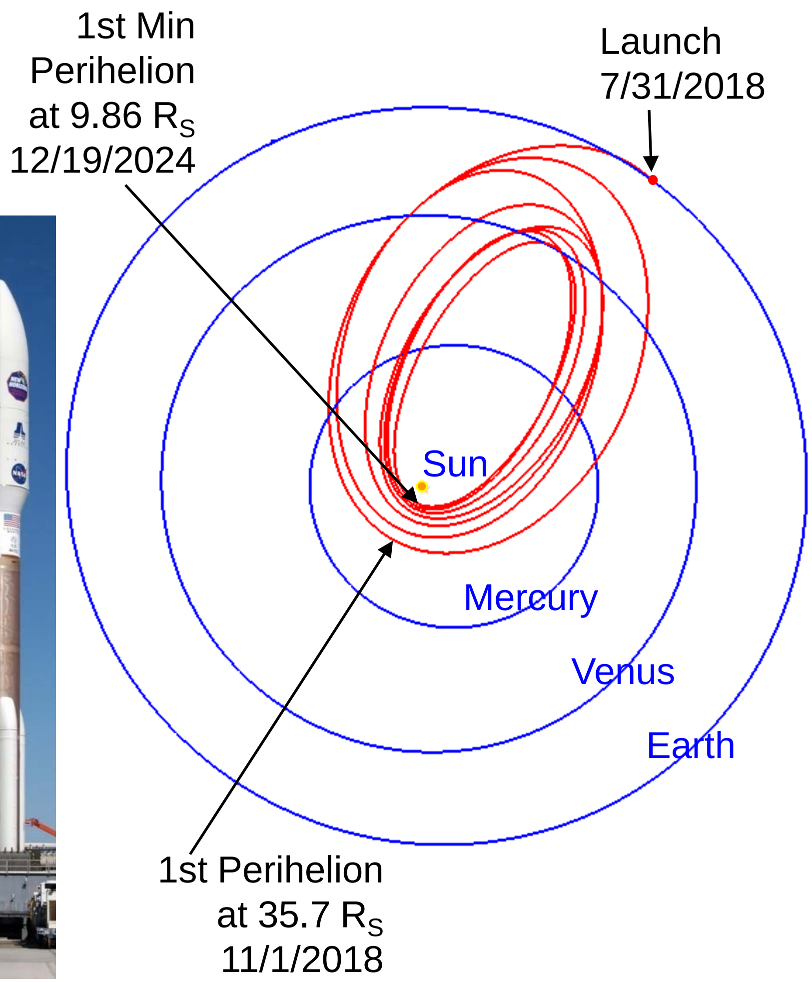
- 24 Orbits
- 7 Venus gravity assist flybys

Final Solar Orbits

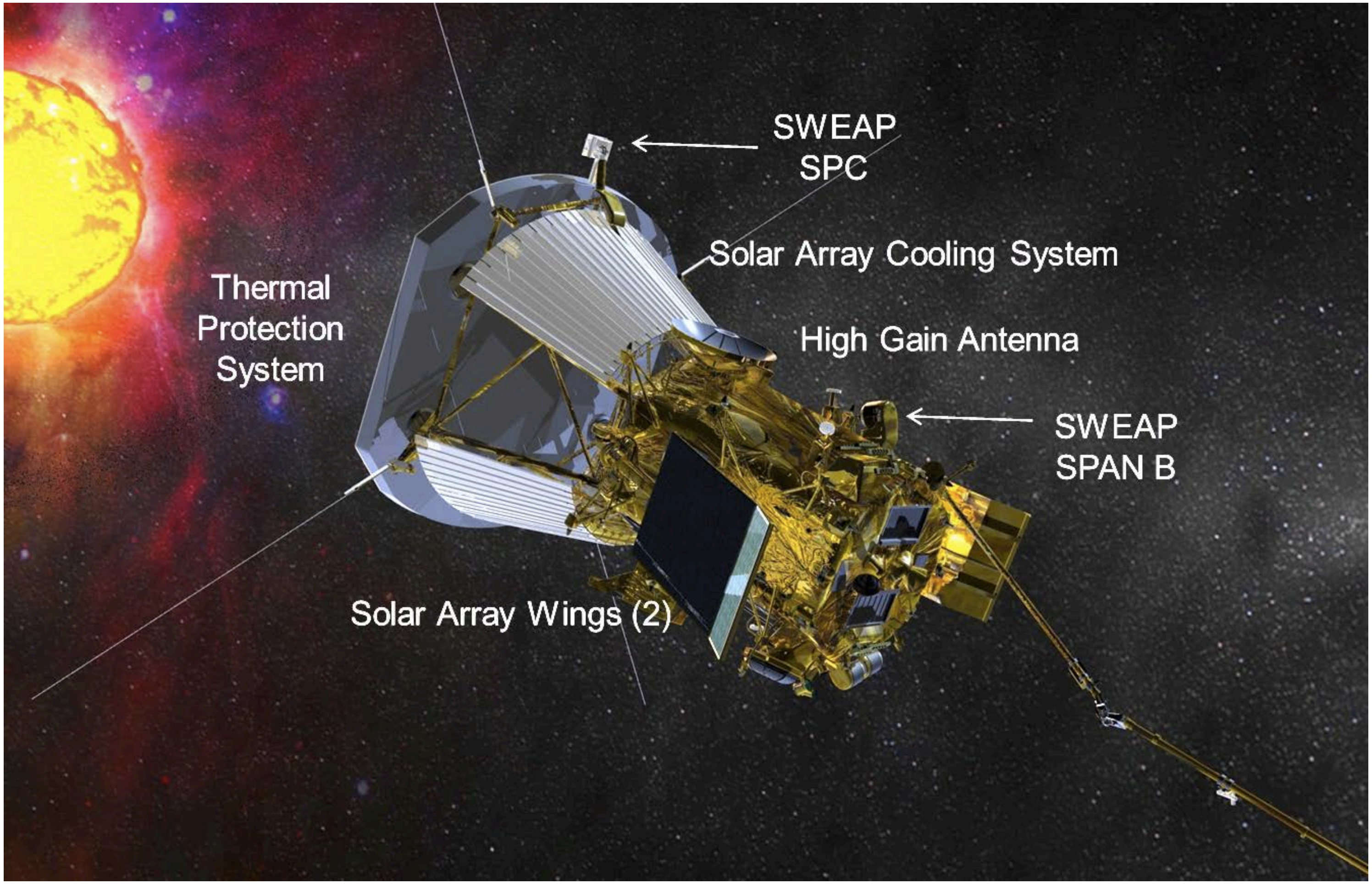
- Perihelion: 9.86 R_S
- Aphelion: 0.73 AU
- Inclination: 3.4 deg from ecliptic
- Orbit period: 88 days

Mission duration: 7 years

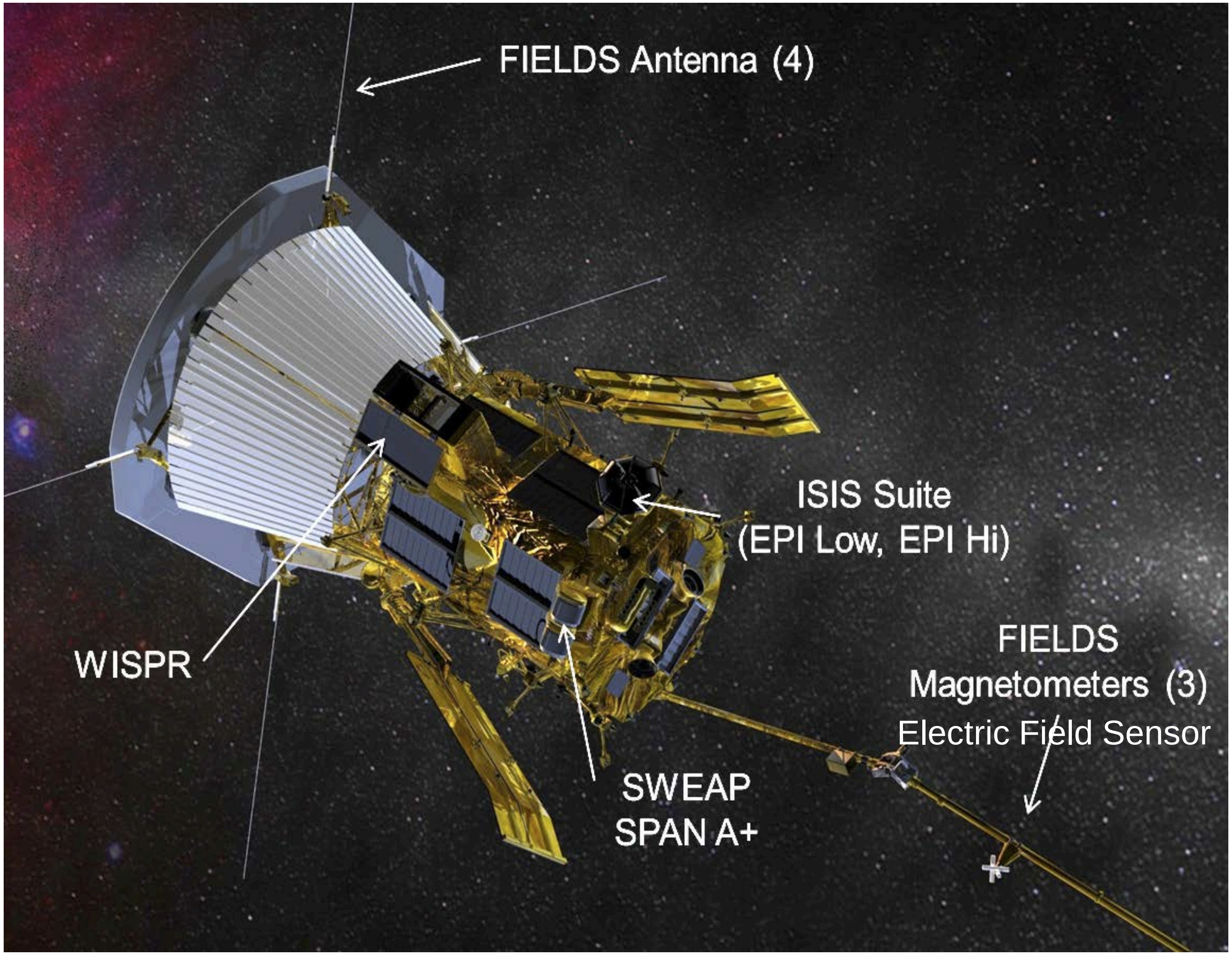




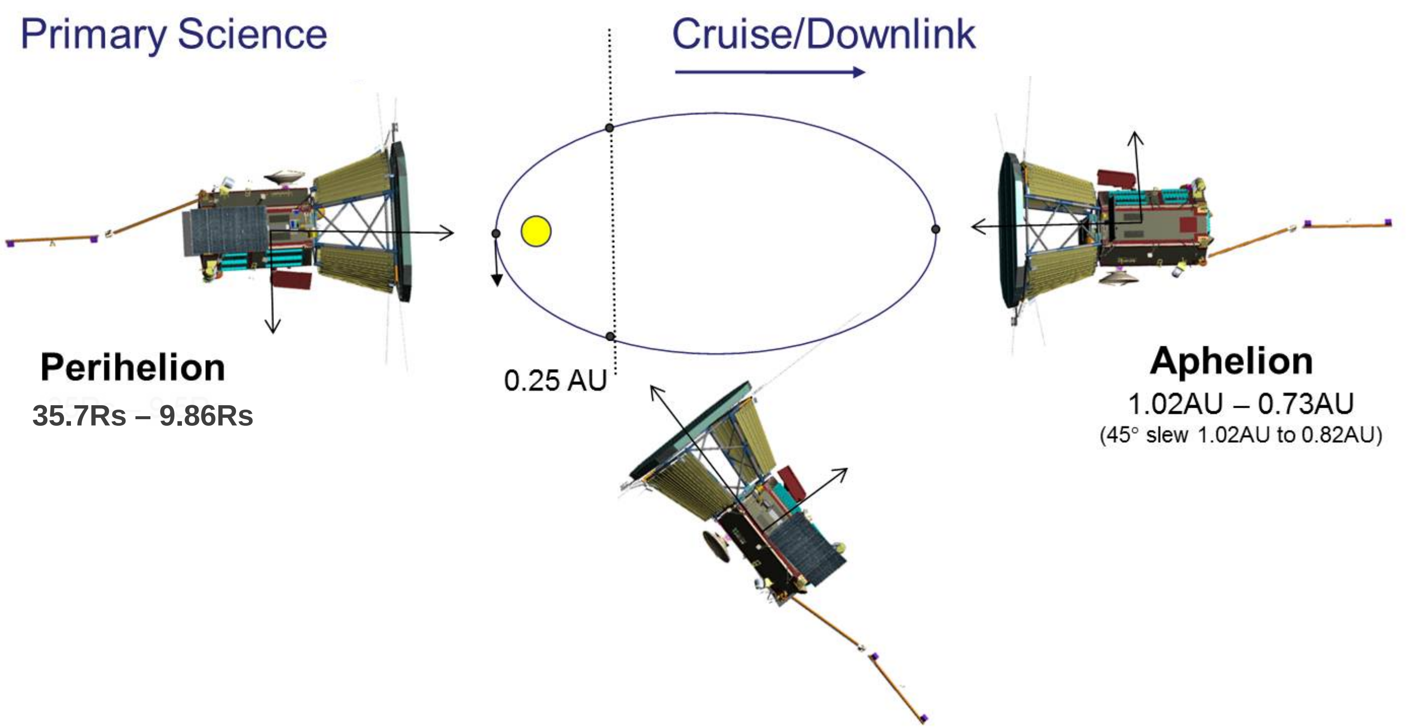
Reference Vehicle: Anti-Ram Facing View



Reference Vehicle: Ram Facing View



Reference Vehicle: Concept of Operations



Critical Events

- **A critical event is defined as (NPR 8705.4):**
  - Any event where the risk exists of a failure or anomaly that could result in loss of mission or serious degradation of spacecraft or payload,
  - That can potentially be mitigated by real-time intervention from the ground,
  - Or that requires real-time telemetry collection to ensure as much data as possible can be obtained (in the case of an unrecoverable loss of data from the spacecraft) to aid in understanding the root cause of a failure or anomaly.

- **Critical events shall be monitored in real-time and every attempt will be made to obtain the resources required to do so.**

SPP Critical Events List

- LV/US separation
- Upper Stage burn
- Spacecraft/US separation
- Critical Sequence following Spacecraft/US separation
- Initial acquisition
- Solar array deployment
- Solar Array, Radiators 1 & 4 warm-up and activation
- Launch Correction Maneuver (TCM1) and backup
- Radiators 2 & 3 warm-up and activation
- HGA Deployment
- TCMs that occur prior to first Venus flyby

Single Point Failures (1/2)

Single Point Failure	Description	Reference
Solar Array Launch Locks	Lock fails to release	Presentation: “Launch Locks Reliability Assessment”
HGA Launch Locks	Lock fails to release	Presentation: “Launch Locks Reliability Assessment”
Solar Array Flap Actuator	Flap actuator stuck (not enough power, overheating system)	Standard
Solar Array Feather Actuator	Feather actuator stuck (not enough power, overheating system)	Standard
Separation Nuts	Nut fails to actuate	Presentation: “Clamp-Band vs. Sep-nut System”
Mag Boom Release	Deploys prematurely, partially, not at all	RBSP PDR AI #19: “Actuator Redundancy Trade”
HGA Actuator	Gimbal actuation fails	Standard
HGA Feed	HGA harness fails	SEM-13-5-153: “Flexible Waveguide Vibration Test”
SLS Reticle	Loss of SLS head(s)	SLS CDR
Accumulator	Internal or external leak	SPP Cooling System PDR
Fuel Tank	External leak	Standard

Single Point Failures (2/2)

Single Point Failure	Description	Reference
Cooling System Isolation Valves	Internal leak prior to activation; valve inadvertently fails to open/closes	Phase B Trade Study #24: "Cooling System Reliability Assessment
Cooling System Piping	Leak	SPP Cooling System PDR
Propulsion System Filter	Filter clogs	Prop System Peer Review
Propulsion System Orifice	Orifice clogs	Prop System Peer Review
Propulsion System Manifold	Leak	Prop System Peer Review
RF Hybrid	Failure to pass Ka-band communications to HGA	SER-03-018: "Use of a Hybrid Coupler on New Horizons"
Short in Unfused Power Bus	Short between power (+) and power return	SPP EPS PDR
Short of S/A Power Bus	Short between power (+) and power return	SPP EPS PDR
REM MUX PWB interfaces w/ GC components & RIUs	Board fails	SPP Avionics PDR
Thermal Protection System	TPS cracks, degrades, breaks	Standard
Spacecraft Structure	Critical structural failure	Standard

Test As You Fly Exceptions

- **Requirement to test flight hardware in flight-like conditions to the maximum extent possible within project constraints.**

- **Many SPP exceptions typical of other mission. Examples:**
  - Deployment tests are often pop-and-catch or walked out
  - Testing in the presence of gravity
  - Attitude control tests involve some measure of simulation
  - Solar array simulators often used in environmental tests

- **End-to-end testing of the spacecraft in perihelion illumination conditions has been identified as major exception since pre-Phase A**
  - No ability to simulate full illumination over realistic-sized source
  - FM tests of attitude excursion involve significant simulation component
  - Discussion of test plan in spacecraft system engineering presentation

- **Management of exceptions**
  - Detailed test planning occurs in Phase C, full list of exceptions presented at CDR
  - Exceptions managed through risk system, residual risks tracked and presented in subsequent reviews

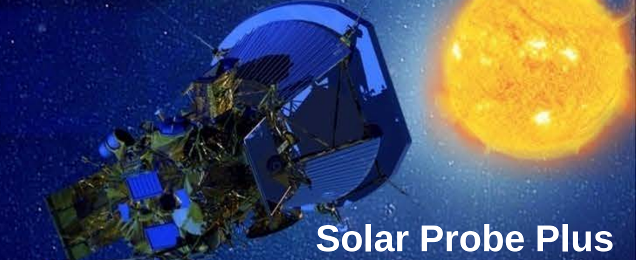
Trade Level Definition

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

Mission Level Changes Minimum Perihelion

- **A mission design study was conducted to optimize mission design to manage risk associated with low mass margins.**
- **Key mission design requirements include:**
    - Time below 10 R_S no less than 4.5 hours per orbit on the minimum perihelion pass
    - Accumulated time below 20 Rs no less than 500 hours
    - 3 passes at minimum perihelion
- **Design Approach**
    - Maximize the reduction in launch C3 by increasing the minimum perihelion distance
- **Selected 9.86 Rs as new minimum perihelion for balance between science and mass margin increase.**

Mission Level Changes
Minimum Perihelion



	MDR Mission Design	PDR Mission Design
Launch dates	30 July - 19 Aug 2018	31 July - 19 Aug 2018
Launch period (day)	21	20
Max launch C3 (km^2/s^2)	159	154
Trajectory	V^7GA	V^7GA
Planetary flybys	7 Venus	7 Venus
Time from launch to 1st Venus Flyby (month)	2	2
Time from launch to 1st perihelion (month)	3	3
Time from launch to 1st min perihelion (year)	6.4	6.4
Mission duration (year)	7	7
Number of solar orbits	24	24
Solar distance of 1st perihelion (Rs)	34.9	35.7
Minimum perihelion (Rs)	9.5	9.86
Number of passes at min perihelion	3	3
Maximum distance from Sun (AU)	1.018	1.018
Maximum distance from Earth (AU)	1.884	1.881
Maximum heliocentric velocity (km/s)	194.6	190.8
Total time within 30-Rs region (hour)	2134.3	2130.9
Total time within 20-Rs region (hour)	965.3	937.6
Total time within 15-Rs region (hour)	458.9	440.0
Total time within 10-Rs region (hour)	27.3	14.8

Mission Level Trades
Mag Boom Concept

- **Early in Phase B, spacecraft carried a 2.7m long boom to accommodate FIELDS magnetometers**

- **As part of Phase A, and due to desire for longer boom by FIELDS team to calibrate out the spacecraft magnetic fields, the spacecraft and FIELDS teams jointly performed a trade study on the mag boom concept**
  - Boom length, sensor placement, S/C accommodation (stowing and deployment), complexity, and reliability were examined
  - Three configurations of a 4m boom were investigated
  - Configurations selected to minimize umbra violation risk
  - 3.5 m length, 2-segment boom and sensor placement defined.

- **FIELDS team performed the compatibility testing between the search coil magnetometer and the fluxgate magnetometer to inform the placement on the boom; the compatibility testing between the 2 fluxgate mags is outstanding**

Instrument DPU Configuration

- **MDR Baseline**
  - FIELDS includes MEP
  - SWEAP includes SWEM
  - EPI-Hi & EPI-Lo each include internal power supply, data buffering (small volume) & commanding
  - APL provides DPU for WISPR

- **Action from NASA HQ after MDR to consider common DPU architecture. Trade widened to consider other options as well.**

  A. MDR Baseline

  B. Common APL-provided DPU for all payload processing, buffering & power services (in a central chassis)

  C. Central chassis for payload-provided elements: FIELDS MEP, SWEAP SWEM, ISIS payload electronics developed by payloads as proposed but centralized in one chassis with WISPR DPU

  D. FIELDS ICU to provide processing, buffer & power services for WISPR, other instruments per MDR baseline

  E. WISPR (NRL)-proposed alternate electronics architecture to simplify requirements for APL-provided DPU to WISPR

Instrument DPU Configuration

- **Fault tree analysis indicates that centralizing payload data processing and/or power in a single DPU would increase overall risk of failure for mission science objectives due to loss of functional redundancy. This is especially true for FIELDS & SWEAP (the 2 largest elements).**

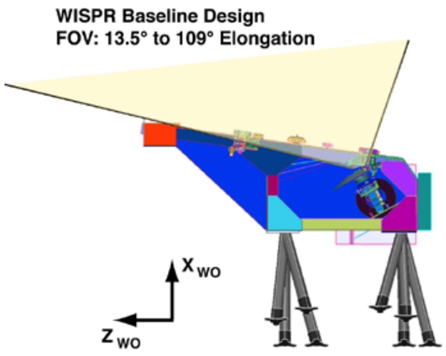
- **Combining payload processing and/or power supplies has strong disadvantages for I&T, preservation of existing heritage & interfaces, science investigation implementation & possibly EMI/EMC.**

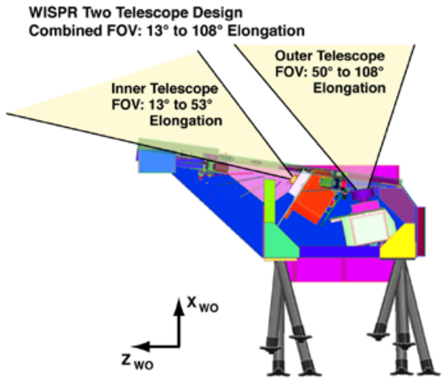
- **Grouping distributed payload electronics in one chassis has more potential to save mass than combining processors and/or power supplies. But it still has system-level disadvantages for: I&T, preservation of existing interfaces, spacecraft Cg balance & thermal design. Chassis mass savings may be offset by harness increases & system-level impacts on spacecraft Cg balance & thermal design.**

- **Will maintain the MDR baseline of multiple, distributed payload electronics boxes for power, data processing & buffer memory.**

Mission Level Trades
WISPR 2-Telescope Design

- **Early in Phase A, WISPR team generated a red risk on the FIELDS antennas interference w/ WISPR unobstructed field of view causing WISPR to not meet L1 science, with a mitigation step to change the WISPR instrument design to one satisfying the stray light rejection requirements.**
  - Alternatives were studied, with designs of 1 and 2 telescopes
- **WISPR team advocated the 2- telescope design because of:**
  - Better transverse coverage across the entire radial extent, allowing to maintain capability to study fast solar wind sources
  - 10x larger aperture in the outer field, allowing for less blur in the images and higher cadences
  - Better spatial resolution for inner telescope even with 2x2 binning
  - Inner telescope was highly robust to the dust impacts and FIELDS antenna reflected/blackbody light, allowing to meet its requirements with less risk from environment
- **Straylight analysis was performed, showing that 2-telescope design had better straylight margins for dust impacts cases**
- **SPP project agreed to proceed with the 2- telescope design, and have incorporated it into the baseline**





Mission Level Changes
FIELDS Redundancy

- **Mission Success Requirement: Make significant progress in addressing 7 of 9 science questions identified Level 1 Document**

- **Reliability analyses showed FIELDS MEP needed to address 4 questions. Alternates to single point failure studied, including:**
  - Full redundancy of FIELDS MEP and splitting of sensors
  - Routing some FIELDS data through another instrument, either as primary or as a backup in case of failure
  - Splitting sensor data in MEP to route data through independent processing chains

- **Configuration chosen:**
  - Add second low voltage power supply to MEP, partition sensors so that failure of one LVPS will allow mission success
  - Reconfigure MEP processing chains to route some sensors through independent paths, add second interface to spacecraft.

Mission Level Trades
FIELDS V5 Addition

- **FIELDS characterization of the 3-d electric field is a key science measurement**
  - As proposed, measuring the electric field by V1-V4 antennas summed together against the S/C body were to provide the electric field measurement along the S/C to sun line

- **Modeling performed as part of Phase B showed that the S/C electrostatic center could not be determined precisely due to changing plasma conditions and S/C charging**
  - Separation of the electrostatic center from the boom plane was inadequate to measure the Z-component of the electric field (electrostatic center varied from ~1.5 m to 0.2 m when s/c is positively charged and inside 20 Rs)
  - Main conclusion was that a sensor needed to be added that would perform the Ez measurement far away from the boom plane. Best location was determined to be on the Mag boom

- **FIELDS team briefed the SPP Project in the March 2013 Quarterly and presented the mass and power impacts, which were minimal**
- **SPP Project agreed with the sensor addition, since this measurement was required to meet L1 science**
- **The sensor (V5) has since been accommodated on the Mag boom**

Technology Development Plan

- **Requirement: Develop new technology on a plan to achieve TRL 6 by PDR**

- **NPR 7123.1A**
  - Definition: System/subsystem model or prototype demonstration in an operational environment.
  - Description: A major step in the level of fidelity of the technology demonstration follows the completion of TRL 5. At TRL 6, a representative model or prototype system or systems, which would go well beyond ad hoc, "patch-cord," or discrete component level breadboarding, would be tested in a relevant environment. At this level, if the only relevant environment is the environment of space, then the model or prototype must be demonstrated in space.

- **Technology Development**
  - Assess technology readiness of individual subsystems and components (completed in Phase A)
  - Develop individual test plans, including test article definition, assessment of relevant environments, tests to be performed with pass/fail criteria (documented in Technology Development Plan)
  - Execute plan, report detailed results in subsystem/instrument PDRs (complete, with small number of actions to be completed in early Phase C) and Technology Readiness Assessment (7434-9518).

Summary

- Mission system engineering processes in place
- Top level requirements are configured
- The mission concept is understood, with good interaction between the engineering team and operations
- Mission-level Phase B trades are complete
- Technology development is complete to TRL 6

System Engineering is ready for Phase C

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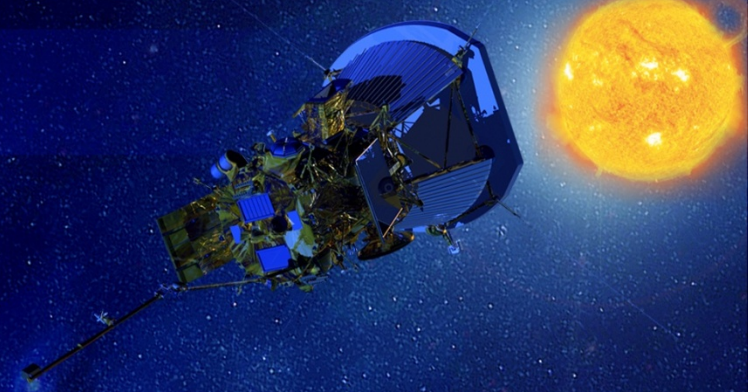

Software System Engineering

R. Michael Furrow

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13 – 16 January 2014

The Johns Hopkins University
APPLIED PHYSICS LABORATORY

Agenda

- Software block diagram
- Software team organization
- NASA IV&V
- Software development process
- Summary

Mission Software Block Diagram

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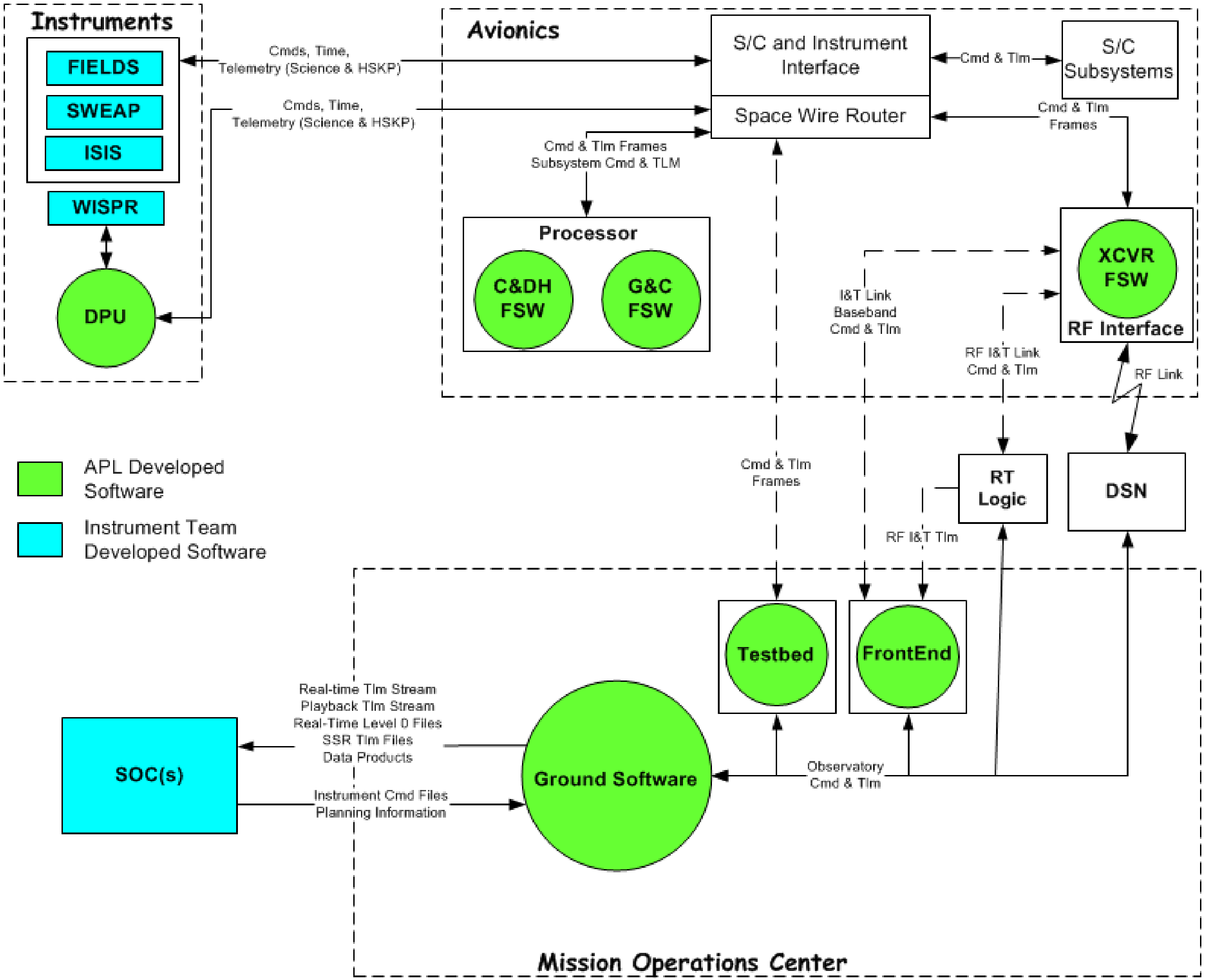

APL Software Development Team

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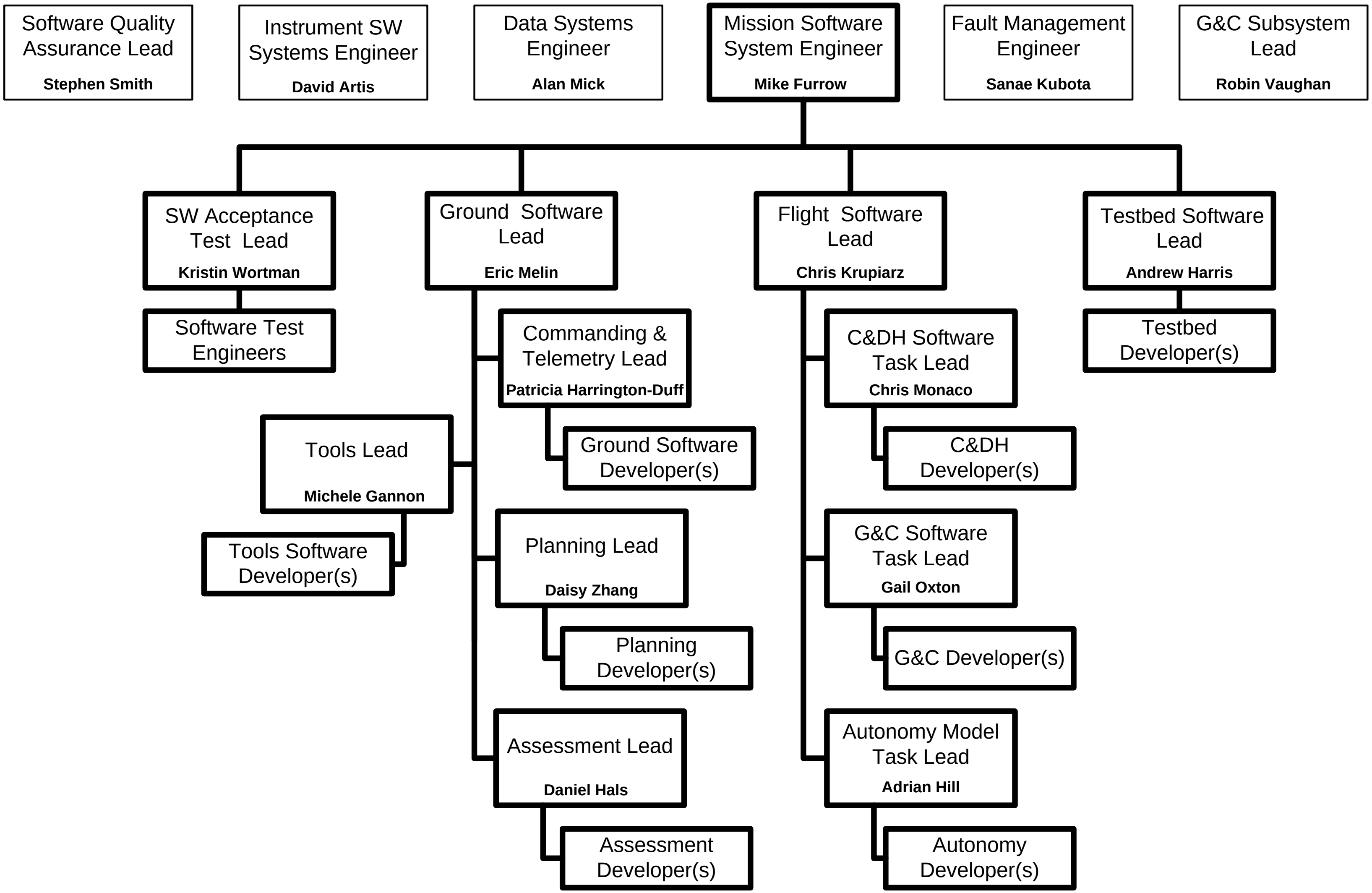


NASA IV&V

- In response to SRR/MDR-13 SPP engaged NASA IV&V
- NASA IV&V provides an independent review of SPP SW development activities
- NASA IV&V started on SPP in October 2012
  - Monthly tag-up meetings
  - Participated in flight software requirements review
  - Participated in flight software pre-PDR application reviews
  - Participated in post government shutdown review of flight software PDR material.
- The IV&V team will be presenting on Day 4

SPP Software Development Process

- SPP 7434-9042 “SPP Software Development Plan”
  - Initial version signed-off and under configuration control.
  - Based on NASA and APL Space Department Standards
    - NASA NPR 7150.2 “NASA Software Engineering Requirements”
    - SD-QP-650 “Software Development Process” of Space Departments Quality Management System
- APL Process
  - Categorizes each software CSC as High or Low Tier based on four ‘CUES’ attributes:
    - Criticality
    - Use/longevity – used operationally/a long-lived project (>2 years)
    - Effort/schedule – significant constraints with regard to effort or schedule
    - Size – development team 4+
    - High Tier must have C or all 3 UES attributes
  - Process formality based on software categorization

Software System Categorization

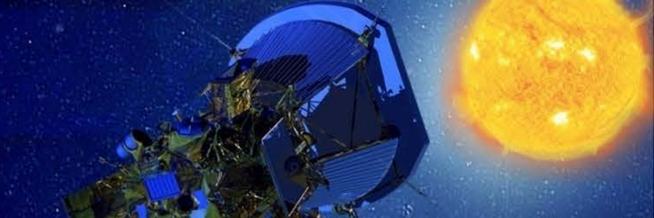
System	Tier	CUES
Flight	High	CUE
Ground	High and Low	UE and CUE
Simulation	High and Low	UE and CUE

Instrument Software Development Process

- **Instrument teams use their own organizations SW process**
  - **Each instrument team generated a Software Development Plan**
  - **Plans were reviewed by APL and found to be consistent with the SPP software development philosophy**

- **APL coordinates spacecraft/instrument software efforts and participates in instrument software reviews**

Flight Software Methodology



Solar Probe Plus
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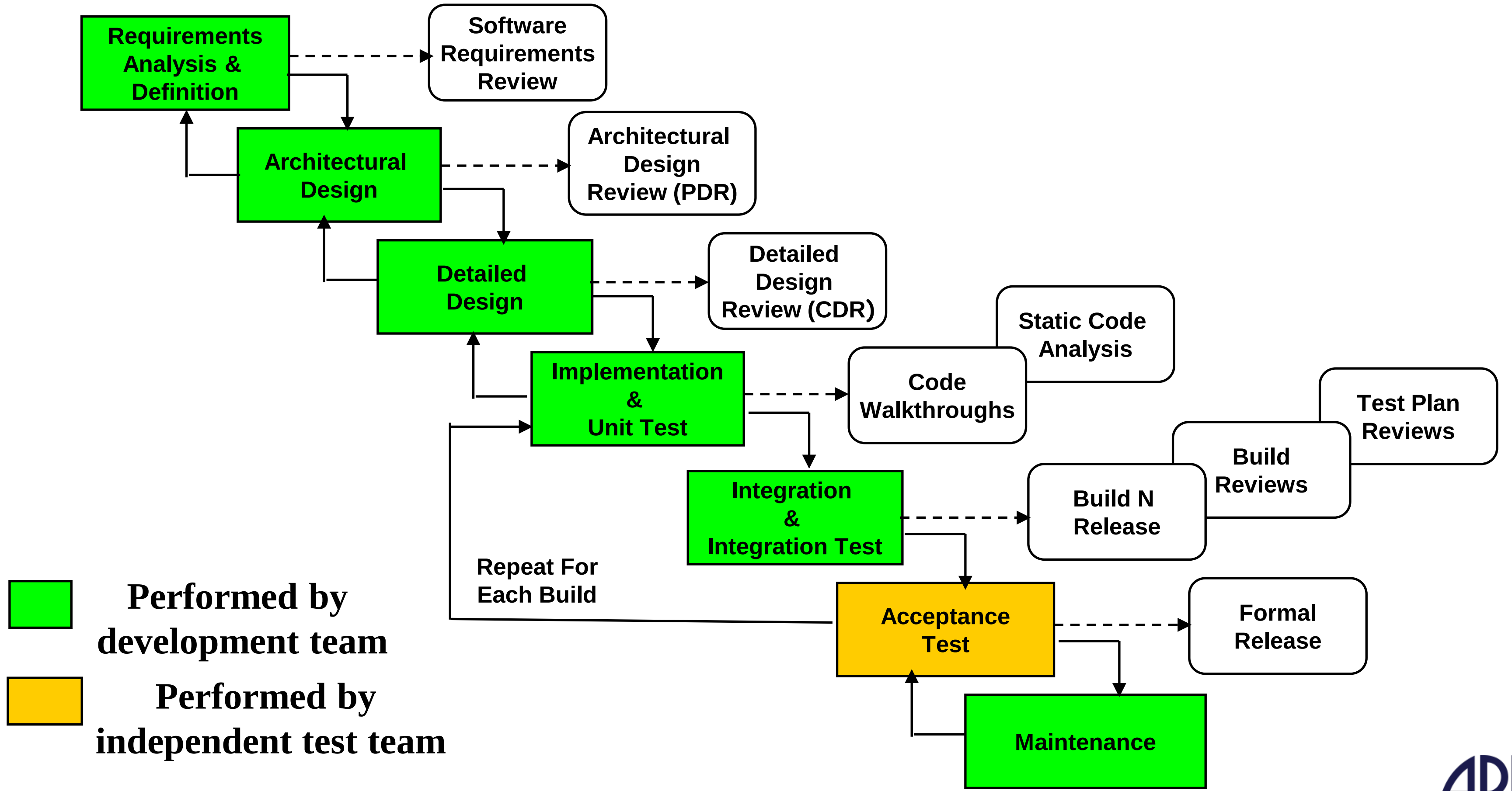
- Incremental waterfall model process
- Process is similar for all SPP APL developed software
- Level of formality changes based on categorization of software



APL

SPP APL Software Reviews

- **Software Reviews**
  - **Requirements**
  - **Preliminary design**
  - **Critical design**
  - **Build**
  - **Acceptance Test plan**
  - **Acceptance Test specification (test cases)**
  - **Code walkthroughs**

- **Review Process**
  - **Documented in Space Department QMS SD-QP-655 “Software Peer Review Process”**
  - **Describes reviews, inspections, walkthroughs and audits**
  - **Review action items documented and tracked to closure**

APL Software Verification & Validation Testing (1 of 2)

- **Unit Testing**
  - **Performed by developers in local software development environment**

- **System Testing (a.k.a. Build Testing)**
  - **Each delivered software build is tested with respect to the requirements implemented and to verify proper interaction between the units being integrated**
  - **Performed by select members of the software development team**

APL Software Verification & Validation Testing (2 of 2)

- **Independent Acceptance Testing**
  - **Requirements-based testing of all critical software**
  - **Exploratory testing**
  - **Scenario testing**
    - **Scenario testing augments requirements-based tests to exercise code in ways that simulate real-world scenarios.**
  - **Regression testing**
    - **Subset of acceptance tests that is used to efficiently confirm basic functionality of the software after updates are made.**
  - **Stress testing**

- **Software continues to be exercised/tested during spacecraft I&T, comprehensive performance test and mission simulations**

APL Change Management

- **Software Issues managed via JIRA tool**
  - **Issues classified by software component, severity & priority**
  - **I&T Problem Reports can result in Software Issue creation**

- **Configuration Control Board (CCB) authorizes changes to configured items**
  - **SPP 7434-9006 “SPP Configuration Management Plan”**
  - **Subsystem CCB responsible for changes prior to integration**
  - **Project CCB responsible for changes after integration**

Software Change Flow

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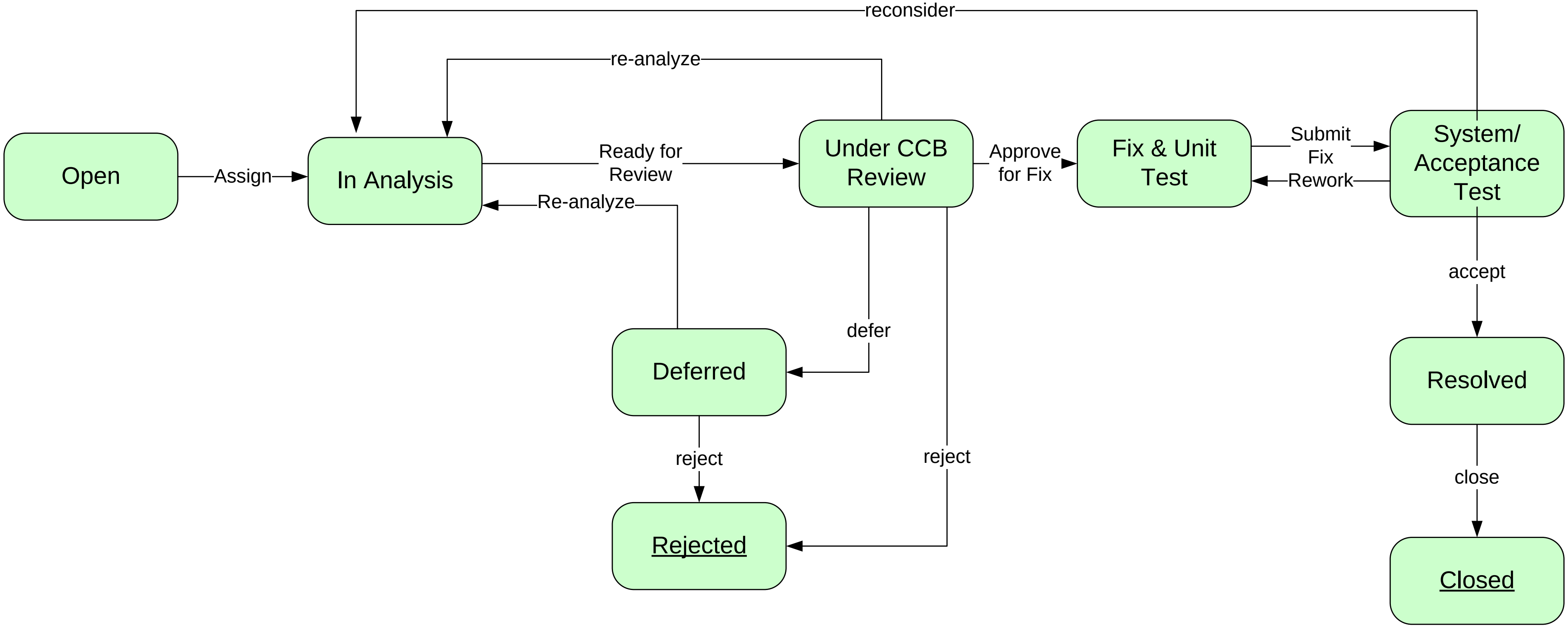

APL

Summary

- **The software team is in place**
- **We have a robust software process in place and are following it**
- **NASA IV&V is an integrated part of the software team**
- **The level 4 software requirements were developed and reviewed**
- **The preliminary design is in place and was reviewed**
- **The SPP software team is ready to proceed to Phase C**

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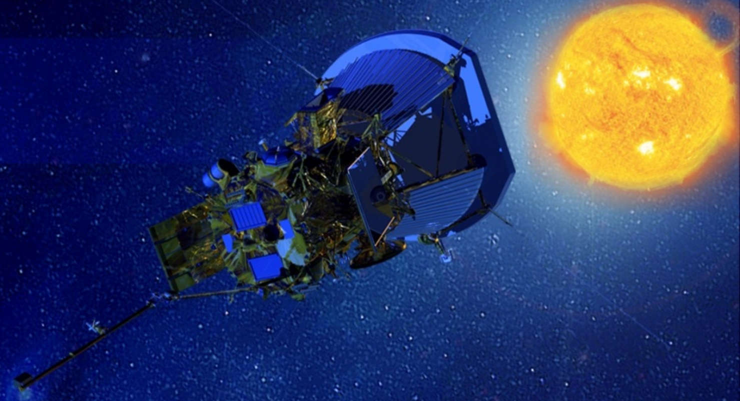

Requirements & Verification Engineering

Dan Kelly

SPP Requirements & Verification Engineer (RVE)

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13 – 16 January 2014

The Johns Hopkins University
APPLIED PHYSICS LABORATORY

Agenda

- **Requirements Management**
- **Requirement Document Tree**
- **Requirements Allocation & Traceability**
- **Document Status**
- **Requirement/Module Definition & Validation**
- **Change Management**
- **Verification**
- **Phase C Work**
- **Summary**

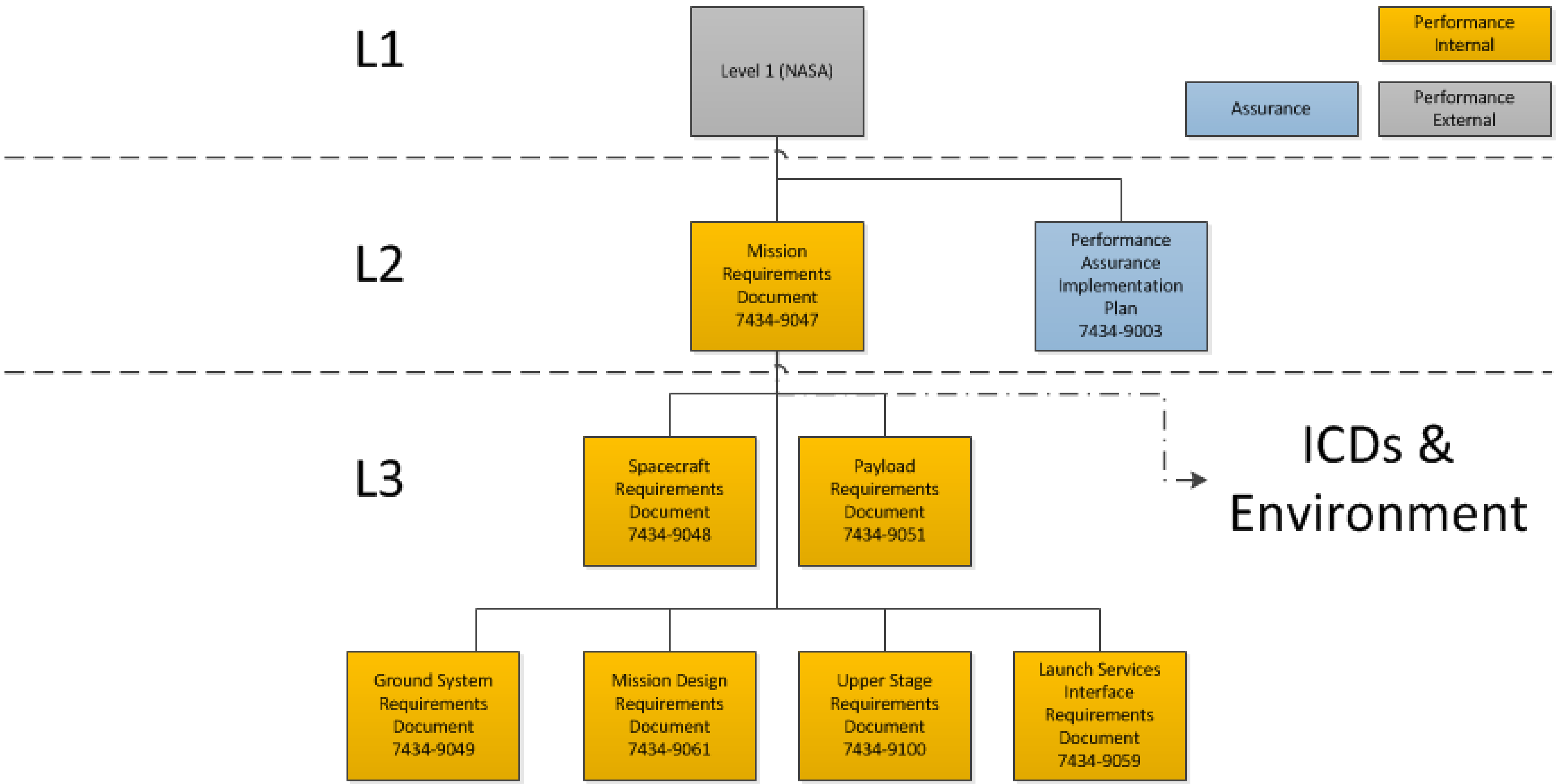
Requirements Management

- **SPP RVE maintains the project DOORS database used to capture and track Level 1 – 4 requirements.**
  - **JHU/APL tracks and maintains traceability to L1 document – does not manage**
  - **External teams have latitude to maintain their Level 4 requirements outside of the JHU/APL DOORS database, but remain subject to requirements engineering process/product review and approval by the Project**
- **Overall Process:**
  - **Stakeholders/document owners (leads) draft requirements using Excel templates with DOORS-compatible formatting;**
  - **When sufficiently developed/ mature, spreadsheets are imported into the DOORS database;**
  - **Once imported to the database, DOORS module becomes the authoritative (controlled) source for the requirements document.**
    - **DOORS module :: requirements document**
  - **Officially-released document from Product Lifecycle Management (PLM) represent DOORS module baselines**
- **Governing Documents**
  - **SD-QP-604 – Space Sector Quality Procedure: Requirements Engineering**
  - **7434-9007 – Systems Engineering Management Plan**
  - **7434-9098 – Requirements Document Tree**
  - **7434-9099 – System Verification & Validation Plan**

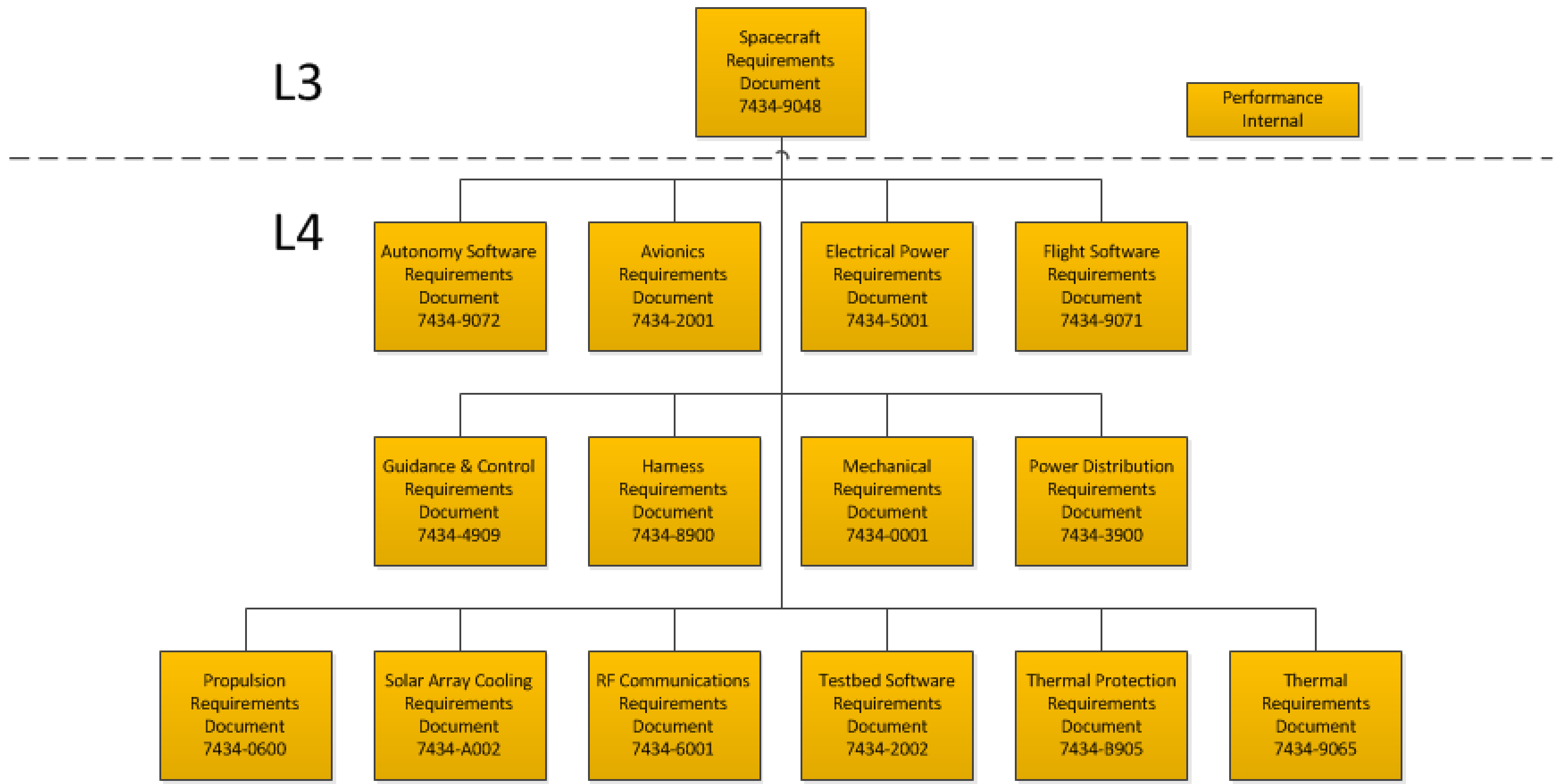
Requirement Document Type

- **Performance –** organized by and assigned to mission products and deliverables in the Product Breakdown Structure. Complete verification of a performance requirements document indicates product readiness.
- **Environmental –** captures information and requirements relating to the testing and flight environments. The definition of environmental conditions imposes requirements upon relevant products (represented by Performance documents).
  - Electromagnetic Environment Control Plan (EMECP)
  - Contamination Control Plan (CCP)
  - Environmental Design and Test Requirements Document (EDTRD)
- **Interface –** captures pair-wise design agreements between two or more segments, elements, or components. Developed to contain only the design information necessary to the common interface and to avoid duplication of information.
- **Assurance –** captures information and requirements related to conformance with JHU/APL- and NASA-imposed standards and practices. Managed by SAM.

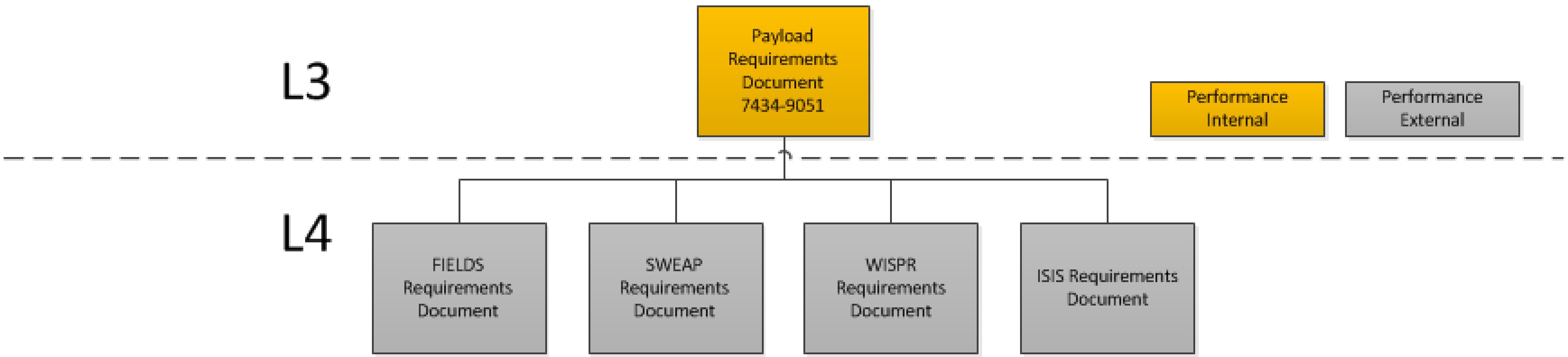
Level 2 Requirements: Mission



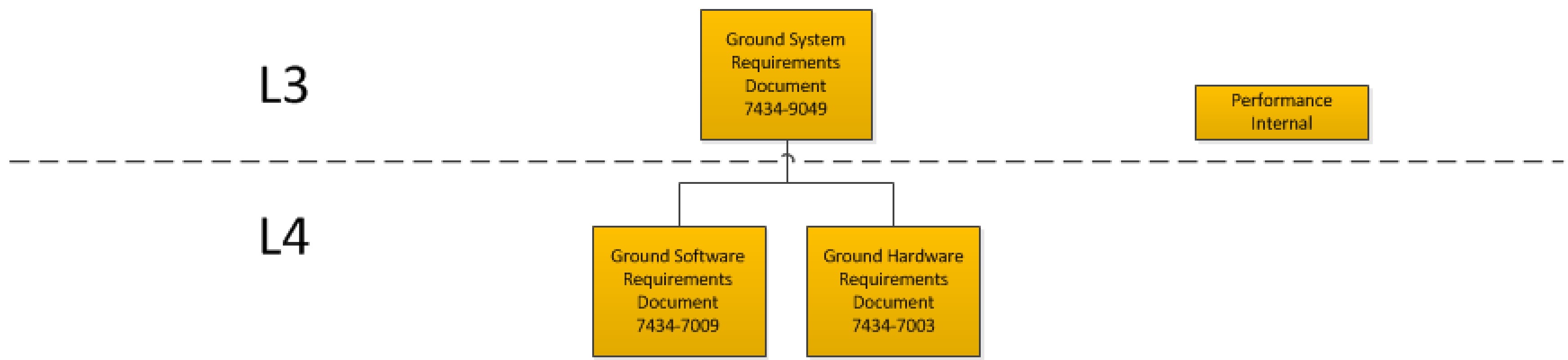
Level 3 Requirements: Spacecraft



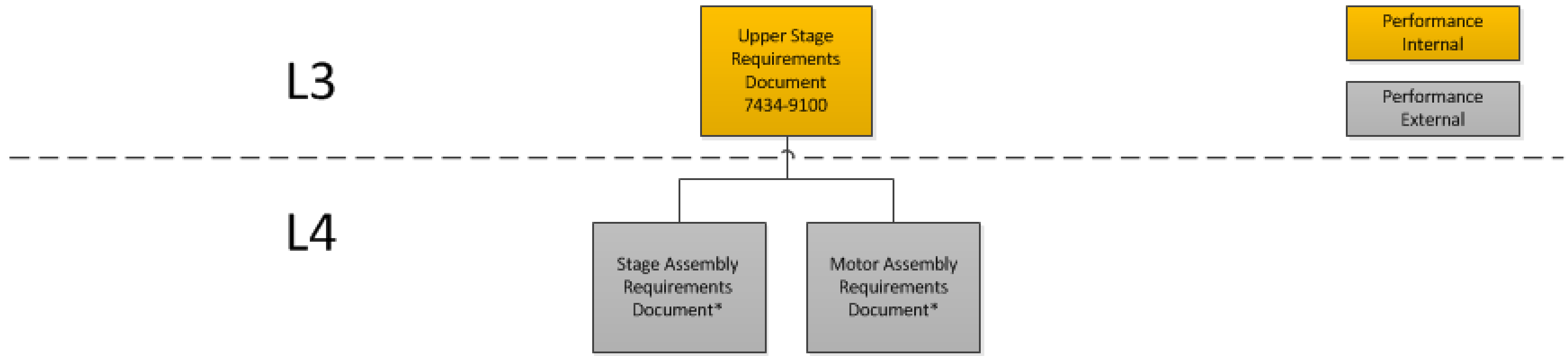
Level 3 Requirements: Payload



Level 3 Requirements: Ground System



Level 3 Requirements: Upper Stage



* Level 4 documents to be developed for Upper Stage PDR

ICDs & Environmental Requirements

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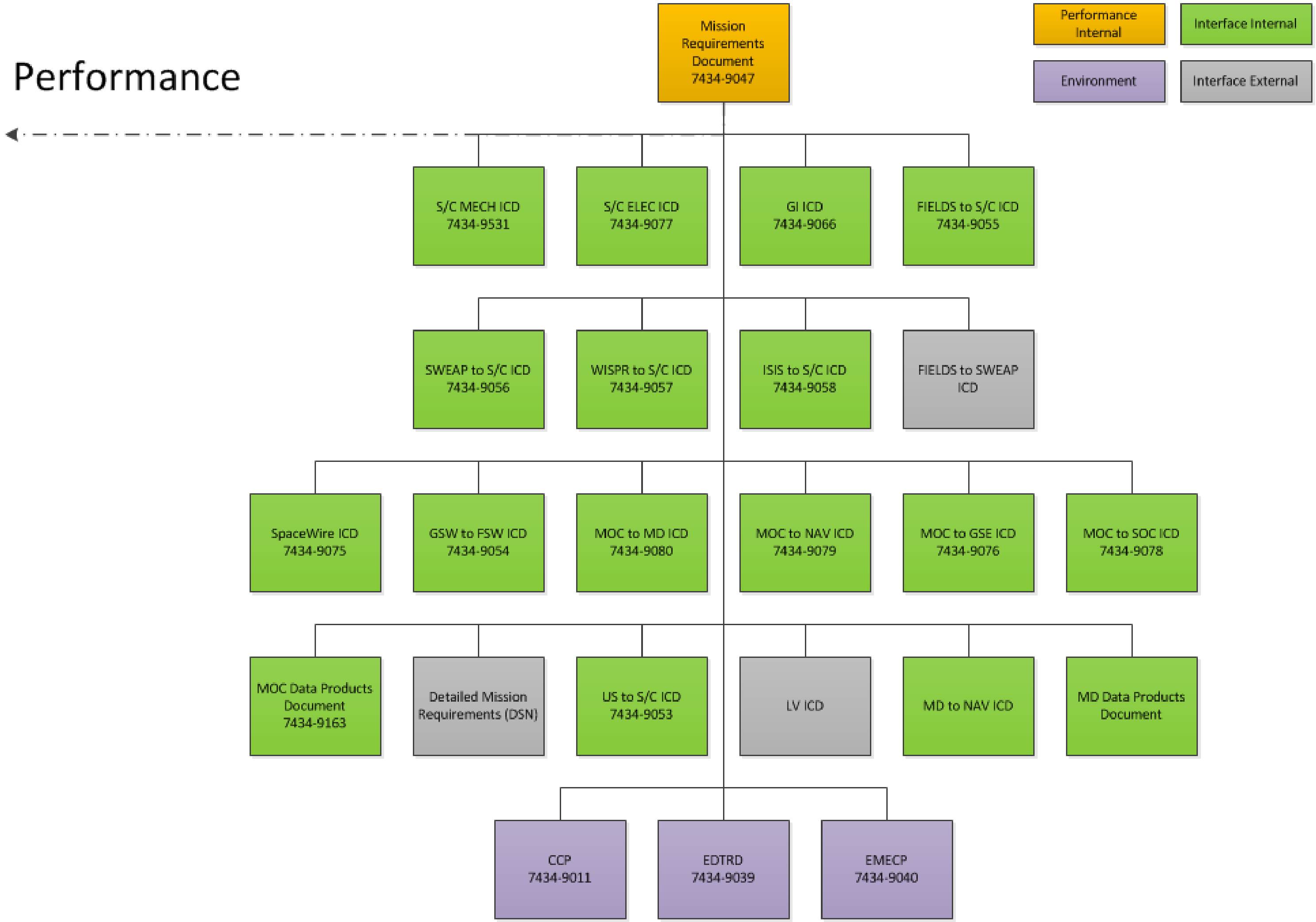

Requirement Allocation, Traceability and Applicability

- Requirements traceable to parent performance document
- Requirements allocated to documents one level below
- Functional leads given oversight into many or all documents (tracking enabled by DOORS)
  - Fault Management
  - Guidance & Control
  - Integration & Test
  - Solar Array Operations & Safing
  - Timekeeping
  - Alignments
- ICDs/Environmental Requirements Documents referenced via "compliance" requirements
- Non-verifiable documents (i.e. plans) handled by derived requirements
- RVE tracks document applicability to ensure full compliance

➢ Performance Document in question is central verification document for subject

Document Status (Performance)

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Level	Name	Code	Number	Lead	PLM Status
L2	Mission Requirements Document	MRD	7434-9047	Kinnison	Released
L3	Spacecraft Requirements Document	SCRD	7434-9048	Lockwood	Released
L4	Autonomy Software Requirements Document	AUT	7434-9072	Hill	In Work
L4	Avionics Requirements Document	AVI	7434-2001	Ottman	Under Review
L4	Electrical Power Subsystem Requirements Document	EPS	7434-5001	Roufberg	Released
L4	Flight Software Requirements Document	FSW	7434-9071	Krupiarz	Released
L4	Guidance and Control Requirements Document	GC	7434-4909	Vaughan	Released
L4	Harness Requirements Document	HRN	7434-8900	Kinder	Released
L4	Mechanical Requirements Document	MECH	7434-0001	Cole	Under Review
L4	Power Distribution Unit Requirements Document	PDU	7434-3900	Sawada	Released
L4	Propulsion Requirements Document	PROP	7434-0600	Bushman	Released
L4	Solar Array Cooling System Requirements Document	SACS	7434-A002	Ercol	Under Review
L4	Telecommunications Requirements Document	RF	7434-6001	Copeland	Under Review
L4	Testbed Software Requirements Document	TBSW	7434-2002	Harris	In Work
L4	Thermal Protection Requirements Document	TPS	7434-B905	Mehoke	Under Review
L4	Thermal Subsystem Requirements Document	THRM	7434-9065	Abel	Released
L3	Payload Requirements Document	PAY	7434-9051	Adams	Released
L4	FIELDS Requirements Document	FIELDS	EXT	Goetz	Released
L4	SWEAP Requirements Document	SWEAP	EXT	Daigneau	Released
L4	WISPR Requirements Document	WISPR	EXT	Van Duyne	Released
L4	ISIS Requirements Document	ISIS	EXT	Dickinson	Released
L3	Ground System Requirements Document	GSYS	7434-9049	Pinkine	Released
L4	Ground Hardware Requirements Document	GHW	7434-7003	Mitnick	Released
L4	Ground Software Requirements Document	GSW	7434-7009	Melin	Released
L3	Upper Stage Specification	USRD	7434-9100	Anderson	In Work
L4	Stage Assembly Requirements Document	STAGE	EXT	Anderson	Future Work
L4	Motor Assembly Requirements Document	MOTOR	EXT	John	Future Work
L3	Launch Services IRD	LVIRD	7434-9059	Vernon	In Work
L3	Mission Design & Navigation Requirements Document	MDNR	7434-9061	Guo	Released

* Several Released documents have updated Revisions Under Review

Document Status (Environmental & ICDs)

Level	Name	Code	Number	Lead	PLM Status
-	Contamination Control Plan	CCP	7434-9011	Nichols	In Work
-	Environmental Design & Test Requirements Document	EDTRD	7434-9039	Lockwood	Released
-	Electromagnetic Environment Control Plan	EMECP	7434-9040	Herrmann	Under Review
-	Spacecraft Mechanical ICD	MICD	7434-9531	Cole	In Work
-	Spacecraft Electrical ICD	EICD	7434-9077	Conde	In Work
-	General Instrument to Spacecraft ICD	GI	7434-9066	Bailey	Released
-	FIELDS to Spacecraft ICD	FIELDS-SCRD	7434-9055	Adams	Under Review
-	SWEAP to Spacecraft ICD	SWEAP-SCRD	7434-9056	Adams	Released
-	WISPR to Spacecraft ICD	WISPR-SCRD	7434-9057	Adams	Released
-	ISIS to Spacecraft ICD	ISIS-SCRD	7434-9058	Adams	Released
-	FIELDS to SWEAP ICD	FIELDS-SWEAP	EXT	Adams	Released
-	SpaceWire ICD	SpW	7434-9075	Mick	In Work
-	Ground to Flight Software ICD	GSW-FSW	7434-9054	Mick	In Work
-	MOC to Mission Design ICD	MOC-MD	7434-9080	Melin	Future Work
-	MOC to Navigation ICD	MOC-NAV	7434-9079	Melin	In Work
-	MOC to GSE ICD	MOC-GSE	7434-9076	Melin	In Work
-	MOC to SOC ICD	MOC-SOC	7434-9078	Melin	In Work
-	Mission Operations Center Data Products Document	MOC DPD	7434-9163	Hudson	In Work
-	Detailed Mission Requirements	DMR	EXT	Pinkine	In Work
-	Upper Stage to Spacecraft ICD	USRD-SCRD	7434-9053	Anderson	Future Work
-	Launch Vehicle ICD	LVICD	EXT	Vernon	Future Work
-	Mission Design to Navigation ICD	MD-NAV	TBD	Guo	Future Work
-	Mission Design Data Products Document	MD DPD	TBD	Guo	Future Work

* Several Released documents have updated Revisions Under Review

Requirement & Module Definition Guidelines

- **Valid requirements are:**
  - **Complete**
  - **Correct (accurately depicts stakeholder intent)**
  - **Unambiguous**
  - **Concise**
  - **Achievable/feasible**
  - **Necessary**
  - **Prioritized**
  - **Verifiable**

- **Valid requirement modules (documents) are:**
  - **Complete**
  - **Consistent**
  - **Traceable**
  - **Non-redundant**
  - **Organized**
  - **Consistent with best established practices**

Requirement Definition Guidelines

- Complete, correct, feasible
  - analyzed, peer-reviewed, stakeholder approval / sign-off
- Unambiguous, concise
  - Concise "shall" statements (no multi-requirements)
  - Explicit subject clauses to denote allocation ("The Spacecraft shall…")
  - Description/Clarification, diagrams, other graphics as needed to aid in correct interpretation of the requirement
- Necessary – All requirements must either:
  - be directly linked to a predecessor requirement (links), or
  - represent a true need not previously addressed (derived)
  - explicit rationale is mandatory for all requirements
- Verifiable
  - Assignment of verification method (test / analysis / demonstration / inspection) and activity
  - All requirements should be quantitative
  - Multiple verification methods / activities allowable

Requirement Completion Guidelines

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- Established attributes that define a complete requirements set
- Requirement
  - Title/name of requirement
  - Explicit subject/indicator clauses (“The Spacecraft shall…”)
  - Requirement text
  - Description/clarification (as needed)
- Traceability & Allocation – together establish complete link
  - Requirement Rationale
  - Parent Traceability: linked to display appropriate parent(s)
  - Requirement Allocation: flowdown to lower-level documents
  - Functional Allocation: identified co-owners
- Verification
  - Method (Test / Analysis / Inspection / Demonstration)
  - Activity (e.g. CPT, TVAC, etc.)
- Project “Definitions” (non-requirements) kept in separate module – linked and appears in module for reference.

Validation

- **Ongoing process relying on functional and traceability analysis**
- **Typically accomplished during technical reviews**
- **Three main types:**
  - **Requirements Validation: ensure all requirements are properly developed and flowed back to top-level mission goals, objectives, constraints ("are the requirements consistent with the mission objectives?")**
  - **Design Validation: top-down evaluation of the system, reliant on successful validation of subordinate elements and subsystems ("does the design meet the requirements?")**
  - **End Product Validation: accomplished prior to launch with end-to-end testing of integrated, functional mission system conducted in a simulated operational environment**

Configuration Control: DOORS and APL PLM System

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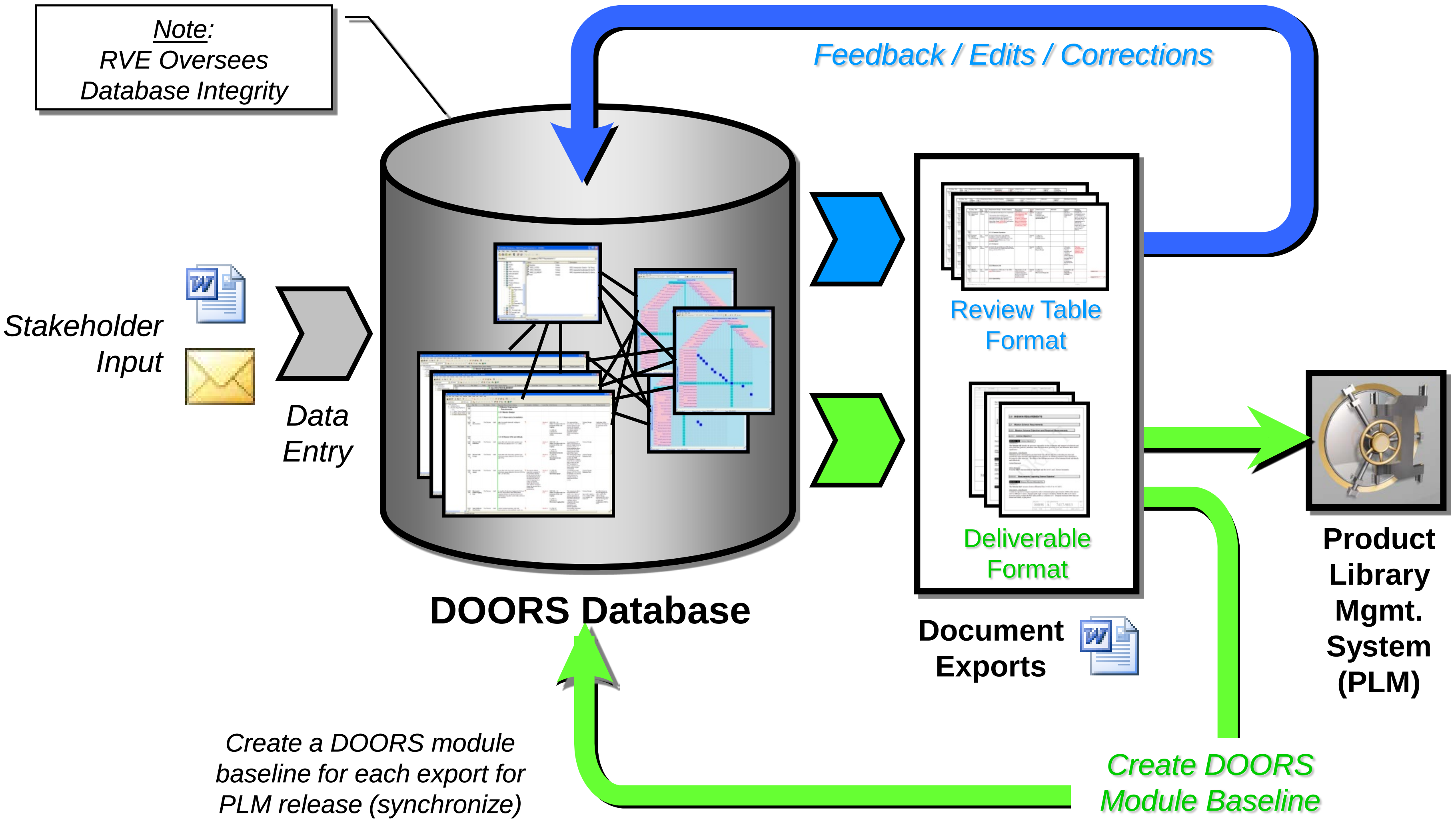
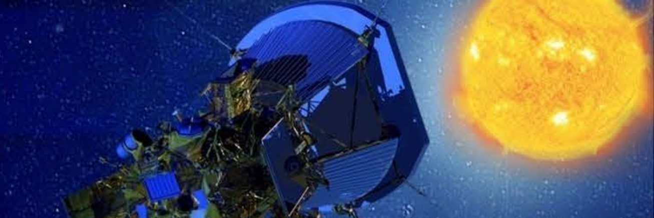


APL

Verification Approach

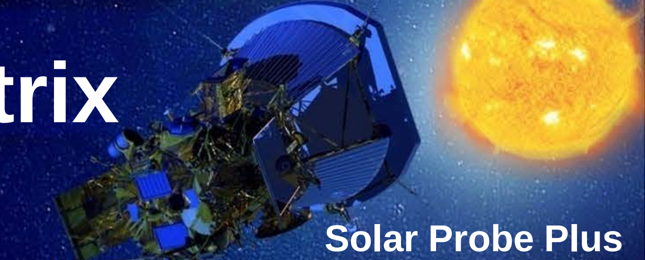


- **Objectives**
  - **Determine support of end-to-end functionality and operations**
  - **Determine compliance with requirements**
- **Guiding Principles**
  - **Preferred method is test**
  - **All requirements formally verified and closed prior to launch**
  - **ICD/Environmental document lead tracks requirement closure; oversight by RVE and participating element leads**
- **Verification of L2-L4 requirements managed by RVE; L5 and lower managed by leads**
- **Verification activities conducted at various levels of assembly**
- **Documentation, tracking and closure via Verification Plans and Requirements Verification Matrices**

Verification Methods

- **Test: Direct, quantitative measurement of performance to show system compliance with a specified requirement, conducted over the full range of specified values and full set of relevant scenarios/ operational combinations.**
- **Analysis: For requirements that cannot be verified by test or by test alone. As is practical, analysis should be validated by correlation to test data.**
- **Demonstration: (1) For qualitative requirements that cannot easily be tested; (2) For requirements that could be verified by test, but not over the entire range of relevant values or scenarios.**
- **Inspection: Used for (1) verification of a design characteristic or method or the evaluation of physical features; (2) verification of records, including "roll-up" verification of lower-level flowdown requirements.**

Requirements Verification Matrix (sample format from EDTRD)



ID	Requirement	Doc. Section	Section Title	Compliance																Verification Method (T, A, D, I)	Verification Description	Closure Status	Closure Date	Responsible Organization	Comments
				AVI	PDU	EPS	RF	PROP	GC	SACS	TPS/TSA	THRM	HRN	MECH	FIELDS	SWEAP	ISIS	WISPR	OBSERVATORY						

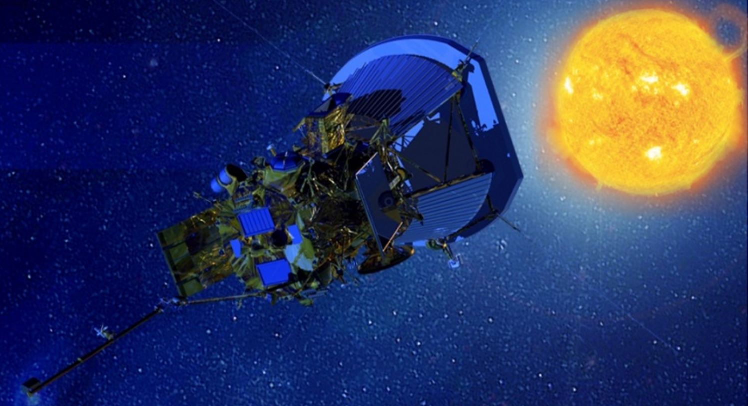
Phase C Work

- **Continued revisions to documents**
  - **Address action items**
  - **Review required attributes**
  - **Resolve link discrepancies**
  - **Perform detailed Verification activities planning**
  - **Resolve TBD/TBR items**
- **Completeness Validation Study**
  - **Requirement intent fully met by traceable/lower level requirements**
  - **Full compliance with ICDs/Environmental requirements established**
  - **Implications of relevant non-verifiable plans identified and documented**
- **Establish formal inter-revision change management process**
- **Develop Functional Allocation generation capabilities**

Summary

- **Process and management of Requirements & Verification Engineering defined**
- **Types of requirements documents, relationship, applicability and flowdown established**
- **Requirements documents at appropriate maturity levels and released**
- **Clear guidelines for requirement and module completion and validation**
- **DOORS and Change Management tools ensure proper revision and oversight practices**
- **Established V&V practices for Verification Program**

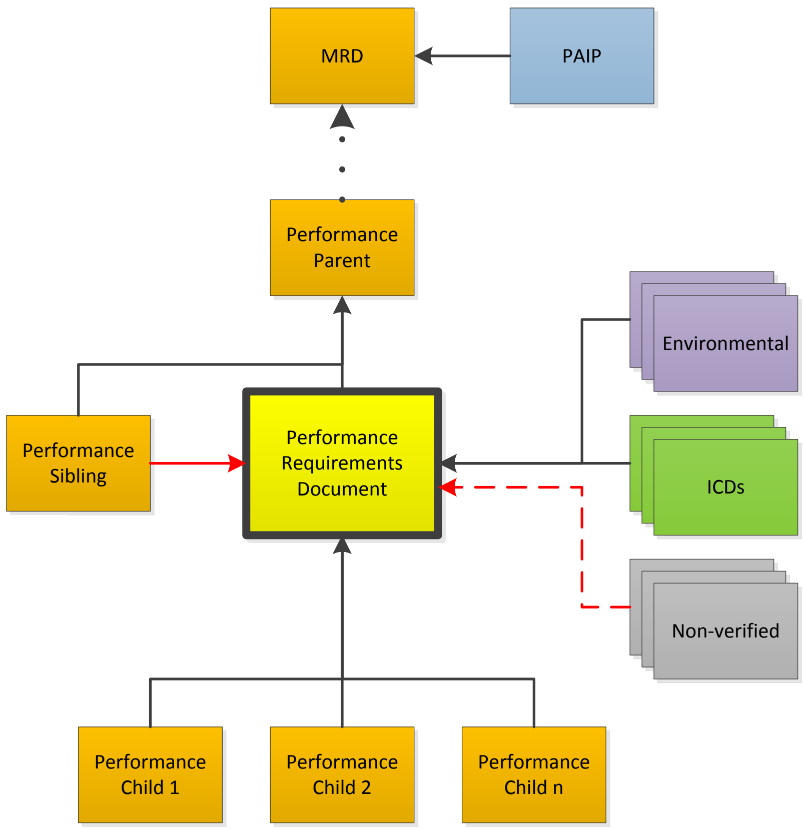
➢ **Requirements & Verification Engineering is ready for Phase C**



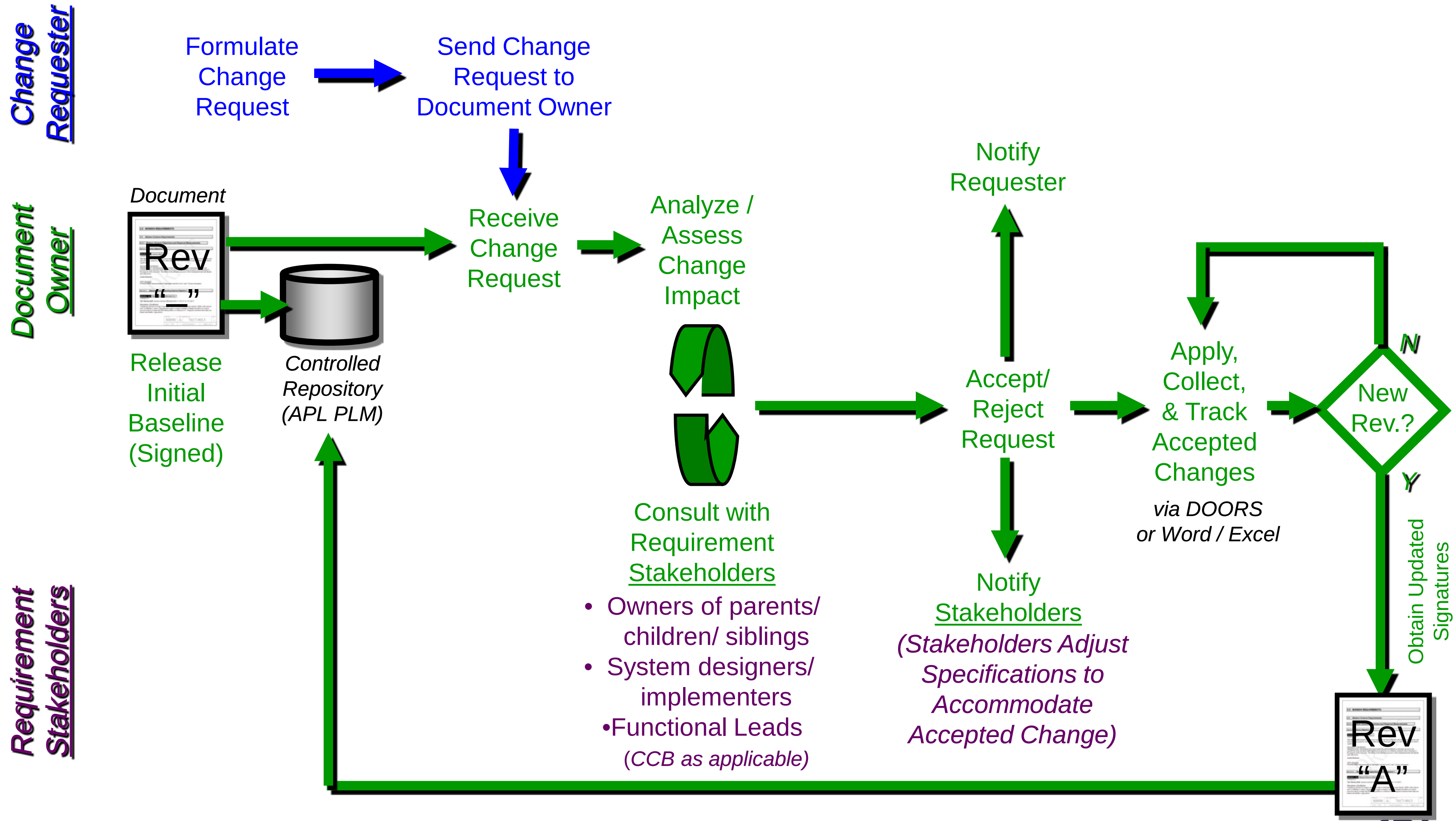
Backup

Allocation & Traceability

- Performance Document in question is central verification document for subject
- Requirements traceable to parent performance document
- Requirements allocated to documents one level below
- Functional leads given oversight into many or all documents (tracking enabled by DOORS)
  - Fault Management
  - Guidance & Control
  - Integration & Test
  - Solar Array Operations & Safing
  - Timekeeping
  - Alignments
- Links traceable between sibling documents in rare cases
- ICDs/Environmental Requirements Documents referenced via "compliance" requirements
- Non-verifiable documents (i.e. plans) handled by derived requirements
- ***RVE Tracks Applicability***



Requirements Change Management – Process Overview



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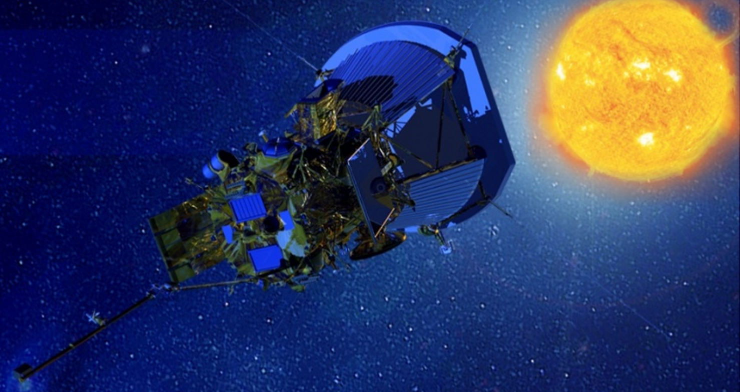

Mission Design

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Mission Design and Navigation Manager

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13 – 16 January 2014

APL

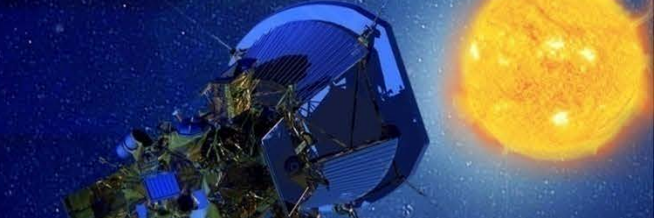
The Johns Hopkins University

APPLIED PHYSICS LABORATORY

Outline

- Mission Design driving requirements
- Phase B trade studies, peer reviews
- Baseline mission design
    - launch
    - mission trajectory
    - Venus flybys
    - solar encounters
    - times spent in near sun regions
    - mission profile, solar eclipses
- Baseline TCM placement and schedule
- Delta-V budget
- Backup mission design
    - launch, mission trajectory, Venus flybys, solar encounters, mission profile, solar eclipses
- Comparison of backup and baseline mission design
- Phase C plan
- Summary

Mission Design
Driving Requirements



Ref	Requirement	Verify
MDNR-1	**Minimum Perihelion Distance** Mission Design shall provide the mission trajectory with minimum distance from the center of the Sun of 9.86 R_S.	Ana., Met
MDNR-2	**Three Orbits at Minimum Perihelion** Mission Design shall provide the mission trajectory with at least three solar orbits having perihelion distance of 9.86 R_S from the center of the Sun.	Ana., Met
MDNR-3	**Near-Sun Hours** Mission Design shall provide the mission trajectory that allows the Spacecraft to spend at least 920 hours below 20 R_S from the center of the Sun, with no less than 14 hours below 10 R_S from the center of the Sun.	Ana., Met
MDNR-4	**Mission Duration** Mission Design shall provide the baseline mission trajectory that achieves at least three orbits at the minimum perihelion within 7 years of launch.	Ana., Met
MDNR-5	**Perihelion Geometry** Mission Design shall provide the mission trajectory with a perihelion geometry such that there is at least one perihelion pass visible from Earth to allow for simultaneous Earth-based observations of the Sun to support Solar Probe Plus observations.	Ana., Met

Mission Design Driving Requirements

Ref	Requirement	Verify
MDNR-6	**Baseline Launch Date** Mission Design shall provide the baseline launch period in July and August 2018.	Ana., Met
MDNR-7	**Baseline Launch Period** Mission Design shall provide a baseline launch period of at least 20 consecutive days.	Ana., Met
MDNR-8	**Baseline Launch C3** Mission Design shall provide the baseline launch period with a maximum launch C3 that does not exceed 154 km^2/s^2.	Ana., Met
MDNR-9	**Backup Launch Period** Mission Design shall provide a backup launch period in 2019 of at least 14 consecutive days.	Ana., Met
MDNR-10	**Backup Launch C3** Mission Design shall provide the 2019 backup launch period with a maximum launch C3 for the 2019 backup launch period that does not exceed 154.5 (TBR) km^2/s^2.	Ana., Met

Mission Design Driving Requirements

Ref	Requirement	Verify
MDNR-13	**Venus Flyby Altitude** Mission Design shall provide the mission trajectory that includes Venus flyby altitudes no less than 300 km.	Ana., Met
MDNR-14	**Maximum Solar Distance** Mission Design shall provide the mission trajectory such that the Spacecraft's maximum distance from the Sun does not exceed 1.1 AU throughout the mission.	Ana., Met
MDNR-15	**Solar Eclipse Duration** Mission Design shall provide the mission trajectory such that the longest time the Spacecraft is in any solar eclipse after launch does not exceed 12 minutes.	Ana., Met

Mission Design Driving Requirements

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Ref	Requirement	Verify
MDNR-69	**TCM Design and Spacecraft Pointing** Mission Design shall design the trajectory correction maneuvers to comply with spacecraft pointing constraints as defined in the Environmental Design and Test Requirements Document.	Ana., Expected Met
MDNR-70	**TCM Minimum Solar Distance** Mission Design shall design trajectory correction maneuvers to occur at spacecraft-sun distance greater than or equal to 0.3 AU (TBR).	Ana., Met
MDNR-71	**Minimum Time between TCMs** Mission Design shall design the trajectory correction maneuvers in such a way that two consecutive burns are separated more than 20 hours apart if the combined duration of the two burns is longer than 7200 seconds (TBR).	Ana., Met
MDNR-72	**Maximum TCM Duration** Mission Design shall design any trajectory correction maneuver with the maneuver burn duration no longer than 7200 seconds (TBR).	Ana., Met

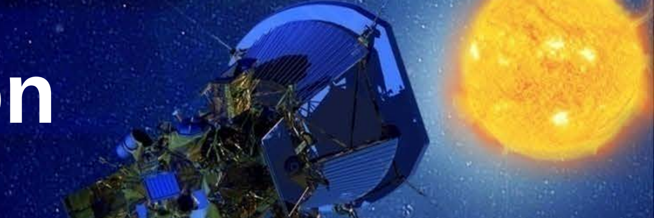
Requirement Changes Since MDR

Requirement	MDR	PDR
Minimum perihelion distance	9.5 R_S	9.86 R_S
Time below 20 R_S	950 hours	920 hours
Time below 10 R_S	25 hours	14 hours
Time to achieve minimum perihelion passes	10 years of launch	7 years of launch

Mission Design and Navigation Phase B Major Trade Study

- **Mission Design Trades -> Revised Mission Design of 9.86 R_S**
  - Alternative mission designs with various min perihelion distances
  - Mission design scenarios for launch opportunities beyond 2018 & 2019
  - Mission design scenarios for launch on Delta IV Heavy
- **TCM Placement Optimization -> Baseline TCM schedule**
  - Mission Design trajectory analysis performed with CATO for selecting optimal TCM locations that minimize TCM Delta-Vs
  - Navigation Capability Ellipse (CAPEL) analysis ensuring selected location has large leverage on all target parameters
- **DSN Tracking Schedule Trade -> Tracking Gaps Acceptable**
  - Sensitivity study of navigation tracking schedule on OD accuracy and statistical Delta-V requirement
  - Cases investigated include reduced tracking during solar encounters, long tracking gaps at some orbits, and reduced ranging coverage over the mission
- **Navigation OD Uncertainties -> Staffing plan supporting OD Requirement**
  - OD strategy/staffing cost versus OD uncertainty requirement
- **Statistical Delta-V Requirement -> CBE of Statistical Delta-V**
  - Delta-V requirements from various estimated injection covariance matrices (ICMs)

Mission Design and Navigation Phase B Peer Reviews



- **Mission Design and Navigation TIM-1, held on June 5, 2013**
  - **Mid-term review of MD and NAV analysis results by the team and other project subsystem teams**
- **Mission Design and Navigation Requirements Peer Review, held on August 6, 2013**
  - **5-member review board including reviewers from APL, JPL, GSFC, and SRB**
  - **10 action items and 7 recommendations**
  - **All action items are closed**
  - **Level-3 MDNR document 7434-9061 released, 9/4/2013**
  - **Rev A of MDNR document 7434-9061, incorporated latest changes, is in PLM, in signature process**
- **Mission Design and Navigation PDR, held on November 15, 2013**
  - **8-member review board including reviewers from APL, JPL, GSFC, KinetX, and SRB**
  - **8 action items and 4 recommendations**

Baseline Mission Design Overview

Launch
- 20-day launch period from Jul 31 to Aug 19, 2018
- Maximum launch C3 of 154 km^2/s^2
- S/C wet mass 665 kg

Mission Trajectory
- A V^7GA type of trajectory requiring 7 Venus gravity assist flybys
- No deep space maneuvers
- Consisting of 24 solar orbits, 3 has minimum perihelion
- Perihelion gradually decreasing to 9.86 R_S
- Maximum solar distance of 1.018 AU

Final Solar Orbit
- Perihelion of 9.86 R_S
- Aphelion of 0.73 AU
- Orbit inclination of 3.4 deg from ecliptic
- Orbit period of 88 days

Mission Timeline
- Launch to 1st perihelion: 3 months
- Launch to 1st min perihelion (9.86 R_S): 6.4 years
- Mission duration (including 3 passes at 9.86 R_S): 7 years

Baseline Mission Design
Launch C3 and DLA Requirement

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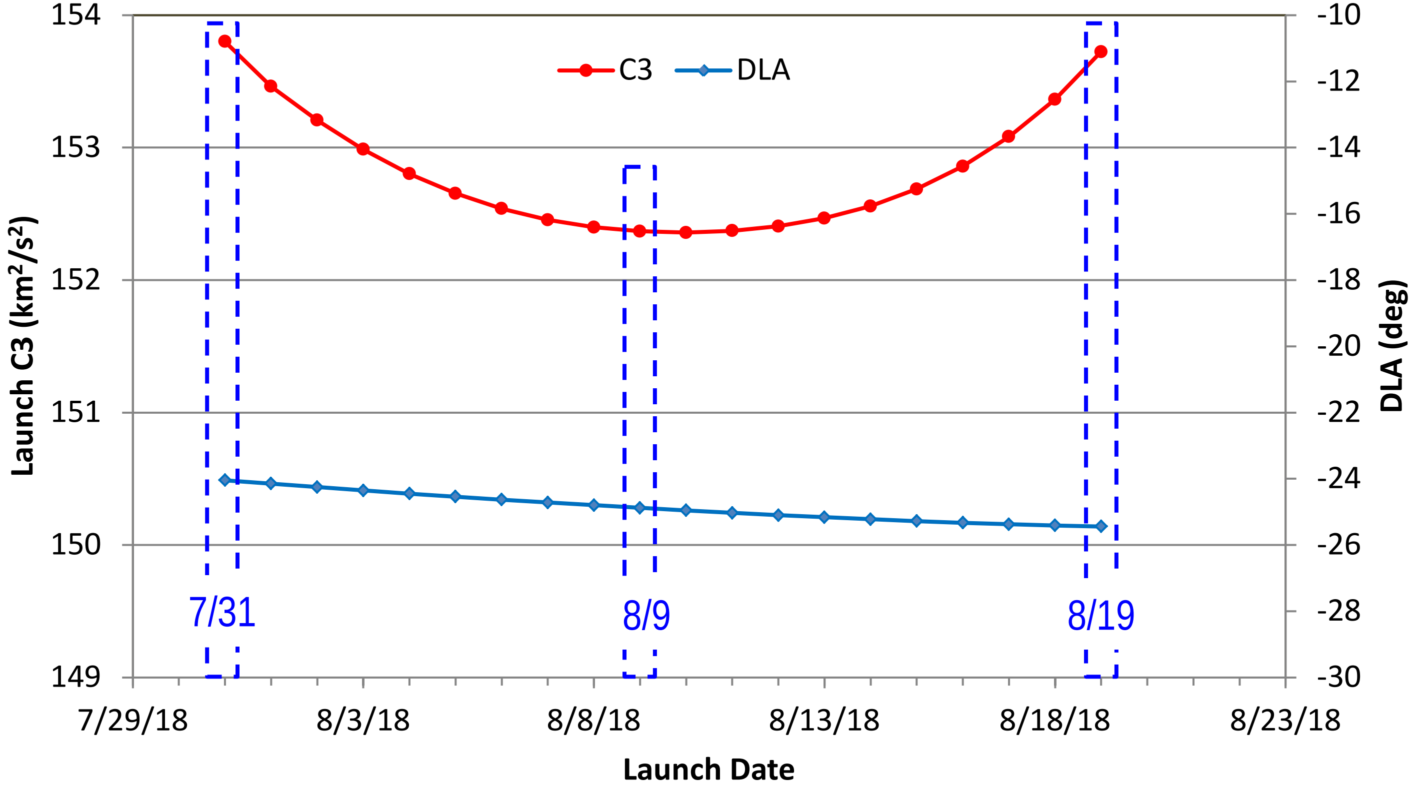


Detailed analysis performed for beginning, middle, and end launch period:

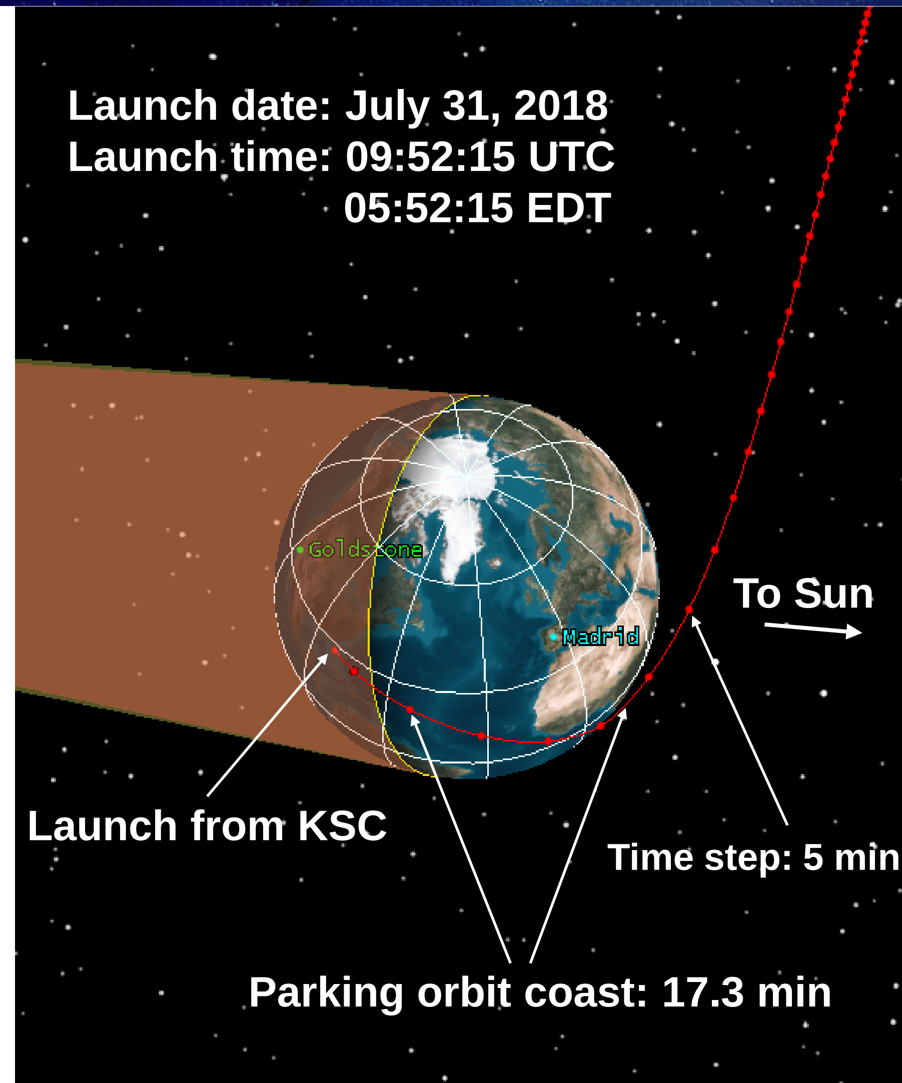
- **End-to-end integrated trajectory, Venus flybys, solar encounters**
- **Entire mission profile: sun & earth distances, solar conjunctions & eclipses**
- **Communication coverage and gaps**

Baseline Mission Design
Launch Details

- **Launch Period**
  - **20 days (Jul 31 - Aug 19, 2018)**
- **Launch Trajectory**
  - **Using an Earth parking orbit**
- **Daily Launch Window**
  - **Launch window with the short coast is selected**
- **Daily Window Duration**
  - **30 minutes or longer (TBR until launch vehicle is selected)**

Launch Period	Beginning	Middle	End
Launch Date	7/31/2018	8/9/2018	8/19/2018
Launch Time* (UTC)	9:52:15	9:35:10	9:05:58
Launch Time* (EDT)	5:52:15	5:35:10	5:05:58
Parking Orbit Coast* (min)	17.3	16.6	16.1

* Estimate based on simulated launch trajectory. Actual launch time and coasting depend on selected launch vehicle.



Baseline Mission Trajectory

Solar Probe Plus

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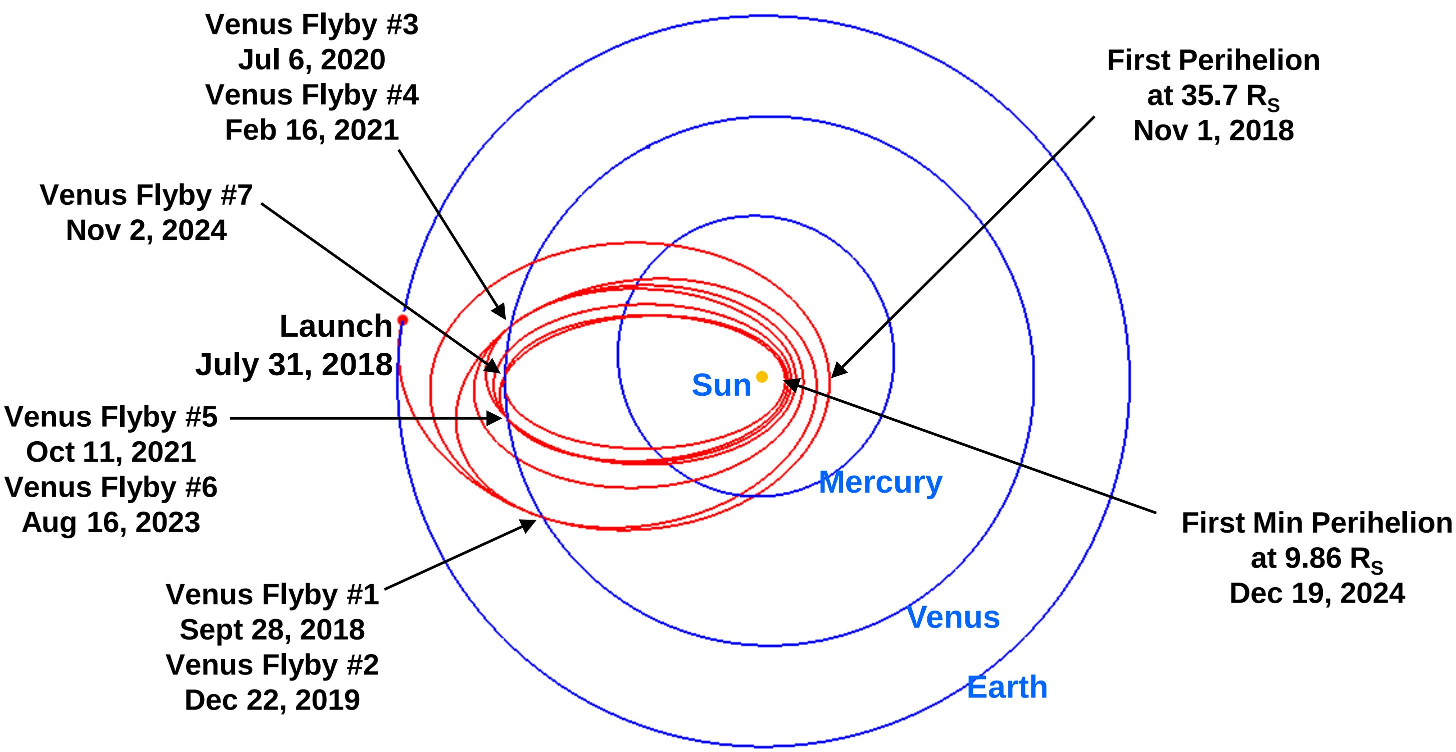
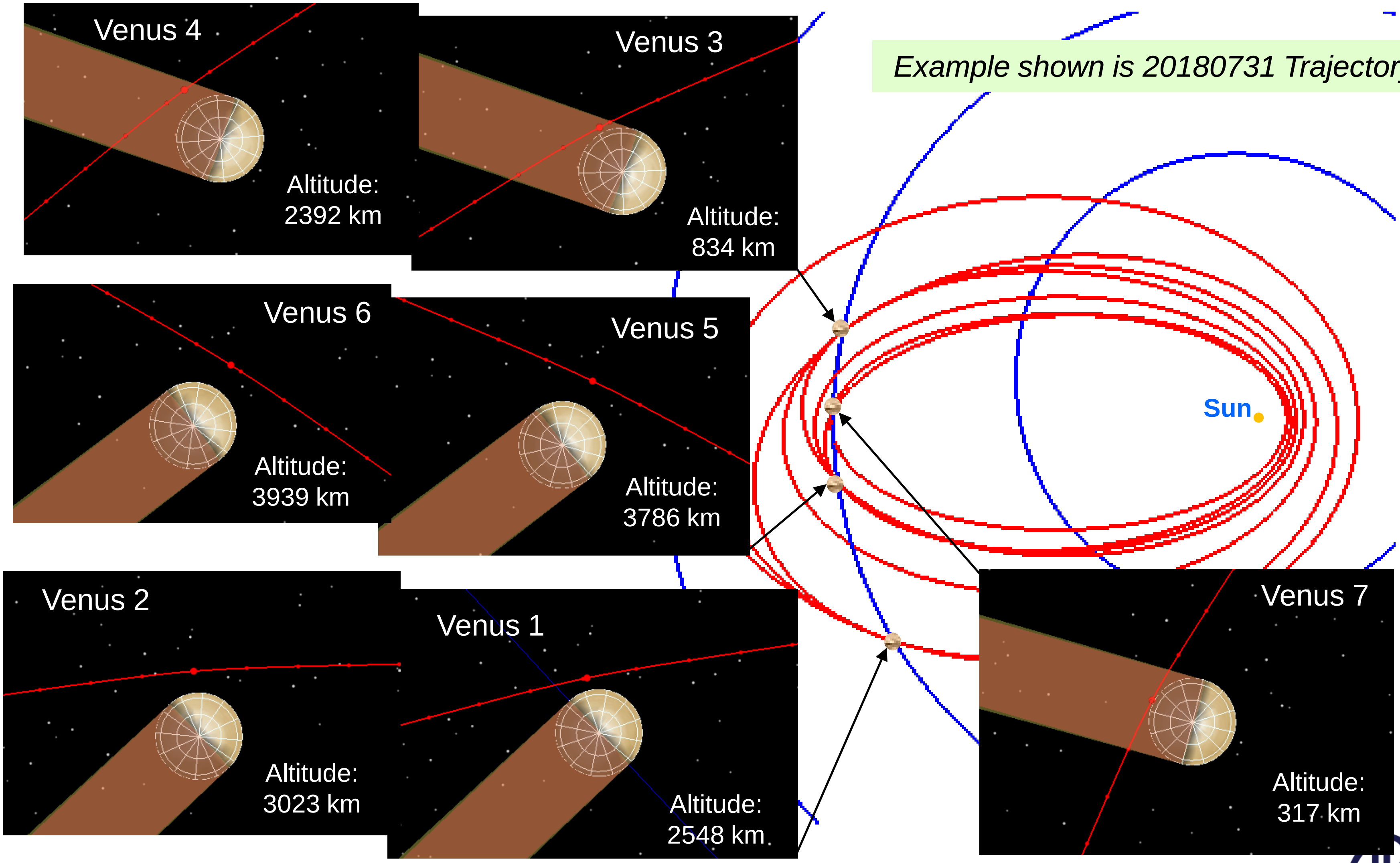
Venus-Venus-Venus-Venus-Venus-Venus-Venus-Gravity-Assist (V^7GA) Trajectory

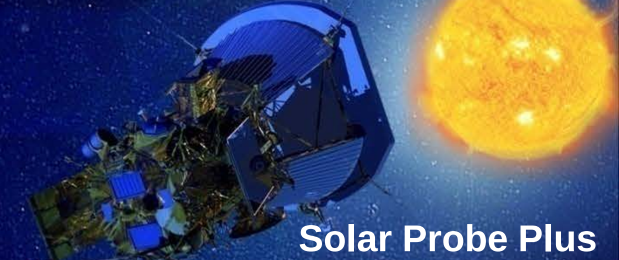


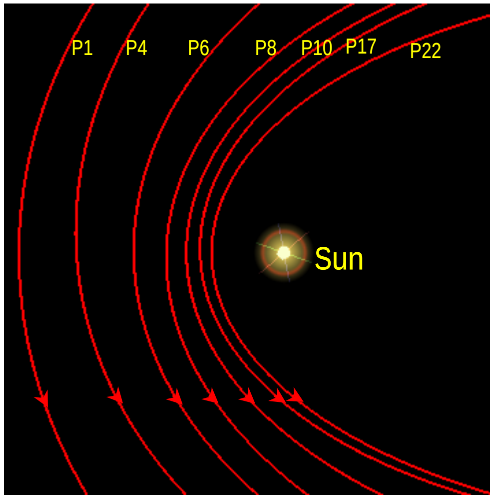
- Repeated 7 Venus gravity assists to reduce velocity in order to get to the Sun within 10 R_S
- Switching between resonant and non-resonant Venus flybys to minimize mission duration
- Orbit phasing matched between flybys so that no deep space maneuvers are required
- Perihelion gradually decreased step by step
- Frequent visits of the Sun 3 to 4 times per year
- Unprecedented 24 solar orbits providing abundant opportunities for science investigations at the Sun
- Solar distances not beyond Earth for a solar powered spacecraft

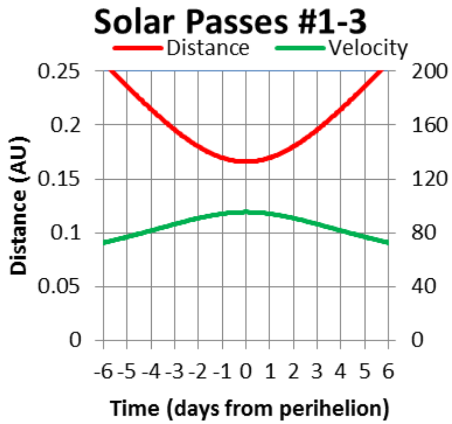
Baseline Mission Trajectory
Venus Flyby Geometry

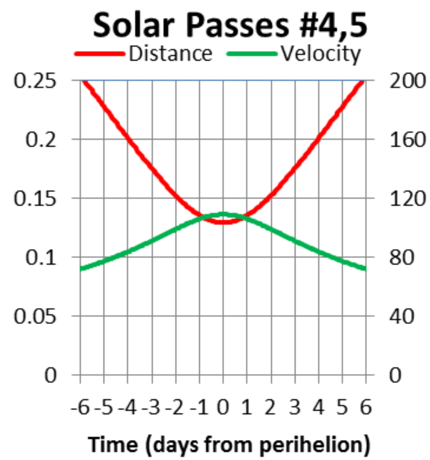


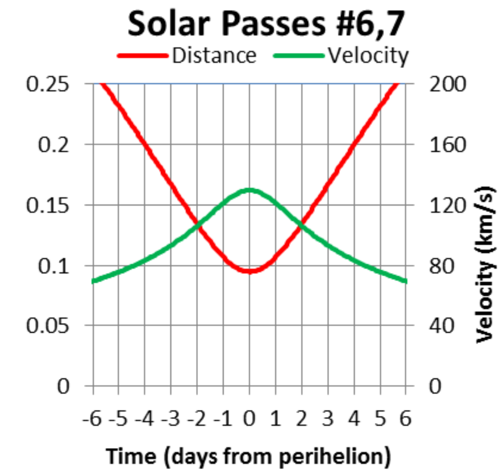
Baseline Mission Design
Solar Encounters

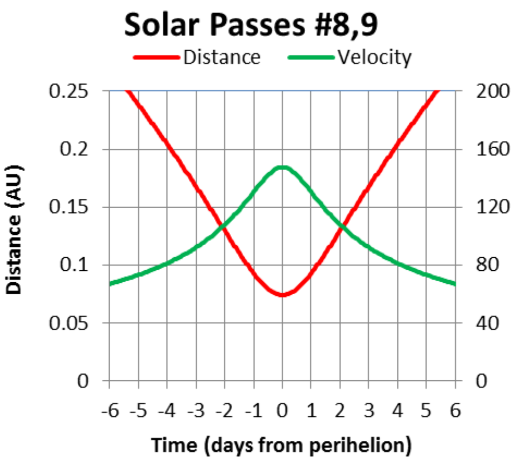


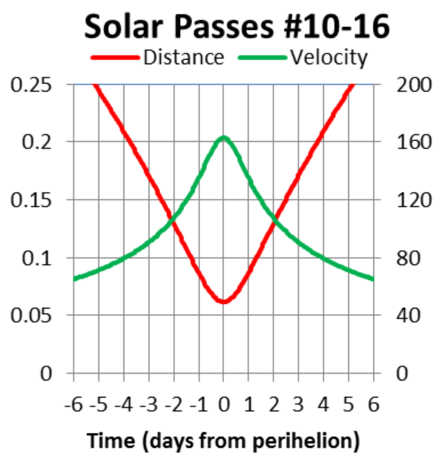


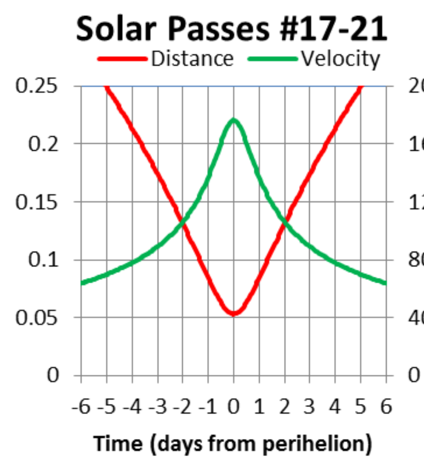


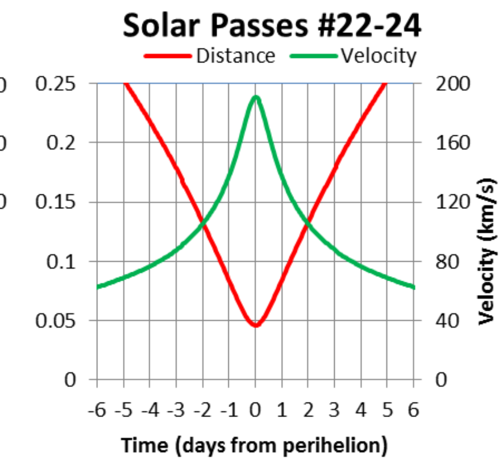












Min Perihelion: 9.86 R_S, Max Velocity: 190.8 km/s, Time within 0.25 AU: 9.8–11.6 days

Baseline Mission Trajectory Minimum Perihelion Geometry

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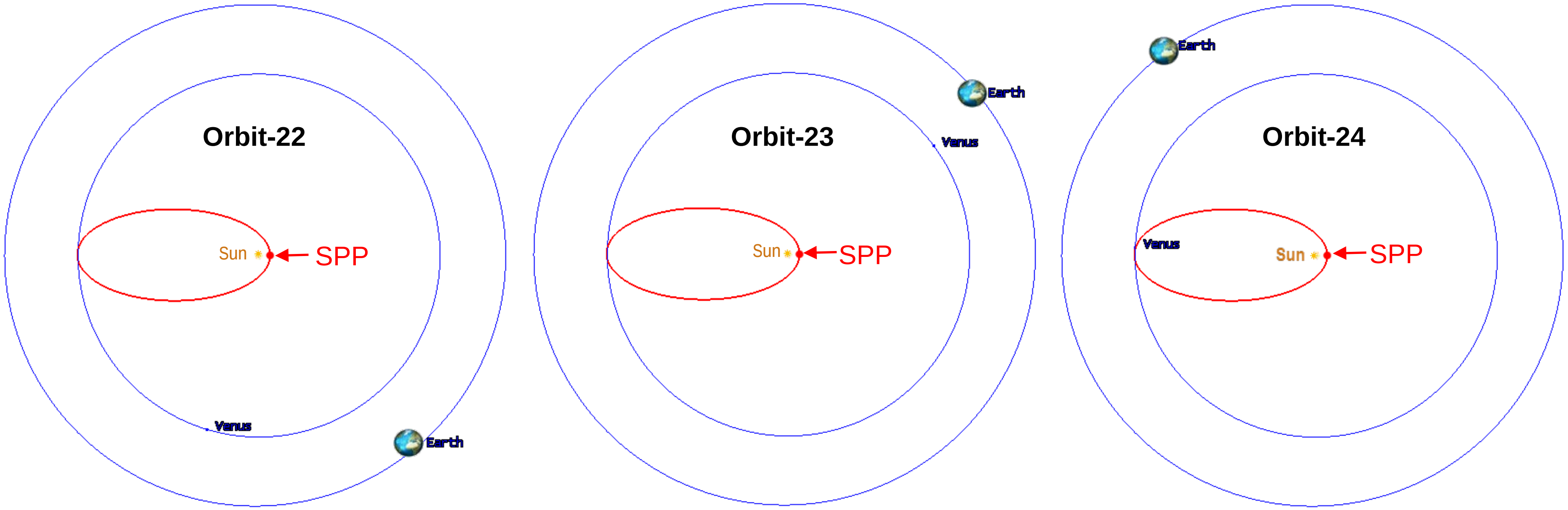
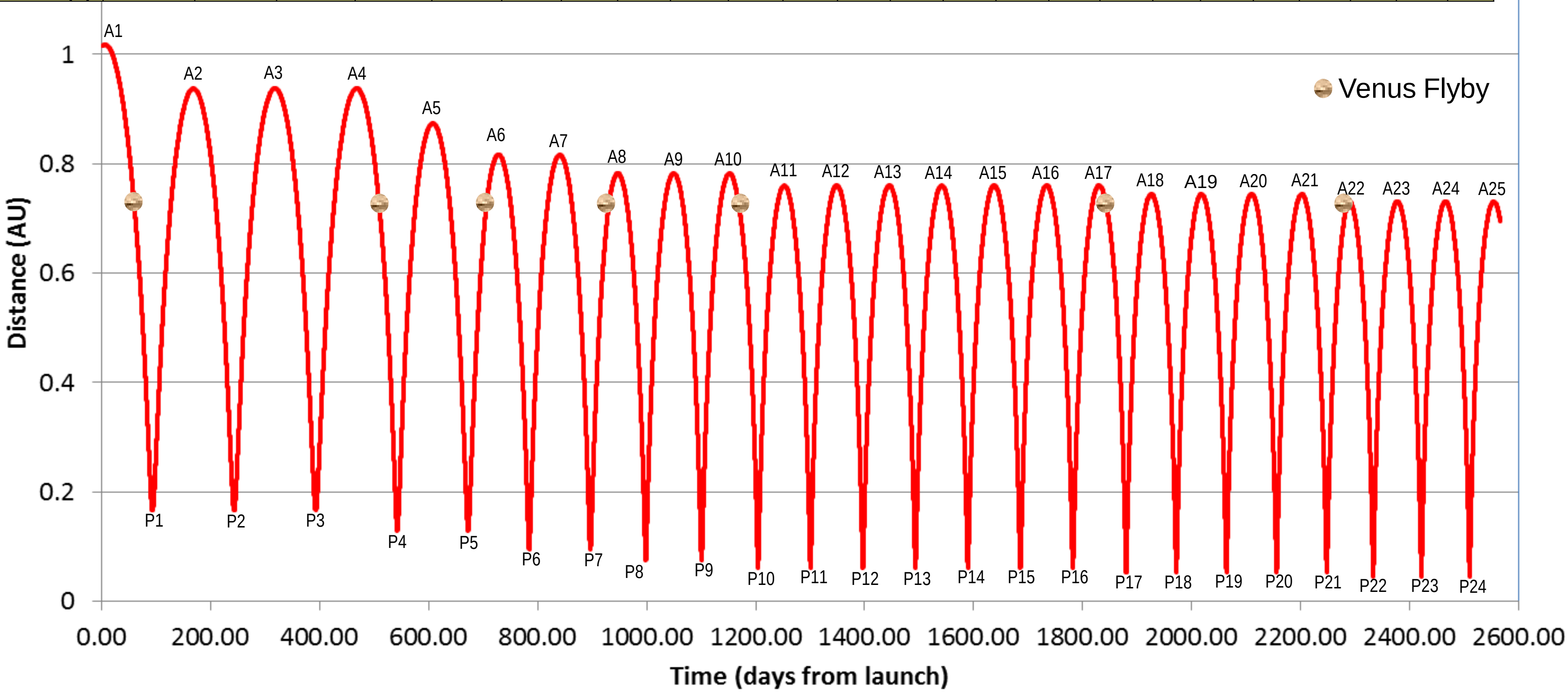
Example shown is 20180731 Trajectory



- **The 9.86-R_S solar orbits are Orbit-22, Orbit-23, and Orbit-24**
- **Three orbits are identical in size: orbital period = 88 days, aphelion =0.73 AU, inclination = 3.4 deg from ecliptic**
- **Solar encounter geometry (Earth position) is different for each of the orbits**
- **Earth position shown is when SPP at perihelion. Spacecraft is visible from Earth for all solar encounters, and different parts of the Sun are observed from the Earth during the solar passes.**

Baseline Mission Design
Solar Distance Profile

Orbit #	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
Period (d)	168	150	150	140	121	112	107	102	102	100	96	96	96	96	96	96	96	92	92	92	87	88	88	88



- **Max solar distance is1.018 AU, and min solar distance is 0.04587 AU (9.86 R_S)**
- **Total of 25 aphelia (A1 through A25) and 24 perihelia (P1 through P24)**
- **Perihelia gradually decreases**

APL

Reference Mission Design

Accumulated Time within the Near-Sun Region

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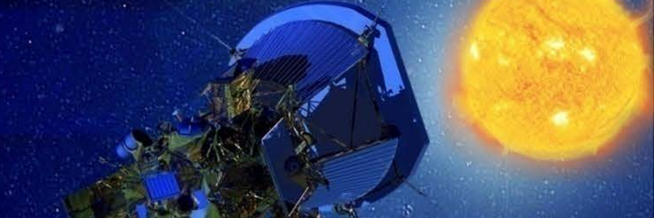
Solar Pass #	Perihelion (AU)	Perihelion (Rs)	Time within			
			30 Rs (hr)	20 Rs (hr)	15 Rs (hr)	10 Rs (hr)
1	0.163	35.66				
2	0.163	35.66				
3	0.163	35.66				
4	0.128	27.85	61.04			
5	0.128	27.85	61.05			
6	0.092	20.35	104.22			
7	0.092	20.35	104.22			
8	0.072	15.98	108.55	48.06		
9	0.072	15.98	108.55	48.06		
10	0.06	13.28	107.27	55.13	24.75	
11	0.06	13.28	107.27	55.13	24.75	
12	0.06	13.28	107.27	55.12	24.75	
13	0.06	13.28	107.27	55.13	24.75	
14	0.06	13.28	107.27	55.12	24.74	
15	0.06	13.28	107.27	55.12	24.74	
16	0.06	13.28	107.27	55.12	24.73	
17	0.052	11.42	105.03	56.91	32.23	
18	0.052	11.42	105.03	56.91	32.23	
19	0.052	11.42	105.03	56.91	32.23	
20	0.052	11.42	105.03	56.91	32.23	
21	0.052	11.42	105.03	56.91	32.23	
22	0.044	9.86	102.40	57.02	35.22	4.94
23	0.044	9.86	102.40	57.02	35.22	4.95
24	0.044	9.86	102.40	57.02	35.22	4.95
Total			**2130.85**	**937.58**	**440.03**	**14.85**
Requirements:				**920**		**14**

- There are 7 different solar orbit groups
- Each orbit group has the same perihelion distance
- Number of perihelion passes of a group varies from 2 to 7.
- Total accumulated times are critical to science investigations
- Total times below 20 R_S and 10 R_S meet requirements
- Repeated passes in a group offer multiple observation opportunities

Baseline Mission Profile



Solar Probe Plus
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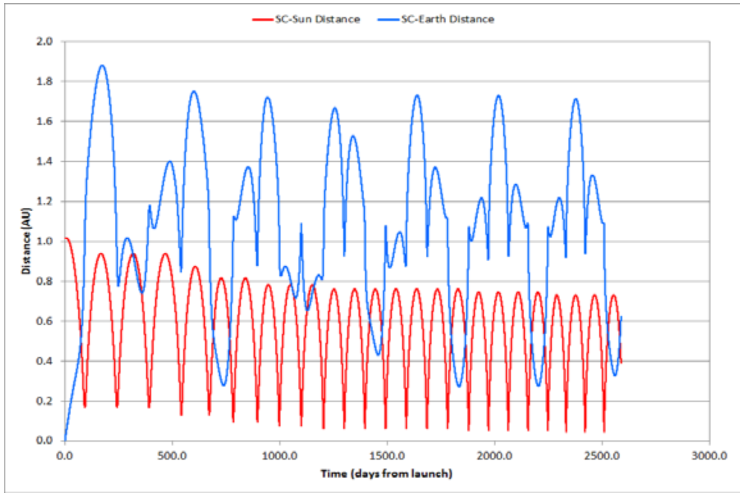
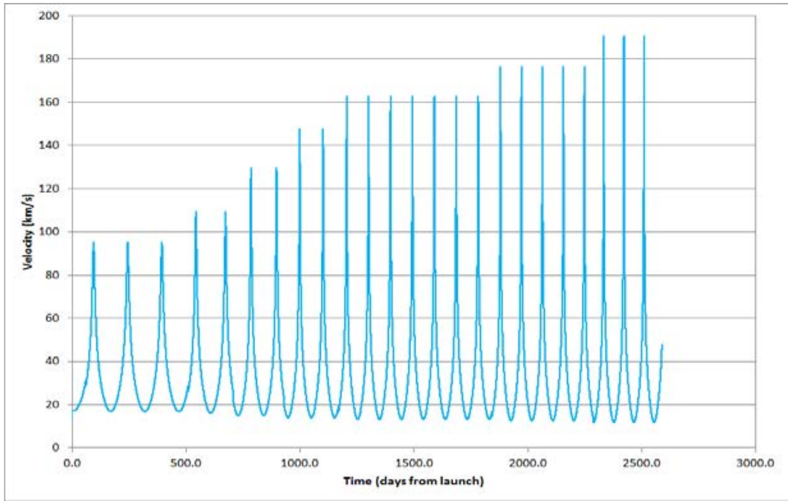
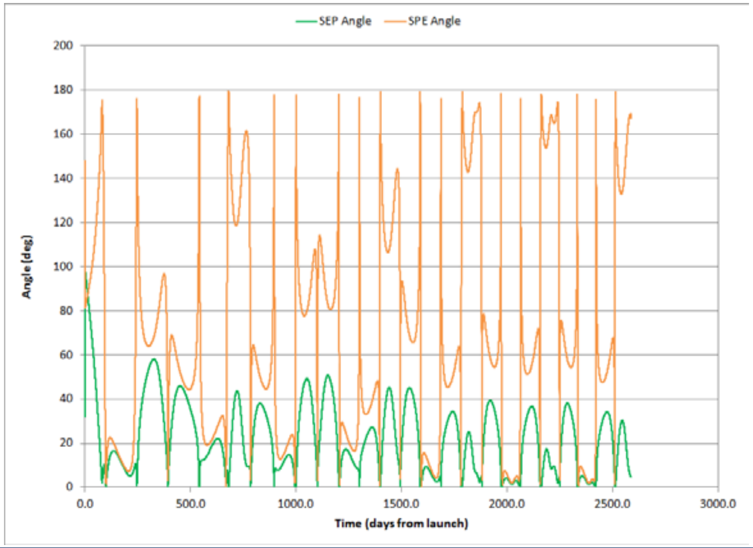
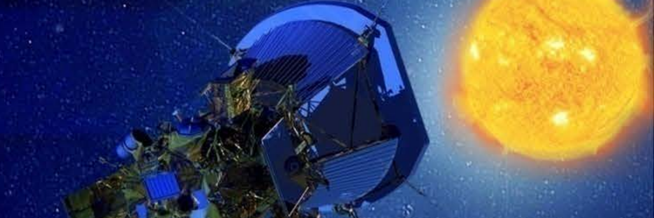






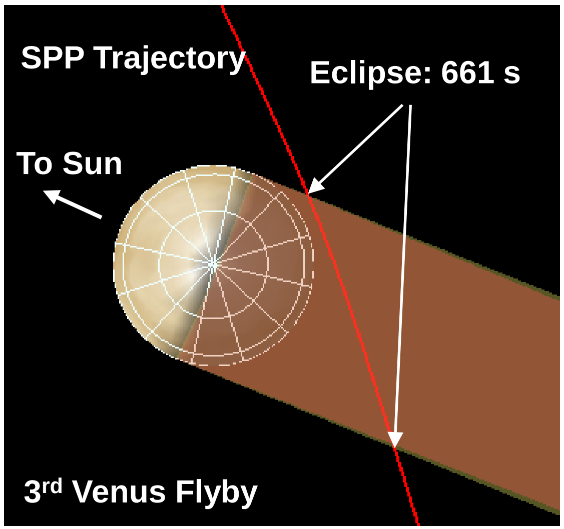
- **Solar distance: 0.04587 - 1.018 AU**
- **Earth distance: 0 - 1.881 AU**
- **Velocity: 11.2 - 190.8 km/s**
- **SEP angle: 0.008° – 98.3°**
- **SPE angle: 0.16° - 179.9°**

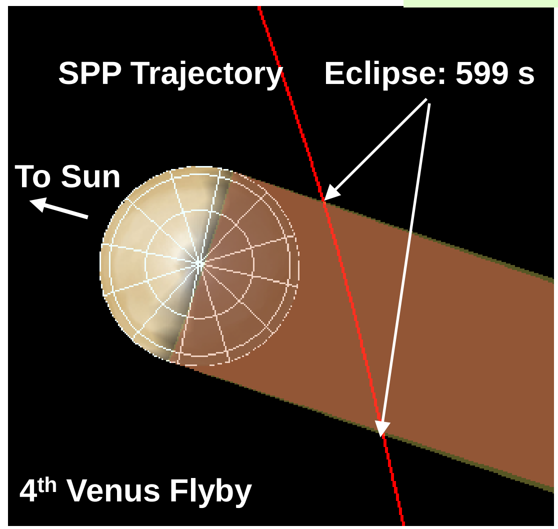
Baseline Mission Design
Post Launch Solar Eclipses

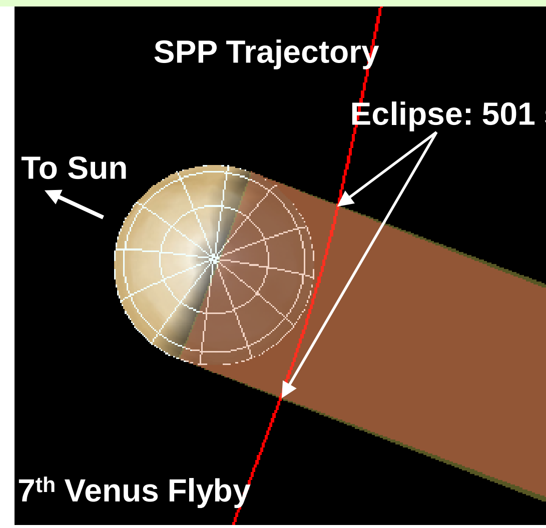


- **Three brief solar eclipses will occur during 3 of the 7 Venus flybys**

Example shown is 20180731 Trajectory







Launch Period	Beginning	Middle	End
Launch Date	7/31/2018	8/9/2018	8/19/2018
Duration of solar Eclipse during 3rd Venus Flyby (s)	660.5	661.3	660.4
Duration of solar Eclipse during 4th Venus Flyby (s)	598.6	600.2	597.6
Duration of solar Eclipse during 7th Venus Flyby (s)	501.2	501.2	501.2

Duration of solar eclipse < 12 minutes

Analysis of Tracking Gaps

- Detailed communication coverage over the entire Solar Probe Plus mission is evaluated orbit by orbit, based on current telecomm system design assumptions and spacecraft orientation constraints.
- The coverage has been analyzed for mission trajectories at the beginning, middle, and end of the launch period of the baseline mission design.
- Long navigation tracking gaps that may cause significant impact on orbit determination, Venus flybys, and trajectory correction maneuvers are identified.
- Trade studies have been performed to investigate the impact of the navigation tracking gaps. S/C pointing rule has been adjusted to improve the coverage, for example, the long gap prior to Venus 4 has been removed.
- Navigation analyses show requirements can be met with the tracking gaps included.
- Coverage differences are observed among the trajectories on different launch dates over the launch period, but the differences are not significant to cause concerns.

Analysis of TCM Placement

- **Trajectory Correction Maneuver (TCM) placement has significant impact on Delta-V budget.**
- **Location of a TCM also affects the navigation delivery accuracy at the Venus flybys as well as the orbit determination uncertainties.**
- **A baseline TCM schedule has been developed to serve as a basis for**
    - **navigation analysis including estimate of the statistical ∆V requirements**
    - **evaluation of mission and spacecraft resource allocation**
    - **mission operations planning**
- **The baseline TCM schedule is derived based on trade studies by both MD and NAV teams in several iterations**
    - **MD used trajectory and maneuver optimization software CATO to select optimal TCM locations that minimizes maneuver Delta-V, which took into account the actual flight conditions and spacecraft operation constraints, such as the tracking gaps, no maneuver zone, etc.**
    - **NAV performed the CAPEL (Capability Ellipse) analysis to evaluate the TCM locations recommended by MD from the CATO analysis. The CAPEL analysis computes angles between the B-plane target's gradient vectors and computes dimensions of ∆V capability ellipse. This analysis ensures a maneuver at the selected location has large leverage on all target parameters.**

Baseline mission TCM Placement

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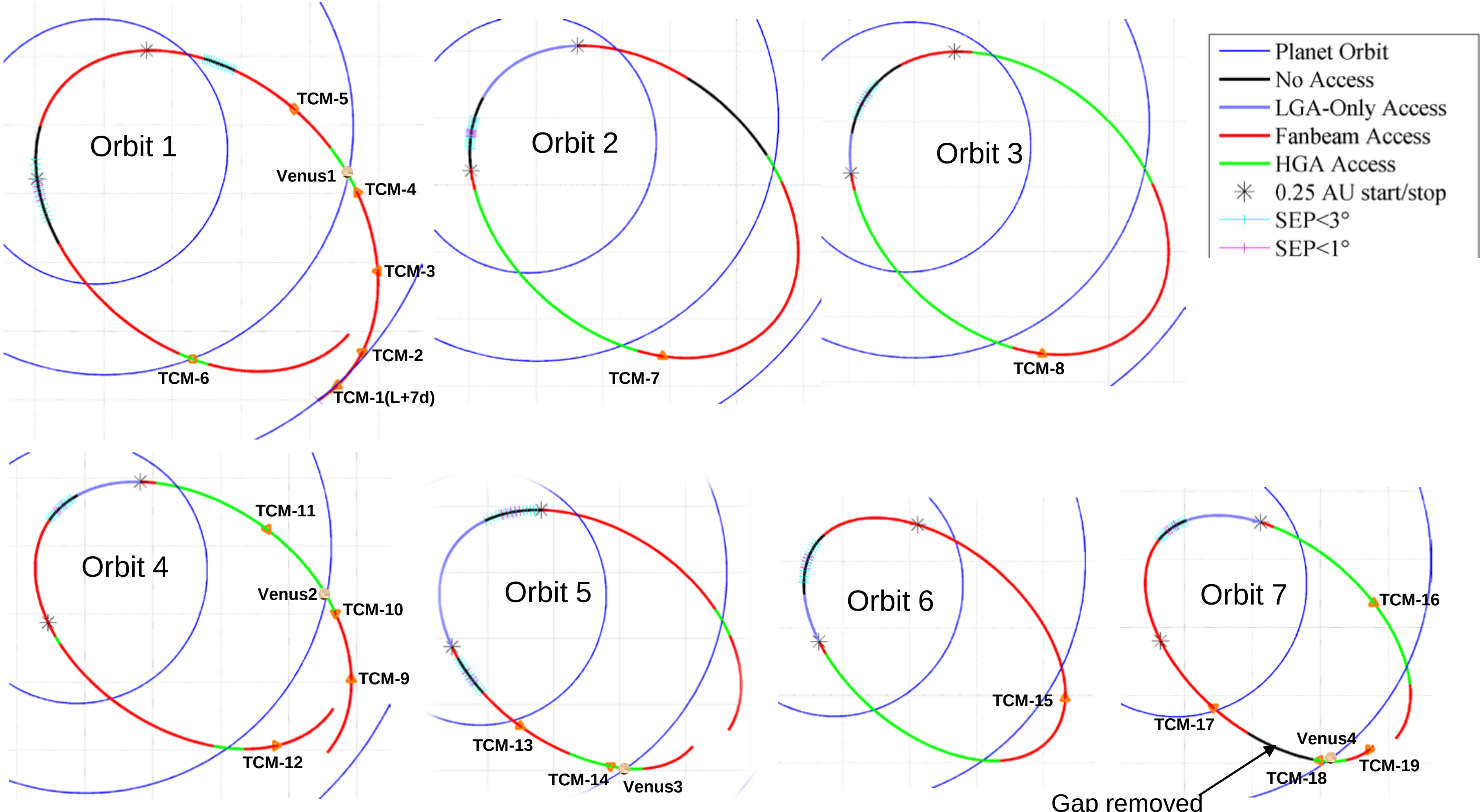

Baseline Mission TCM Placement

Solar Probe Plus
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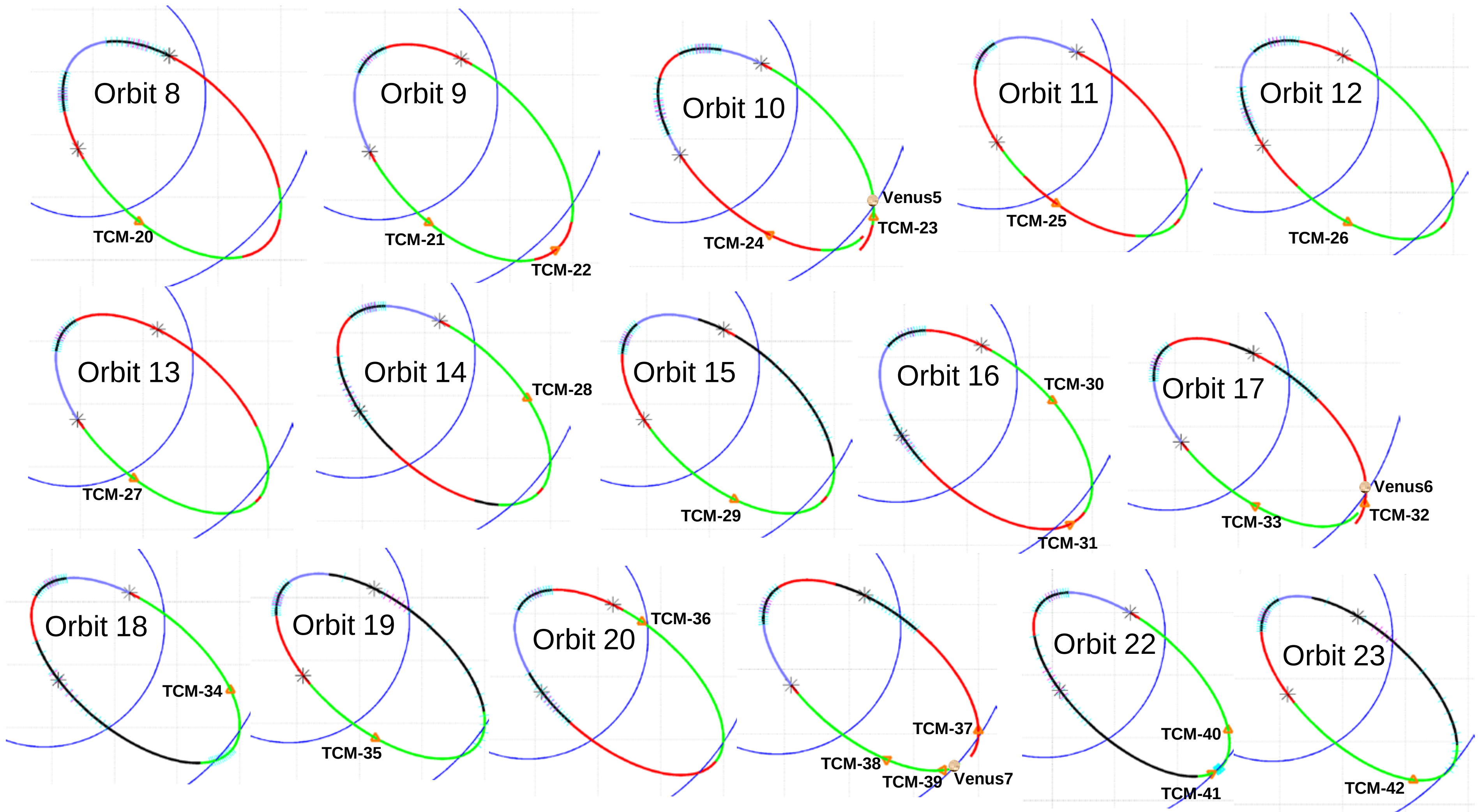

Baseline TCM Schedule (1 of 2)

Event	Launch	Venus 1	Venus 2	Venus 3	Venus 4	Venus 5	Venus 6	Venus 7
Date	7/31/2018	9/28/2018	12/22/2019	7/6/2020	2/16/2021	10/11/2021	8/16/2023	11/2/2024

TCM	Function	Time	Date	Earth Distance (AU)	Solar Distance (AU)	SEP Angle (deg)	Orbit
1	Launch correction	L+7d	08/07/2018	0.05	1.02	92.62	1
2	TCM-1 cleanup	L+19d	08/19/2018	0.14	1.00	81.34	1
3	Venus 1 targeting	V1-19d	09/09/2018	0.27	0.90	59.69	1
4	Venus 1 targeting	V1-3.0d	09/25/2018	0.36	0.76	39.31	1
5	Venus 1 cleanup	V1+13d	10/11/2018	0.48	0.55	15.50	1
6	Venus 1 cleanup	V2-381d	12/05/2018	1.63	0.73	15.97	1
7	Venus 2 targeting	V2-223d	05/12/2019	1.01	0.81	47.10	2
8	Venus 2 targeting	V2-72d	10/10/2019	1.15	0.82	44.15	3
9	Venus 2 targeting	V2-18d	12/03/2019	1.40	0.88	38.38	4
10	Venus 2 targeting	V2-3.4d	12/18/2019	1.35	0.76	33.55	4
11	Venus 2 cleanup	V2+14.6d	01/05/2020	1.19	0.54	26.38	4
12	Venus 3 targeting	V3-119d	03/09/2020	1.72	0.82	15.96	4
13	Venus 3 targeting	V3-18d	06/18/2020	0.56	0.48	12.65	5
14	Venus 3 targeting	V3-2.8d	07/03/2020	0.44	0.70	34.41	5
15	Venus 4 targeting	V3+36d	08/11/2020	0.28	0.78	29.01	6
16	Venus 4 targeting	V4-54d	12/23/2020	1.26	0.57	26.03	7
17	Venus 4 targeting	V4-20d	01/26/2021	1.40	0.45	7.83	7
18	Venus 4 targeting	V4-1.5d	02/14/2021	1.67	0.72	9.24	7
19	Venus 4 cleanup	V4+15d	03/02/2021	1.72	0.78	12.28	7
20	Venus 5 targeting	V5-154d	05/10/2021	0.85	0.50	29.95	8
21	Venus 5 targeting	V5-52d	08/20/2021	0.71	0.50	27.03	9

Baseline TCM Schedule (2 of 2)

Solar Probe Plus
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Event	Launch	Venus 1	Venus 2	Venus 3	Venus 4	Venus 5	Venus 6	Venus 7
Date	7/31/2018	9/28/2018	12/22/2019	7/6/2020	2/16/2021	10/11/2021	8/16/2023	11/2/2024

TCM	Function	Time	Date	Earth Distance (AU)	Solar Distance (AU)	SEP Angle (deg)	Orbit
22	Venus 5 targeting	v5-17d	09/23/2021	0.73	0.78	50.68	9
23	Venus 5 targeting	V5-3d	10/08/2021	0.80	0.75	47.50	10
24	Venus 5 cleanup	V5+56d	12/06/2021	1.45	0.57	16.03	10
25	Venus 6 targeting	V6-527d	03/07/2022	1.34	0.49	17.21	11
26	Venus 6 targeting	V6-426d	06/16/2022	0.62	0.57	29.59	12
27	Venus 6 targeting	V6-335d	09/15/2022	0.88	0.47	28.17	13
28	Venus 6 targeting	V6-272d	11/17/2022	1.02	0.56	32.57	14
29	Venus 6 targeting	V6-136d	04/02/2023	1.29	0.58	25.45	15
30	Venus 6 targeting	V6-75d	06/02/2023	1.14	0.49	25.29	16
31	Venus 6 targeting	V6-17d	07/29/2023	0.30	0.75	24.02	16
32	Venus 6 targeting	V6-3d	08/13/2023	0.28	0.74	12.01	17
33	Venus 7 targeting	V7-389d	10/09/2023	1.01	0.52	29.98	17
34	Venus 7 targeting	V7-338d	11/29/2023	1.20	0.63	31.89	18
35	Venus 7 targeting	V7-205d	04/10/2024	1.19	0.52	25.40	19
36	Venus 7 targeting	V7-138d	06/17/2024	1.07	0.33	18.27	20
37	Venus 7 targeting	V7-72d	08/21/2024	0.30	0.72	8.63	21
38	Venus 7 targeting	V7-17d	10/15/2024	1.05	0.58	32.64	21
39	Venus 7 targeting	V7-3d	10/29/2024	1.15	0.71	38.05	21
40	Venus 7 cleanup	V7+19d	11/20/2024	1.22	0.67	33.61	22
41	Peri adjustment	V7+87d	1/27/2025	1.71	0.72	3.27	22
42	Peri adjustment	V7+166d	4/16/2025	1.33	0.68	29.81	23

TCM Implementation Constraints and Delta-V Requirement

- **TCM has to be applied while S/C maintains orientation constraints - S/C is mostly oriented with the Thermal Protection System (TPS) pointed at the Sun.**
- **All S/C thrusters are canted.**
- **All TCMs except TCM-1 are to be implemented in a vector mode.**
- **Adequate ΔV budget is required for trajectory and attitude control**
  - **Trajectory Control**
    - **Trajectory correction maneuvers (TCMs)**
      - **All trajectory maneuvers are statistical, for correcting launch and navigation errors**
      - **No deterministic deep space maneuvers required for the nominal SPP mission trajectory**
  - **Attitude Control**
    - **Momentum dumps**
- **Trajectory Control related Delta-V is comprised of two components:**
    - **idea TCM Delta-V – navigation statistical ΔV99%**
    - **implementation penalty – additional fuel usage due to canted thrusters, vector-mode, and attitude control during TCM burn**

Delta-V Budget

SPP Delta-V Budget (Tank Capacity)

Usage	Maneuver	ΔV (m/s)	Propellant (kg)	Comment
Trajectory Control	TCMs	197	59.3	Maximum in tank capacity
Attitude Control	Momentum Dumps		7	Provided by G&C
Total			66.3	

Current Estimate of Trajectory Control Delta-V

	TCM-1 (m/s)		All Other TCMs (m/s)		Total TCMs (m/s)				
Cases	**ΔV99%**	**Burn Penalty***	**Other TCM ΔV**	**Burn Penalty****	**ΔV99%**	**Burn Penalty**	**Total Burn ΔV (m/s)**	**Margin from Capacity (m/s)**	**Comment**
Case 1	44.65	8.62	63.95	35.81	108.6	44.43	153.03	43.97	ATK ICM
Case 2	43.32	8.36	65.98	36.95	109.3	45.31	154.61	42.39	NESC ICM
Case 3	103.66	20.01	62.54	35.02	166.2	55.03	221.23	-24.23	Orbital 1st ICM
Case 4	**59.98**	**11.58**	**64.32**	**36.02**	**124.3**	**47.60**	**171.90**	**25.10**	**Orbital 2nd ICM**
Case 5	45	8.69	56.5	31.64	101.5	40.33	141.83	55.18	NESC ICM, BL

* 19.3%, provided by G&C based on Monte Carlo simulation results (19.3% mean, 39.8% mean+3-sigma, assumes B group thrusters to be used)
** 56%, provided by G&C based on Monte Carlo simulation results (56% mean, 114% mean+3-sigma, all possible Delta-V vector directions, including penalties due to thruster cant angles and vector-mode and attitude control)

Case 4 is considered as current best estimate of the trajectory control Delta-V

Delta-V Budget Changes from MDR

	MDR	PDR	Comment
Propellant of Tank Capacity (kg)	67	66.3	About the same
Propellant Usage of G&C on Momentum Dumps (kg)	4	7	Increased by 3 kg
Maximum Capacity of Trajectory Control Delta-V (m/s)	230	197	Reduced by 33 m/s
Idea TCM ΔV99%	164	124.3	Reduced by 40 m/s, mainly due to different ICM
TCM Implementation Penalty (m/s)	19	47.6	Increased by 28.6 m/s
Margin in terms of ΔV (m/s)	47	25.1	Reduced by 22 m/s
Margin in terms of Propellant (kg)	12.29	6.74	Reduced by 5.55 kg

2019 Backup Mission Design Overview

Solar Probe Plus
A NASA Mission to Touch the Sun

Launch

- 14-day launch period: May 21 - June 3, 2019
- Maximum launch C3: 154.5 km^2/s^2
- S/C wet mass: 665 kg

Trajectory Design

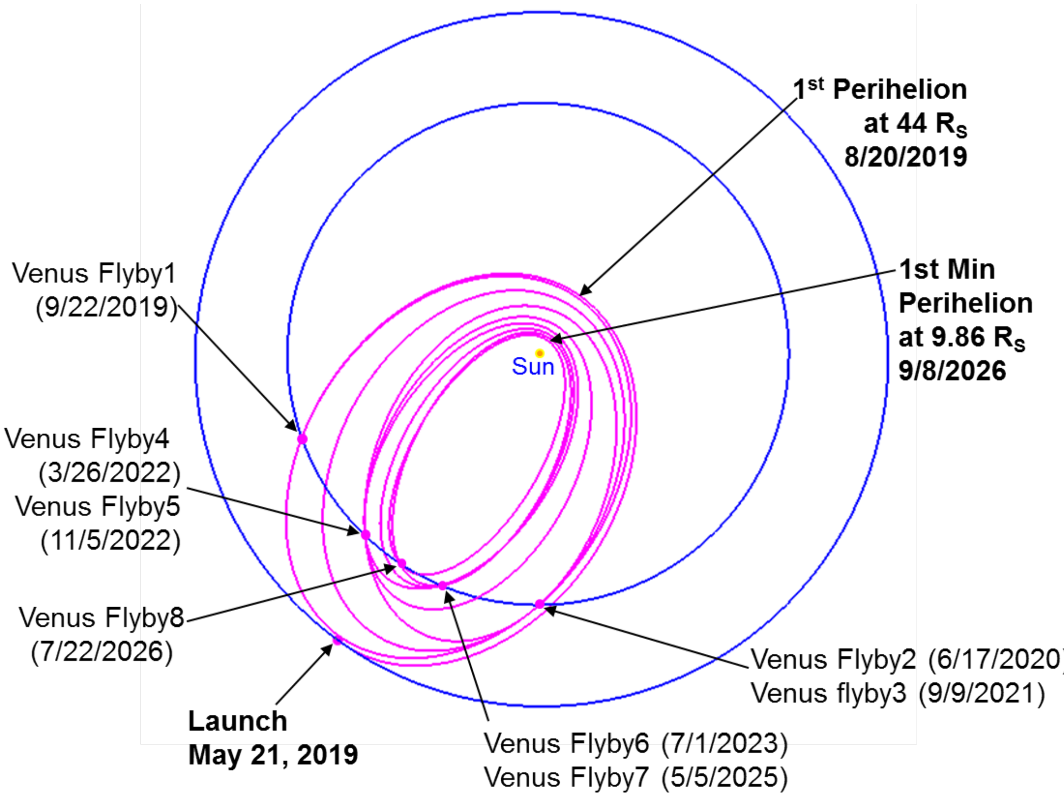
- V^8GA trajectory requiring 8 Venus flybys
- No deep space maneuvers
- Consisting of 26 solar orbits
- Perihelion decreasing from 44 to 9.86 R_S
- Maximum solar distance of 1.0135 AU

Final Solar Orbit

- Perihelion of 9.86 R_S
- Aphelion of 0.73 AU
- Orbit inclination of 3.4° from ecliptic
- Orbit period of 88 days

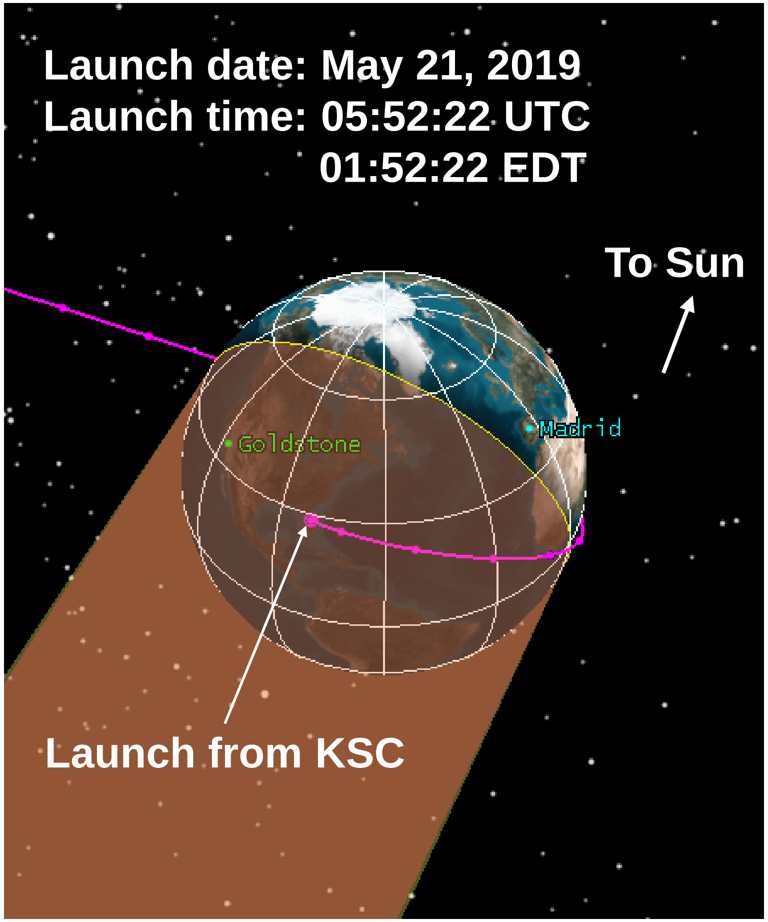
Mission Timeline

- Launch to 1st perihelion: 3 months
- Launch to 1st Venus flyby: 4 months
- Launch to 1st min perihelion (9.86 R_S): 7.3 years
- Launch to 3rd min perihelion: 7.8 years
- Mission duration (including data playback): 8 years

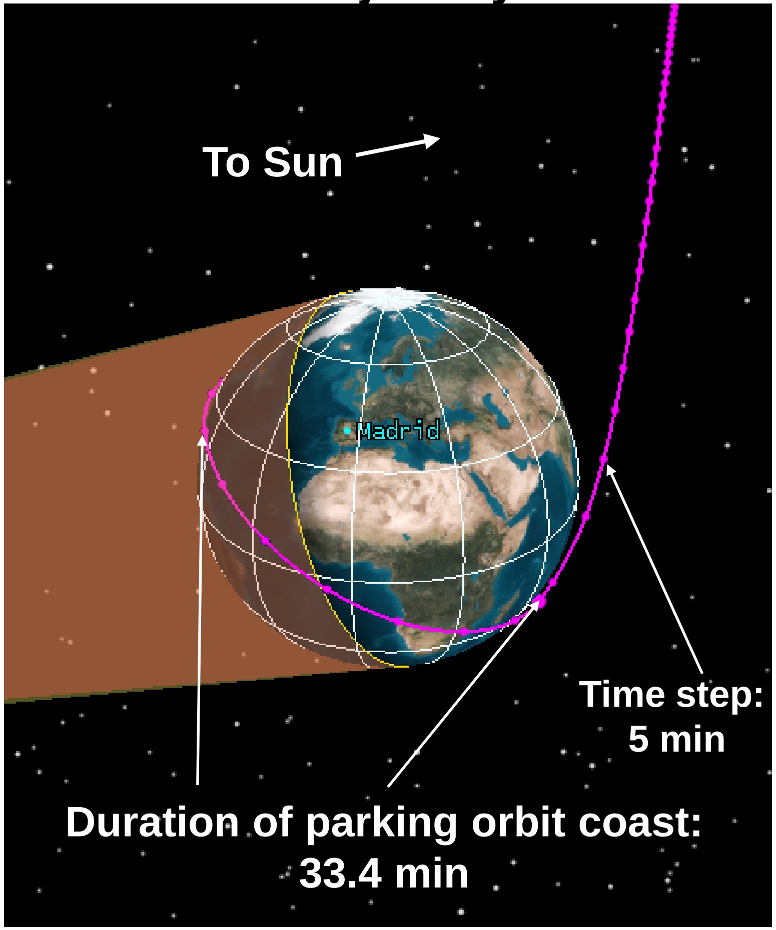


2019 Backup Mission Launch Time and Trajectory

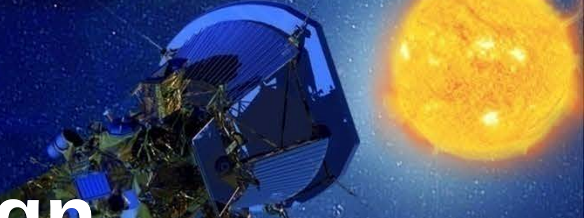
- **Launch will be at midnight local time**



- **A short coast is selected for the launch trajectory**



Comparison of 2019 Backup and 2018 Baseline Mission Design



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	2018 Baseline	2019 Backup
Launch dates	Jul-Aug 2018	May-Jun 2019
Launch period (day)	20	14
Max launch C3 (km^2/s^2)	154	154.5
Trajectory	V^7GA	V^8GA
Planetary Flybys	7 Venus	8 Venus
Parking orbit coast time (min)	17	33
Time from launch to 1st flyby (month)	2	4
Time from launch to 1st perihelion (month)	3	3
Time from launch to 1st min perihelion (year)	6.4	7.3
Mission Duration (year)	7	8
Number of solar orbits	24	26
Number of passes at 9.86-R_S	3	3
Max solar distance (AU)	1.018	1.014
Min solar distance (R_S)	9.86	9.86
Solar distance at 1st perihelion (R_S)	36	44
Max Earth distance (AU)	1.881	1.978

Additional differences for 2019 backup mission

- **Different solar conjunction profile, long gaps in early mission and no long gaps after orbit 10**
- **Long communication gaps prior to Venus 1 and around Venus 5 flybys**

Different strategy and plan may needed for the 2019 backup mission on launch error correction, Venus flyby targeting, and TCM schedule. More studies are planned in Phase C.

Phase C MD/NAV Plan

- **Milestones**
  - **Mission Design and Navigation CDR Peer Review, Dec 2014**
  - **Project Critical Design Review (CDR), March 2-4, 2015**
  - **Project Mission Operations Review (MOR) Oct 14, 2015**
  - **Launch Target Spec Doc release for Trajectory Cycle 1, Jan 2016 (draft)**
- **Major Study/Analysis**
  - **2018 Baseline Mission**
    - **Detailed mission design for 2018 baseline launch**
    - **End-to-end integrated trajectories for each day of the 2018 launch period**
    - **Analysis of backup maneuver opportunities**
    - **Analysis of TCM schedule for mission trajectories of other launch dates**
    - **Analysis of statistical ΔV requirement for 2018 launch: worst ICM of Atlas and Delta IVH**
    - **OD analysis for predicted and reconstructed trajectory**
  - **Backup Mission**
    - **Detailed mission design analysis for 2019 backup launch: middle and end launch period**
    - **Analysis of TCM schedule for 2019 launch**
    - **Analysis of statistical ΔV requirement for 2019 launch: worst ICM of Atlas and Delta IVH**
    - **Alternative backup mission design for launch beyond 2019**
  - **Development of launch target spec document for Trajectory Cycle 1**
  - **Analysis of spacecraft initial acquisition coverage at launch**
  - **Development of a navigation operation SRP model**

Summary

- **Mission Design requirements are documented**
- **2018 baseline mission design has been developed**
- **2018 baseline TCM schedule has been developed**
- **2019 backup mission design has been developed**
- **Analyses show the mission design requirements are met**
- **Mission Design is ready for Phase C**

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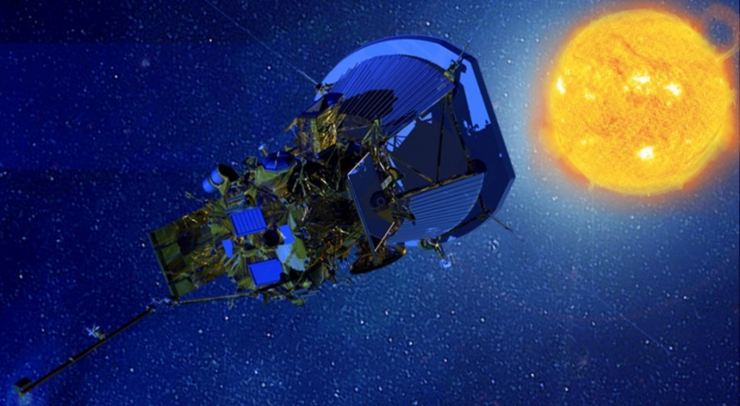

Backup Slides

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Phase-B Mission Design Modeling

Planetary ephemeris file: de424

Planetary body GM values: de424 memo

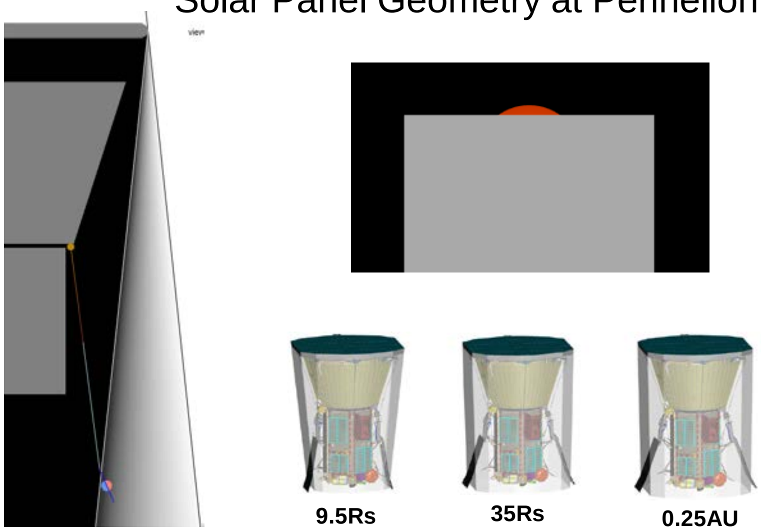
Leap second file: naif0010

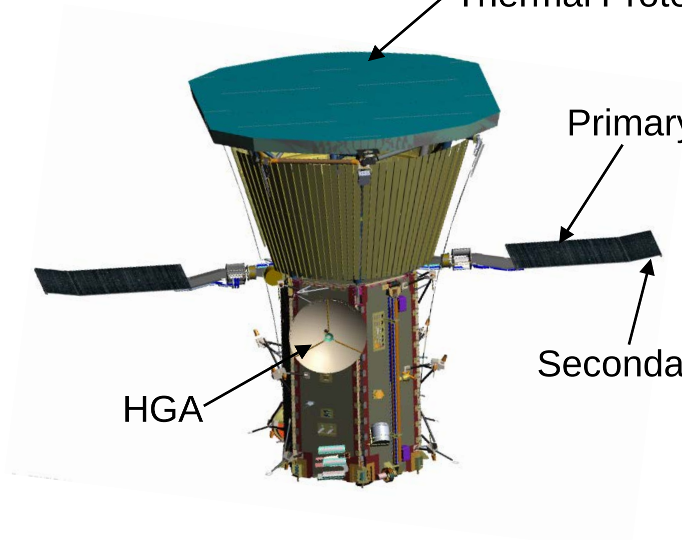
Spacecraft attitude: +Z-axis pointed at Sun for the entire trajectory

Spacecraft mass: 610 kg

Solar Radiation Pressure (SRP) model: SRP Plug-In Delivery03 (details documented in memos)

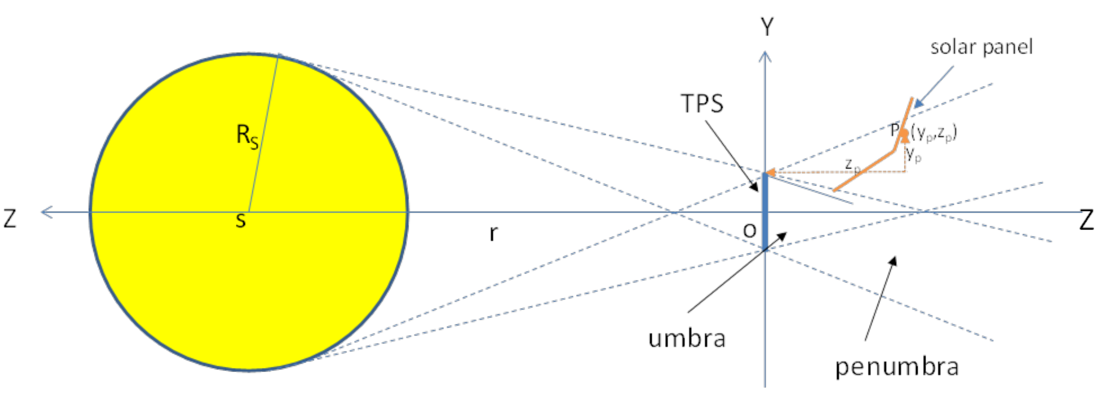
Solar Panel Geometry at Perihelion

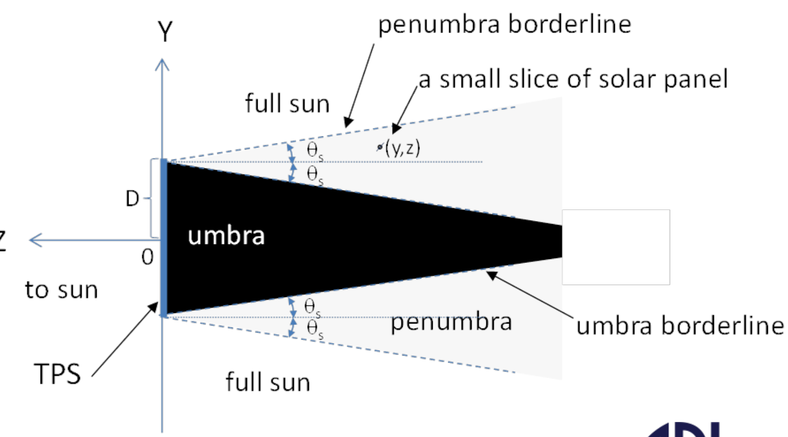




Solar Radiation Pressure Modeling

- **Preliminary version of the SRP Plug-In model is used in the Phase B Mission Design software**
  - **SRPs from TPS, 2 primary solar panels, and 2 secondary solar panels included**
  - **Rotations of the solar panels, defined by the flap angle, over the mission follow a baseline profile provided by S/C team**
  - **Sun limb darkening effect is considered**
  - **Shadows of TPS casted on solar panels are taken into account**
- **An updated SRP model (under development), including S/C general orientation and thermal radiation pressure, is planned for Phase C modeling**





Baseline Mission Venus Flyby Altitudes over Launch Period

Launch Period		Beginning	Middle	End
Launch Date		7/31/2018	8/9/2018	8/19/2018
Venus 1	Date	9/28/2018	10/2/2018	10/6/2018
	Altitude (km)	2548	2312	2578
Venus 2	Date	12/22/2019	12/25/2019	12/29/2019
	Altitude (km)	3023	3038	2809
Venus 3	Date	7/6/2020	7/10/2020	7/13/2020
	Altitude (km)	834	837	818
Venus 4	Date	2/16/2021	2/19/2021	2/23/2021
	Altitude (km)	2392	2394	2369
Venus 5	Date	10/11/2021	10/15/2021	10/19/2021
	Altitude (km)	3786	3802	3826
Venus 6	Date	8/16/2023	8/20/2013	8/24/2023
	Altitude (km)	3939	3973	4026
Venus 7	Date	11/2/2024	11/5/2024	11/9/2024
	Altitude (km)	317	316	317

- Venus flyby geometry across the launch period is similar, no issue/concern

TCM Placement Assumptions

- **The baseline TCM schedule is developed based on the following assumptions, including relevant mission and spacecraft constraints:**
  - **Baseline mission trajectory for launch on July 31, 2018**
  - **Baseline navigation tracking schedule**
  - **Mission profile and solar conjunctions of the 31-July-2018 baseline mission trajectory**
  - **Navigation tracking gaps of the 2018 baseline mission trajectory**
  - **Navigation data cut offs (DCOs) being 5 days before the TCM execution time**
  - **One to two tracks available after each TCM**
  - **Maneuvers during actual DSN passes and working hours (typically a Goldstone pass)**
  - **Avoiding placing maneuvers over weekends and holidays where possible**

TCM Implementation Strategy

- **TCM-1**
  - **Oriented with thrusters along the Delta-V vector direction**
  - **to minimize penalty**
  - **Max burn duration < 7200 s (limited by battery)**
- **Other TCMs**
  - **Orientation constrained by S/C pointing**
  - **TCM Delta-V executed with vector mode**

- **Further Study planned in Phase C**
  - **Evaluate the TCM schedule for the mission trajectories at Middle and End of the 2018 baseline launch period**
  - **Analyze backup maneuver opportunities**
    - **Trade study for moving the last TCM prior to a Venus flyby to V-5 days to leave more time for a backup TCM schedule**

Baseline Mission Design Summary

- **2018 baseline mission design is developed, including**
  - A 20-day Launch period, requiring max. C3 of 154 km^2/s^2
  - Finite daily launch window, opening in early morning
  - A short coast in the parking orbit
  - A V^7GA mission trajectory, with a time duration of 7 years
  - 7 Venus flybys, for gravity assists to get to the Sun
  - 24 solar orbits, gradually reduced size from orbital period of 168 to 88 days
  - 24 solar passes, perihelia decreasing from 36 to 9.86 R_S
  - 937.58 hours in the 20-R_S region and 14.85 hours in the 10-R_S region
- **End-to-end integrated mission trajectories created at Beginning, Middle, and End of the launch period, and analyzed**
  - Each of the 7 Venus flyby geometry and altitudes
  - Solar encounter geometry and times spent in 30, 20, 15 , and 10 R_S regions
  - Detailed mission profiles on solar distances, perihelion passes, solar eclipses
  - Communication coverage and navigation tracking for each of the 24 solar orbits
- **Baseline TCM schedule developed, with 42 maneuvers on 23 orbits**
- **Current estimate of Delta-V requirements**

Comparison of Current and Previous Baseline Mission Design

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	Previous Design (MDR)	Current Design (PDR)
Launch dates	30 July - 19 Aug 2018	31 July - 19 Aug 2018
Launch period (day)	21	20
Max launch C3 (km^2/s^2)	159	154
Trajectory	V^7GA	V^7GA
Planetary flybys	7 Venus	7 Venus
Time from launch to 1st Venus Flyby (month)	2	2
Time from launch to 1st perihelion (month)	3	3
Time from launch to 1st min perihelion (year)	6.4	6.4
Mission duration (year)	7	7
Number of solar orbits	24	24
Solar distance of 1st perihelion (Rs)	34.9	35.7
Minimum perihelion (Rs)	9.5	9.86
Number of passes at min perihelion	3	3
Maximum distance from Sun (AU)	1.018	1.018
Maximum distance from Earth (AU)	1.884	1.881
Maximum heliocentric velocity (km/s)	194.6	190.8
Total time within 30-Rs region (hour)	2134.3	2130.9
Total time within 20-Rs region (hour)	965.3	937.6
Total time within 15-Rs region (hour)	458.9	440.0
Total time within 10-Rs region (hour)	27.3	14.8

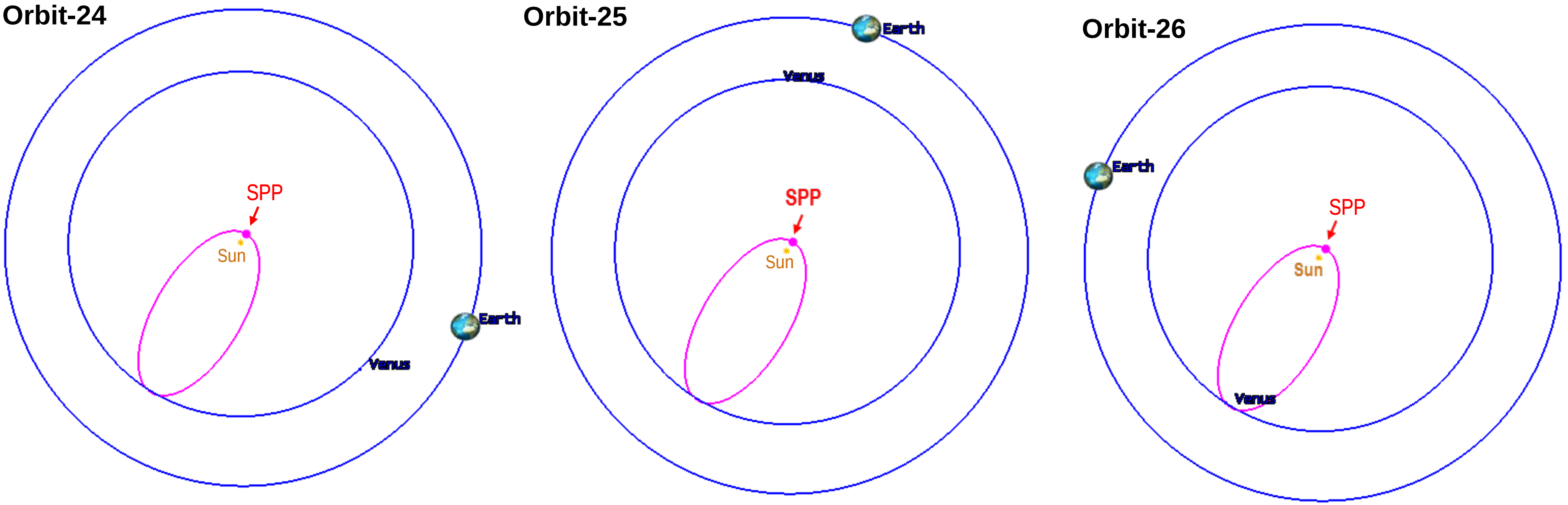
Backup Mission Design

- **Backup mission design is an important part of SPP mission planning**
  - **To ensure high probability of launch of the mission against uncertainty in program funding, delay in development schedule, and other unforeseen situation**
- **Could we just move the baseline mission to a later launch date if needed?**
- **The SPP mission concept is formed on the Venus-Venus-Venus-Venus-Venus-Venus-Venus Gravity Assist (V^7GA) trajectory, utilizing repeated 7 Venus flybys to reduce orbit energy to get close to the Sun**
- **Launch opportunities for the V^7GA trajectory occur every synodic period of Venus, which is 19.2 months**
- **The next launch opportunity from the July-August 2018 launch (baseline) is March 2020**
- **There are some issues with this launch opportunity:**
  - **Required launch C3 (165 km^2/s^2) is to too high to fit S/C within the capacity of the baseline launch vehicle**
  - **19-month of waiting time is little too long -- longer waiting time costs more to maintain the entire development team**
- **A new trajectory has been created for the backup mission**
  - **It requires lower launch C3, comparable to the 2018 launch C3**
  - **It launches in 2019, shortening waiting time to 9 months**

Trajectory Design for the 2019 Backup Mission

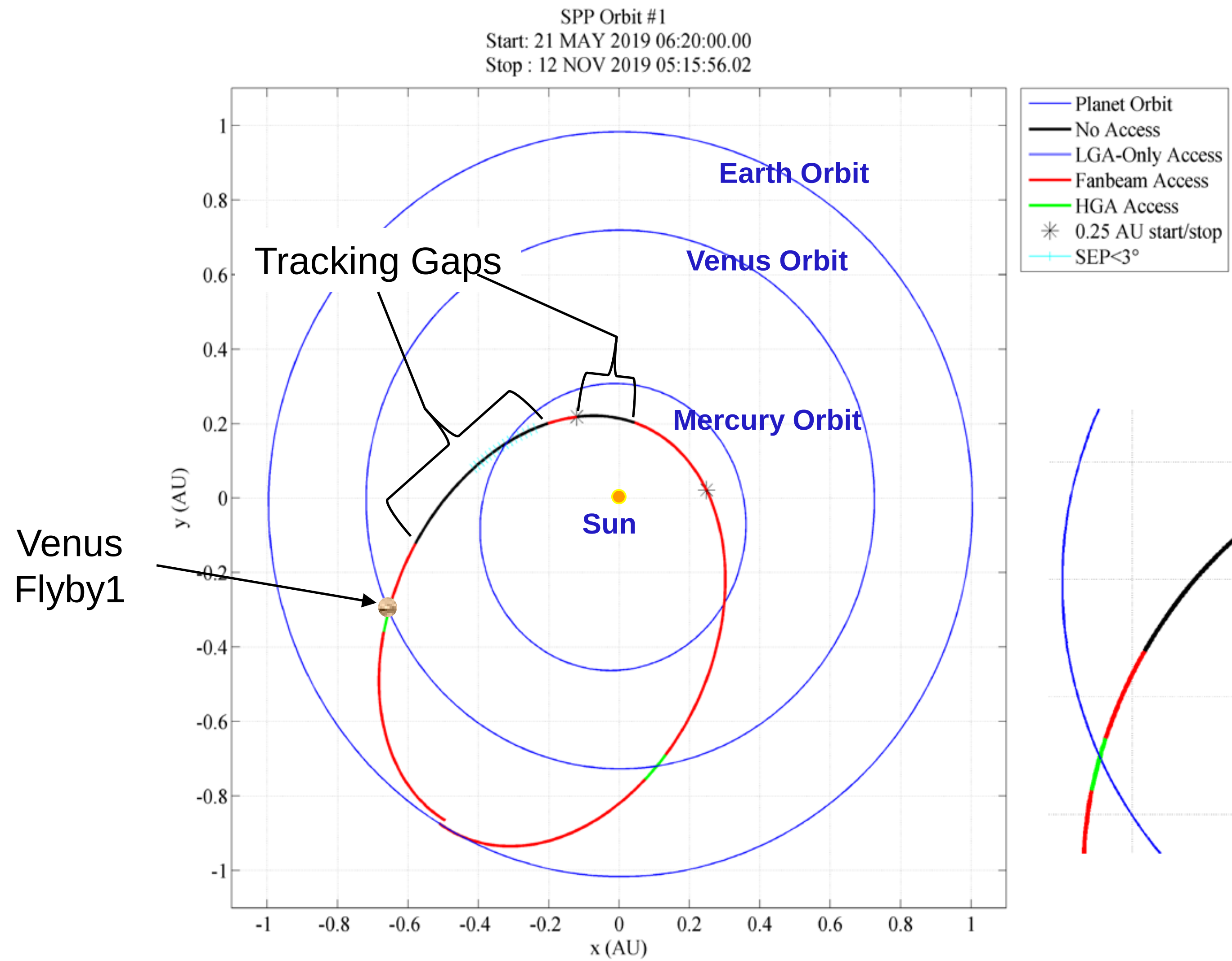
- **Key Drivers for the trajectory design:**
  - **to enter the near Sun region at a distance of 9.86 R_S from Sun center**
  - **to spent at least 920 hours below 20 R_S and 14 hours within 10 R_S**
  - **to have 3 solar passes at 9.86 R_S**
- **2019 backup mission trajectory**
  - **Requires 8 Venus gravity-assist flybys to reduce enough speed to get to 9.86 R_S**
  - **Reaches the minimum perihelion distance after 8 times of orbit change over a time period of 7.3 years**
  - **Has the first solar encounter at 9.86 R_S on the 24th solar orbit**
  - **Has a total of 26 solar orbits with the last 3 orbits at 9.86 R_S**

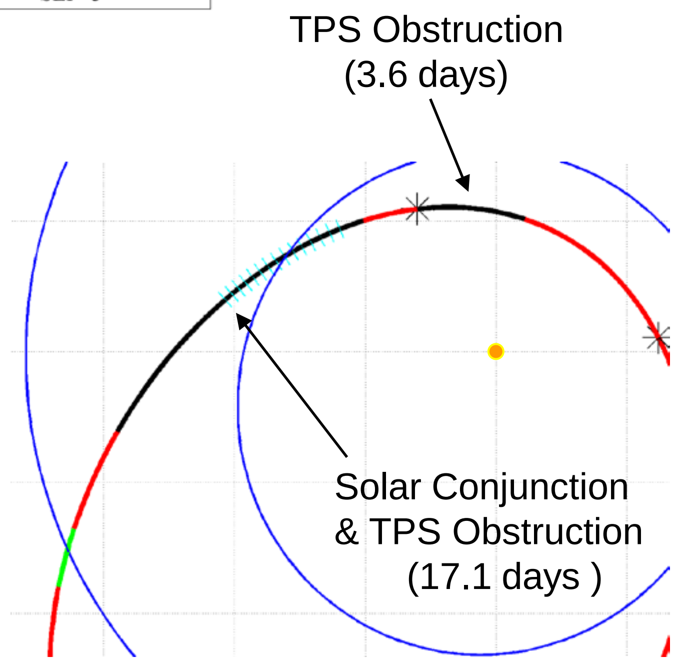
2019 Backup mission
Geometry of the 9.86-R_S Solar Orbits



- The 9.86-R_S solar orbits are Orbit-24, Orbit-25, and Orbit-26
- Three orbits are identical in size: orbital period = 88 days, aphelion =0.73 AU, inclination = 3.4 deg from ecliptic
- Solar encounter geometry (Earth position) is different for each of the orbits
- Earth position shown is when SPP at perihelion. Spacecraft is visible from Earth for all solar encounters, and different parts of the Sun are observed from the Earth during the solar passes.

2019 Backup Mission
Detailed Communication Coverage: Orbit 1





2019 Backup Mission
Detailed Communication Coverage: Orbits 2-10

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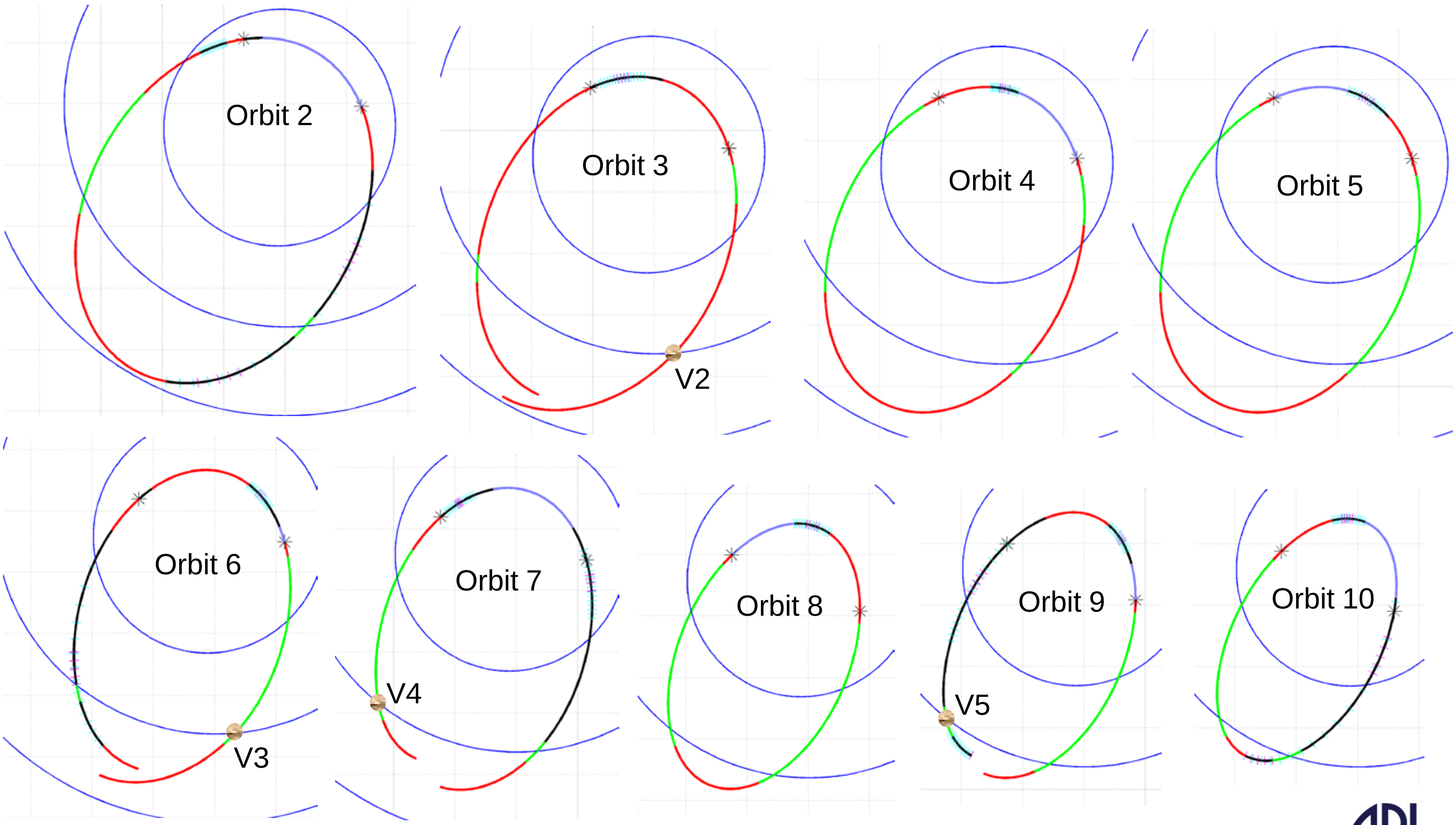
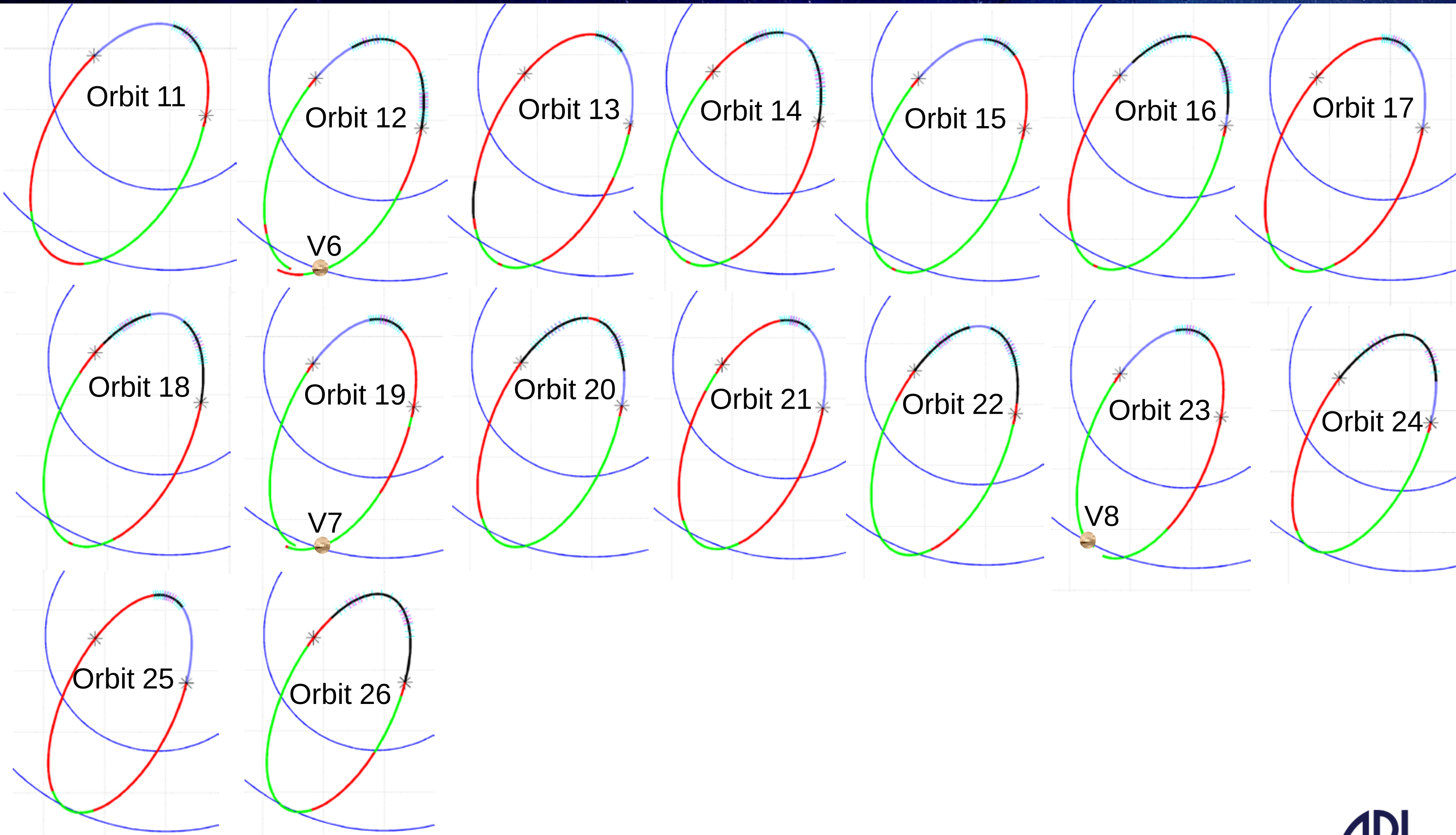


2019 Backup Mission
Detailed Communication overage: Orbits 11-26



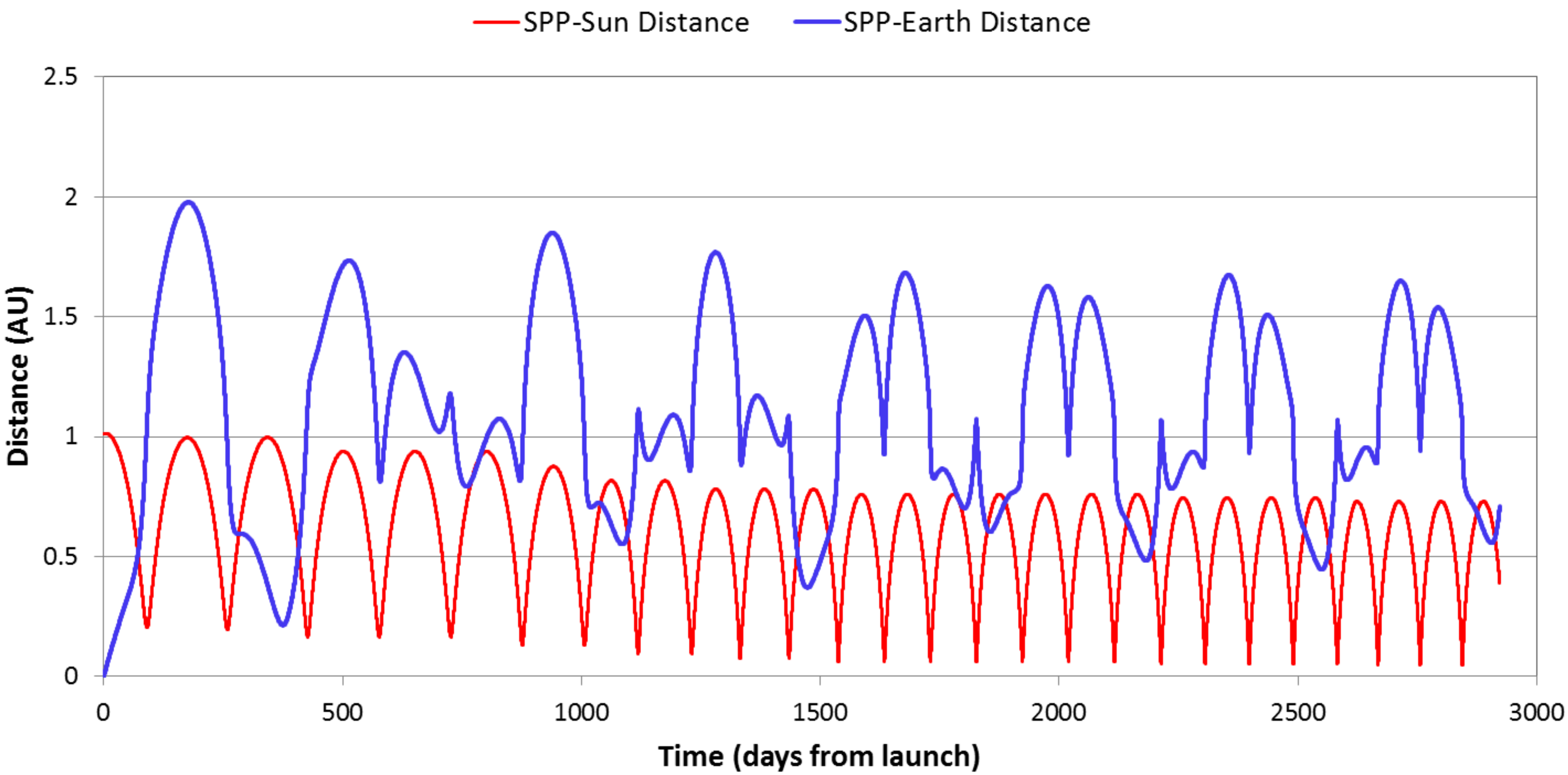
2019 Backup Mission Trajectory Summary of Communication Coverage (1)

- **Navigation tracking prior to the Venus flybys**
  - **Good tracking prior to V2, V3, V6, V7, and V8**
  - **Tracking prior to V4 is ok, a long gap (27.7 d) prior to P7 is noticed**
  - **Tracking prior to V1 has 1 short (3.6 d) & 1 long tracking gap (17.1 d) post P1**
  - **Tracking prior to V5 is not good, a long gap (28.4 d) right before V5 (ending at V-2d), followed with a long gap (21 d) post V5 (starting at V+7d)**
- **Navigation tracking prior to perihelion passes**
  - **Majority of tracking prior to the perihelion passes are good except for:**
    - **P2, P7, and P10**
- **Different from 2018 baseline trajectory, the long coverage gaps occur in the early phase of the mission. There are no long gaps after orbit 10 – this is good for data download, especially for the 9.86-R_S orbits**

2019 Backup Mission Trajectory Summary of Communication Coverage (2)

- **Possible solutions & mitigations for the long tracking gaps**
  - **Venus 1**
    - **Target the Venus flyby using TCMs prior to entering the first perihelion**
    - **Shorten the duration of the long gap to allow for placing a clean-up TCM (navigation tracking + TCM design time) prior to V1 to correct trajectory errors due to thruster firing for momentum dumps during the perihelion pass**
  - **Venus 5**
    - **Target the Venus flyby using TCMs prior to entering perihelion #9**
    - **With the long gap ends 2 days before V5, there is no sufficient navigation tracking to warrant a TCM prior to V5**
    - **Shorten the duration of the pre-Venus long gap to allow for placing a TCM (navigation tracking + TCM design time) prior to V5 to correct trajectory errors due to thruster firing for momentum dumps during perihelion # 9 pass**
    - **Shorten the duration of the post-Venus long gap to allow for placing a clean-up TCM (navigation tracking + TCM design time) post V5 to correct trajectory errors from the Venus5 flyby, and to allow for a OD update and upload to S/C before entering perihelion #10**

2019 Backup Mission
Spacecraft Distance from Earth



- **The greatest distance from Earth is 1.978 AU. It occurs at the first aphelion after launch**
- **Earth distance profile shows 8 large cycles (8 years of mission duration)**

2019 Backup Mission SEP and SPE Angles

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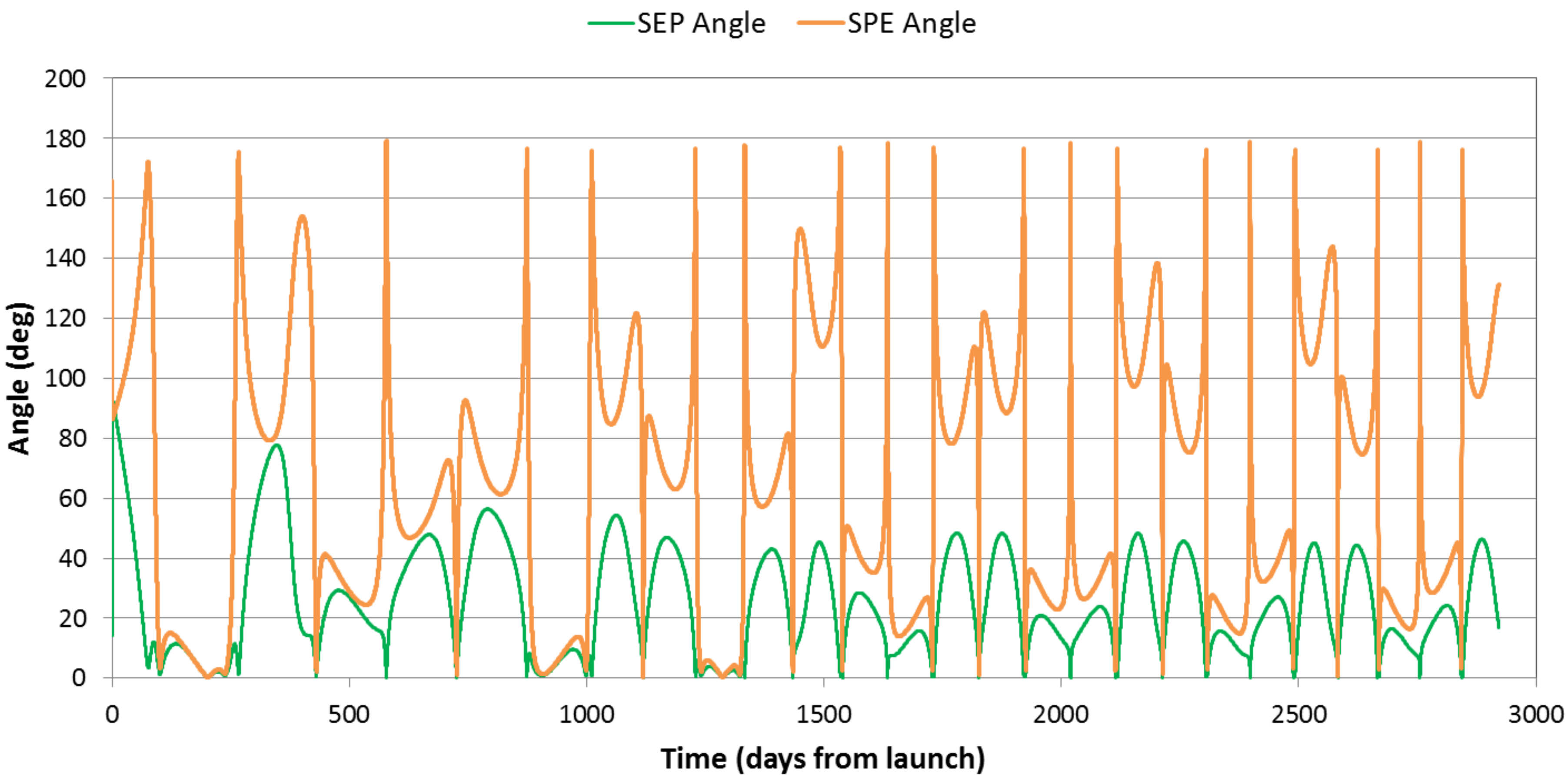
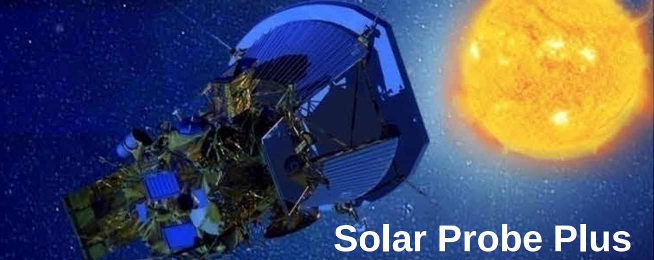


- **Solar conjunction occurs when SEP angle < 3 deg (X-band) or < 1 deg (Ka-band)**



2019 Backup Mission Design Summary

- **SPP backup mission launches in May 2019, 9 months from baseline launch**
- **Backup launch period is 14 days (versus 20 days of 2018 baseline launch)**
- **Launch C3 is comparable to 2018 launch C3, with the same S/C wet mass**
- **Parking orbit coast is longer than baseline launch (34 min vs. 17 min)**
- **S/C flies on a V^8GA trajectory to the Sun at 9.86 R_S, requiring 8 Venus gravity-assist flybys, 1 more Venus flyby than 2018 trajectory, more additional TCMs and Delta-Vs**
- **Trajectory consists 26 solar orbits, 2 more orbits than 2018 trajectory, the last 24 orbits are identical to 2018 trajectory in orbit sequence and size**
- **All science requirements are met, accumulated times, solar passes and geometry**
- **Mission duration is 8 years, 1 year longer than baseline mission**
- **Max. solar distance is about the same of 2018 trajectory**
- **Max. Earth distance is slightly greater (1.978 AU vs. 1.881 AU) than 2018 trajectory**
- **Solar eclipse occurrence and duration are similar to the 2018 trajectory**
- **Solar conjunction profile is different, long gaps in early mission phase and no long gaps after orbit 10 – better date downloading profile for late orbits**
- **Some challenges for Venus 1 and Venus 5 flybys and for solar passes of P2, P7, and P10, due to long communication gaps**
- **Different strategy, plan, and schedule for launch error correction, trajectory correction maneuvers, and Venus flyby targeting, especially in early mission phase**
- **Different event/activity timeline for early mission operations**

2019 Backup Launch Period

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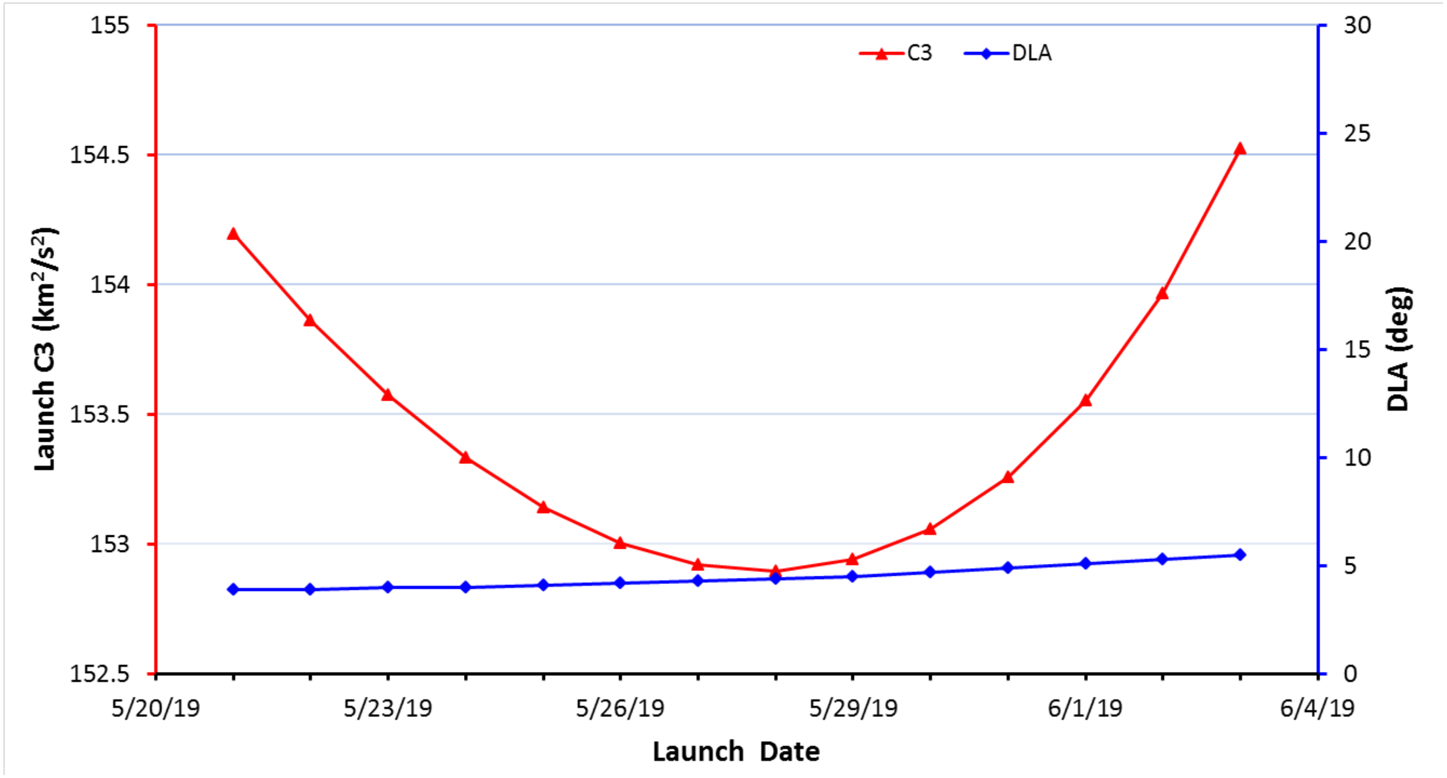
- **2019 backup launch has a 14-day period: May 21 - June 3, 2019**
- **Chart shows the C3 requirement for each day, with max at 154.5 km^2/s^2 on June 3**
- **Launch DLAs are within LV limit of 28.5° (no performance penalty)**



2019 Backup Mission Solar Distance Profile

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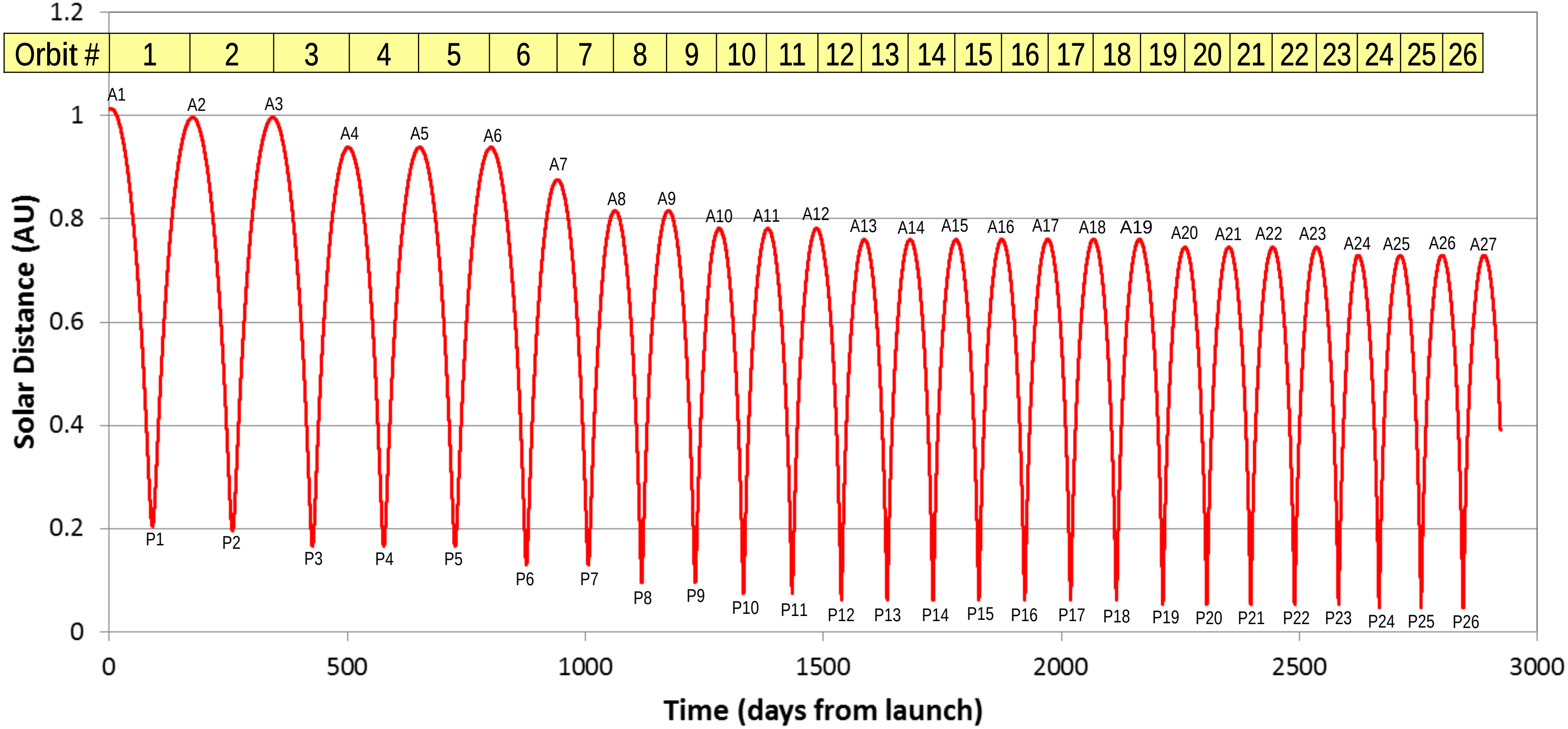
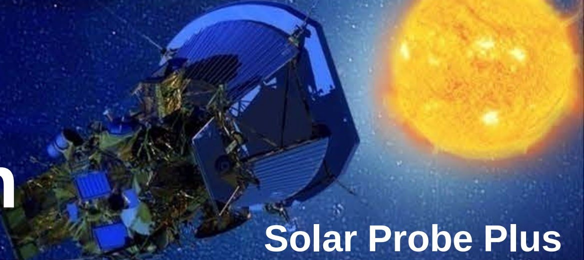


- **Max solar distance is 1.0135 AU, and min solar distance is 0.04587 AU (9.86 R_S)**
- **Total of 27 aphelia (A1 through A27) and 26 perihelia (P1 through P26)**
- **Perihelia gradually decreasing**

APL

2019 Backup Mission
Times Spent in the Near-Sun Region



Perihelion #	Date of Perihelion	Perihelion (Rs)	Time (hours) within			
			30 Rs	20 Rs	15 Rs	10 Rs
1	8/20/2019	43.93				
2	2/4/2020	42.15				
3	7/21/2020	35.57				
4	12/18/2020	35.57				
5	5/16/2021	35.57				
6	10/13/2021	27.86	60.87			
7	2/20/2022	27.86	60.87			
8	6/12/2022	20.38	104.17			
9	10/3/2022	20.38	104.17			
10	1/12/2023	16.01	108.57	47.97		
11	4/24/2023	16.01	108.57	47.97		
12	8/6/2023	13.35	107.35	55.02	24.31	
13	11/10/2023	13.35	107.35	55.02	24.31	
14	2/14/2024	13.35	107.35	55.02	24.31	
15	5/21/2024	13.35	107.35	55.02	24.32	
16	8/25/2024	13.35	107.35	55.02	24.31	
17	11/29/2024	13.35	107.35	55.02	24.31	
18	3/6/2025	13.35	107.35	55.02	24.30	
19	6/11/2025	11.56	105.23	56.84	31.86	
20	9/11/2025	11.56	105.24	56.84	31.86	
21	12/13/2025	11.56	105.24	56.84	31.86	
22	3/15/2026	11.56	105.24	56.84	31.86	
23	6/15/2026	11.56	105.24	56.84	31.86	
24	9/8/2026	9.86	102.42	57.03	35.23	4.94
25	12/6/2026	9.86	102.42	57.03	35.22	4.94
26	3/4/2027	9.86	102.42	57.03	35.22	4.94
Total			2132.09	936.38	435.16	14.83

- **There are 9 different solar orbit groups**
- **Each orbit group has the same perihelion distance**
- **Number of perihelion passes of a group varies from 1 to 7.**
- **Total accumulated times are critical to science investigations**
- **Total times below 20 R_S and 10 R_S meet requirements**
- **Repeated passes in a group offer multiple observation opportunities**

2019 Backup Mission Trajectory Venus Flyby Geometry

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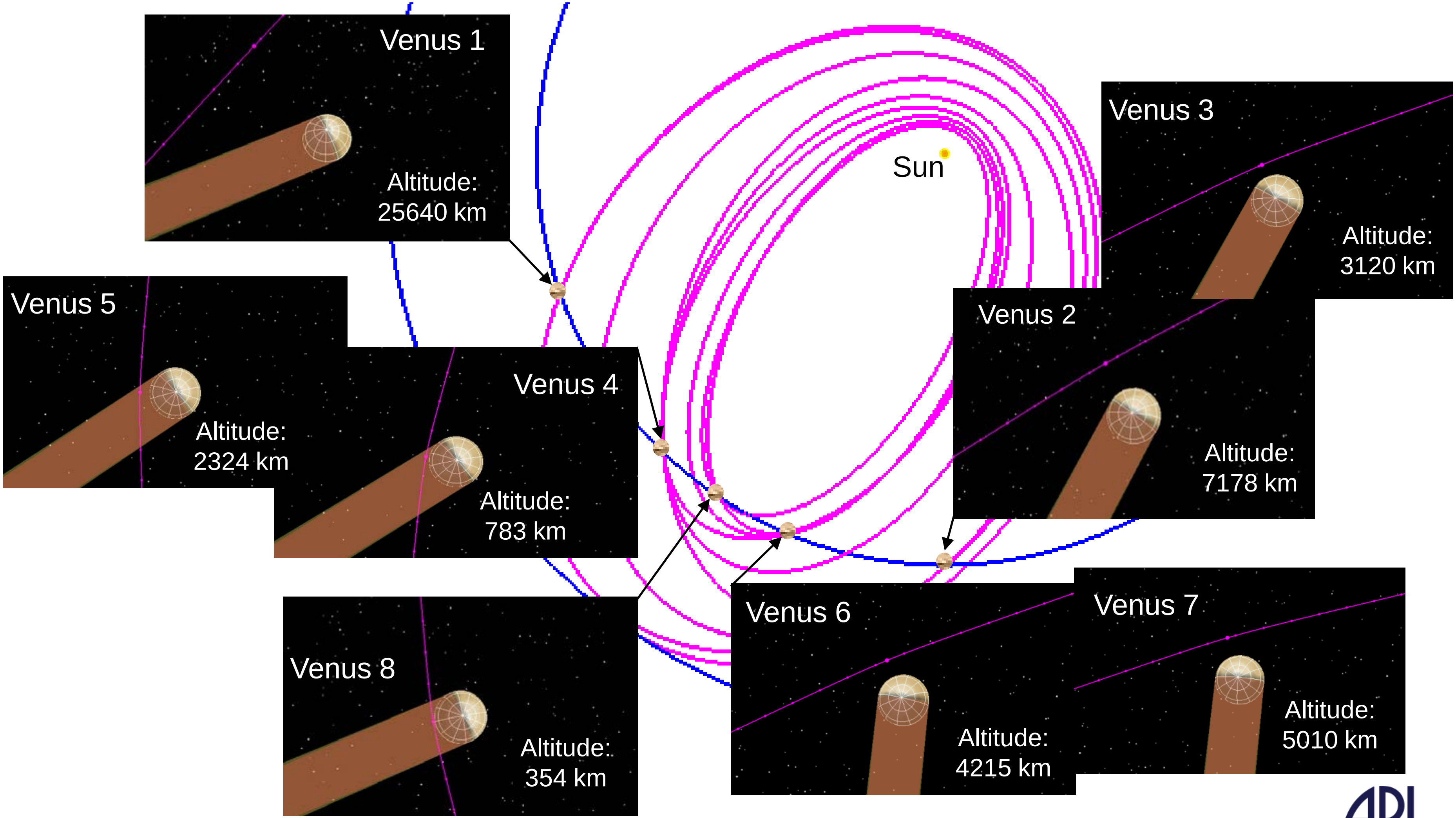
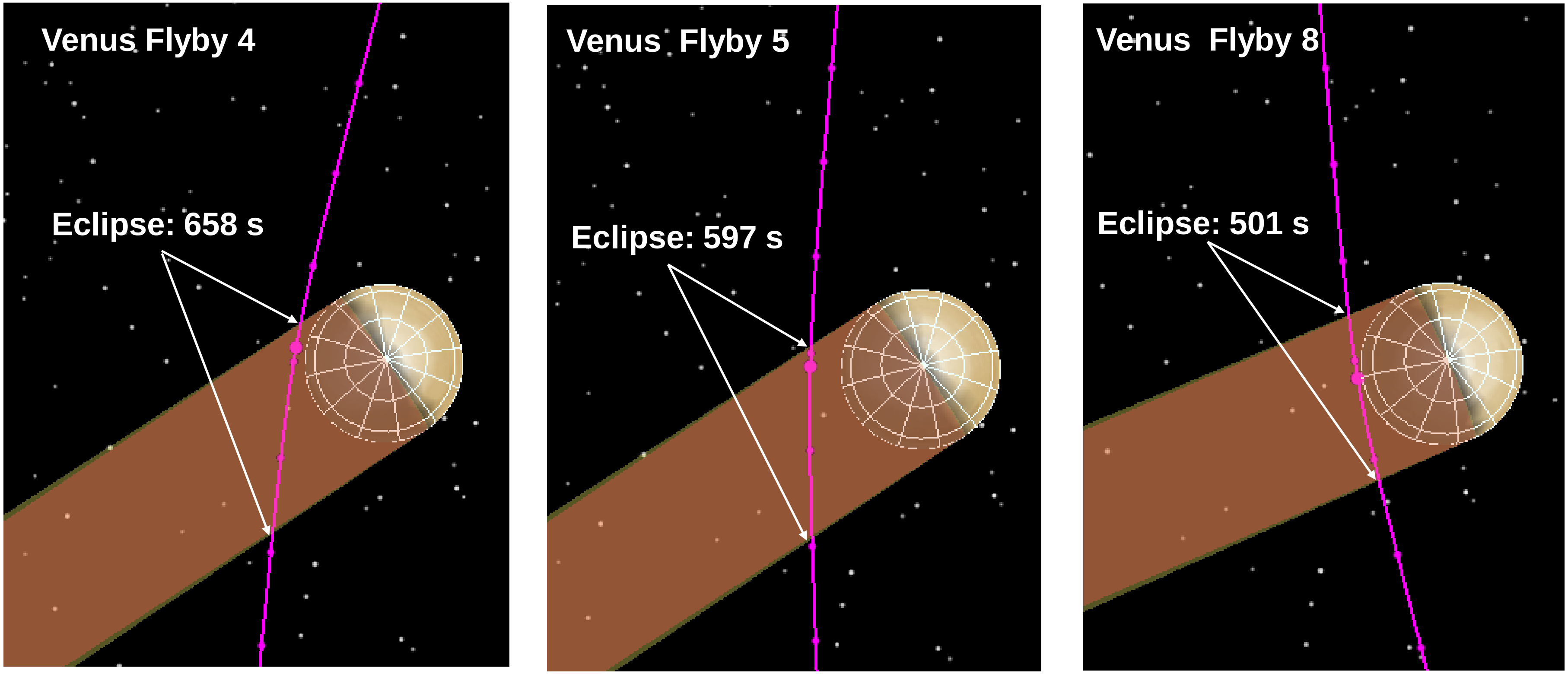


2019 Backup Mission Periods of Solar Eclipse

- **There are three brief periods of solar eclipse post launch, occurring during the flybys of Venus #4, #5, and #8**
- **Maximum duration of eclipse is less than 11 minutes**



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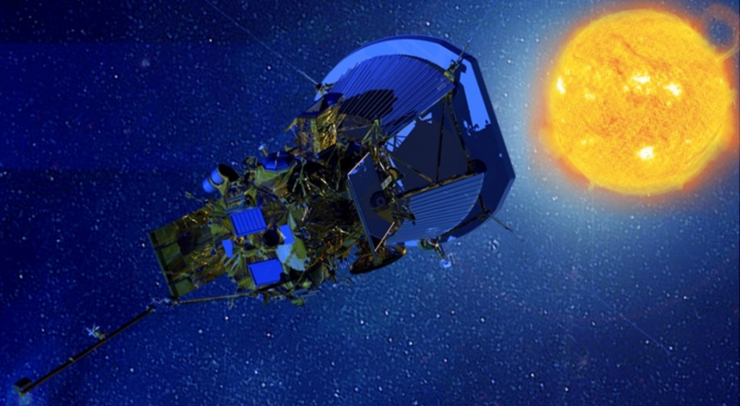

Solar Illumination

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Deputy Project Scientist

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13 – 16 January 2014

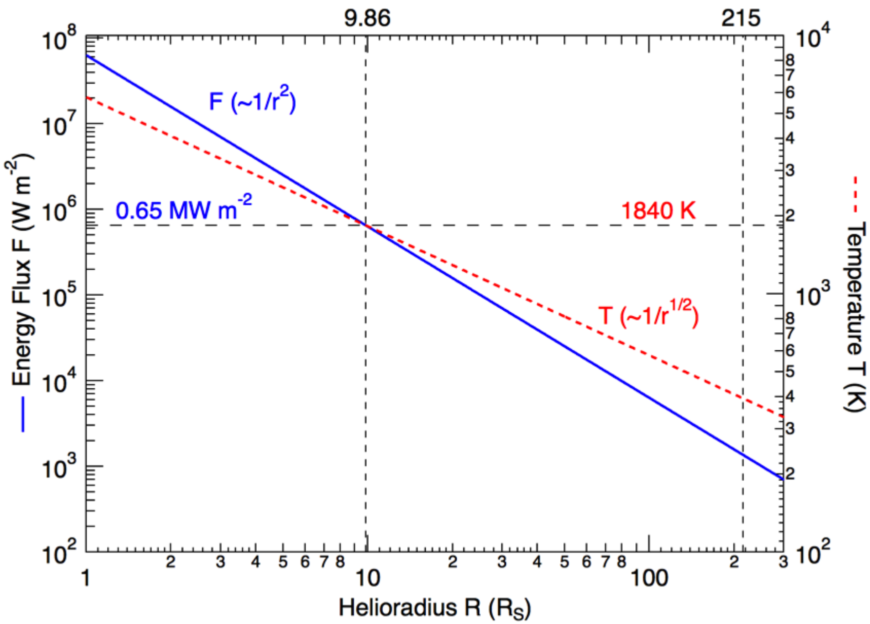
The Johns Hopkins University
APPLIED PHYSICS LABORATORY

Solar Illumination

- **Motivation:** Quantify solar irradiance levels to which the observatory will be exposed during all phases of the SPP mission.
- **Methodology:** Perform trades to develop models to compute as functions of SPP helioradius (*R*) the bolometric and spectral energy fluxes on area elements exposed to the full or partial limb-darkened sun and to coronal brightness.
- **Topics**
  - Total Solar Irradiance (TSI)
  - Secondary Solar Array (SSA)
    - Bolometric irradiance
    - Spectral irradiance
  - Solar Limb Sensors (SLS)
    - Effects of transient solar activity
    - Effects of penumbra bounded by non-planar TPS edge
  - Irradiance by K and F corona
    - White-light maps
    - Spectral dependence
  - Summary

Solar Illumination
A Few Relevant Quantities

- solar radius (R_S) = 6.955 x 10^8 m
- 1 AU =1.496 x 10^{11} m = 215.1 R_S
- solar radiant power: 3.845 x 10^{26} W
- solar radiant flux: 6.325 x 10^7 W m^{-2}
  - 0.651 MW m^{-2} at 9.86 R_S (476 “suns”)
    => 1.367 kW m^{-2} at 1 AU
  - Also, T_S (1 R_S) = 5779 K
    => T(9.86 R_S) = 1840 K (1567 C)



Energy flux F (left) and blackbody temperature T (right) versus radial distance from sun R

Solar Illumination
Total Solar Irradiance (TSI)

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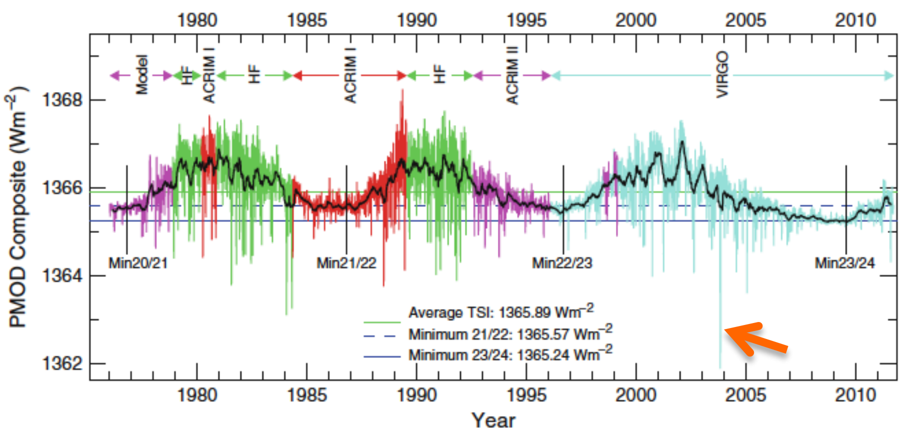
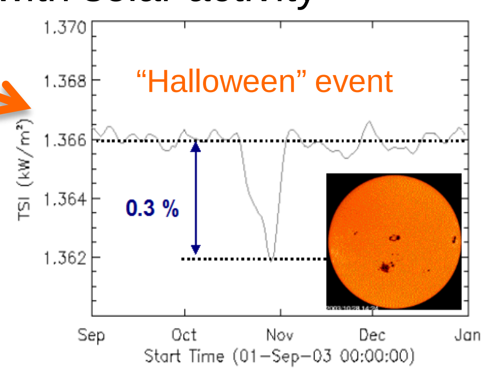
Bolometric (wavelength-integrated) TSI

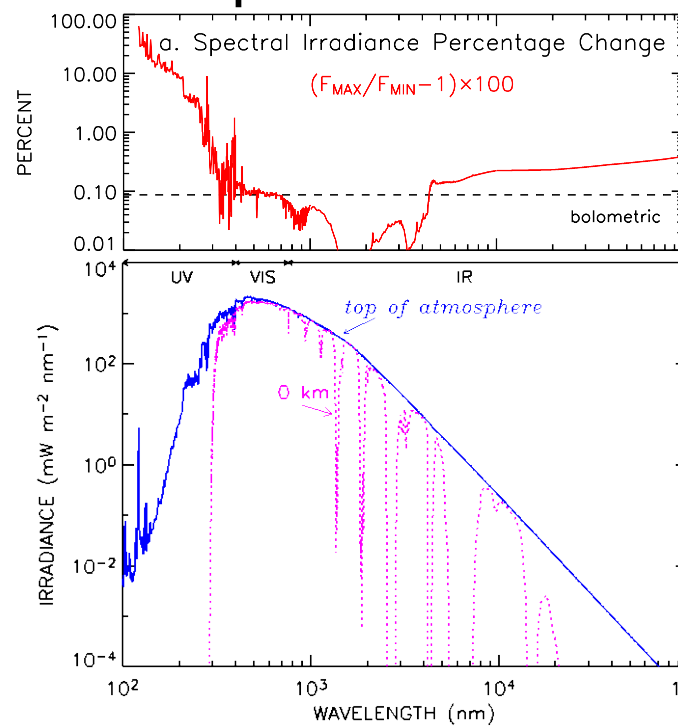


- Composite of daily TSI measurements during solar cycles 21-23 [2-5]. Mean 1366.1 ± 0.6 W m^{-2}, with 0.37% min.-to-max. range (1363-1368 W m^{-2}) [4]
- TSI has shown solar-cycle variations ~0.1% that are positively correlated with solar activity

Larger short-term variations (spikes above) are associated with the most intense active regions and solar events



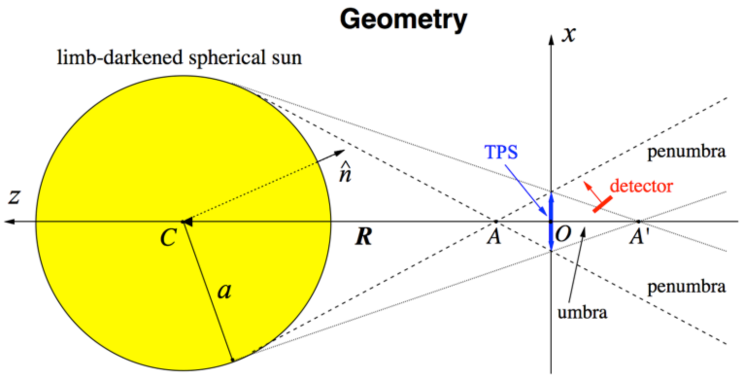
Spectral Irradiance



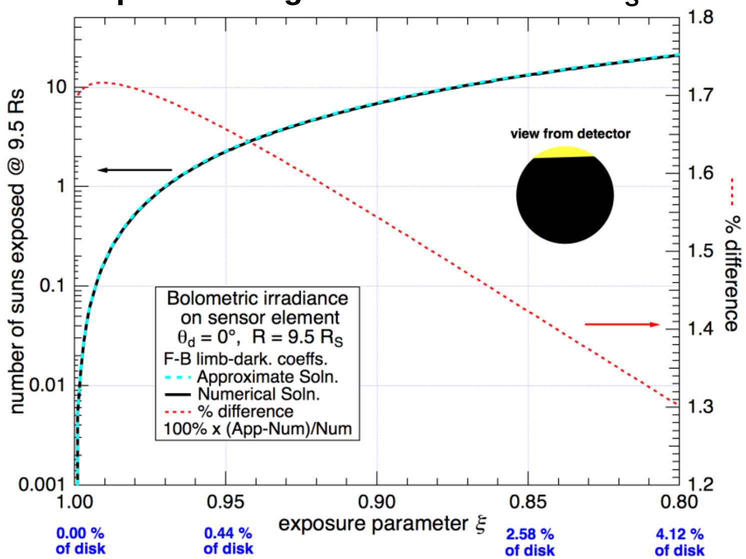
Upper: % change between solar max. and min. of spectral irradiance vs. wavelength; <0.1% in near-UV, visible, and near-IR

Lower: Irradiance spectrum at the top of Earth atmosphere [4]

Solar Illumination
SSA: Bolometric Irradiance



Wavelength-integrated irradiance from spherical segment of sun at 9.86 R_S



- Secondary solar arrays (SSA) will view spherical solar segments as arrays enter penumbra bounded by TPS straight edge
- Trades were performed to calculate energy flux *F* on a differential area element of a tilted SSA as a function helioradius (*R*) for limb-darkened sun, using [6,7]:

$$F = \int_{\Delta\omega} d\omega \cos\theta\, I(\omega) = \int_{\Delta\phi} d\phi \int_{\Delta\theta} d\theta \sin\theta \cos\theta \sum_{n=0}^{N} I_0 L[\mu(\theta)]$$

$$L(\mu) = \sum_{n=0}^{3} c_n \mu^n, \quad \mu = \left| -\hat{r} \cdot \hat{n} \right|$$

- Integrals that extend over solid angle ⊗7 subtended by spherical solar segments can be done numerically
- Analytic approximations also derived by expanding integrands in ascending powers of $R_S/R \le 0.101$; accuracy verified by comparing with numerical integrations

Solar Illumination
SSA: Spectral Irradiance

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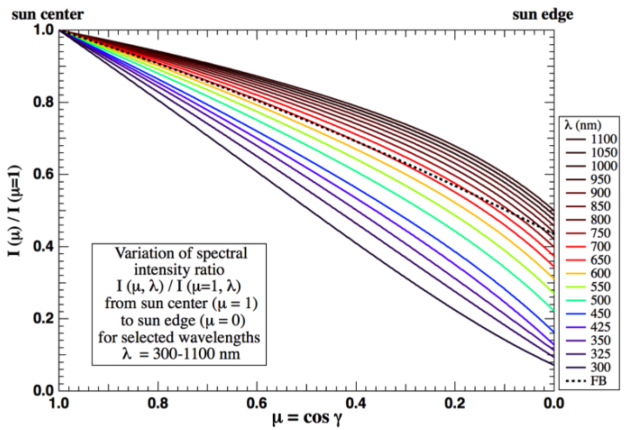
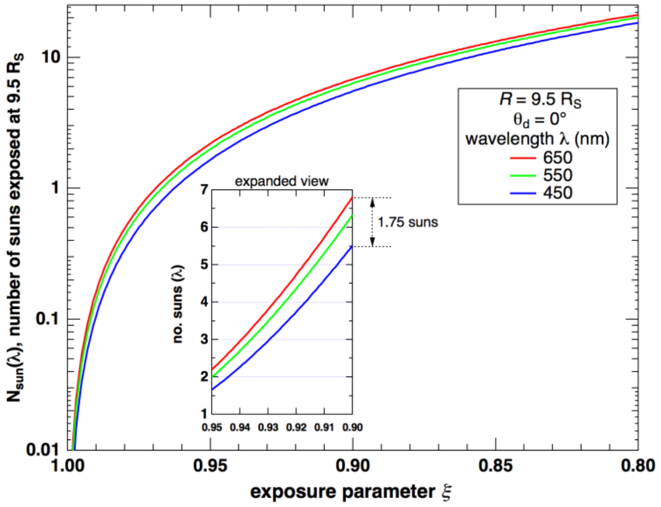
Variation of relative spectral intensity for a range of wavelengths versus parameter μ = cosine of angle between vector from observer to solar area element and normal vector to solar area element





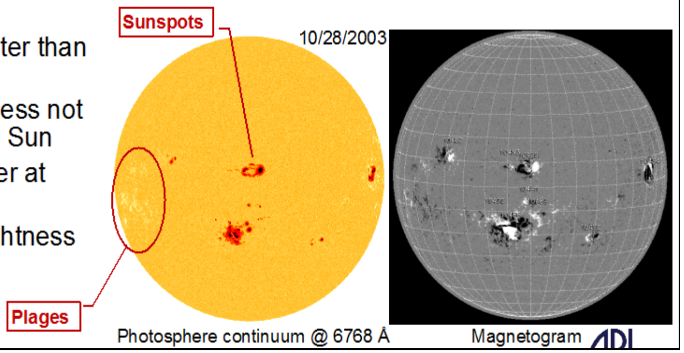
- Relative to the central-disk intensity, shorter or "bluer" wavelengths are more severely limb-darkened than are longer or "redder" wavelengths
- Effects must be included to predict performance of wavelength-sensitive photon sensors (e.g., solar cells) when such sensors will view small segments of the sun
- Previous analysis for bolometric case was generalized to include spectral dependence of limb-darkening by using specific intensity [7,8]:

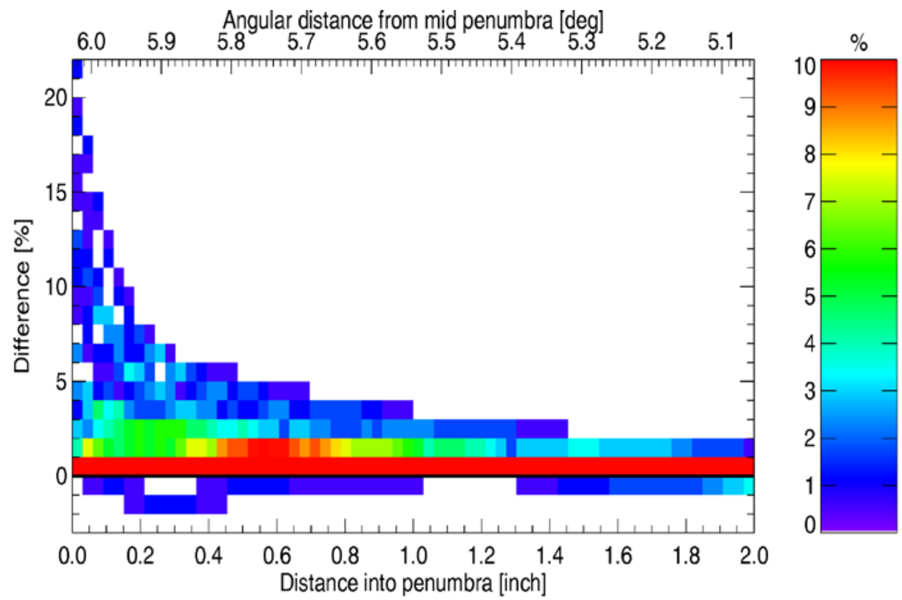
$$I(\lambda,\mu)=I_{cen}(\lambda)\sum_{m=0}^{5}\left(\sum_{n=0}^{5}a_{mn}\,\lambda^{-n}\right)\mu^{m}=I_{cen}(\lambda)\sum_{m=0}^{5}a_{m}(\lambda)\,\mu^{m}$$

- Curves at left show the equivalent wavelength-dependent number of suns at 9.86 R_S for three wavelengths. The inset shows expanded view of abscissa interval 0.95-0.90 (0.44-1.34% of disk)

Solar Illumination
SLS: Transient Solar Activity

- **Sunspots: Intense magnetic fields block heat from Sun's interior**
  - Cooler & Less bright than surroundings
  - Divided in Umbra & Penumbra
- **Plages & faculae: Weaker magnetic field allows to "see" deeper in solar interior**
  - Hotter & Brighter than surroundings
  - Excess brightness not uniform across Sun
  - Faculae brighter at Solar limb
  - Little to no brightness at Sun center

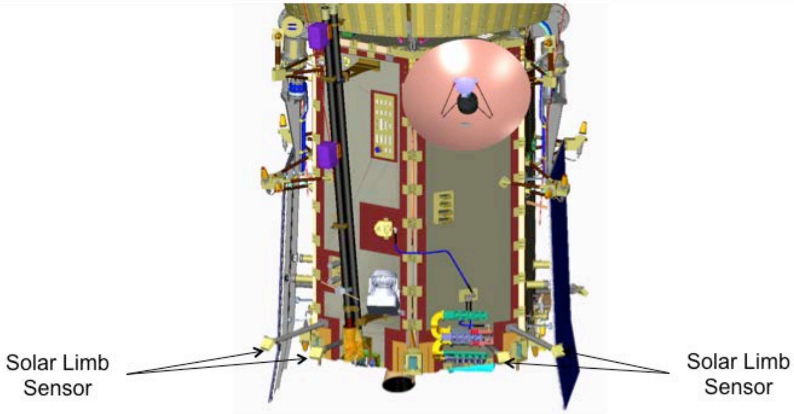




Percent signal difference, relative to blank sun, measured by a single SLS due to transient solar activity (y axis) as function of its penetration into the sun's penumbra (x axis) when spacecraft is at 9.86 R_S. Color code indicates the % probability that for a given penumbra penetration, a given irradiance difference is measured by the SLS. Values are derived from a Monte Carlo simulation using a series of realistic active regions distributions on the solar disk with modeled realistic total irradiance of sunspot, faculae and plages as function of their location on the solar disk [9].

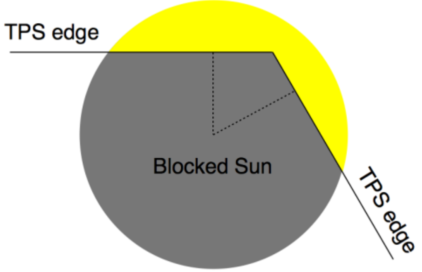
- Only Solar Limb Sensors are affected, since Secondary Solar Arrays will view polar regions [9]
- Model to simulate sun's appearance provides estimates for deviation of radiant intensity from blank sun when active regions are present
- Conclusions
  - SLS is marginally affected by transient activity
  - **% difference is < 2% beyond 1 inch penetration into penumbra**
  - **At small penetrations (< 0.1 inch) SLS sees 15% to 20% signal *increase* in only 1% of the cases**
  - Results in small **overestimate** of spacecraft tilt that can be accounted for in design

Solar Illumination
SLS exposure behind TPS "corner"

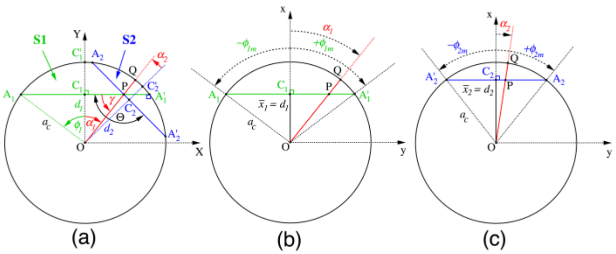


Solar limb sensors, anti ram side

SPP will carry several solar limb sensor (SLS) heads mounted on brackets around the bottom perimeter of the hexagonal bus, some of which can view the sun from behind a TPS edge, and others from behind a TPS "corner"



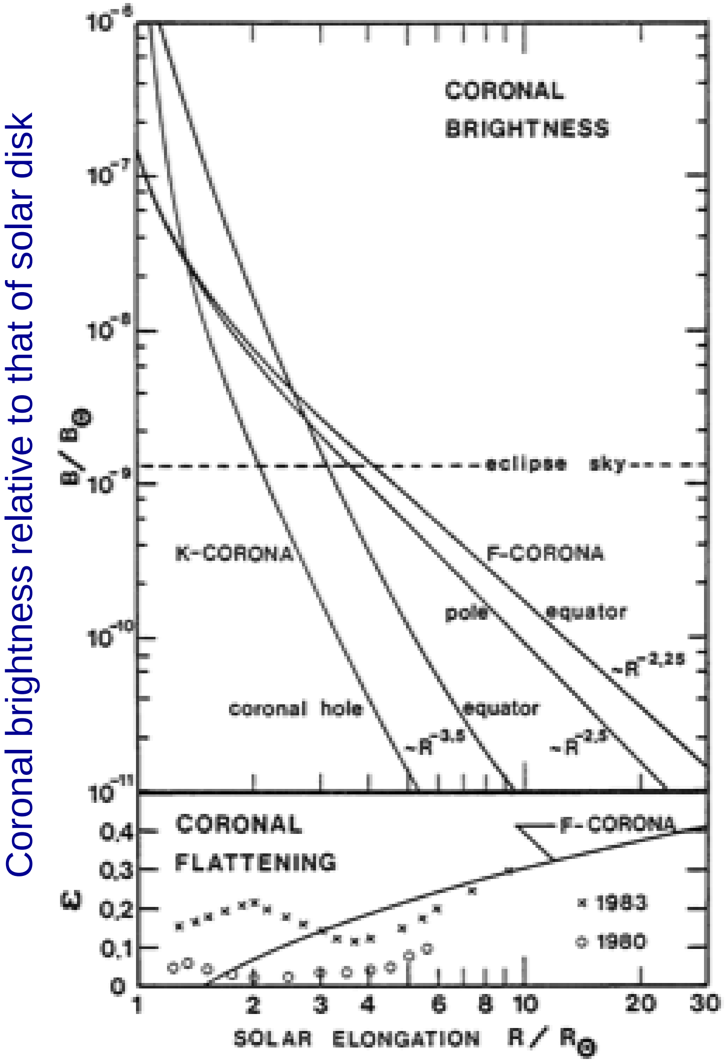
Schematic view from a differential area element located on a solar limb sensor exposed to the penumbra outside an obtuse corner of the TPS.



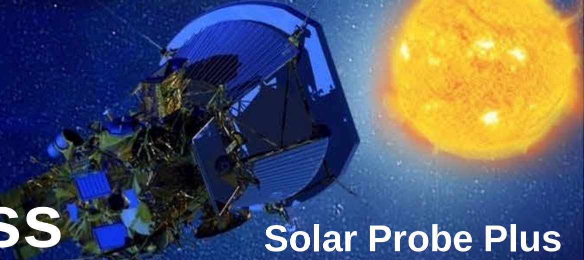
Method divides irradiated area (a) into two partial segments (b) and (c), and calculates the irradiance on each from the corresponding partial spherical segments of the sun

- Irradiance of a solar limb sensor (SLS) that enters the penumbra bounded by a TPS straight edge can be computed with techniques developed for the SSA
- Most of the seven SLSs will at some point along the SPP orbit enter the penumbra bounded by an obtuse "corner" of the TPS (lower left figure)
  - In this case irradiance can be computed by treating the exposed area as two partial spherical segments (lower right figure)
  - Necessary input: (1) known angle of the TPS "corner;" (2) the distance from (blocked) sun center to the chord of each partial spherical segment
  - Model developed to compute SLS irradiance includes several angular integrals that can be evaluated numerically or using approximate, but accurate analytical expressions [10].
  - Bolometric limb-darkening effects are included (spectral effects can be included if necessary)

Solar Illumination Coronal brightness



- Require the irradiance of the spacecraft and payload by coronal brightness for $R \geq 9.86\ R_S$
- Immediately off the limb of the sun, irradiance drops by several orders of magnitude, and radiant exposure is dominated by:
- **K-corona**: Scattering of solar radiation off free coronal electrons
  - Doppler broadening of the reflected photospheric absorption lines completely obscures them, giving the spectrum a continuous (**K**ontinuierlich) appearance with no absorption lines
  - The K-corona dominates particularly within a few solar radii from the solar surface (4-5 R_S)
- **F-corona**: Scattering of solar radiation off heliospheric and interplanetary dust
  - The name F-corona is relative to the observation of the Fraunhofer absorption lines that are present in the solar spectrum
  - This source of coronal light extends from small (i.e., a few R_S above the solar disk) to very high elongation angles from the Sun
  - The contribution at large elongations is the so-called “Zodiacal light”



Solar Illumination
K and F corona white light brightness

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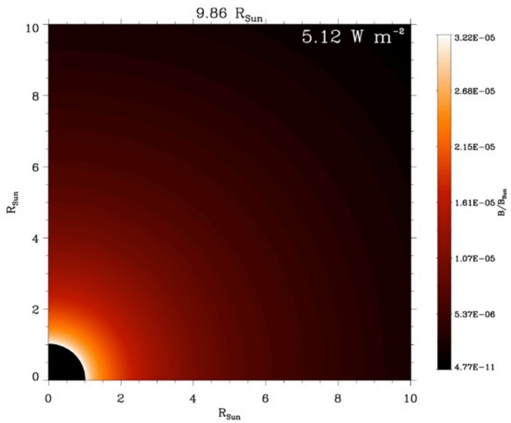
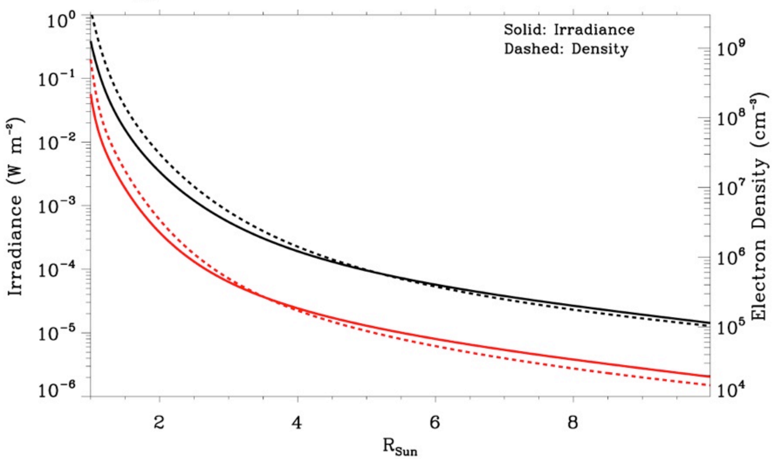
K corona radiance



Radiance of K corona, (solar disk is occulted), viewed from 9.86 R_S for enhanced coronal electron density. Color bar units are B/B_{sun}. Integrated irradiance is ≈ 5.12 W m^{-2}

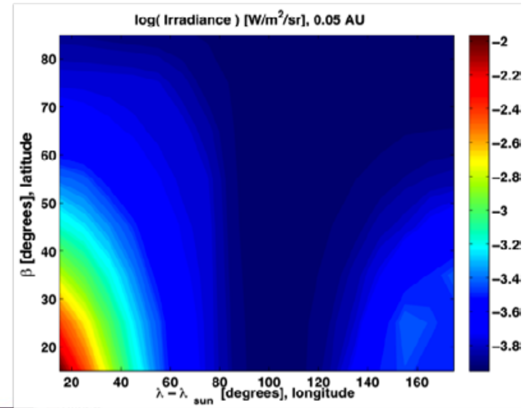


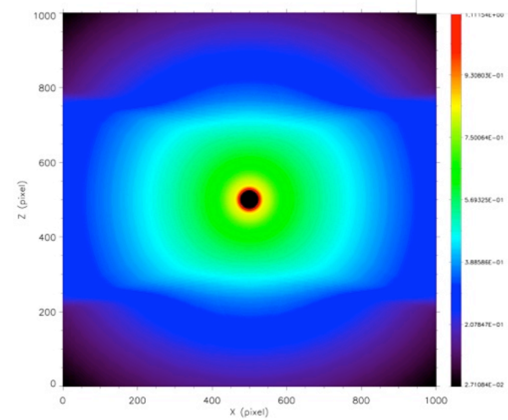
Line-of-sight irradiance (left, solid) at 9.86 R_S for nominal (red) and enhanced (black) coronal electron densities (right, dashed), integrated over concentric circles and plotted versus helioradius *R*. For reference, the irradiance from solar disk is 0.65 MW m^{-2}

F corona radiance

- Can affect white light imaging instruments (e.g., star trackers) as sunlight is scattered by dust
- Model developed by [11] using dust model in review by Mann et al. (2004) [12]

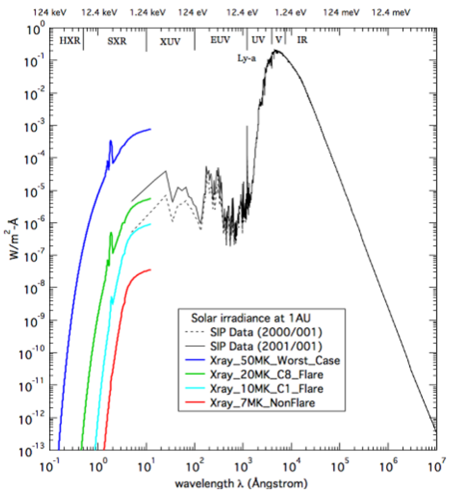
Simulated all-sky map showing color-coded radiance (W m^{-2} sr^{-1}) at a virtual star tracker with 25° FOV located in-ecliptic at 0.05 AU. Abscissa is ecliptic longitude (sun at 0°), ordinate ecliptic latitude



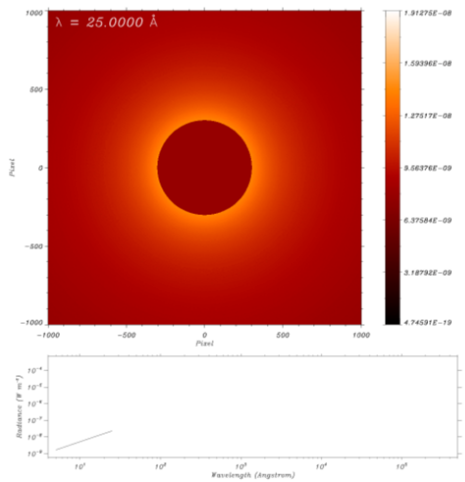


Simulated F corona contribution to radiance (W m^{-2} sr^{-1}) viewed from 25 R_S looking toward the occulted sun (center) [color range, 0.03-1.1 W m^{-2} sr^{-1}]

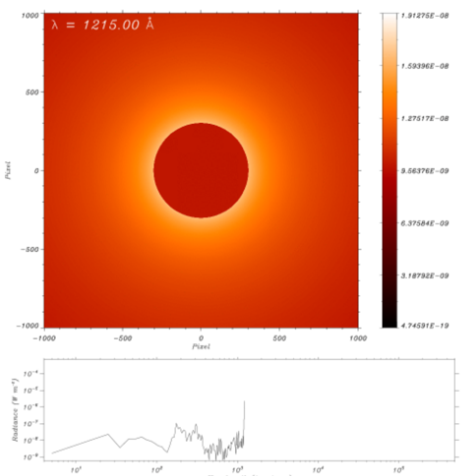
Solar Illumination
K and F corona spectral brightness



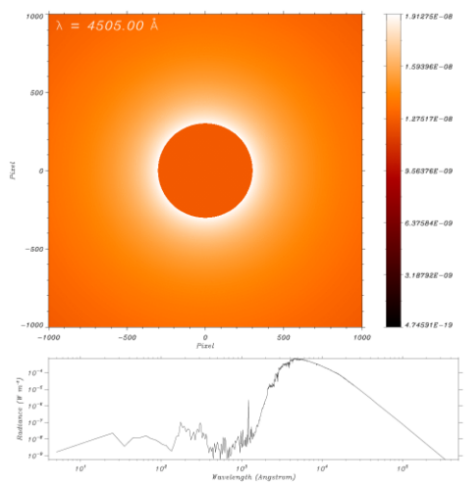
Solar spectral radiance measured 1 AU.



Coronal radiance at 9.86 R_S at 25 Å (XUV).



Coronal radiance at 9.86 R_S at 1215 Å (Lya, UV).



Coronal radiance at 9.86 R_S at 4505 Å (visible)

- Most SPP science investigations and on-board sensors, such as star trackers, will not view the solar disk directly
- As noted, photons from the disk will be scattered to the spacecraft bus and to instrumentation by the K and F corona
- The model used to produce the spectral images shown in this talk simulates exposure to the coronal radiation [13]
  - Upper left panel: Spectral radiance from solar disk measured at 1 AU at solar max. during 2000 and 2001. These data are used as input to the model
  - Color images: Coronal spectral irradiance predicted at 9.86 R_S at wavelengths 25 Å (XUV), 1215 Å (Ly-〈), and 4905 Å (visible). Results are for Thomson scattering only
  - Code takes as input the location of virtual detector, its spatial orientation, and solid angle opening, all of which can be set to values required

Summary

- Models developed to calculate wavelength-integrated and wavelength-dependent radiation flux on tilted area elements exposed to the full or partial limb-darkened sun and to coronal brightness as functions of SPP helioradius *R*
- Solar irradiance
  - Equations (in integral and approx. analytic forms) developed to compute energy flux (and pressure) on secondary solar arrays (SSA)
  - Monte Carlo simulations show that irradiance of solar limb sensors (SLS) only marginally affected by transient activity, e.g., at small penetrations (< 0.1 inch) into penumbra, SLS sees 15% to 20% signal increase in only 1% of the cases
  - Equations (in integral and approx. analytic forms) developed to compute energy flux on SLS exposed to penumbra bounded by obtuse “corners” of TPS
- Coronal brightness
  - Continued to improve and expand capability of code developed in pre-phase A to calculate irradiance of SPP spacecraft components and instrumentation by K and F corona
  - Code used to
    - Determine background in star trackers and placement of star trackers on SPP
    - Calculate contribution of coronal brightness to background energy flux at SPP
    - Compute bolometric and spectral irradiance of specific spacecraft instrumentation as requested

References

1. *Allen's Astrophysical Quantities*, 4th Ed., Arthur N. Cox, editor, Springer, New York, 2000.
2. Fröhlich, C., Total solar irradiance observations, *Surv. Geophys*., *33*, 2012.
3. Kopp, G., and J. L. Lean, A new, lower value of total solar irradiance: Evidence and climate significance, *Geophys. Res. Lett*., *38*, 453, 2011.
4. Publication E 490 00a: *Standard, Solar Constant and Zero Air Mass Solar Spectral Irradiance Tables*, ASTM International, 2006.
5. Fröhlich, C. and J. Lean, Solar radiative output and its variability: Evidence and mechanisms, *Astron. and Astrophys. Rev.*, *12*, 273, 2004.
6. Foukal, P, and P. Bernasconi, Do photospheric brightness structures outside magnetic flux tubes contribute to solar luminosity variation?, *Solar Phys.*, *248*, 1, 2008.
7. SPP SharePoint: Shared_Documents/Science Trade Documentation/Solar_array_energy_and_momentum_flux/*Radiant_Energy_and_Momentum_Flux_25Jul12*
8. Neckel, H., Analytical reference functions F(λ) for the sun's limb darkening and its absolute continuum intensities (λλ 300 to 1100 nm), *Solar Phys.*, *229*, 13, 2005.
9. SPP SharePoint: Shared_Documents/Science Trade Documentation/Solar_limb_sensors/*SPP_SLS_solar_activity_20Jul11_draft*
10. SPP SharePoint: SPP SharePoint: Shared_Documents/Science Trade Documentation/Solar_limb_sensors/*Irradiance_of_SLS_by_Overlapping_Solar_Segments_25Dec13_draft*
11. SPP SharePoint: Shared_Documents/Science Trade Documentation/Interplanetary_dust/space_weather_v3
12. Mann, I., et al., Dust near the sun, *Space Sci. Rev*., *110*, 269, 2004.
13. SPP SharePoint: Shared_Documents/Science Trade Documentation/Coronal Brightness/*Radiation_Scattering_Solar_Corona*

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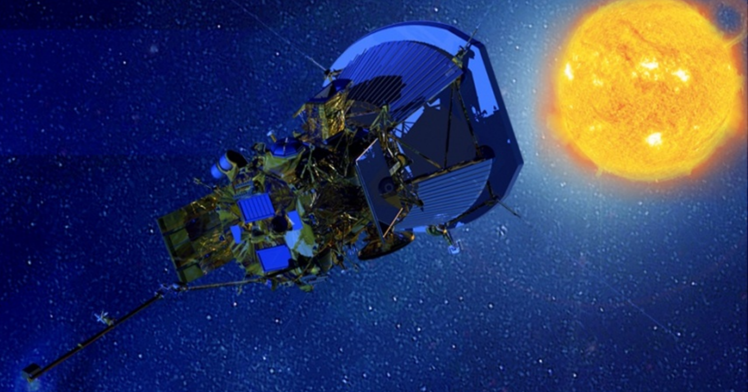

Radiation

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13 – 16 January 2014

The Johns Hopkins University
APPLIED PHYSICS LABORATORY

Introduction

- **External Radiation Environment**
- **Transported Radiation Environment**
- **Radiation Requirements**
- **Parts**

External Radiation Environment Introduction

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- **Proton Significant for:**
  - **Total Ionizing Dose (TID)**
  - **Total Non-Ionizing Dose (TNID)**
  - **Single Event Effects (SEE)**
  - **Solar Cell Degradation**

- **Electrons Significant for:**
  - **Surface Charging**
  - **Deep Dielectric Discharge**

- **Heavy Ions Significant for SEE only**

- **Gamma ray, X-ray, uV, Neutron, and alpha particle models**
  - **Not significant for TID, TNID, SEE and Solar Cell Degradation**

External Radiation Environment Proton and Electron Model

- **Statistical Model developed by:**
  - **Dr. Robert B. Decker**
  - **Dr. David Lario**
  - **Lario D., R. B. Decker, Estimation of solar energetic proton mission-integrated fluences and peak intensities for missions traveling close to the Sun, Space Weather, VOL. 9, S11003, doi:10.1029/2011SW000708, 2011**

- **Extensive data sets of particle intensities at 1 AU**
- **Model successive launch dates for the mission trajectory**
- **Apply appropriate radial dependence**
- **Model Generates**
  - **Mission integrated fluence**
  - **Peak intensities**
  - **Probability distributions of peak intensities**

External Radiation Environment Proton Model

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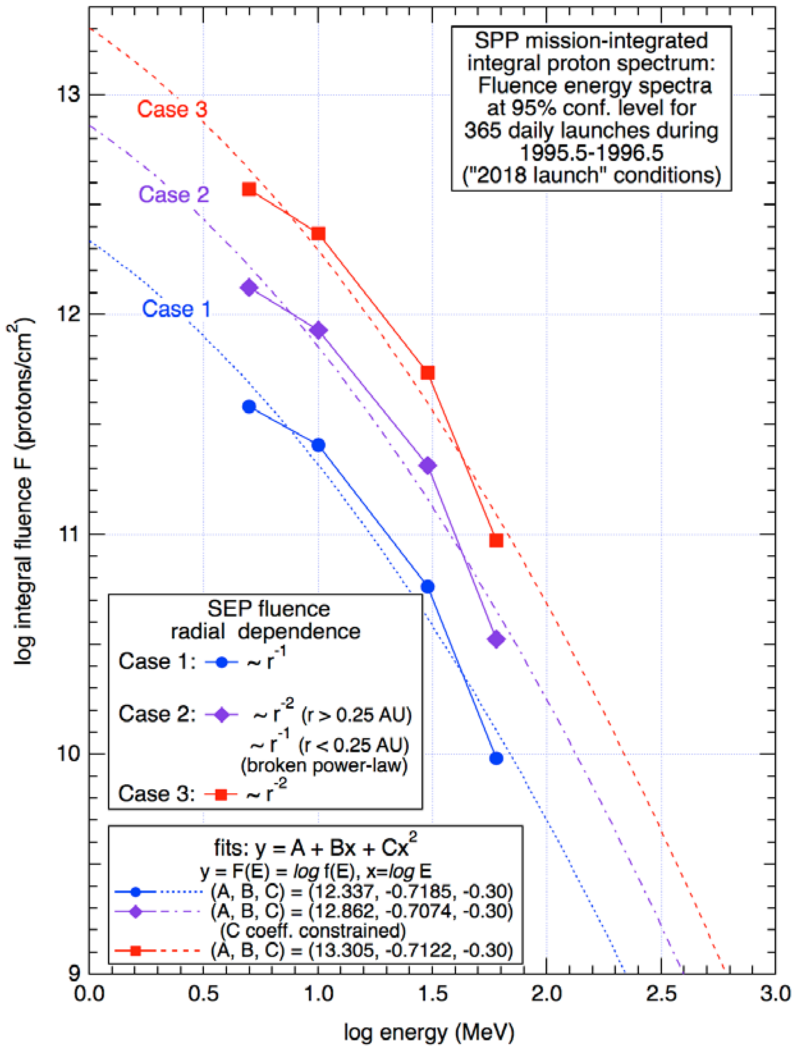
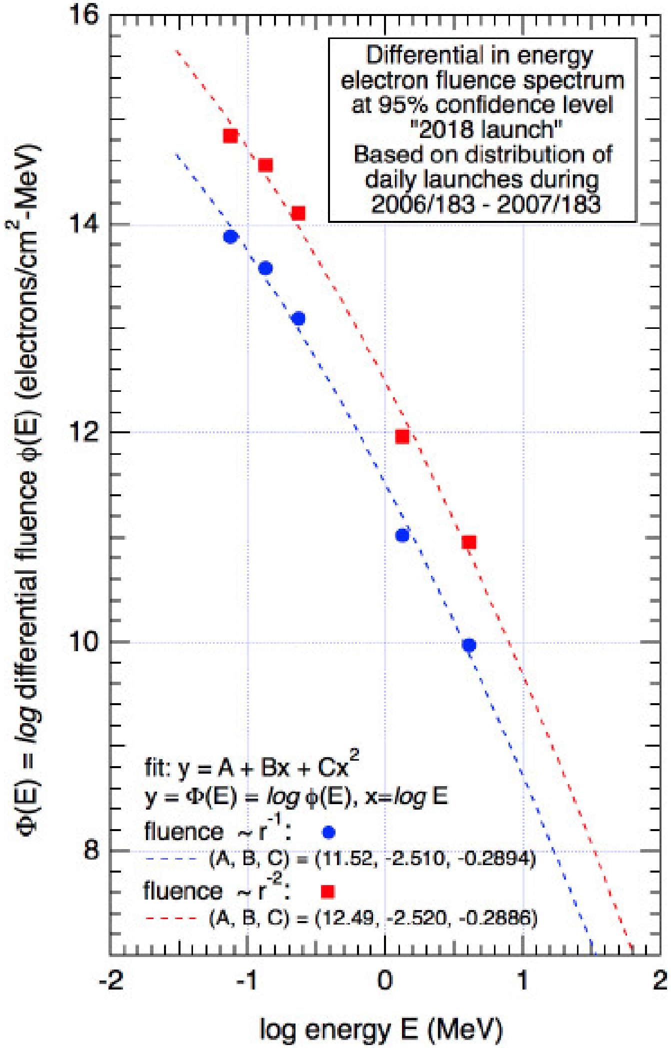
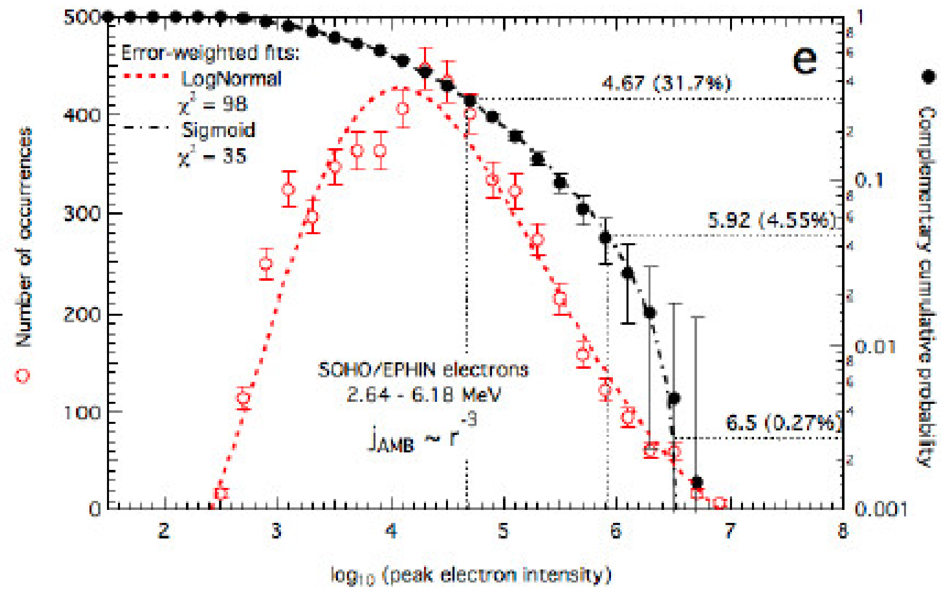


- **365 daily launches simulated**
- **Launch dates 1995.5 to 1996.5**
  - **Similar solar condition as 2018 launch window, gives "worst-case" fluence compared to other one-year launch periods during solar cycles 21-23**
- **Radial dependence**
  - **Proton Fluence 95% Confidence level**
    - **Broken power law**
    - **r^{-2} > 0.25 AU**
    - **r^{-1} < 0.25 AU**
  - **Peak proton intensities**
    - **r^{-3}**

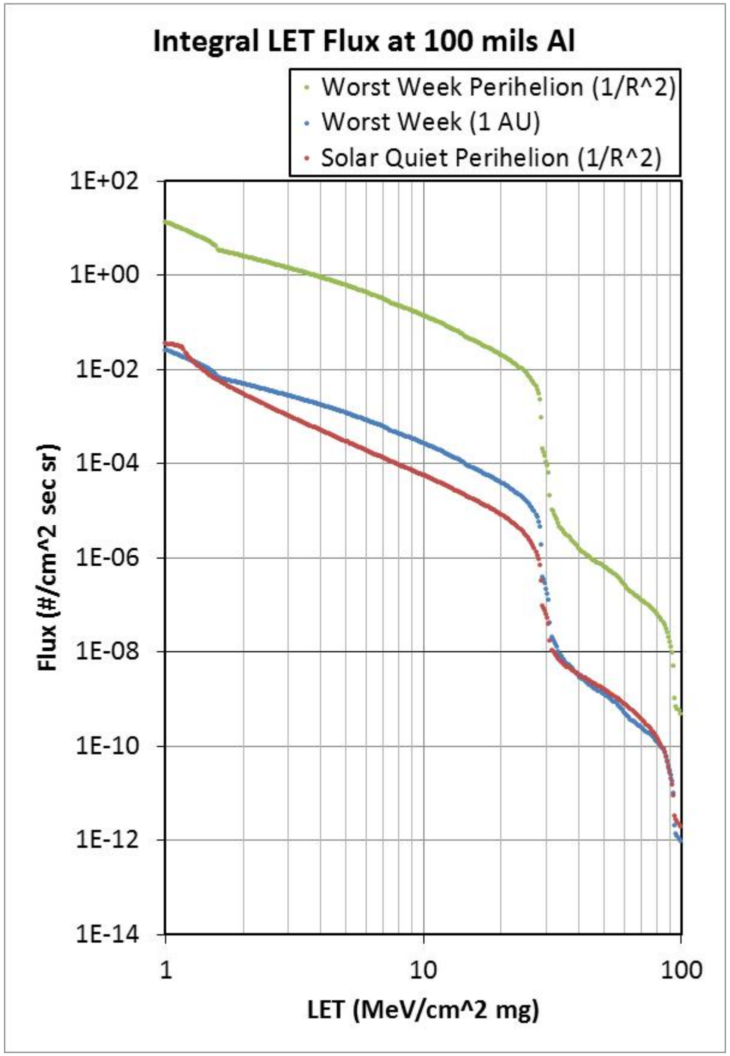
APL

External Radiation Environment Electron Model





External Radiation Environment
Heavy Ion Model

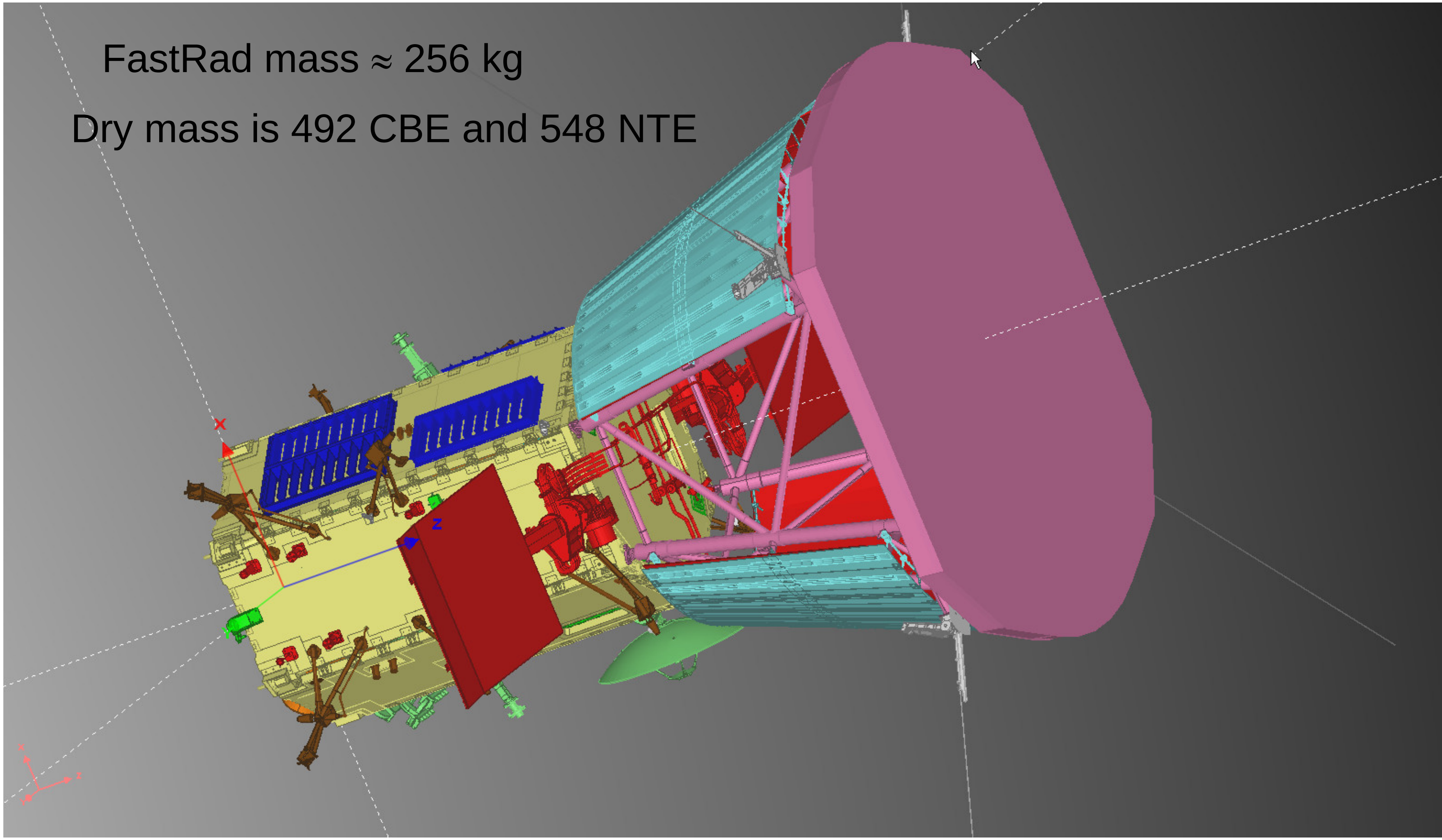


- **CREME-96 used to generate raw data**
- **Worst week model used**
  - **October 1989 events**
  - **99% Confidence level**
- **Radial dependence r^{-2}**
  - **Perihelion intensity >500**
- **LET of Fe at 110 MeV**
  - **≈ 30 MeV-cm^2/mg**

Radiation Transport Introduction

- **Radiation Transport Modeling used for**
  - **Total Ionizing Dose (TID) and Total Non-Ionizing Dose (TNID)**
- **Protons dominate TID, TNID and solar cell degradation**
- **Proton transport easier than electrons transport**
  - **Tools available to model complex structures**
  - **Higher percentage of mass can be used by the transport code**
  - **FastRad selected for use on SPP.**
- **FastRad implementation**
  - **Medium level detailed model frozen April 2013**
    - **Electronic boxes represented as simple shells**
    - **Primary structure and other assemblies have higher fidelity**
    - **TID/TNID estimates made at the box level**
  - **High fidelity model of box can used on a case by case basis**

Radiation Transport
SPP in FastRad mass ≈ 256 kg



Radiation Transport
Simple and complex Transponders

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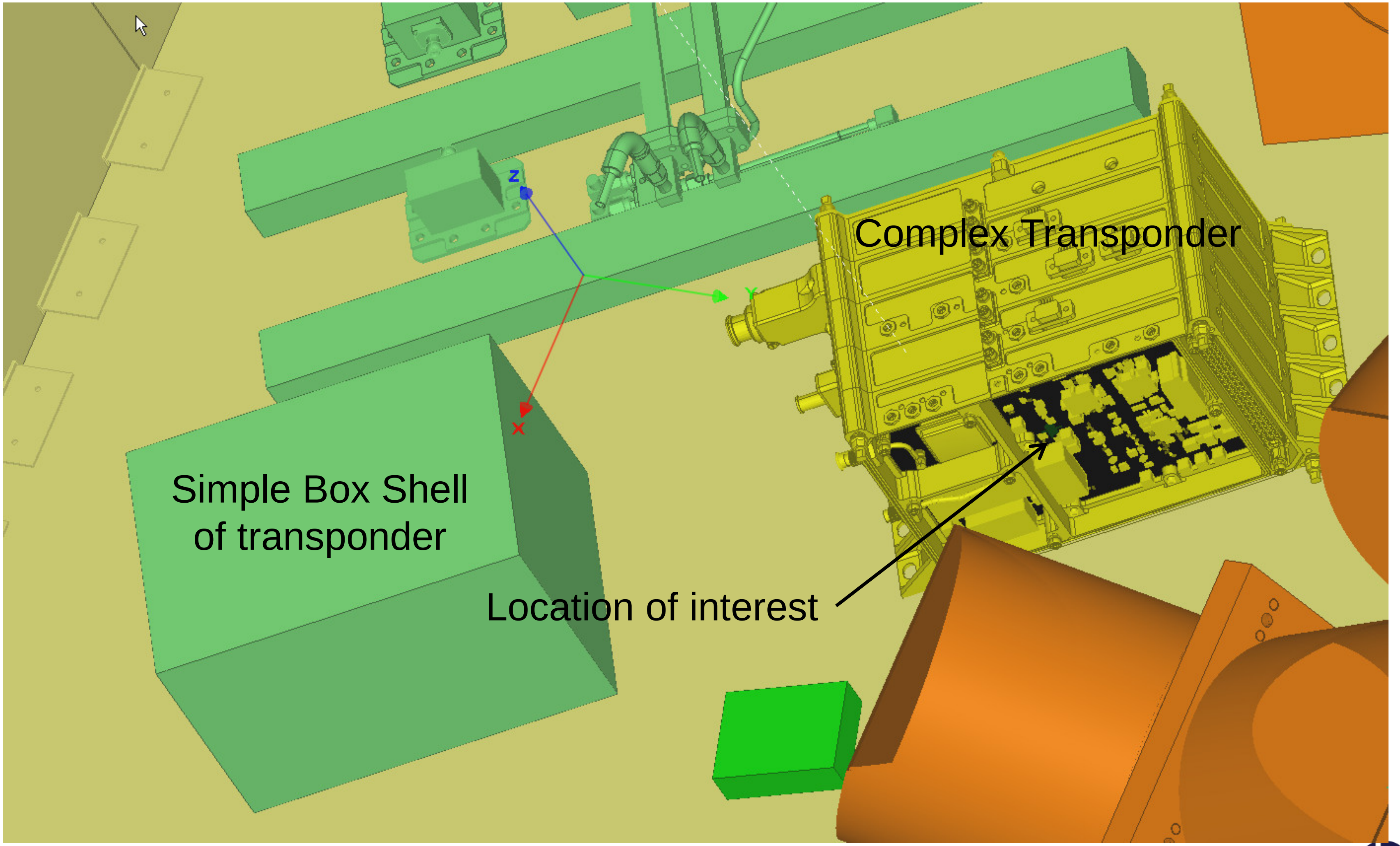

Radiation Transport
Solar Cells Degradation

- **Scream version 7 was used to calculate solar cell degradation**
- **ZTJ triple junction solar cells from Emcore**
- **20 mil CMG cover glass**
- **End-Of-Life to Beginning-Of-Life or EOL/BOL Ratio**
  - **Pmax = 0.918**
  - **Voc = 0.933**
  - **Isc = 0.994**

Radiation Requirements
TID

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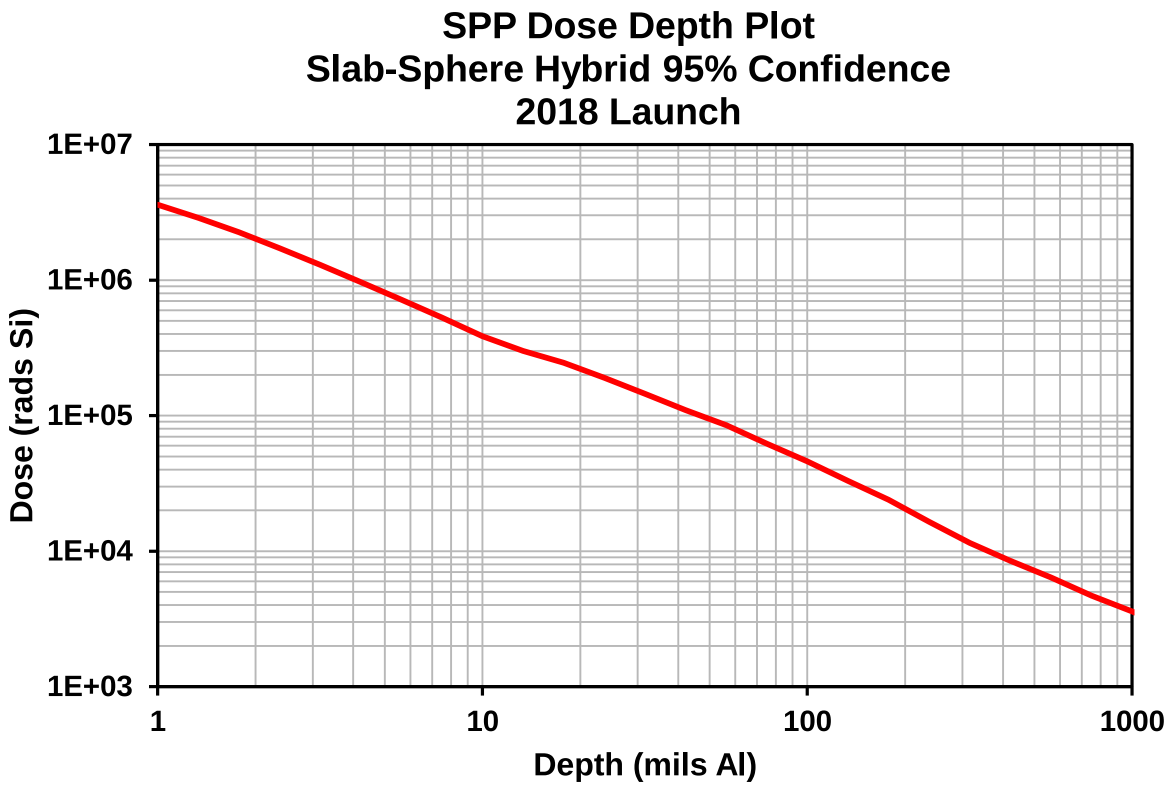
- Materials located externally shall be tested to 5 Mrads
- The TID requirement is the dose depth curve
- FastRad simulations refined most TID requirements



Radiation Requirements
TID and TNID

Sub Assemblies	TID (krads Si)	Displacement Damage (10 MeV Eq. Protons) (Protons/cm^2)	Sub Assemblies	TID (krads Si)	Displacement Damage (10 MeV Eq. Protons) (Protons/cm^2)
SPP_RIU (4 devices at 60 krads)	40	N/A	SPP_SPC_HMB	20	1.0E+11
7434-2300REM_SW_01-03-13	25	1.0E+11	SPP_Solar_Limb_Sensors	40	1.3E+11
7434-2100RPM_SW_01-03-13	25	1.0E+11	SPP_PROPULSION_DIODE_BOX	25	1.0E+11
SPP_PDU_ASM	25	1.0E+11	SPP_COOLING_SYS_DIODE_BOX	20	1.0E+11
SPP_ADCOLE_SSE_SW_02-07-13	25	1.0E+11	SPP_HS_PUMP_ELEC_SW_2-2-12	25	1.0E+11
SPP_STAR_CAMERA	30	2.0E+11	SPP_RF_DIODE_BOX	25	1.0E+11
SPP_Reaction_Wheels	25	1.0E+11	SPP_TRANSPONDER	25	1.0E+11
SPP_NG_SCALABLE_SIRU_ASM	25	1.0E+11	SPP_PI10959-01	20	1.0E+11
SPP_Battery	40	2.0E+11	SPP_DIPLEXER-PI10925-1A	20	1.0E+11
SPP_TBU_SW_02-01-11	25	N/A	SPP_PI10957-01	20	1.0E+11
SPP_5-CHAN_RED_ECU	20	1.0E+11	SPP_X-BAND_EPC	25	1.0E+11
SPP_DPU_SW_01-21-13	20	1.0E+11	SPP_KA-BAND_EPC	25	1.0E+11
SPP_PSE_SW_02-13-13	20	1.0E+11	SPP_11W_X-BAND_TWT	10	1.0E+11
SPP_SWEAP_SWEM_SW_01-29-13	20	1.0E+11	SPP_KA-BAND_TWTA2	10	1.0E+11
SPP_FIELDS_MEP_SW_01-28-13	20	1.0E+11			

Radiation Requirements
Single Event Effects (SEE)

- **SEL device shall not latch-up at an LET below 80 MeV-cm^2/mg**
  - **Devices not meeting this requirement will require additional screening**
- **SEU shall not cause mission critical failures or compromise flight system health**
  - **Rate estimate and system level analysis are required on critical devices**
- **SEGR/SEB Power devices require derating to operate within the safe operating area**
- **Proton induced SEE cannot be ignored**

Radiation Requirements
Peak Proton Flux

Proton Energy	Proton Intensity (number/cm^2-sec-sr)
>300 keV	6.31e+08
>1 MeV	1.26e+08
>5 MeV	5.75e+07
>10 MeV	2.95e+07
>30 MeV	6.31e+06
>60 MeV	1.35e+06

Maximum peak fluxes at a 95% confidence level to be observed by the SPP mission using an r^{-3} extrapolation radial dependence. Probability distribution information available in backup slides.

Parts

- To date 268 device types have been identified as requiring radiation analysis
- TID: 218 out of 268 devices TID analysis complete
  - Remaining 50 devices TID analysis is ongoing
  - Smallest TID margins on the spacecraft
    - SSR flashes at x1.8 (model refinement ongoing)
    - 2 device types in the transponder x2
      - Model refinement on one of the devices increases to the margin to x6
    - Next lowest margin x4
  - Similar analysis ongoing on instruments
- SEL: 3 devices without SEL data
- SEU: 15 devices with analysis ongoing
- SEGR/SEB: Awaiting worst case operating conditions

Radiation Summary and Future Work

- **Requirements listed in EDTRD (7434-9039)**
- **Radiation Transport Analysis beneficial at Reducing TID levels.**
  - **Model refinement for SSR flashes ongoing.**
  - **Identifying lowest TID margin for instrument parts ongoing.**
- **Part TID and SEE analysis in good shape at PDR.**
  - **50 devices TID analysis ongoing.**
  - **3 devices SEL analysis ongoing.**
  - **15 devices SEU analysis ongoing**
  - **Awaiting worst case operating conditions for power FETs.**
    - **SEGR/SEB**
- **Detailed analysis of 2019 backup launch ongoing.**
  - **Plenty of margin in TID/TNID to accommodate backup trajectory**

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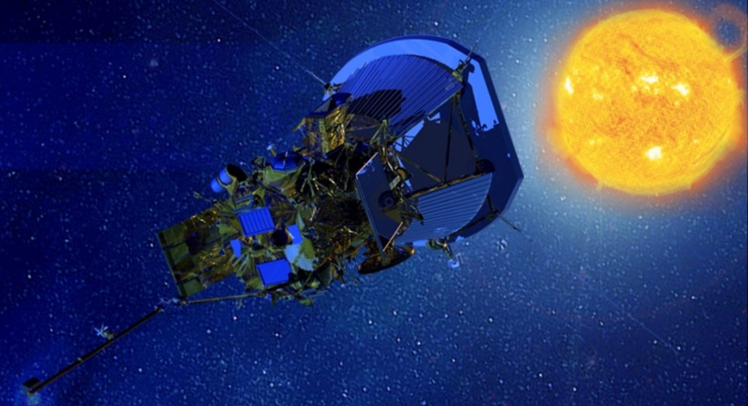

Back-up

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Radiation Transport
Path Length w/i Complex Transponder

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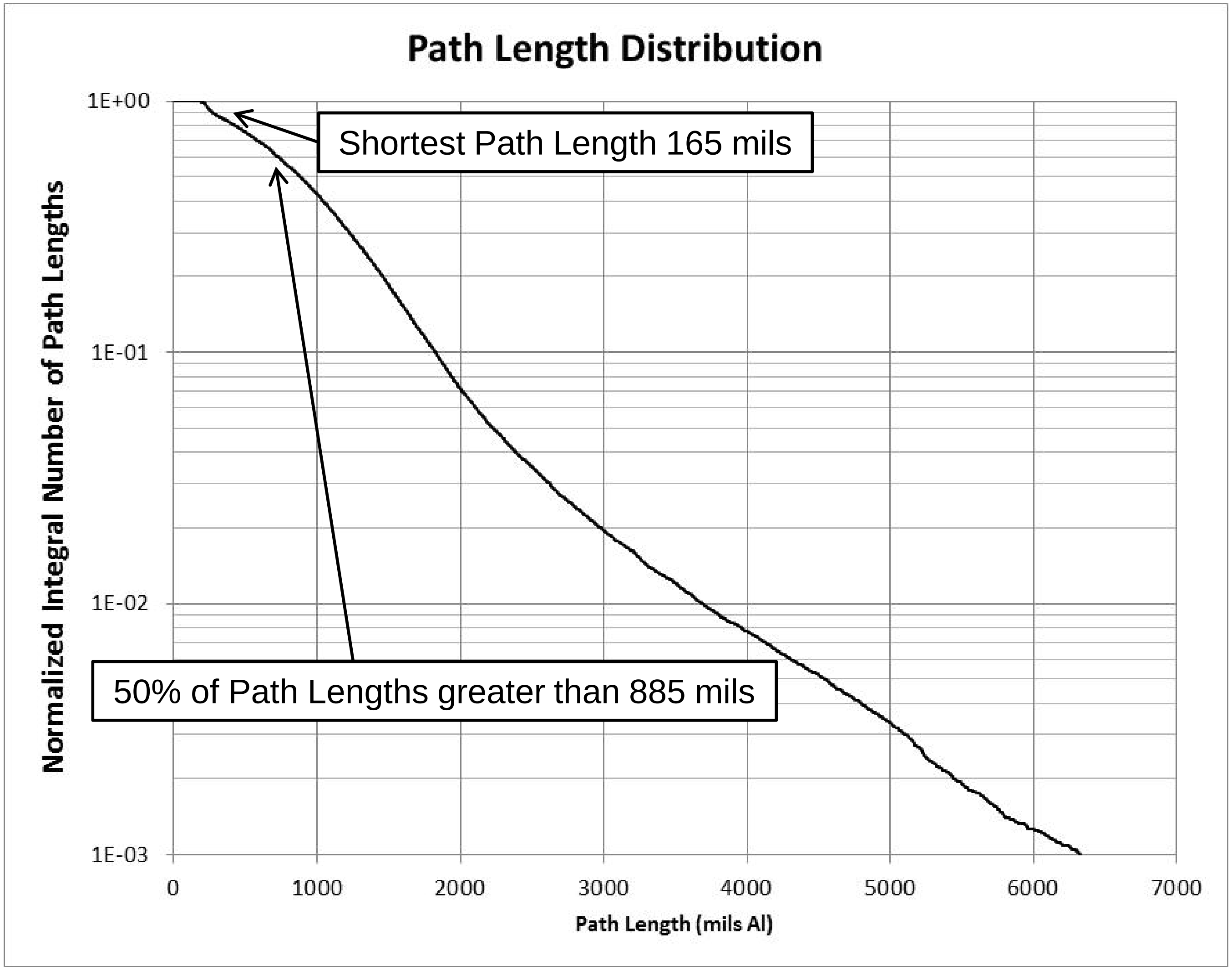

External Radiation Environment Trajectory

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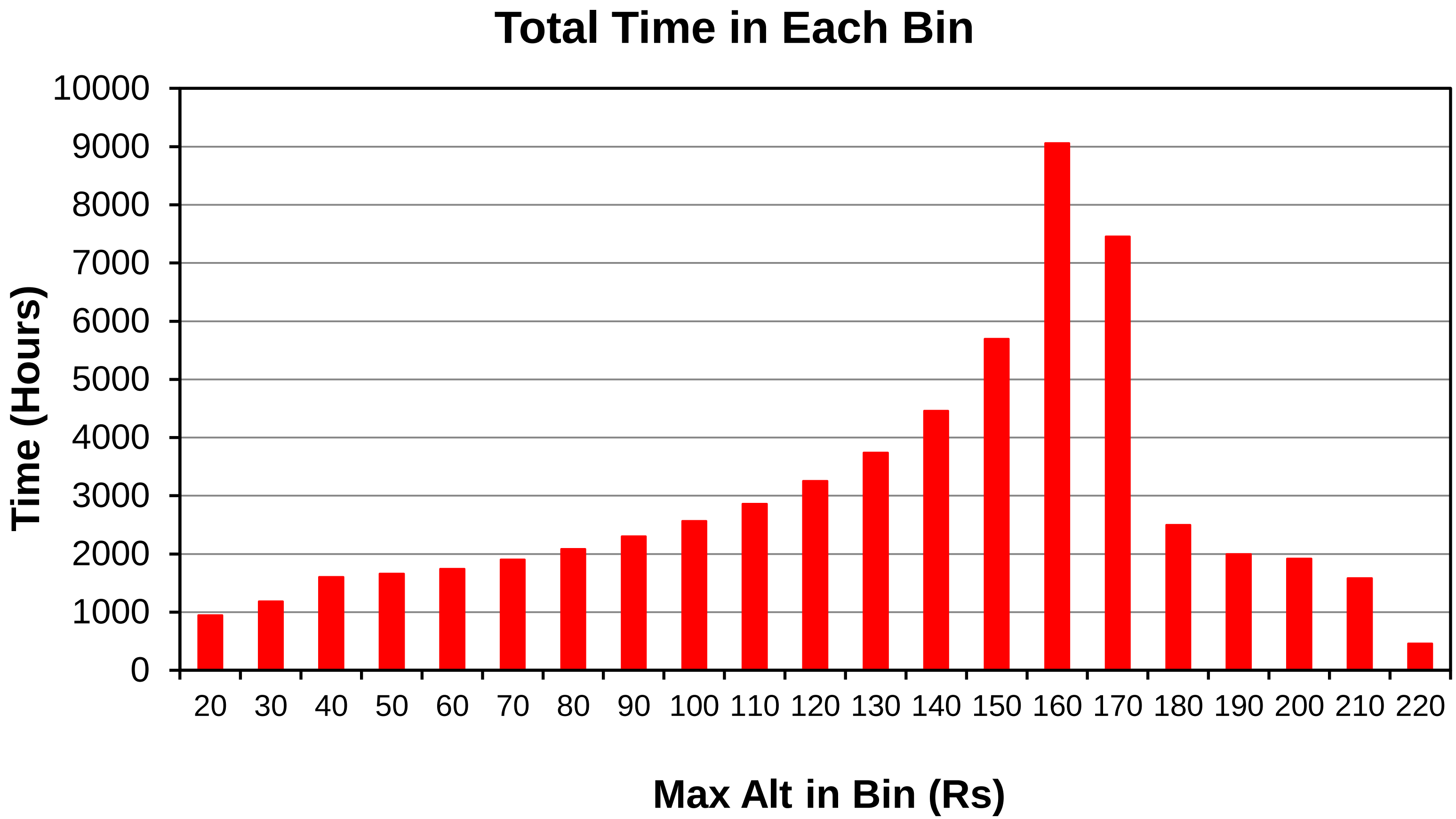

External Radiation Environment Trajectory

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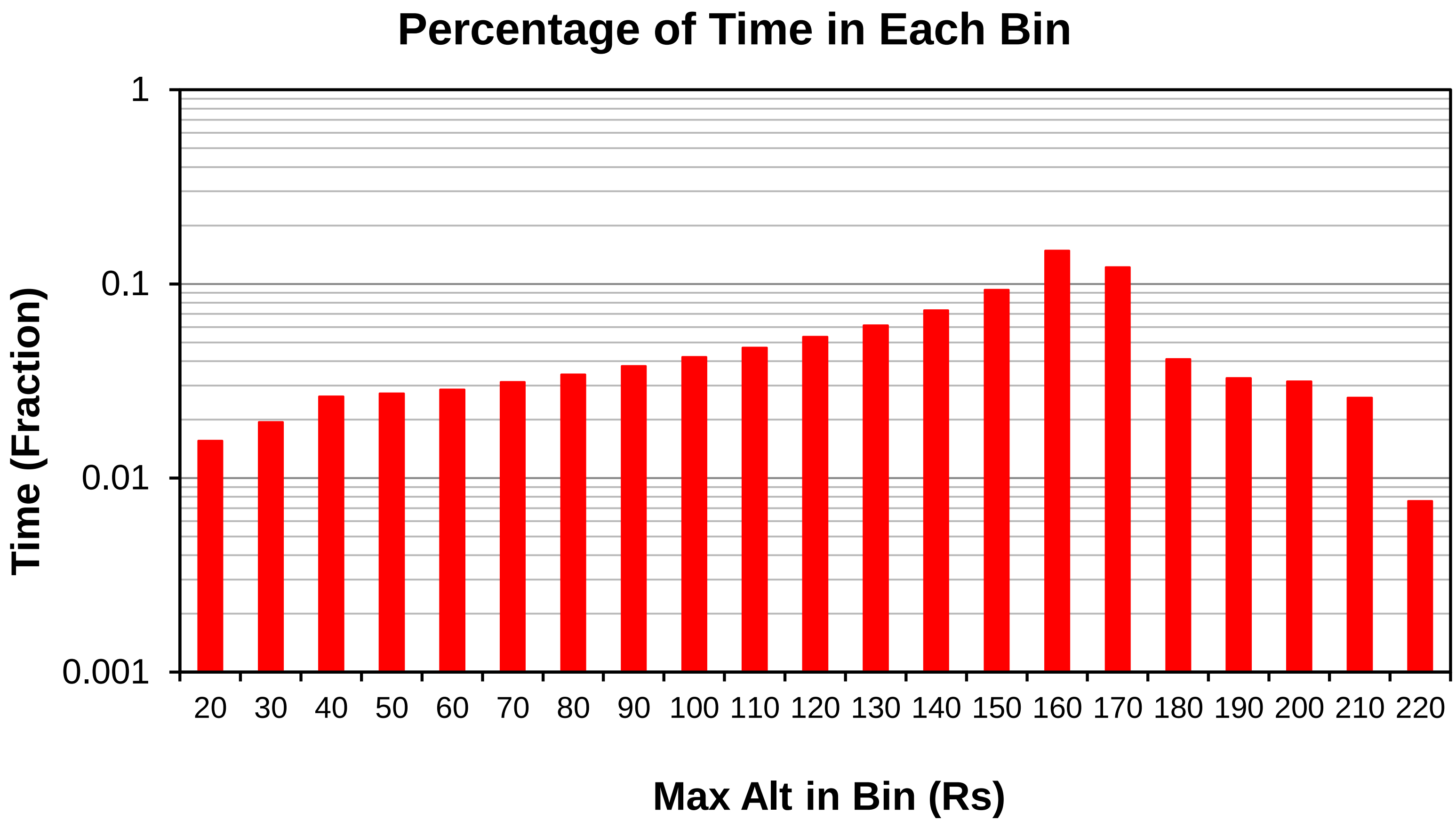

External Radiation Environment Peak Proton Distributions

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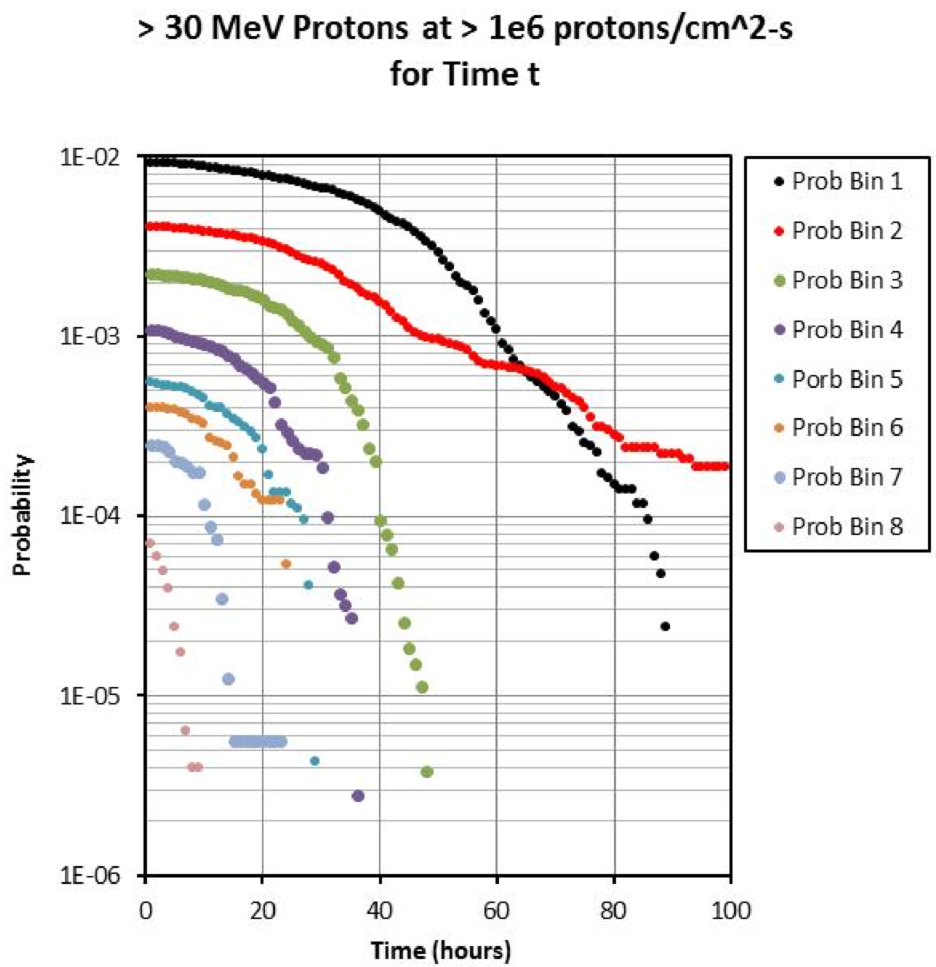
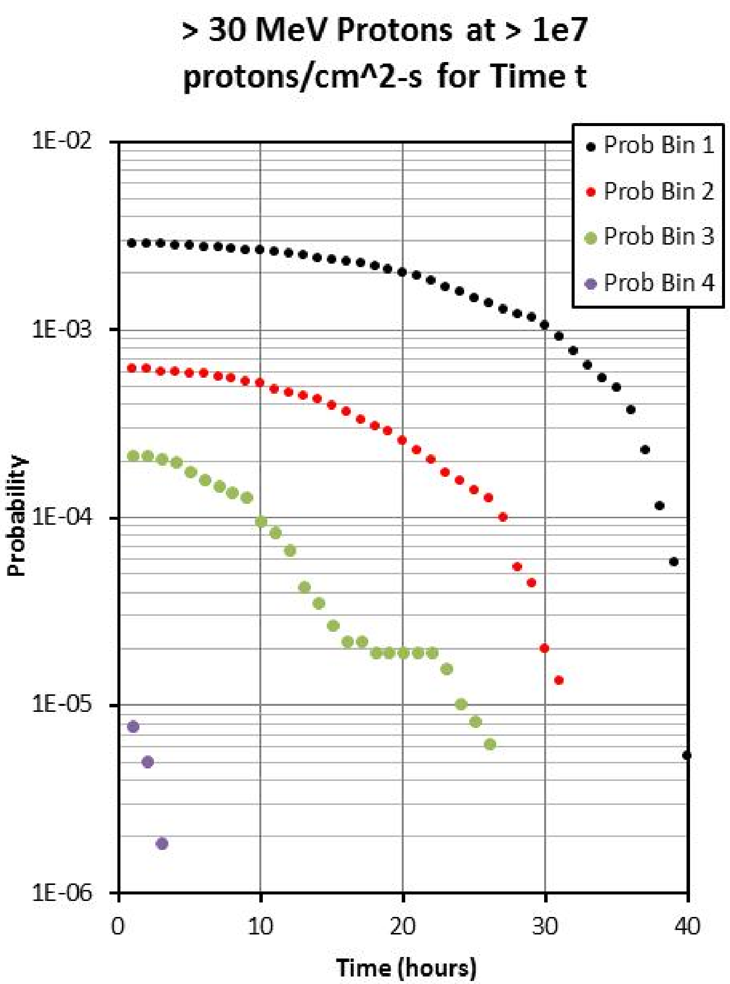
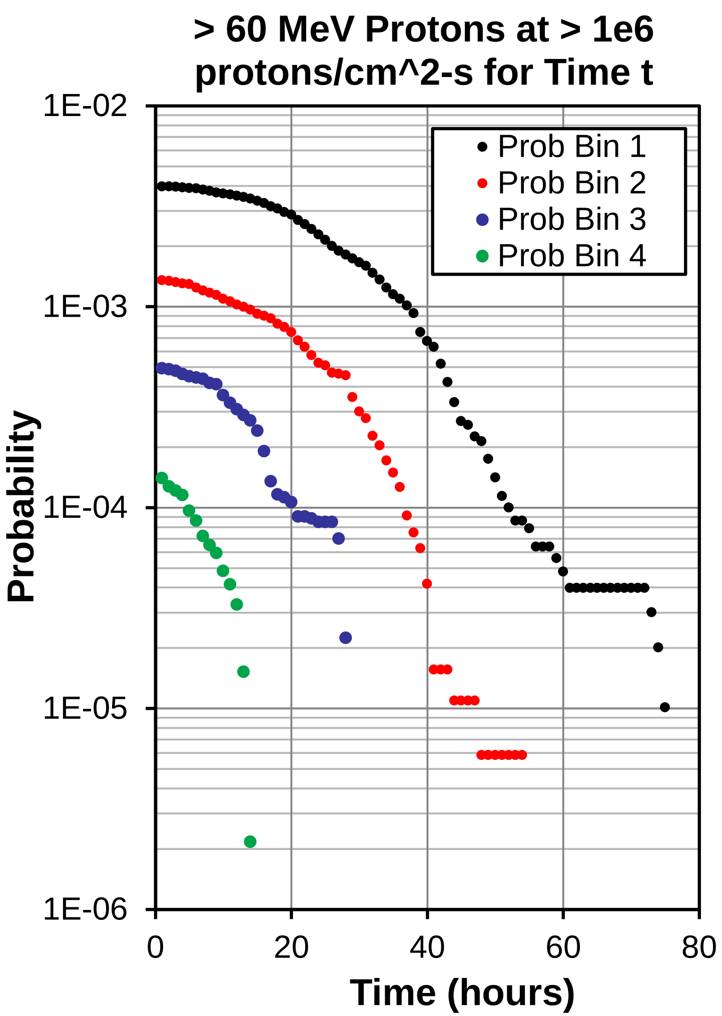
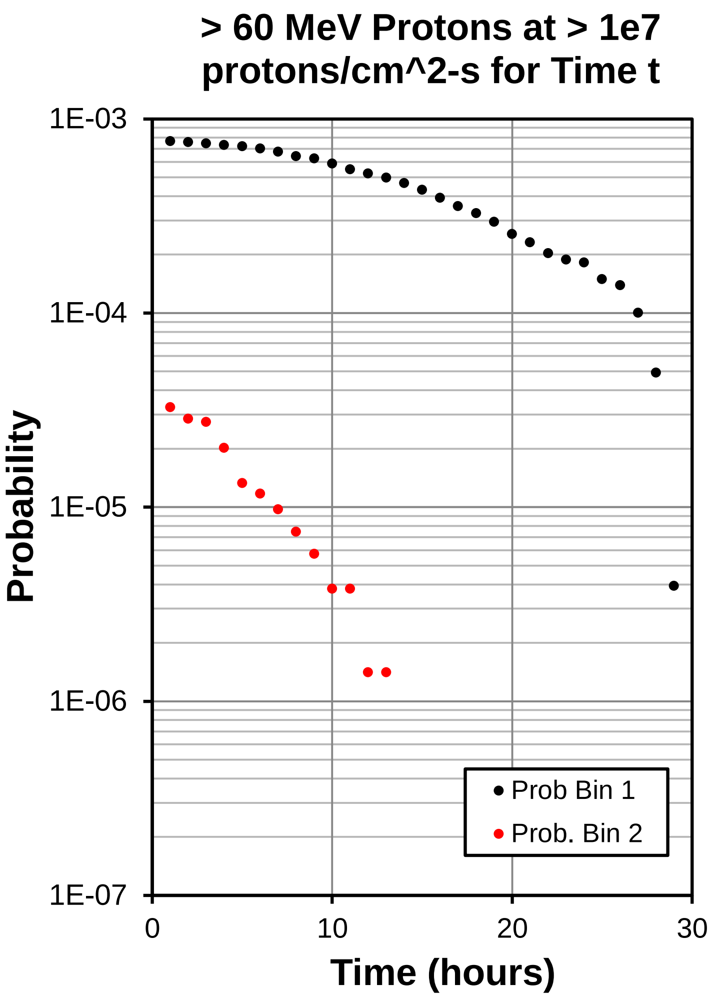




External Radiation Environment Peak Proton Distributions





External Radiation Environment
Peak Proton Distributions

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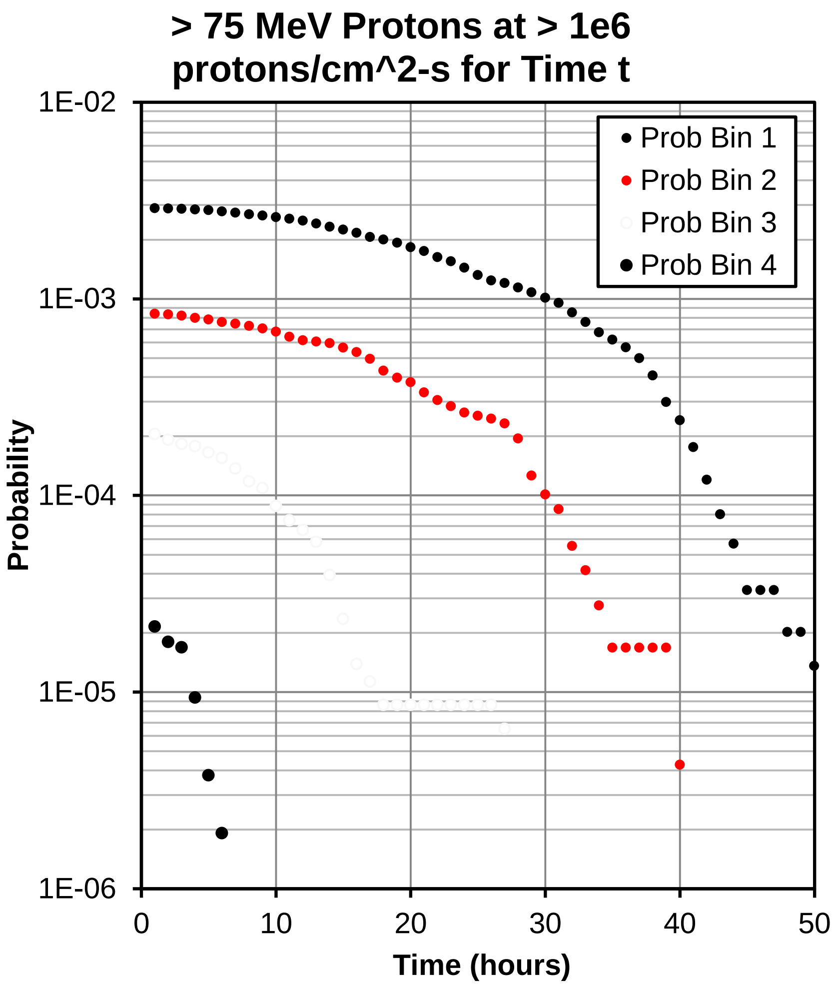

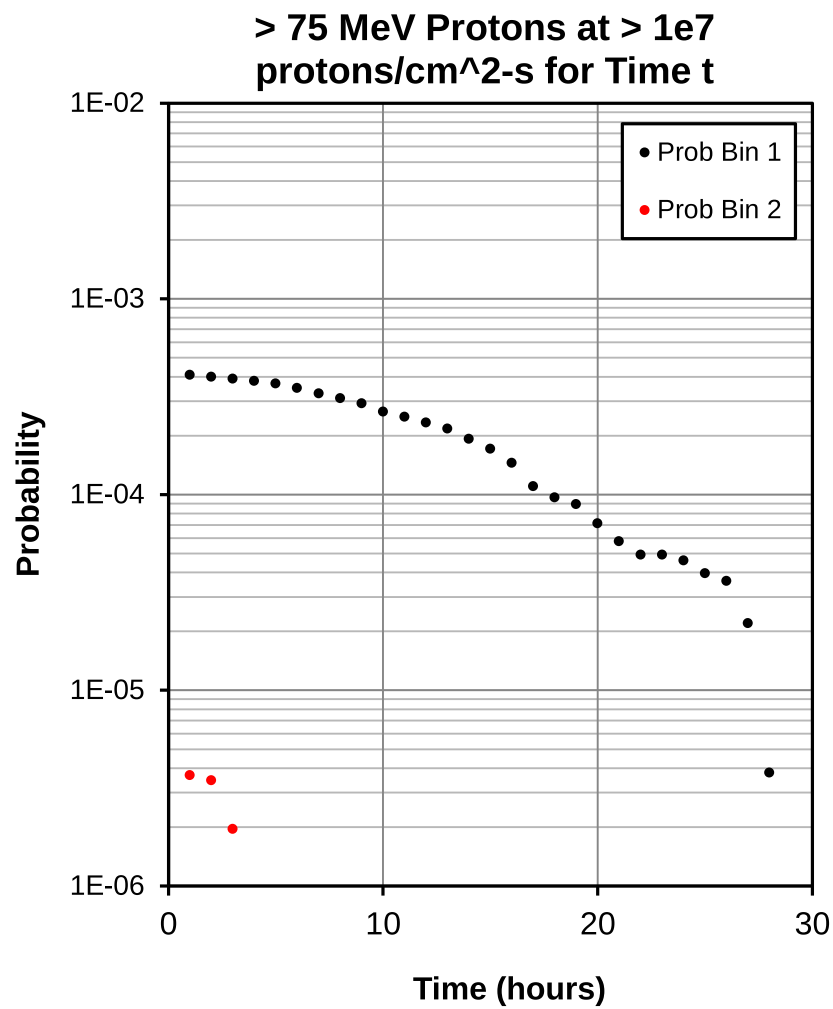

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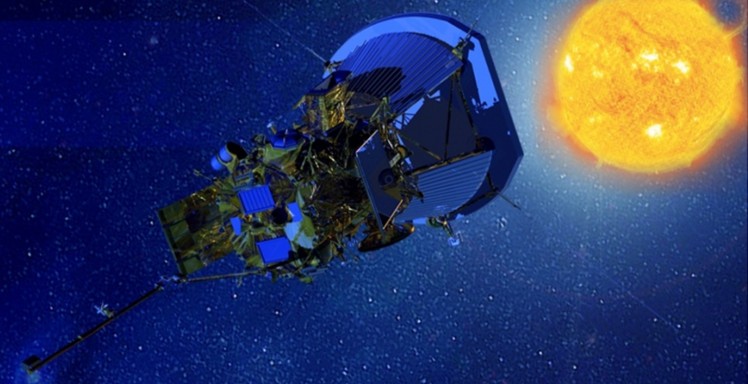

Spacecraft Surface Charging

Michelle Donegan
Lead Charging Engineer

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13 – 16 January 2014

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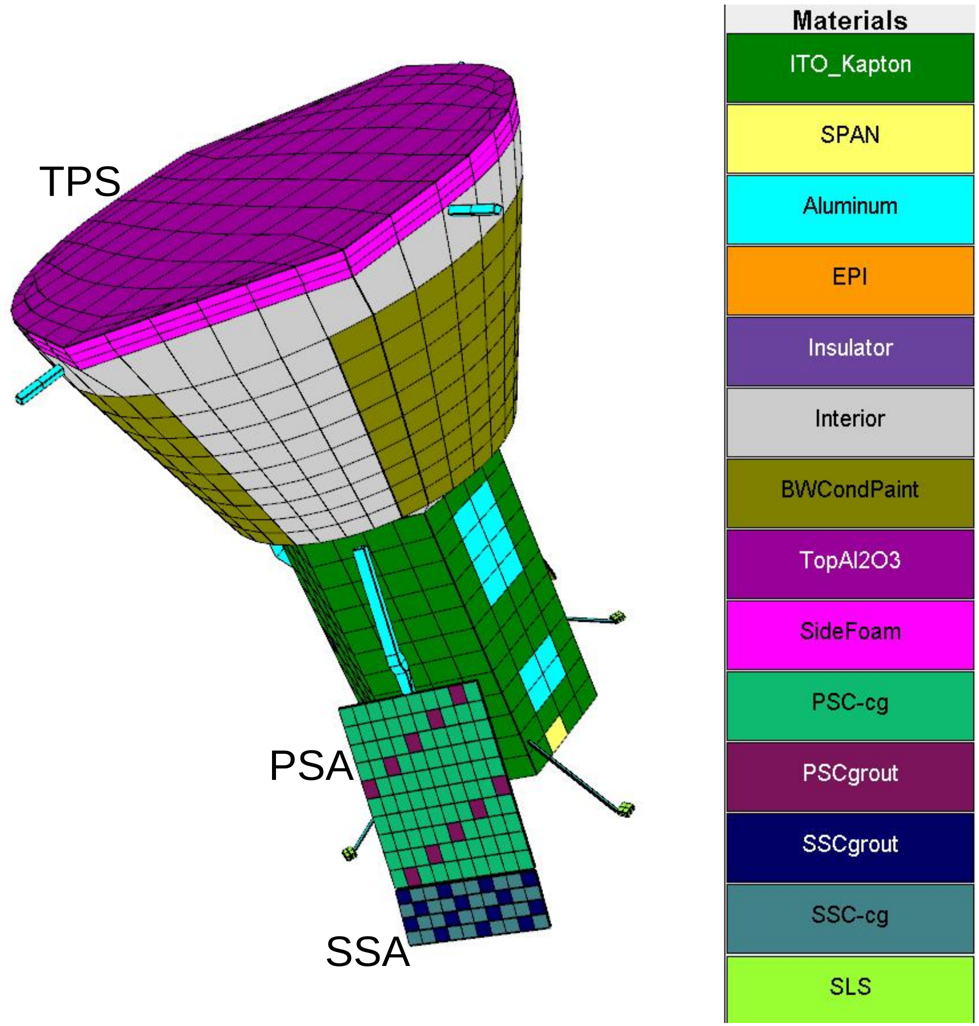
Introduction

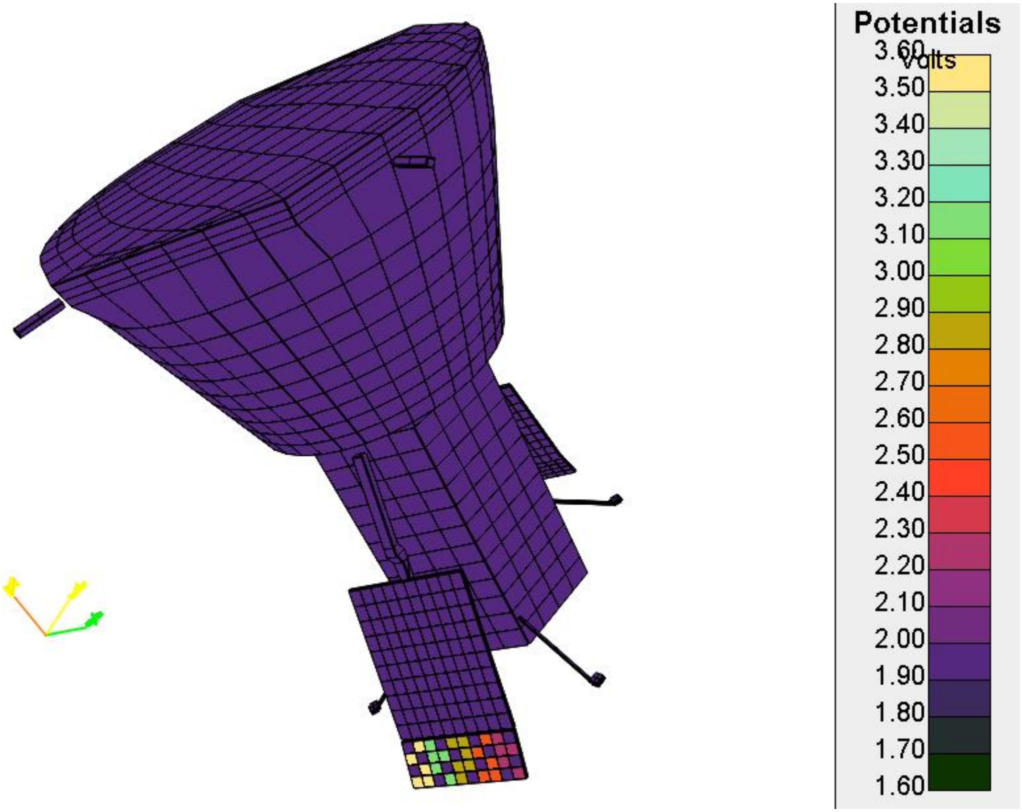
- **Motivation: in order to allow low-energy electron measurement, spacecraft surfaces should in general remain within 10 V of the local plasma “ground”**
- **Modeled surface charging for SPP over a range of trajectory points and environmental conditions using:**
  - **Best estimates of key solar wind plasma parameters**
  - **Detailed spacecraft geometry model**
  - **Best estimates of material properties (temperature-dependent)**
  - **Nascap-2k version 4.1 (standard US charging code)**
- **Results:**
  - **Potentials on surface and in space; wake effects**
  - **Reverse-tracked electrons**
  - **For 3 helioradii: minimum perihelion, 0.15 AU, and 0.25 AU**

Spacecraft model



- **Model is shown at 0.25 AU**
- **TPS coating conductivity is highly dependent on temperature**
- **Primary solar array coverglasses and grout on both array segments have conductive coating**
- **Secondary array coverglass coating is non-conductive**

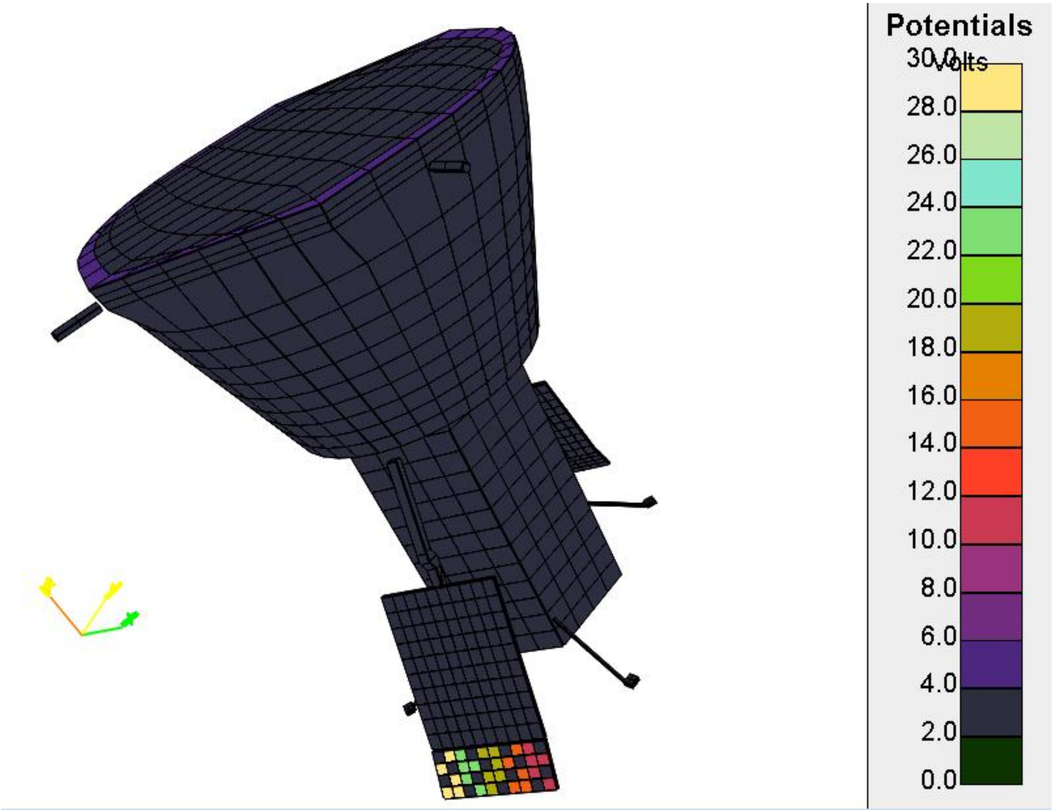
Surface potentials
at minimum perihelion



Component	Potential (V)
Chassis	+1.9
Primary array	+1.9
Secondary array	+1.6 to +3.5

SPP with CMG secondary array coverglass for fast solar wind conditions

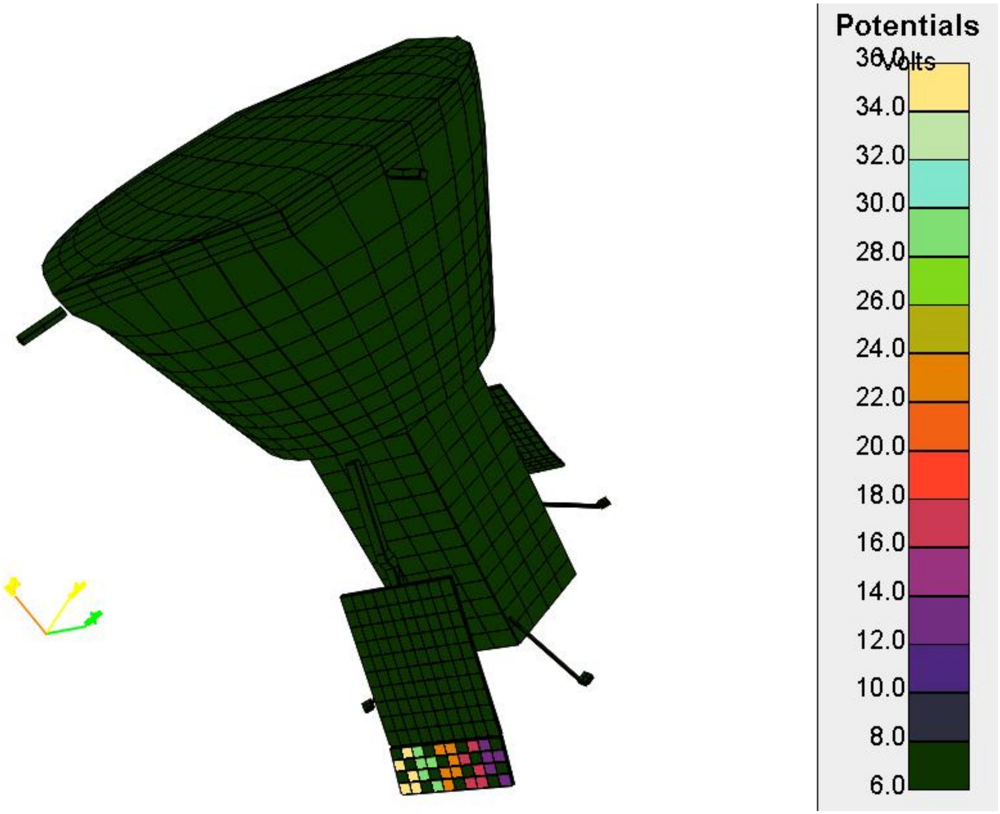
Surface potentials
at 0.15 AU



Component	Potential (V)
Chassis	+3.5
Primary array	+3.5
Secondary array	+11.7 to +28.4

SPP with CMG secondary array coverglass for fast solar wind conditions

Surface potentials
at 0.25 AU

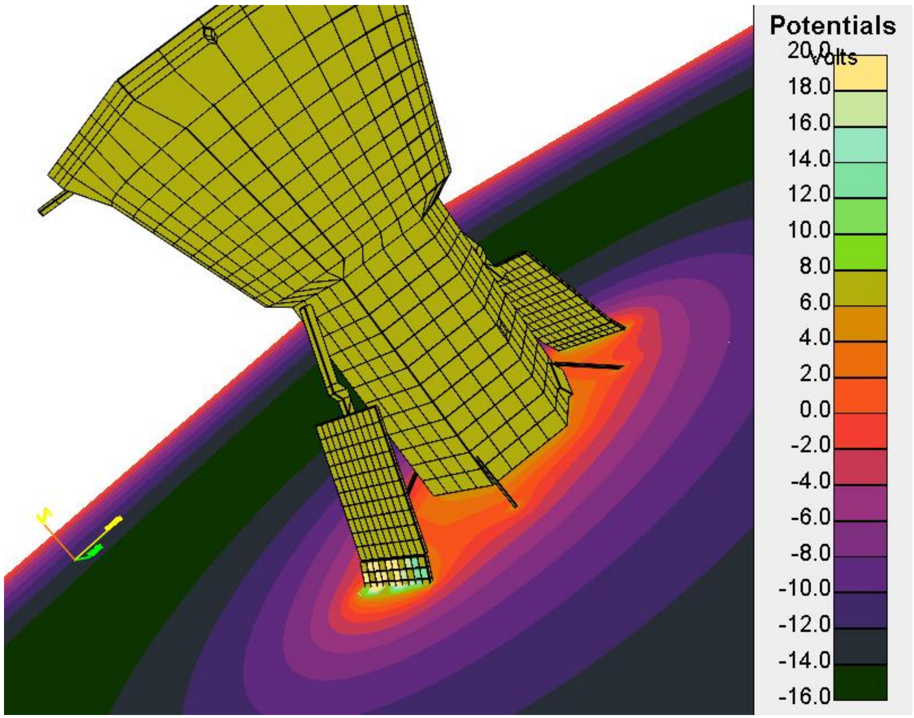


Component	Potential (V)
Chassis	+6.3
Primary array	+6.3
Secondary array	+13.2 to +34.3

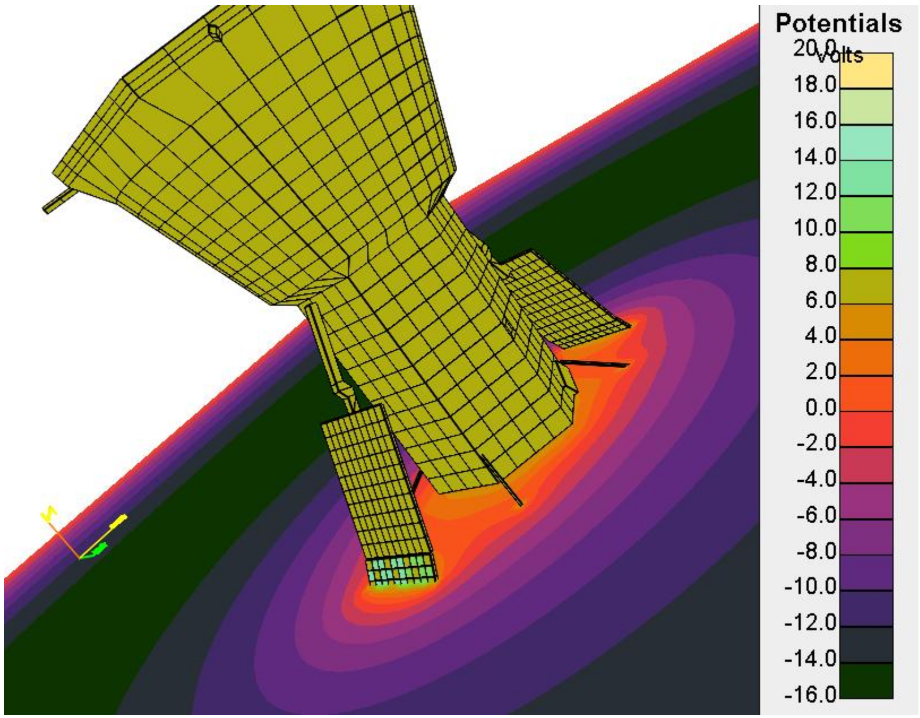
SPP with CMG secondary array coverglass for fast solar wind conditions

Solar array shine-through:
Space potentials at 0.25 AU

CMG (has shine-through)



No shine-through



Effect on space potentials from shine-through is minor and limited to points very close to the array surface

Solar array shine-through:
20 eV electrons near SPAN-A+

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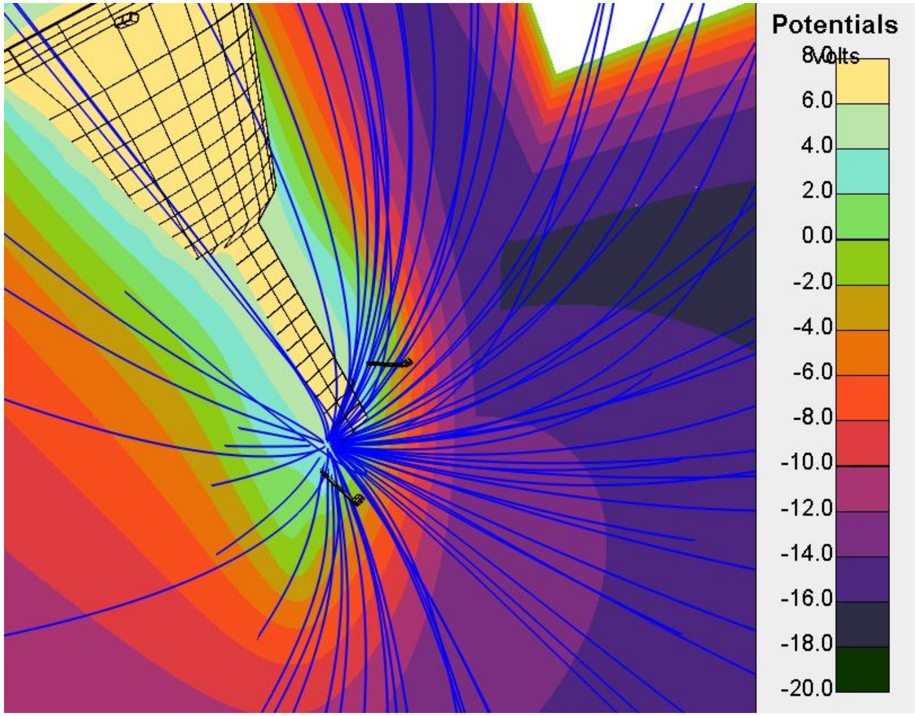
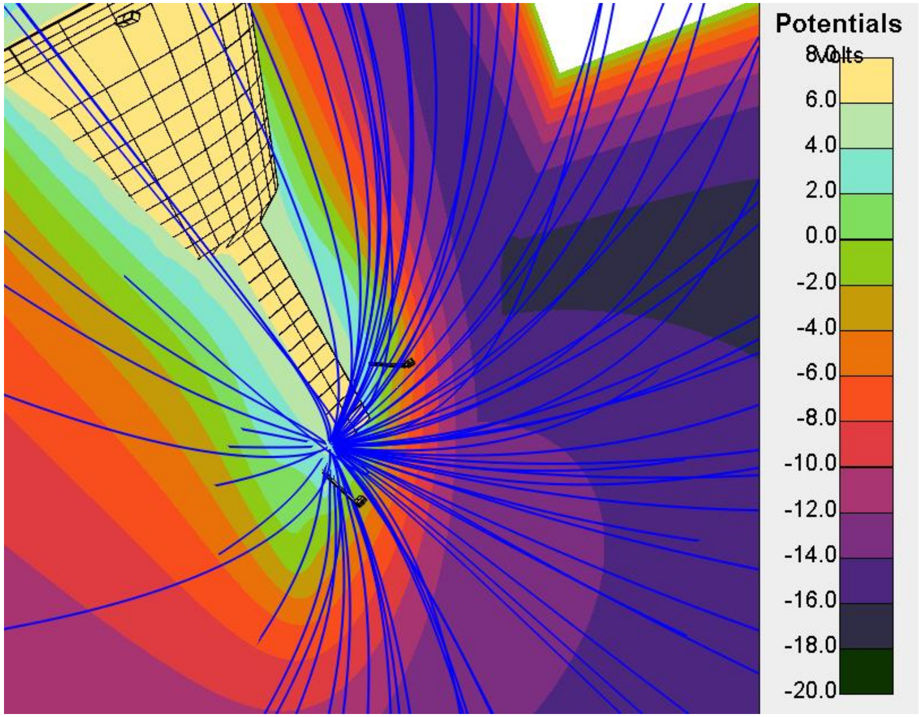
With shine-through



Without shine-through



Electron trajectories are dominated by the chassis potential and the spacecraft wake; shine-through has no visible effect

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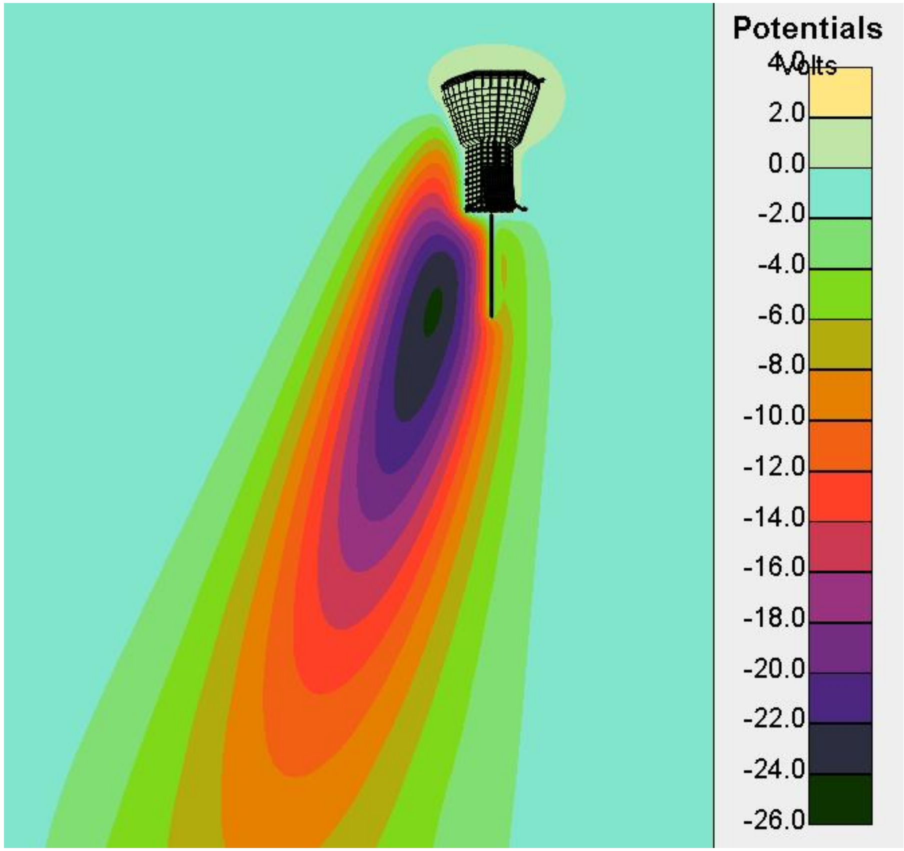
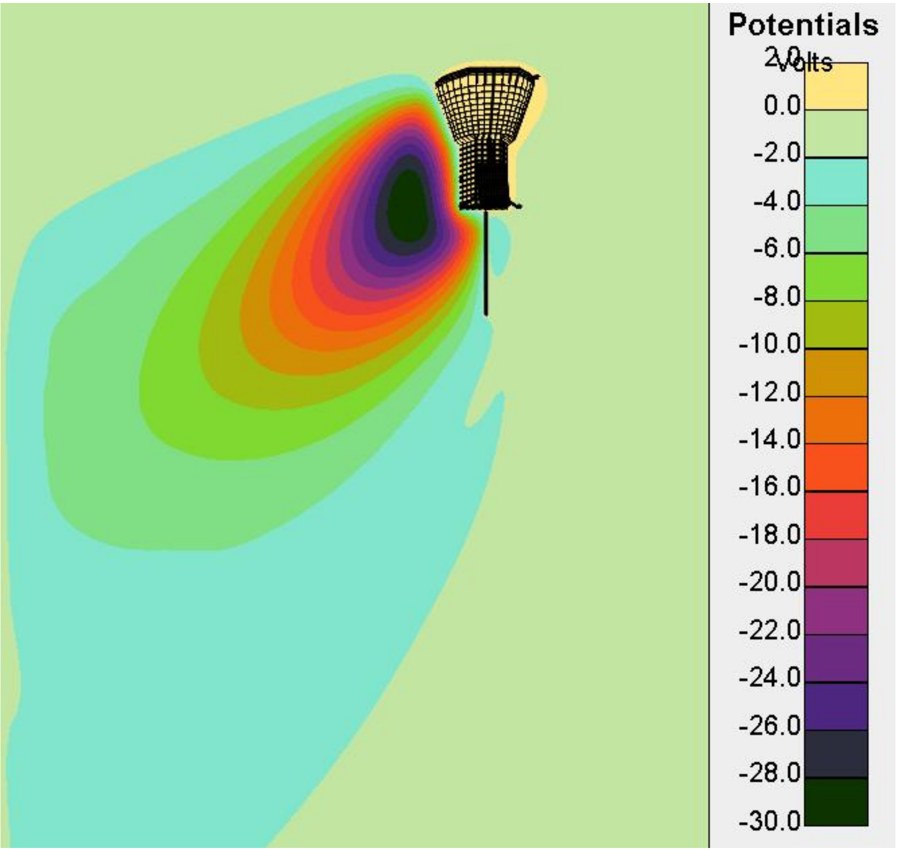
Wake structure
at minimum perihelion

Fast solar wind



Slow solar wind

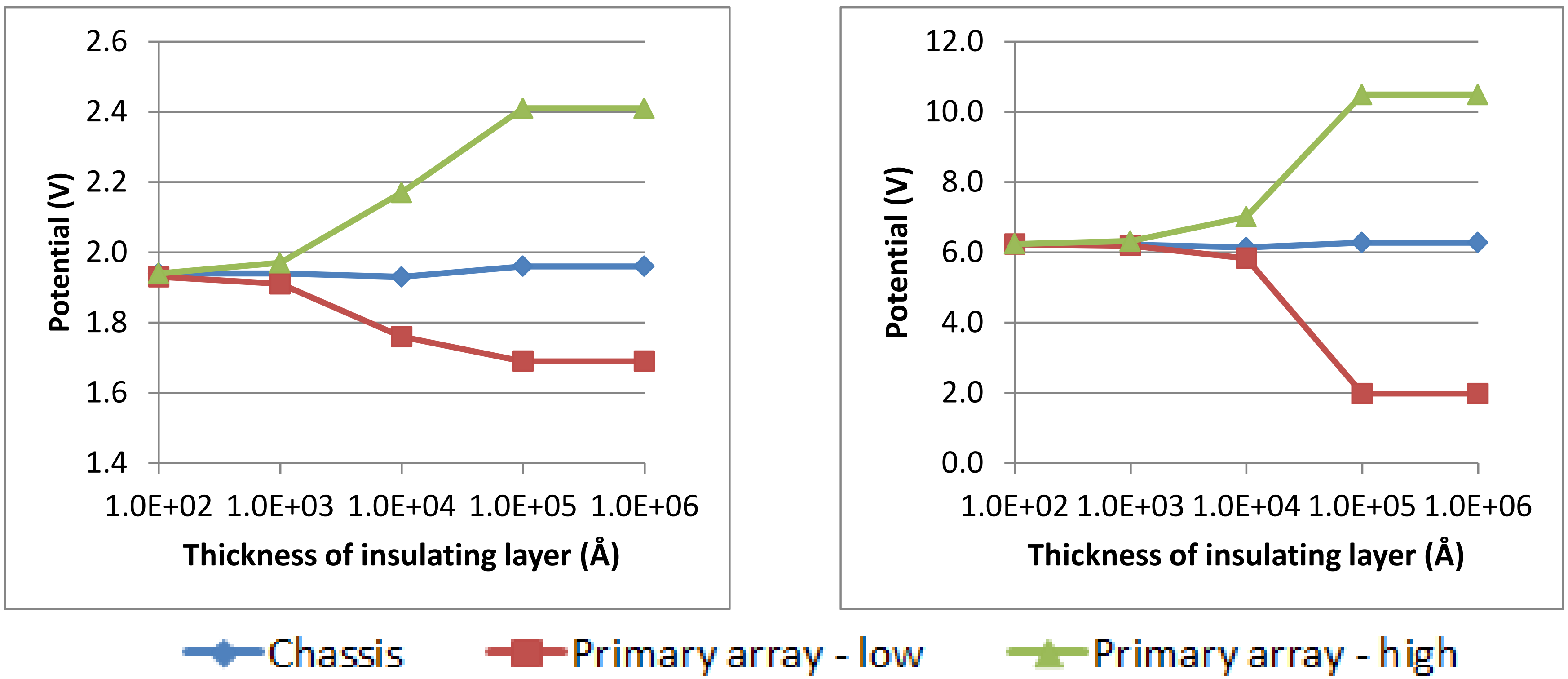


Effect of thin-film contamination:
Introduction

- **Outgassing testing has indicated that a thin layer of methylated siloxanes from cured silicone adhesive can deposit on solar array surfaces**
- **This electrically insulating material becomes polymerized in sunlight and is only removable by scraping**
- **Parametric study assumes a very high resistivity for a range of thicknesses deposited on the arrays and evaluates charging for each**

Effect of thin-film contamination:
Results

Minimum perihelion | **0.25 AU**



A thin layer of electrically insulating materials will cause only mild (< 10 V) differential charging on the primary arrays

Possible negative charging

- **Concern:**
  - **Nascap-2k surface charging results have generally shown slightly positive overall S/C potentials near perihelion**
  - **Other published results show significant negative charging (~10-40 V negative) near perihelion; dependent on assumptions made about secondary electron emission yield**
  - **Negative S/C potentials could limit the energies for low-energy electron measurements**
- **Two-pronged approach:**
  - **Subcontract with Leidos (formerly SAIC) to resolve discrepancies and predict likelihood of negative spacecraft potentials**
  - **Build SPP model in SPIS (European code)**

Possible negative charging

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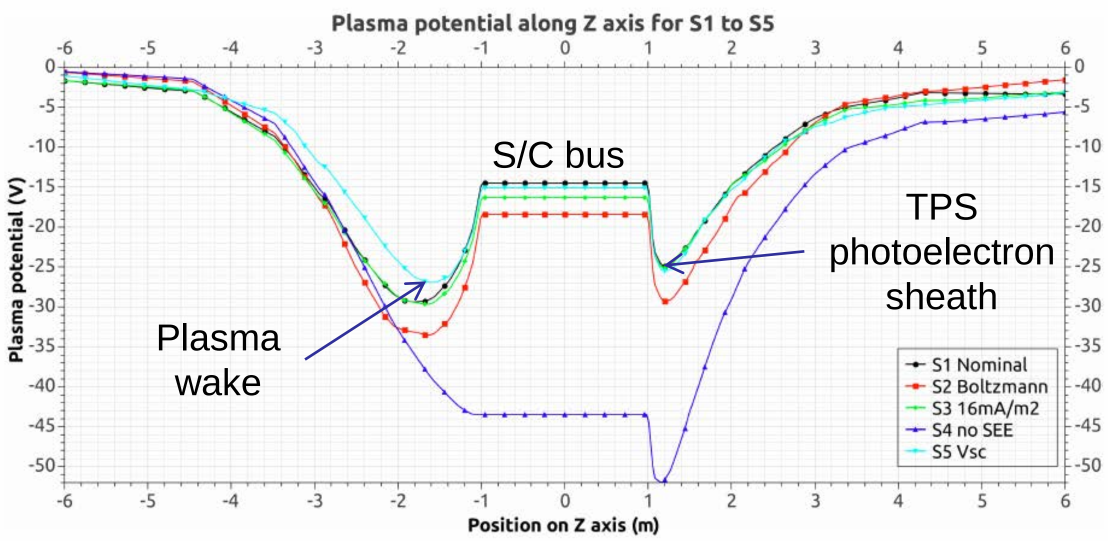
- Ergun et al. (2010) used a 3D self-consistent numerical code to show that in in a high photoelectron environment, a spacecraft may acquire a negative surface charge due to "an electrostatic barrier near the surface of the spacecraft that can reflect a large fraction of the photoelectron flux"
- Guillemant et al. (2012), using a different code (SPIS), confirmed the possibility and performed parametric studies of surface charging at SPP
- SPIS predicted potentials of about -15 to -20 V on the bus



Since the predicted potential is only ~25% of the expected electron thermal energy (T_e ~ 85 eV, used in the cases shown), the majority of the electron velocity distribution would remain measurable

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Summary

- **Predicted surface potentials with Nascap-2k:**
  - **Chassis potentials are a few volts positive for minimum perihelion through 0.25 AU**
  - **Secondary solar array shine-through is a minor effect that influences space potentials only very close to the array**
  - **A thin layer of electrically insulating materials will cause only mild (< 10 V) differential charging on the primary arrays**
- **Plan is in place to address disparity in results between Nascap-2k and other codes**
- **Ready to proceed to Phase C**

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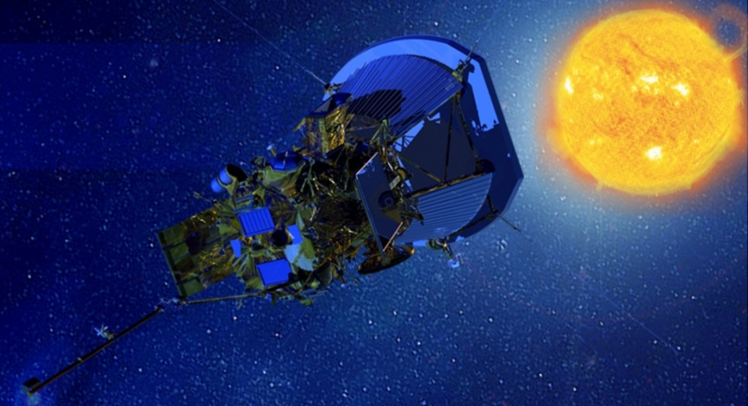

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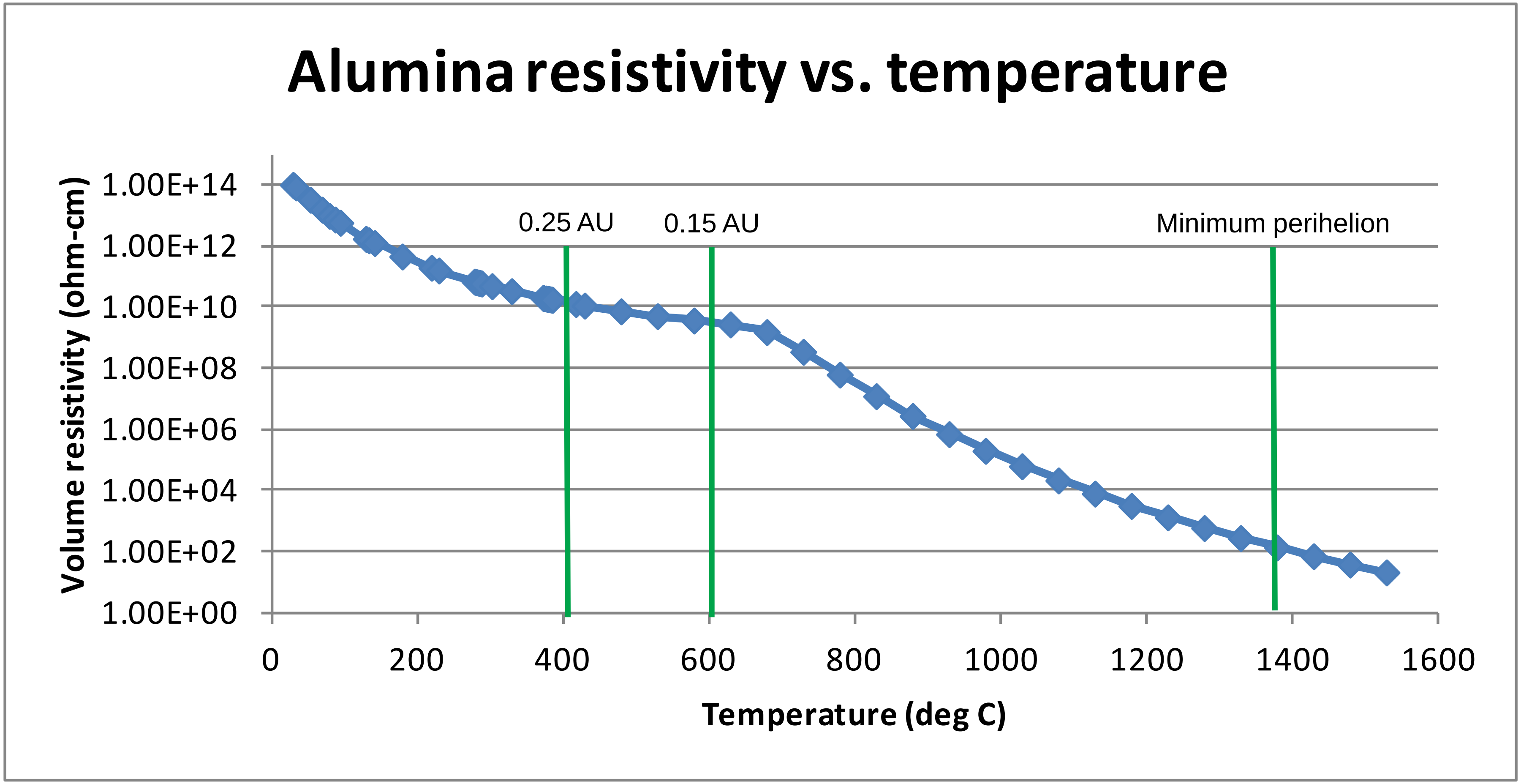
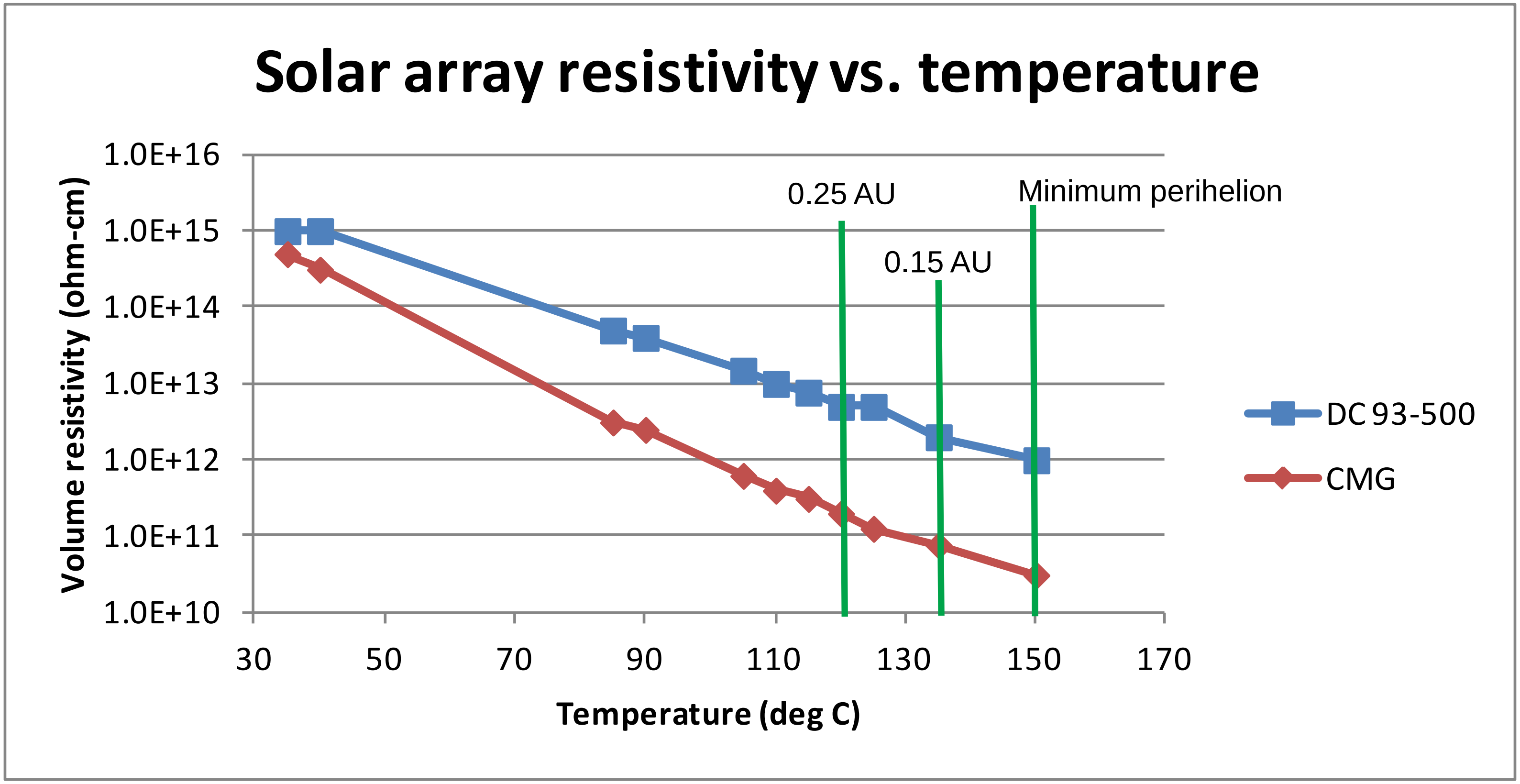
TPS composition

- **TPS composition:**
  - **Carbon foam core**
  - **Carbon-carbon facesheet**
  - **Tungsten barrier coating**
  - **Thin ceramic top coating – Al_2O_3 / MgO / BN**
- **All are electrically conductive except for the ceramic top layer**
- **Top layer is very thin (4 mils)**
- **Nascap-2k models the spacecraft as a collection of surfaces that are either conductive or are a dielectric film over a conductive substrate**

TPS coating resistivity



Solar cell coverglass and grout resistivity

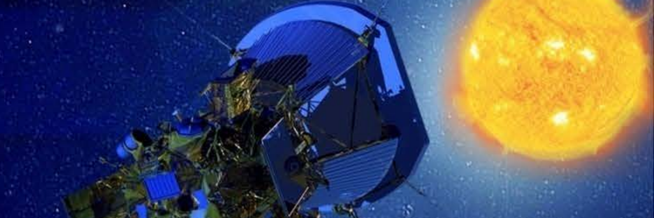


CMG – secondary array coverglasses

DC93-500 – primary and secondary array grout

(primary array coverglasses are coated with ITO and therefore conductive)

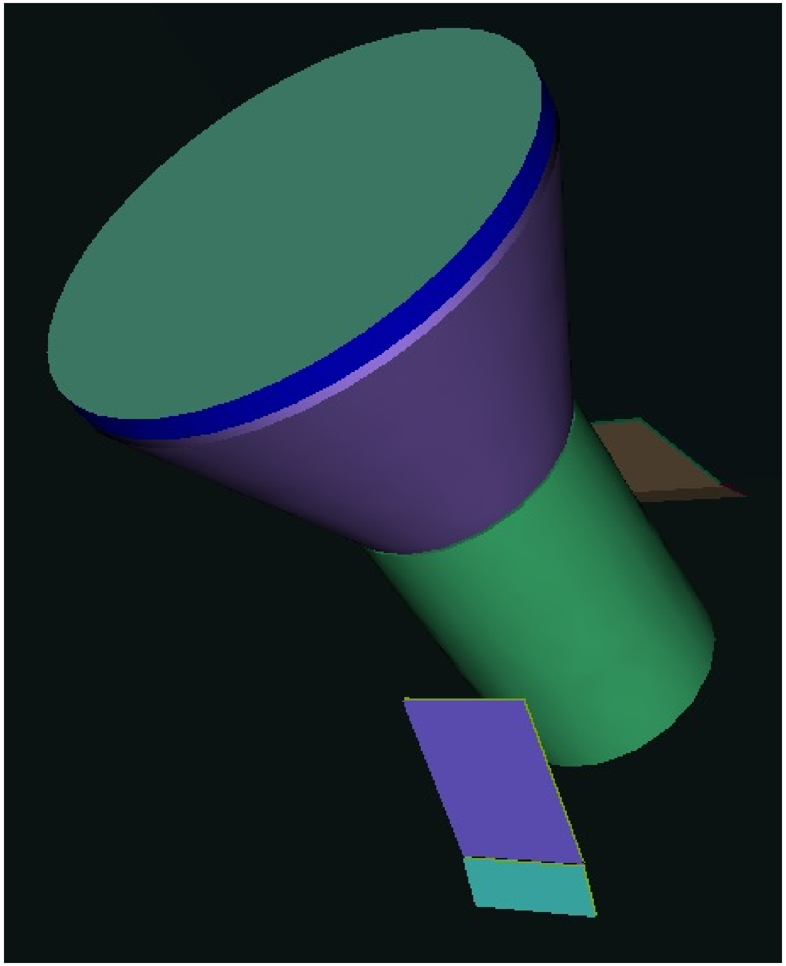
Nascap-2k:
Overview



- **Capabilities of Nascap-2k:**
  - **Define spacecraft surfaces and geometry and the structure of the computational space surrounding the spacecraft**
  - **Solve the electrostatic potential on spacecraft surfaces and around the object**
  - **Generate, and track particles of various species, represented as macro-particles, in the computational space**
  - **View surface potentials, space potentials, particle trajectories**
- **Includes physical models appropriate to tenuous (e.g. interplanetary, GEO) plasma environments**

SPIS:
Overview

- SPIS = Spacecraft Plasma Interaction System
- Freely available and open-source
- Powerful code:
  - PIC (particle-in-cell) based calculations
  - Complex geometries are possible
  - Most of the same capabilities as Nascap-2K



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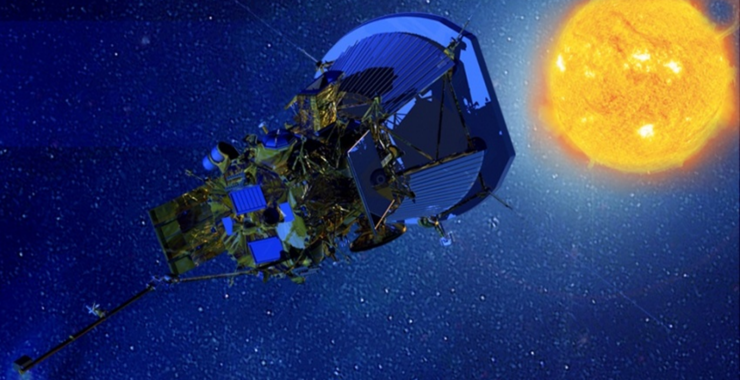

SPP Dust Protection

Douglas Mehoke

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13 – 16 January 2014

APL

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Overview

- **Dust study team**
- **Activities**
- **Study status**
- **Peer reviews and action item status**
- **Spacecraft and component damage assessment summary**
- **Studies and trades**
- **Conclusions**

Dust Study Team

SPP Dust Team

D. Mehoke	APL
P.K. Swaminathan	APL
R. Brown	APL
K. Iyer	APL
C. Carrasco	UT-El Paso
R. Batra	Va Tech

EOS Development

Kerley Technical Service

Material Testing

Southwest Research Institute
Georgia Tech

HVI Testing

White Sands
Univ of Dayton Research Institute
Univ of Colorado

CTH Code Support

Sandia

Advanced Computing Facility

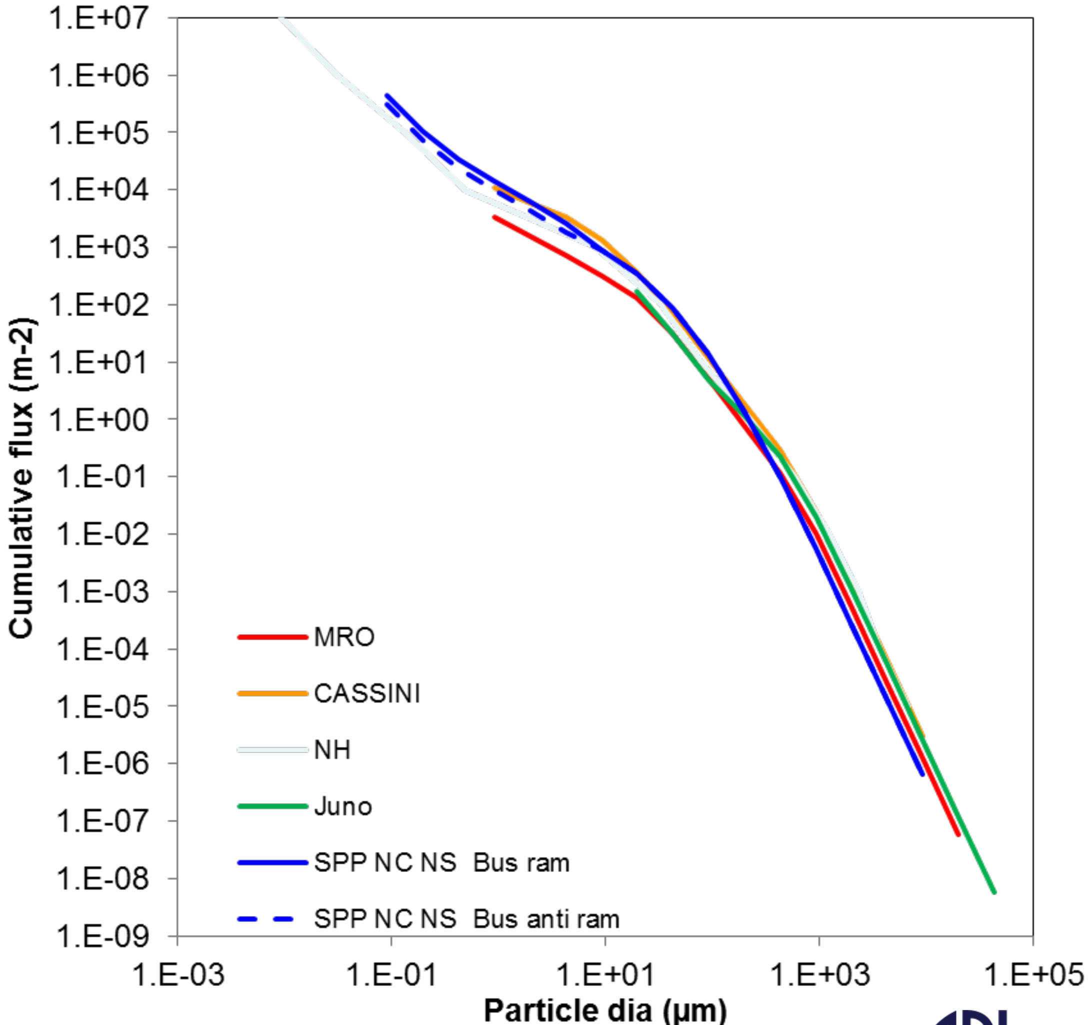
Univ of Texas Advanced Computing Cluster

SPP Dust Study Activities

- Provide a realistic estimate of the probability of dust impact damage to key spacecraft components during the SPP mission
- Identify dust protection options and requirements for critical spacecraft surfaces
- Provide quantitative comparison between competing alternatives in subsystem trade studies
- Update material models, as needed, to more accurately reflect the damage and failure mechanism occurring during hypervelocity impacts
- Anchor analytical models with material and hypervelocity testing
- Identify and define conservatism and risk drivers in shielding analyses

Dust Flux Historical Comparison

- **The cumulative mission dust flux for SPP is similar to that seen on other missions**
- **The major different in the SPP damage assessments are the higher velocity impacts**
  - **The SPP velocity range is between 0 to 300 km/s**
  - **Typical values ~ 20 km/s**
  - **Test capabilities < 10 km/s**
- **The SPP dust flux includes the effects of spacecraft trajectory and surface shielding**
- **The Near–Sun dust model includes the Collision A assumption (Mann 2004) as an upper bound of the particles greater than ~ 10 µm (Kumar 2011)**



Dust Study Status

- **S/C Damage assessment**
  - **Preliminary assessment of S/C surfaces completed**
  - **3D CTH capability developed at UT ACC computing cluster**
    - **Off-axis impacts damage**
    - **Low-velocity, spaced-MLI runs**
  - **Assessments of component/instrument protection focusing on mission survivability analysis and component design improvement**
  - **On-going assessment of materials used in CTH analysis**
- **Dust environment**
  - **Dust environments for updated S/C geometry and detailed instrument surfaces are defined in the EDTRD**
  - **Collision assumptions used in dust model have been updated for the present state of knowledge of the dust environment**
  - **Conservative estimates are used for the density, porosity, and shape of the dust particles**
  - **The SPP dust model has been verified against other dust models and the shadowing algorithm has been checked**

Dust Study Status

- **Material Model Development**
  - **Material models and EOS developed for Ti Grade 4, Kapton, and CV 2942 developed for cooling system analyses**
  - **Extensive review of literature data and modeling provides confidence in approach and damage assessment capability**
- **Detailed Damage Model Development**
  - **Detailed material models developed for glass and metals**
  - **Functional BLE developed for SPP specific spaced-MLI configurations**
  - **On-going review of surrogate materials**
- **HVI and Material Testing (White Sands, UDRI, U of Col, Heidelberg) is used to validate material models and anchor damage calculations**
  - **MLI bumper shields over titanium and aluminum honeycomb targets**
    - **S/C bus and cooling system shielding**
  - **Harness vulnerability**
  - **Glass surface damage**
  - **Thin foils**

Peer Reviews and Actions

- **All Phase A Design Review and Peer Reviews**
  - **All actions have been completed**
- **Mid Phase B Review Sept 2012**
  - **All comments from the mid year review were completed and presented at the PDR Peer review**
- **PDR Peer review Nov 12, 2013 Minutes released**
  - **Review board**

D. Kusnierkiewicz	APL	Chair
E. Christiansen	JSC	
D. Crawford	Sandia	
K. Hemker	JHU	
A. Moorhead (W. Cooke)	MSFC	
N. Murphy	JPL	SRB
D. Seal	JPL	

  - **No actions, 9 comments and 1 concern**
  - **The conclusion of the reviewers was that this is a very high quality study that has gone into an impressive amount of detail, and is driving towards credible conclusions**

SPP Observatory Damage Assessment

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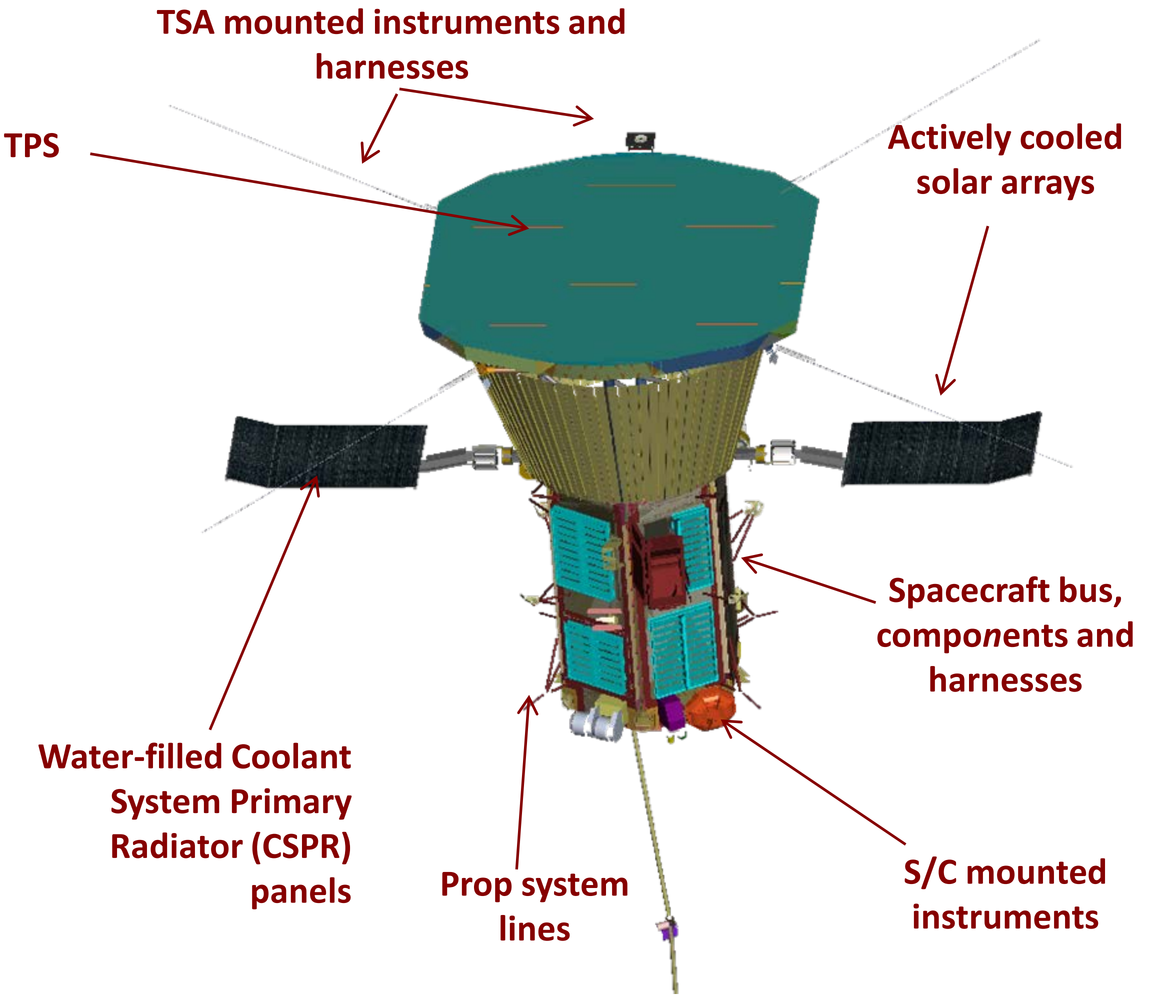
- Preliminary damage assessments have been completed for the spacecraft and instruments to prioritize the surfaces damage
- SPP unique surfaces
  - TPS
  - Solar array cooling system
- Standard S/C surfaces
  - Propulsion system
  - S/C instruments
  - Bus externally mounted components
  - External harness
  - Internally mounted S/C components and harnesses



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Damage Assessment - Observatory Results

- The Observatory Probability of No Failure (PNF) goal is 95%
- The vulnerability model is divided into zones made up of detailed surfaces, each with a separate Probability of No Impact (PNI) calculation
  - Above PNI allocation is good
- There are no single failures of instruments that result in loss of mission
  - Instrument values will be updated using the PRA model in Phase C/D

Observatory Allocation	94.98%		
Observatory PNF	95.69%		
S/C Allocation	95.2%	Inst Allocation	99.73%
S/C PNF	95.7%	Inst PNF	100.00%

Spacecraft surface		PNI	Value
	Solar array	99.00%	99.1%
	Radiator	98.00%	98.6%
TPS			
	Top surface	99.90%	99.9%
Spacecraft			
	+X+Y panel	99.75%	99.5%
	+Y panel	99.75%	99.9%
	-X+Y panel	99.75%	99.8%
	-X-Y panel	99.75%	99.8%
	-Y panel	99.75%	99.9%
	+X-Y panel	99.75%	99.5%
	Bottom panel	99.75%	99.6%

Instrument Surface						PNI	Value
ISIS			EPI Lo		Aperture	99.99%	100%
	Allocation	99.90%			Base	99.99%	100%
	Value	100.00%	EPI Hi	LET1	App 1	99.99%	100%
					App 2	99.99%	100%
					Body	99.99%	100%
				HET	App 1	99.99%	100%
					App 2	99.99%	100%
					Body	99.99%	100%
				LET2	App 1	99.99%	100%
					App 2	99.99%	100%
					Body	99.99%	100%
SWEAP			SPAN- A Electron		App 1	99.99%	100%
	Allocation	99.89%			App 2	99.99%	100%
	Value	100.00%			Body	99.99%	100%
			SPAN- A Ion		App 1	99.99%	100%
					App 2	99.99%	100%
					Body	99.99%	100%
			SPAN- B Electron		App 1	99.99%	100%
					App 2	99.99%	100%
					Body	99.99%	100%
			SPC			99.99%	100%
WISPR			Objective Lens			99.99%	100%
	Allocation	99.98%	Forward baff Top Edge			99.99%	100%
	Value	100.00%					
FIELDS			Antenna 1			99.99%	100%
	Allocation	99.96%	Antenna 2			99.99%	100%
	Value	100.00%	Antenna 3			99.99%	100%
			Antenna 4			99.99%	100%

Damage Assessment - Observatory Summary

- The Observatory assessment indicates the largest vulnerabilities of the system are
  - Solar array
  - Cooling system radiators
- Based on historical experience the propulsion system and external harness are expected to produce the largest S/C vulnerabilities
  - Cassini, New Horizons, and Juno dust damage assessments reviewed
- The areas that are not expected to driver the Loss of Mission probability are
  - Instruments (no single instrument is mission critical)
  - TPS
  - Prop tank and electronics packages inside the S/C structure
  - HGA
- Due to the nature of the dust analysis, trades between alternative design concepts involve very small differences in probability

Component PNF Calculations

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- Damage assessments have been completed for the following instruments and components
- The results have been presented to the SPP team and at the peer review

Components

- Solar array
- Cooling system radiators
- S/C decks
- S/C external harness
- Instruments
  - ISIS – EPI Lo
  - ISIS – EPI Hi
  - WISPR
  - FIELDS
  - SWEAP – SPAN
  - SWEAP - SPC

Component assessment contents

- Surface configuration
- Dust environment
  - Surface area adjustment
  - PNI
- Damage particle correlation
  - BLE
  - CTH analysis
  - Use of surrogate materials
- Damage particles
- Model updates
- Testing

SPP Dust Protection – S/C Surfaces

- **The protection approach and vulnerability for the different S/C and Instruments surfaces are listed in the EDTRD**

Component		Protection Approach	Vulnerability
Solar array	Front surface	Layered Solar cell stack (Interposer and Semi standard) Pri array flow reduction area	Perforation of cooling system
		Titanium substrate	
	Back surface	MLI bumper, spacing = 1"	
		Titanium substrate	
CSPR	Front surface	Layered Al radiator / Ti tube	Perforation of cooling system
	Back surface	MLI bumper, spacing = 1"	
		Layered Al radiator / Ti tube	
	External plumbing lines	MLI/Kevlar wrap	Perforation of cooling system
S/C Deck	MLI covered areas	MLI bumper, spacing = 2"	Perforation of int harness or elec box wall
		Aluminum honeycomb	
	Louver areas	Aluminum honeycomb	
External harnesses		MLI/Kevlar wrap	Severing of conductor
		Limit exposure length	
		Redundant wiring	
Prop system	Tanks and internal lines	S/C enclosure	Perforation of propellant enclosure
	Thruster and external lines	MLI/Kevlar bumper	
TPS		Carbon foam	Loss of surface area

SPP Dust Protection – Instrument Surfaces

Instruments		Protection Approach	Vulnerability
ISIS - EPI Lo	Aperture foils	Small exposed area	Loss of foil area
	Housing	MLI bumper/housing wall Redundant sections	Perforation of int electronics
	Harness	MLI/Kevlar wrap	Severing of conductor
ISIS - EPI Hi	Aperture foils	Small exposed area	Detector sensitivity
	Housing	MLI bumper/housing wall Redundant sensors	Perforation of int electronics
	Harness	MLI/Kevlar wrap	Severing of conductor
WISPR	Optics	Reduced area	Increase in reflected light
	Baffle edge		
	Housing	MLI bumper/housing wall Redundant sensors	Perforation of int electronics
	Harness	MLI/Kevlar wrap	Severing of conductor
FIELDS	Harness Ring	Niobium bumper	Distortion of thermal protection shields
	Whip Cylinder	Niobium bumper	
	antenna thermal shield	cylinder diameter	Severing of antenna
SWEAP - SPC	Modulator Section	reduced area	Perforation of grid wires
	Thermal shield	Niobium bumper	Distortion of thermal protection shields
	External harness	Niobium tube / sapphire capillary	Severing of conductor
	Electronics module	MLI / wall thickness	Perforation of int electronics
SWEAP - SPAN	Housing	MLI bumper/housing wall Redundant sensors	Perforation of int electronics
	Harness	MLI/Kevlar wrap	Severing of conductor

Studies and Trades

- **Dust environment - Complete**
  - **Collision model, particle material, shape, and density update**
  - **Population distribution of particles below 90 nm**
- **Material models - Complete**
  - **Metal and glass model development and verification**
  - **MLI bumper shielding model development and verification**
  - **Ti Grade 4, Kapton, CV2942 material model**
- **Solar array trades - Complete**
  - **Cell stack area: Semi-standard cell stack, interposer stack**
  - **Platen: with or without MMOD layer**
  - **Area between cells: gap area, adhesive location**
  - **Solar array back surface: MLI spacing**
- **Radiator trades - Complete**
  - **Cooling tube: round surface to space or inward facing**
  - **MMOD layer on tubes**
  - **Radiator back surface: MLI spacing**
- **Plumbing lines and harness - Complete**
- **Instrument foil modelling - Complete**

Phase C Plans

- **Develop detailed component vulnerabilities**
  - **S/C internally mounted electronics and components**
  - **SPP specific harness wrap configurations, internal and external**
  - **Non-catastrophic damage that results in degraded science**
  - **Areas of reduced MLI-spacing**
- **Update dust environment**
  - **Update environments for S/C configuration changes**
  - **Perform analyses of detailed geometries**
  - **Include effects for particle density, porosity, and shape**
- **Incorporate results into S/C PRA model**
  - **Multiple failures resulting in loss of mission**
  - **Instrument impacts resulting in loss of science return**
- **Verification and validation**
  - **Refine and improve material models**
  - **HVI and material testing of design driving configurations**
  - **Review of surrogate materials**
- **Implementation of shielding approaches into flight designs**
- **Investigate S/C observables to verify dust environment**

Summary

- **The SPP probability of mission survival is above its target value**
  - **The analysis uses conservative assumptions that are continually reviewed**
  - **Failure criteria have been defined for all generic surfaces**
  - **Complex surface configurations are simplified into generic surfaces**
- **The dust model used for SPP has been checked against other environmental dust models and the shadowing algorithms verified**
- **Computationally-derived HVI shielding data used for high velocity calculations is co-equal to experimentally-derived data in terms of quality and reliability**
  - **A significant effort has been undertaken to ensure the validity of the analytical approach used**
  - **The analyses include conservative assumptions**
  - **The limited number of damage/failure material models requires the use of surrogate materials for the analyses**
  - **The SPP BLEs used are anchored by test and literature data**
- **The damage modeling methodology has been developed, verified, and is ready for the detailed assessments to be done in Phase C/D**

Backup

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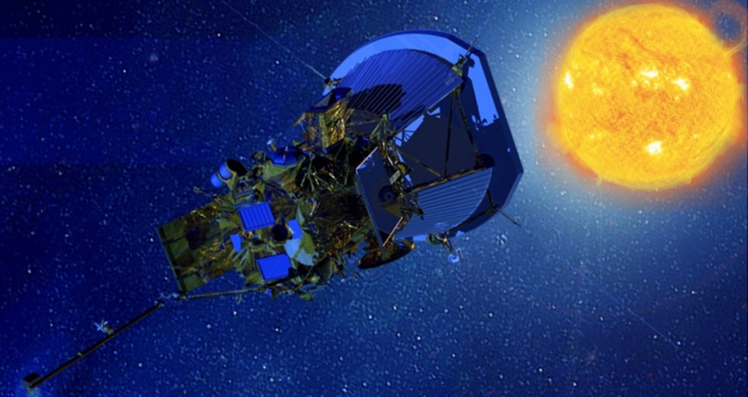

Mission EME Requirements

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ElectroMagnetic Environment (EME) Lead

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13 – 16 January 2014

The Johns Hopkins University
APPLIED PHYSICS LABORATORY

ElectroMagnetic Environment (EME) Agenda

- **Driving Requirements**
  - **Survivability**
  - **Valid Science**
- **EME Program**
  - **Working Group is meeting**
  - **Control Plan is released**
- **EME Derived Requirements**
  - **Deep-Dielectric Charging**
  - **Surface Charging**
  - **Magnetic Cleanliness**
  - **EMC**
- **EME Verification**
  - **Planned Testing**
  - **Analysis and Testing performed so far**

Driving Requirements

- **Survive Environment**
  - I&T and Launch
    - Conducted Susceptibility
    - Radiated Susceptibility
  - Space Plasma
    - Internal Charging
    - Surface Charging
    - Electrostatic Discharge
- **Valid Science**
  - Magnetically Clean
    - DC and Low frequency for Magnetometers
    - Up to 1 MHz for Search Coil
  - Electrostatically and RF Clean
    - Low and uniform spacecraft potential
    - Up to 20 MHz for Electric Field Measurements

EME Program

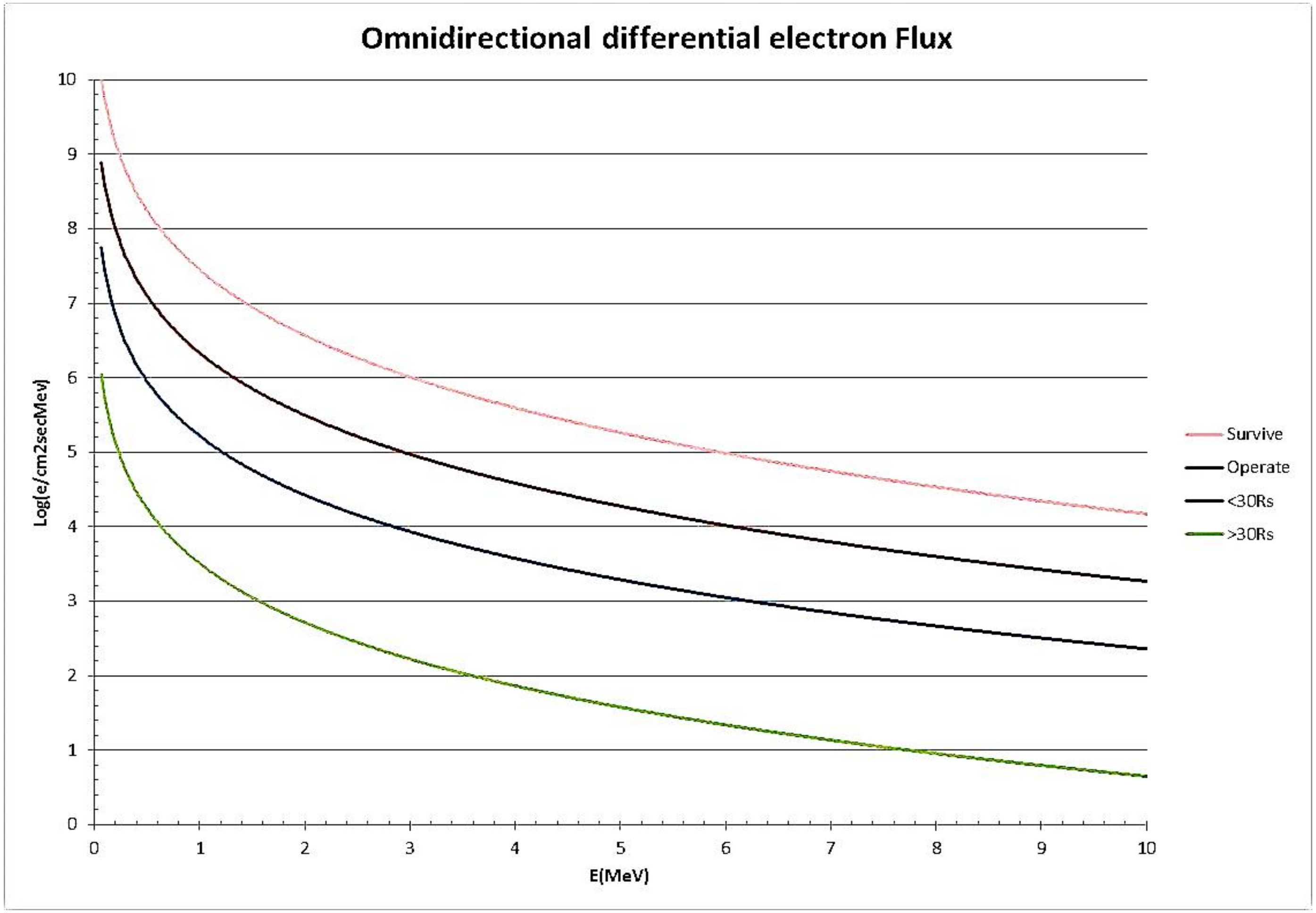
- EME Working Group Telecoms 1st and 3rd Thursday
  - Over 60 people on meeting list Consists of PIs, Scientists, and Spacecraft and Instrument System, Design and Test Engineers
- Control Plan out with minor modifications since MDR
- Instrument weekly telecoms cover EME issues
- EME Engineer is a member of the Material Review Board
- EME Engineer attends Hardware Sub-System and Instrument reviews (Requirements, Design, PDR, CDR, TRR, PSR)
- Watching Magnetic Issues
  - Control magnetic materials
  - Review board layout to limit current loops
- Watching Charging Issues
- Approval of Hardware Sub-System and Instrument EMC Test plans and Procedures
- Conducted Emissions Testing as part of Installation Procedure
- Spacecraft Compatibility Test

Lessons Learned from Previous Missions

- **MESSENGER and prior missions**
  - **Work with spacecraft sub-system designers to prevent EMC issues**
  - Prototype testing of spacecraft sub-systems to guide design
  - Work closely with I&T

- **STEREO and RBSP**
  - Include Instruments in early design and testing to prevent EMC issues
  - Don’t allow any magnetic materials on MAG booms
  - **Try to do qualification testing on EM if acceptable**
  - **CE and RE sniffing at bread board level important**
  - Streamline EME waiver process
  - **Regular EMC Telecoms**

Charging Environments



Internal Charging vs Depth

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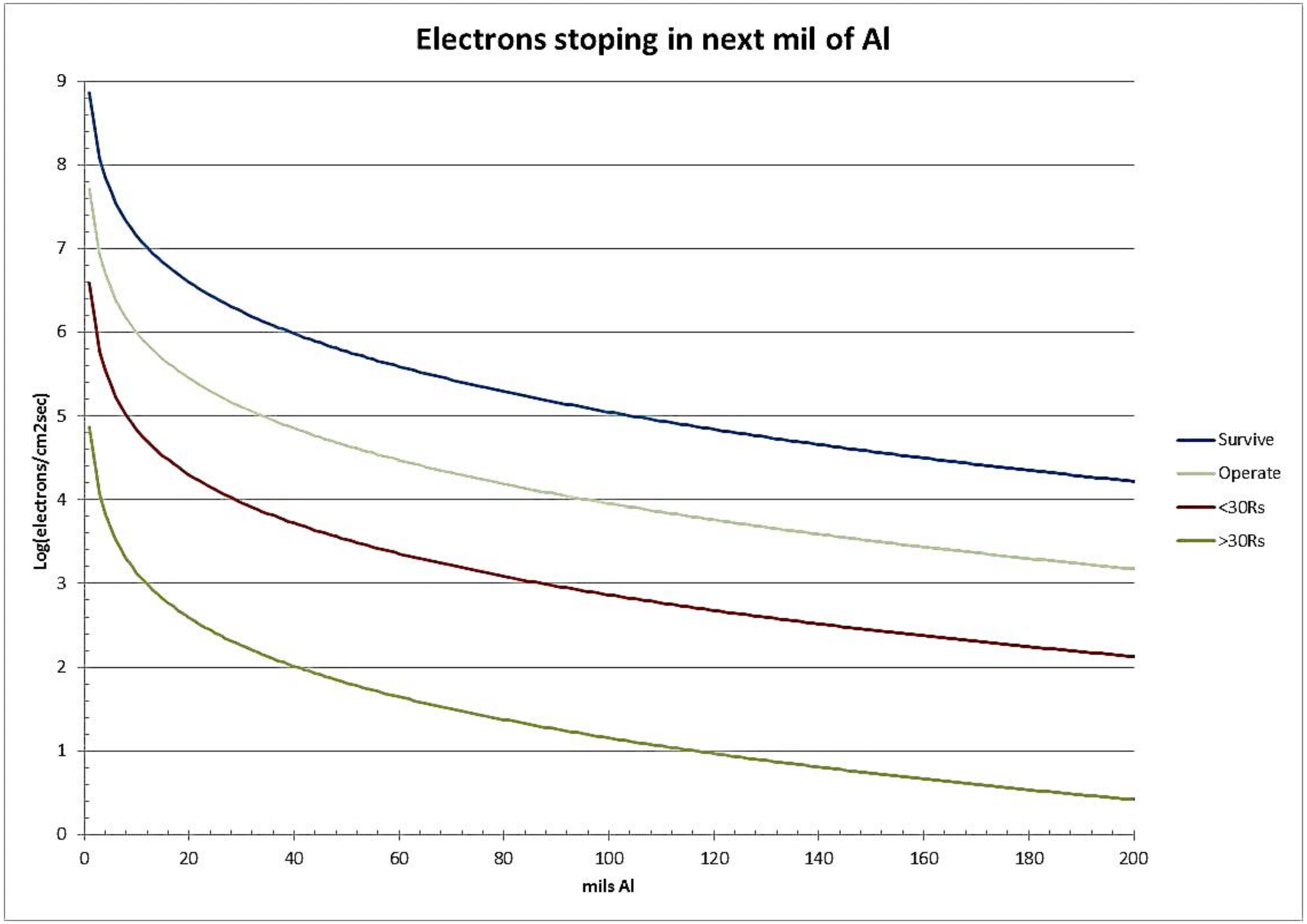
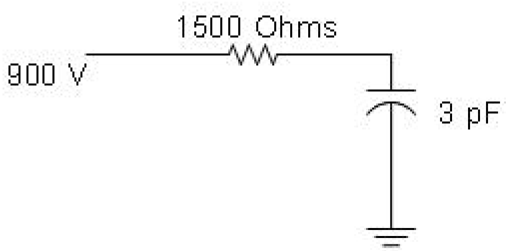
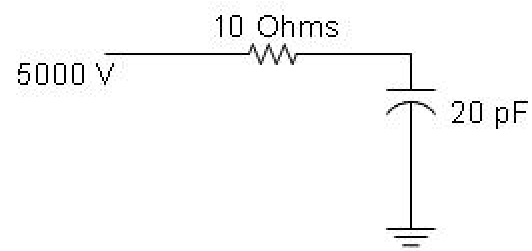


APL

Discharge Models



a) Internal Dielectric



b) Conductor/Surface

For Discharge direct to wire from insulation producing electron injection or insulation to shield causing image charge positive injection

For Discharge from Floating metal or open dielectric surface to harness

Allowed Floating Material or required drain resistance

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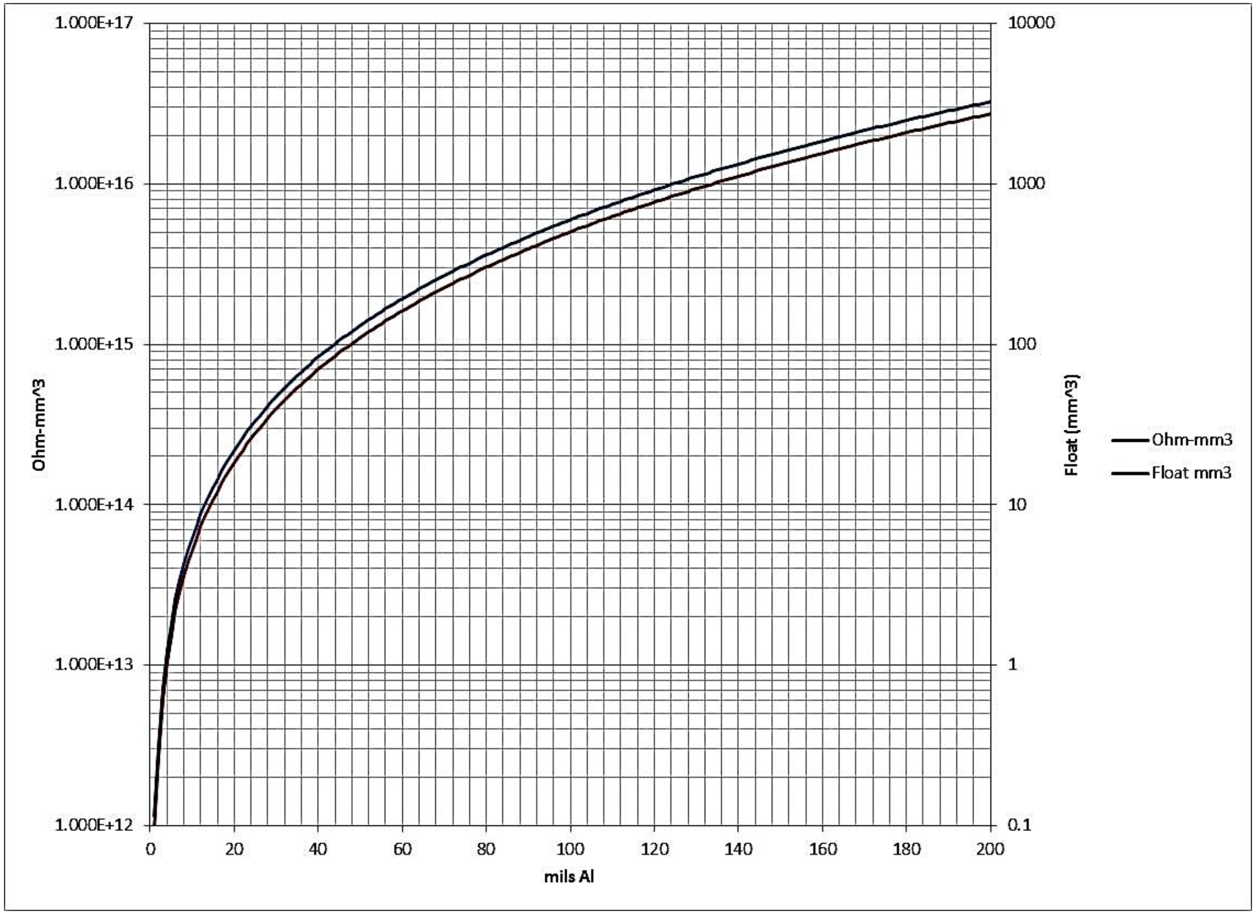


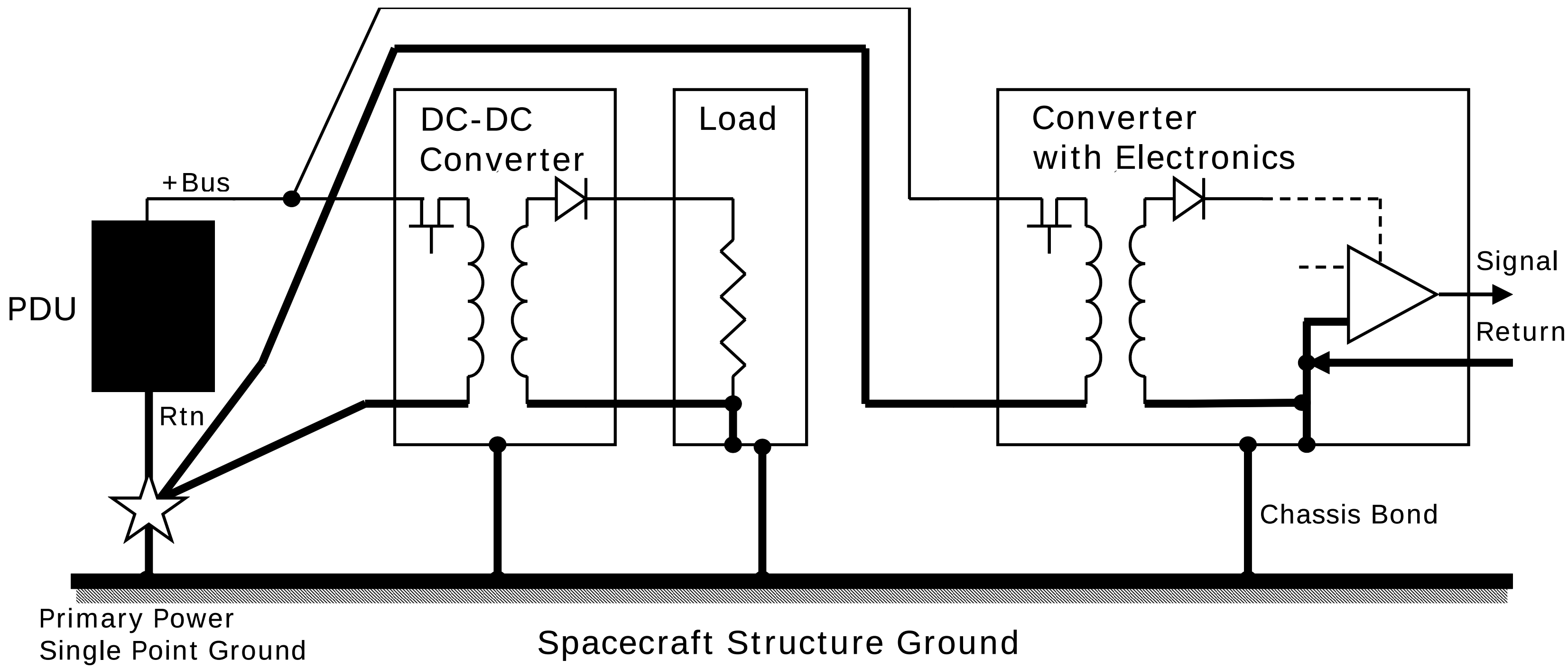
EMC Design Requirements

- **Any device attached to a cable outside the spacecraft body must have first circuit DDD protection or the cable must have 13 mils shielding**
- **Power supplies crystal controlled to a frequency window centered at n*50 kHz with n>=3 and 500 ppm wide over all operating conditions and time.**
- **Place any transformers or big inductors as far from Box walls as possible.**
- **Stable currents to minimize changes in Magnetic Emissions**
- **Control all current paths inside your box to minimize loop area. Cannot use a solid return plane if a trace is the source. Any circuit over 100 milliamps AC or 1 amp DC must be analyzed**
- **All Cables outside the metal box must be twisted shielded with 360 degree shields terminated to the Box with less than 20 mOhms.**
- **Connector shell to Box resistance before mated < 5 mOhms**
- **All use of Magnetic Materials (Nickel, 400 Series CRSS, etc) must be identified and approved by the project. High Phosphor Nickel coating is allowed because it is not magnetic.**

EMC Grounding

- **Primary power supplies isolated by >1 MΩ from everything**
- **Secondary power supply returns tied to chassis with <2.5 mΩ in only the Box using the power. (RIU's excepted)**
- **Grounding Diagrams will show all chassis grounds, primary and secondary power feeds and returns, shields, and signals with returns**
- **ID all connector pins with first circuits**
- **Connectors unused in flight shall have a conductive cover with less that 10 mΩ from cover to Box chassis**
- **"Conductive" Box exterior**
- **Box design must be at least tongue and groove or EMI gaskets on flat joints.**

Device Grounding Methods



Required EMC Testing – Spacecraft Devices

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Subsystem and Component	B&I	Conducted Emissions CE - xx			Conducted Susceptibility CS - xx			Radiated Emissions and Susceptibility RE – xx, RS - 03			Turn on/ off	Mag sniff	ESD
		01	03	07	01	02	06	01	02	03			
Guidance and Control													
Sun sensor detectors and electronics	x	x	x	x	x	x	x	x	x	x	x	x	x
Reaction Wheels	x	x	x	x	x	x	x	x	x	x	x	x	x
IMU	x	x	x	x	x	x	x	x	x	x	x	x	x
Star Trackers	x	x	x	x	x	x	x	x	x	x	x	x	x
Propulsion													
Latch Valve	x						a			a		x	
Pressure Sensor	x	x	x	x	x	x	a	x	x	a		x	
Avionics													
REM*	x	x	x	x	x	x	x	x	x	x		x	x
RIU	x											x	x
PDU	x	x	x	x	x	x	x	x	x	x		x	x
RPM	x	x	x	x	x	x	x	x	x	x		x	x
Telecommunications													
Active devices	x	x	x	x	x	x	x	x	x	x	x	x	x
Passive devices	x											x	
Power													
Solar panels	x											x	
PSE	x	x	x	x	x	x	x	x	x	x		x	x
Battery	x											x	
Harness													
Terminal Board Unit	x											x	
Thermal													
Thermal Blankets	x												
Louvers	x											x	
Thermostatically controlled heaters	x									a	x	x	

Required EMC Testing - Instruments

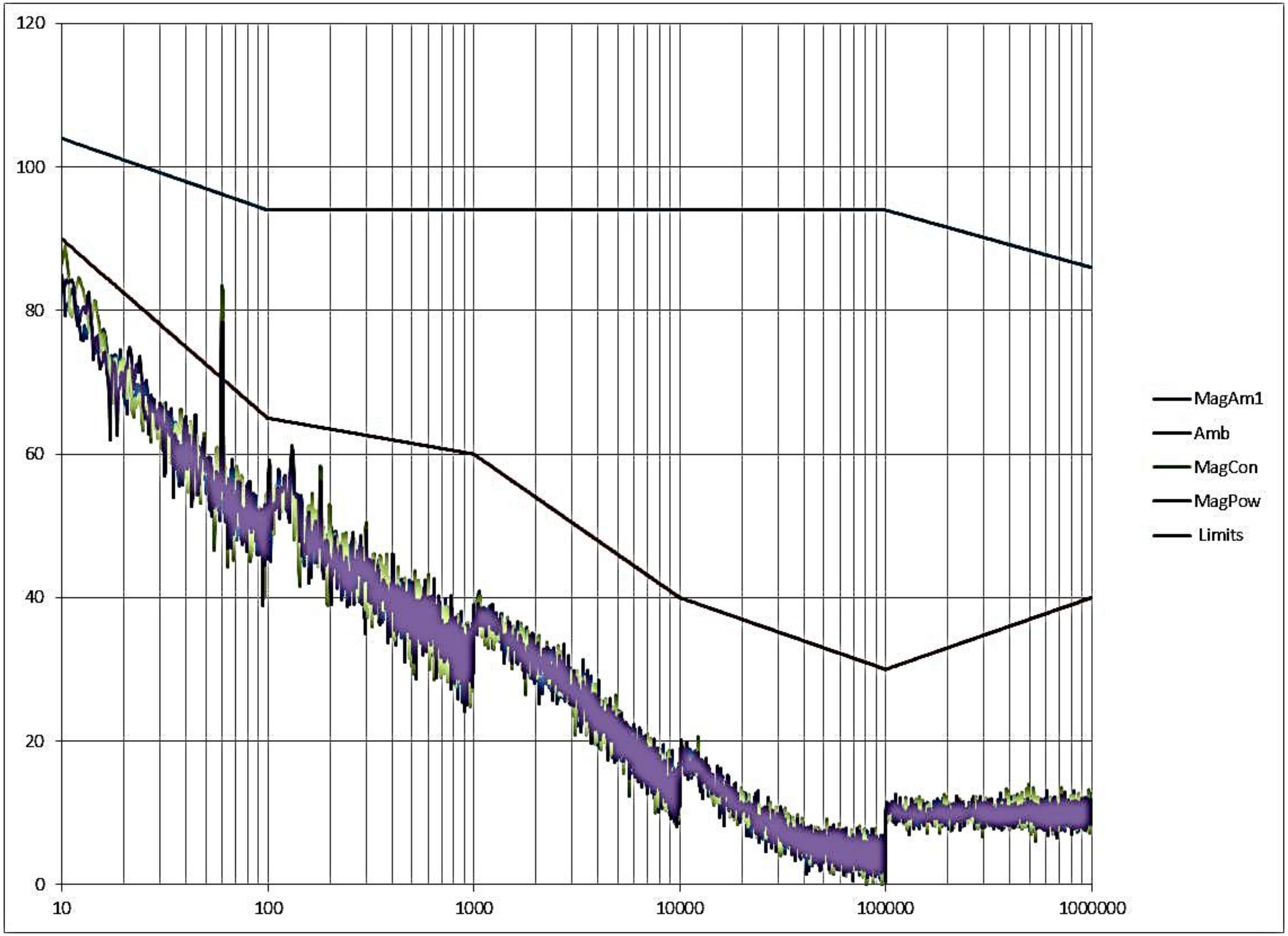
Subsystem and Component	B&I	Conducted Emissions CE - xx			Conducted Susceptibility CS - xx			Radiated Emissions and Susceptibility RE – xx, RS - 03			Turn on/ off	Mag sniff	ESD
		01	03	07	01	02	06	01	02	03			
SWEAP													
SPC	x	x	x	x	x	x	x	x	x	x	x	x	x
SPAN A	x	x	x	x	x	x	x	x	x	x	x	x	x
SPAN B	x	x	x	x	x	x	x	x	x	x	x	x	x
Controller	x	x	x	x	x	x	x	x	x	x	x	x	x
FIELDS													
Controller	x	x	x	x	x	x	x	x	x	x	x	x	x
Electric Field Antennas	x						a			a		x	
E Field preamps	x						a	x	x	a		x	a
MAGo,MAGi	x	x	x	x	x	x	x	x	x	x	x	x	x
Search Coil	x	x	x	x	x	x	x	x	x	x	x	x	x
WISPER	x	x	x	x	x	x	x	x	x	x	x	x	x
ISIS	x	x	x	x	x	x	x	x	x	x	x	x	x

Early Testing (Breadboard, Card level, Engineering Model (EM)) can identify a problem when it can still be fixed without major schedule slip.

Doing conducted emissions (CE) can find most issues.

EM Testing can be used to reduce testing on the FM if the EM passed and is close to flight like. A list of all differences must be supplied prior to approval of FM test procedure. CE and Mag testing required on every unit. The conducted emissions of the EM and the FM must be the same. If not, FM testing may be required.

RE-01 Magnetic Field



The DC Magnetic Field at the inboard Magnetometer shall be less than 50 nt and the Low Frequency magnetic field shall be less than 10 nT over all science periods

RE-02 Electric Field

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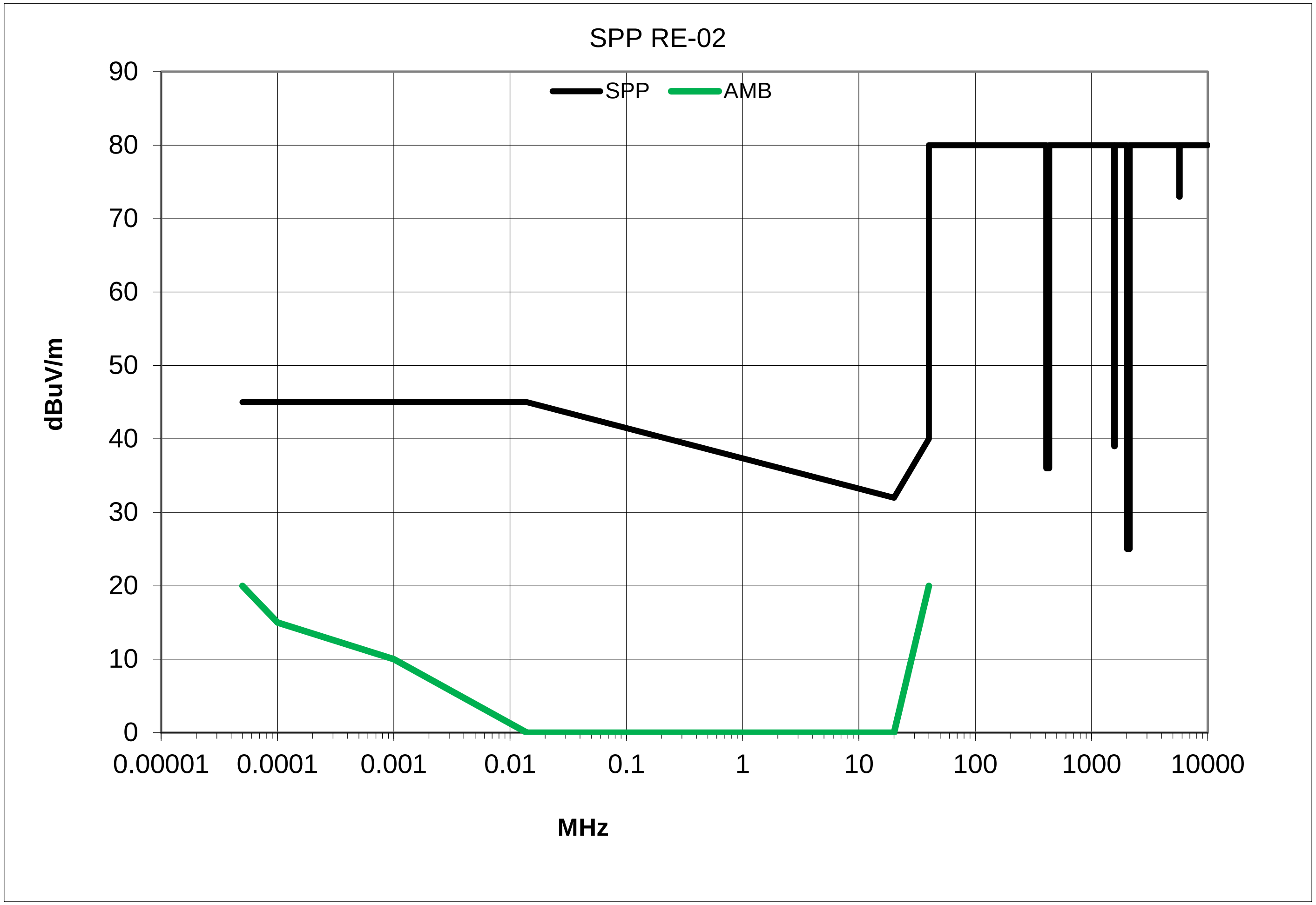
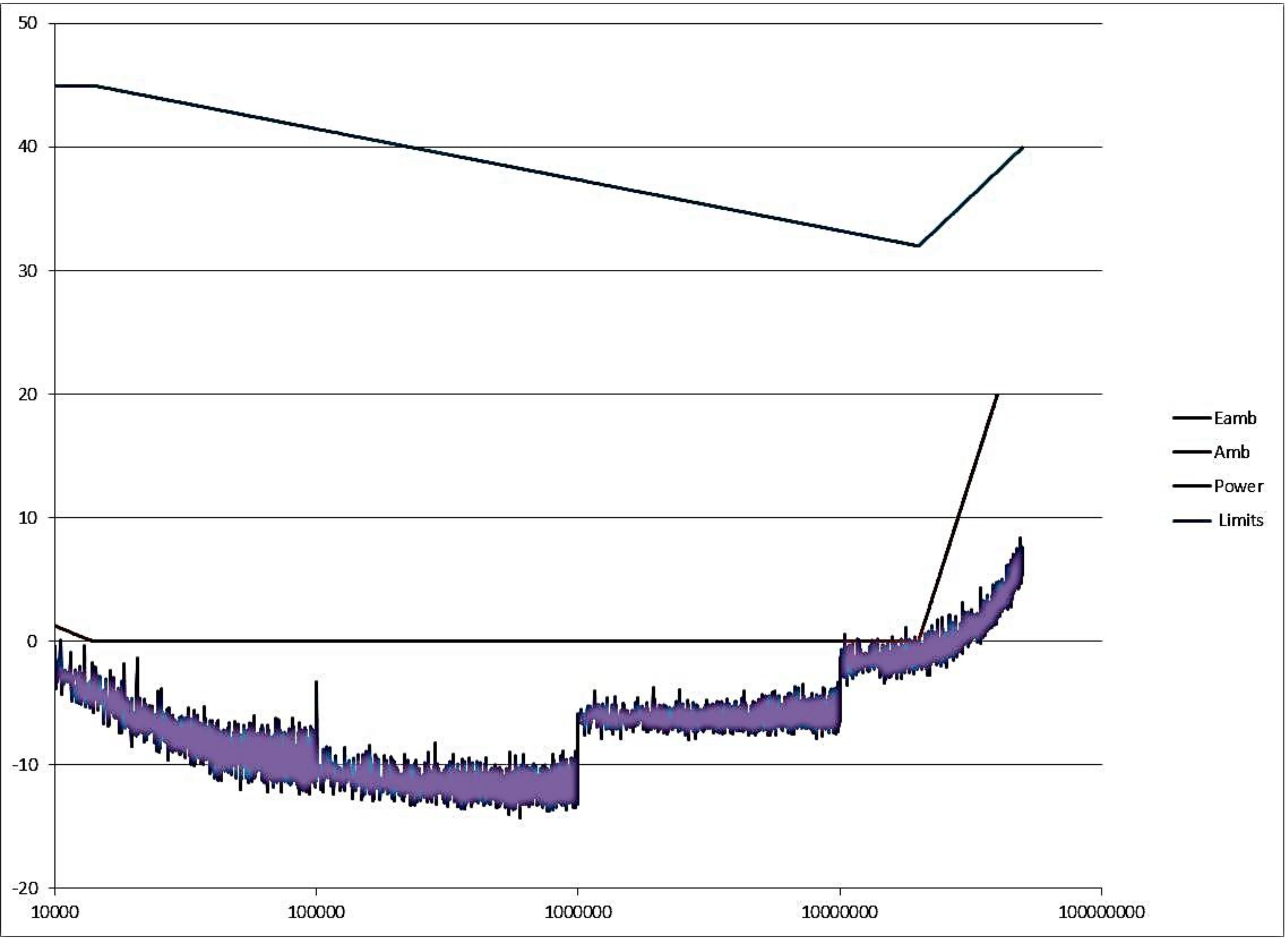
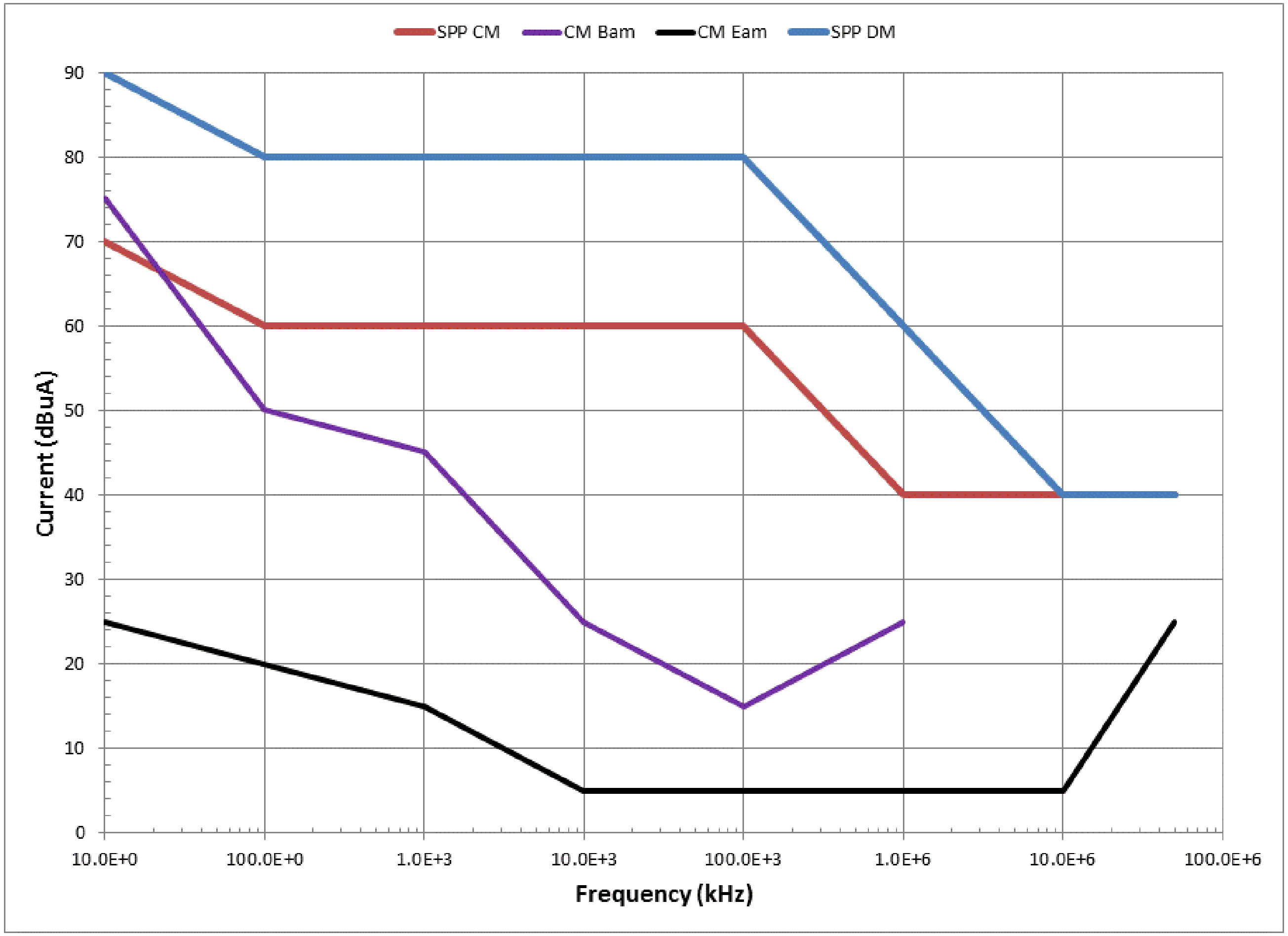


Yes, It can be done!



See Backup Slides for full story

Conducted Emissions



SPP DM is the differential current spec which is higher than the common mode current spec SPP CM because differential current couples less to other devices

CM Bam is a common mode current level associated with the ambient level of RE-01. Any common mode conducted emissions above this line have the possibility of producing RE-01 emissions above the ambient level which would need explanation

CM Eam is a common mode current level associated with the ambient level of RE-02.

These last two lines allow you to identify possible RE issues early in the development stage.

Radiated Susceptability

Emitter Source	Start (GHz)	End (GHz)	RF Field Level @ Pad (V/m)	RF Test Level (V/m)	Comments
Baseline Level	14kHz	18	10	20	**All devices ON**
Vehicle S-Band (TLM)	2.200	2.300	12.8	25.6(8)	**Devices Off at launch can be OFF.** **Devices On at launch shall be ON and operate with no degradation and with no intervention after exposure.**
WSR-88D	2.860	2.870	12.7	31	
WSR-74C	5.620	5.630	10.6	27	
Range Radars	5.400	5.900	20	40	
Vehicle C-Band (Tracking)	5.760	5.770	48.3	96.6(8)	
Miscellaneous Radars	**9.380**	**9.440**	**13**	**26(9)**	**All devices can be OFF**

Table 4-1. RS-03 Survival Electric Field Limit

•All subsystems must operate within specification during exposure to 1 Volt/meter from 14 kHz to 15 GHz.

•All subsystems must operate within specification during exposure to 20 Volts/meter in the band 2.1 to 2.3 GHz since the Downlink transmitter may be operated at any time.

•Test frequencies at and above 100 MHz shall be pulse modulated at 1 kHz with 50% duty factor. Lower frequencies shall be CW.

•Frequency shall be swept over the indicated range while monitoring the Subsystem for susceptibility. The sweep shall be paused at appropriate intervals (e.g., no less than 1,2,5,10 steps and 500 MHz intervals above 1 GHz) to exercise the Subsystem and record performance.

•If susceptibility is encountered, then threshold levels are to be determined and recorded.

•Specific criteria for determining susceptibility shall be documented in the required EMC Test Procedure and approved by the EME Engineer prior to testing.

Turn On Transient

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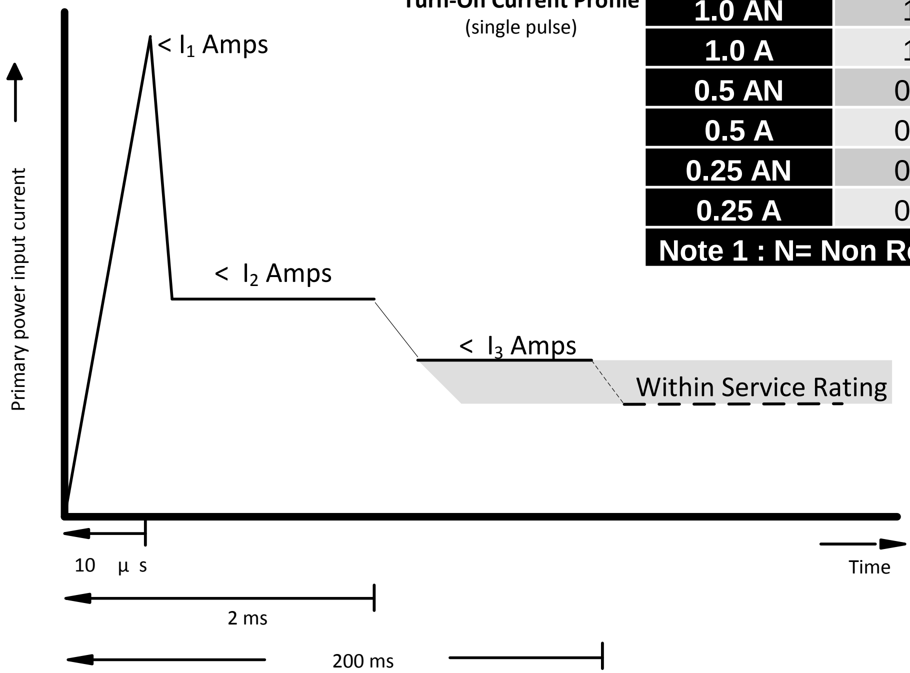
			Peak Current (Amps)		
Service Rating	Fuse (EM) AMPS	Fuse (FM) AMPS	First 10us ($<I_1$)	Next 2 ms ($<I_2$)	Next 200 ms ($<I_3$)
4.0 A	5	7.5	15	10.5	5.5
3.5 A	5	7.5	15	10.5	5.5
3.0 A	5	6	12	8.5	4.5
2.5 A	5	5	10	7	3.75
2.0 A	3	4	10	5.5	3
1.0 AN	1.5	3	10	4.00	1.8
1.0 A	1.5	2	10	2.50	1.5
0.5 AN	0.75	2	10	2.50	1
0.5 A	0.75	1.5	10	2.00	1
0.25 AN	0.75	2	10	2.50	1
0.25 A	0.75	1	10	1.00	0.75
Note 1 : N= Non Redundant Service					

Turn-On Current Profile
(single pulse)



EME Verification Plans

- **Prototype Testing**
  - **Conducted emissions, RF & Magnetic "sniffing" on prototype/EM units**
- **Device Qualification Testing – Matrix in Requirements**
  - **One of each device full qualification testing**
  - **Rest of devices CE workmanship acceptance test**
- **I&T Device Installation Testing**
  - **Measure Power Common and Differential Mode on every device**
  - **Measure Bulk Common Mode noise on every cable**
- **I&T Conducted Noise Compatibility Testing**
  - **Everyday part of I&T operations, check as each device added**
  - **Run devices in "noisy" mode while monitoring Instruments and Receiver**
- **Magnetic Swing Test (TBR)**
- **I&T Radiated Noise Compatibility Test**
  - **Will check launch vehicle requirements but device testing is the official proof**
- **I&T "Plugs Out" Compatibility Test**

Preliminary Testing

- Pump System
  - Radiators
  - Pump and Electronics
  - Latch Valves
- Battery Relay
- PDU Command/Telemetry BB
- Avionics RPM Mode Controller BB
- 3rd Stage motor gimbal drive
- MAG Boom Hinge Materials

Summary

- **The EME requirements are defined and allocated to each device**
- **The EME Control Plan is in PLM**
- **EMEWG meeting are on going**
- **Material list are coming in for review**
- **Board layouts are coming in for review**
- **Preliminary tests are starting**

- **EME is Ready for Phase C**

  (when I get some real data!)

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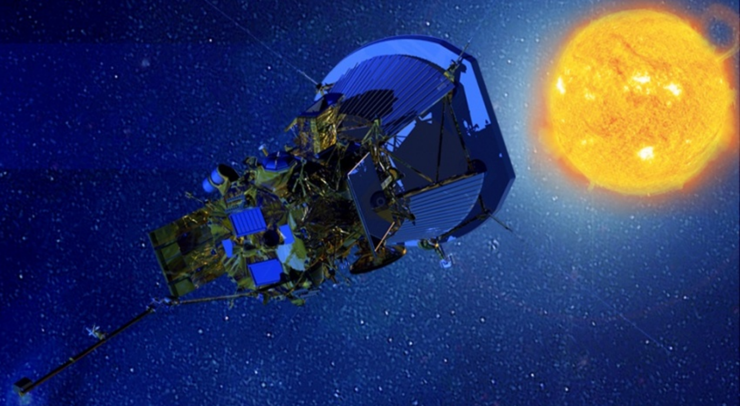


Backup Slides

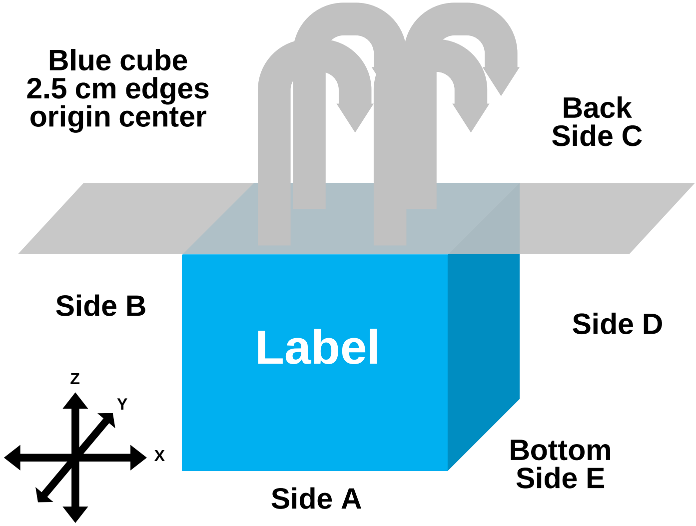
Harness Requirements

- Wiring
  - POWER:
    - All lines group twisted having the same number of feeds and returns
    - All feeds and returns isolated from chassis by at least 1 MegaOhm
    - Shall not be in same connector as signals unless approved by EME Engineer
  - Signals:
    - All lines either twisted with returns or impedance controlled lines
    - Internal Shields will be terminated at the transmission end and open at the receiver end unless otherwise directed. Never will a shield terminate at chassis on one end and connect to a pin at the other end.
- Over Shielding
  - All lines will be bulk wrapped with an un-insulated external shield connected to chassis at all ends. If the connector has an EMC Backshell, the shield will be circumferentially terminated in the backshell. Otherwise the wrap will cover the connector base and all wires and have less than 10 milliohms resistance between the wrap and the box chassis.

GSE

- Mock Solar Array Panel for Compatibility Test
- Support stands for FIELDS Mock-up Antennas
- Portable Magnetometer for “sniffing” and compatibility tests
- Portable Spectrum Analyzer with Current and Field Probes
- I&T Spacecraft Harness Break-Out boxes
- Filtered Solar Array Simulator
- Degausser

Magnetic Testing
SPP Battery Relay

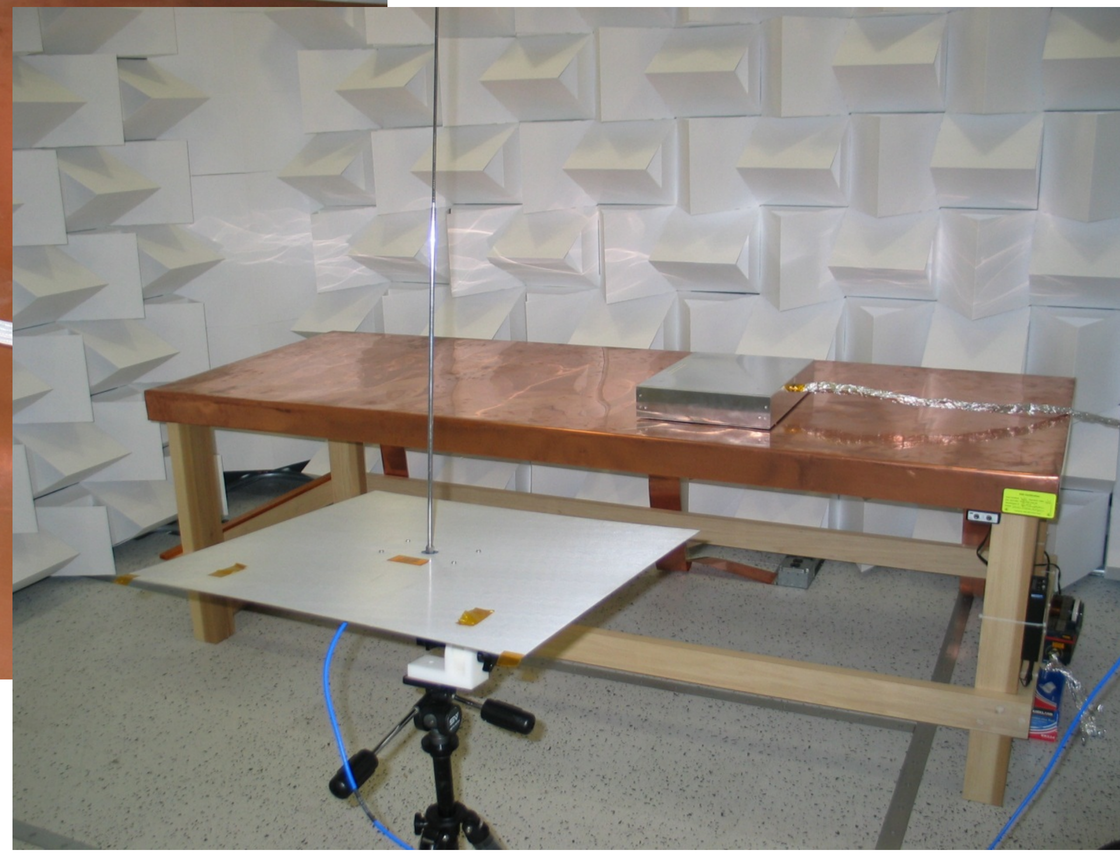


Measured Magnetic Moment
location = 0.25,-0.1,-0.35 cm
Magnitude = 0.112,0.06,0 Am^2

	B Calc G	Bmeas
D1	27.8	28.0
D3	3.6	3.1
D5	1.1	1.2
E1	18.2	17.0
E3	2.1	2.3
E5	0.6	1.1
A1	13.4	13.3
A3	2.2	1.1
C1	9.2	11.9
C3	1.8	1.4
B1	14.1	2.7
B3	2.5	0.5

PASS

EMC Testing
PDU Power Board



Power Distribution Unit (PDU)

PDU EM/CT Slice BB EMI Test Results

- **EMI Requirement:**
- DC/DC converter frequencies shall be crystal controlled to a frequency window centered at n*50 kHz with n>=3 and 500 ppm (TBR) wide over all operating conditions and time. Units not meeting this requirement must present their grounding, wiring, power and frequency characteristics for waiver approval. Operation at any frequency greater than 20 MHz is allowed. (Note: @500Khz, 500ppm = +/-125 hz)
- **CT Slice 28V to 5V DC/DC Converter (IR2805S) does not meet this requirement**
- Operating frequency is not synchronized and has a tolerance of 500Khz +/- 75Khz
- Therefore Conducted Emissions testing (CE01, CD03)was performed on the RBSP EM in the Mission Ops Center. The CE Tests passed. Analysis was performed to extrapolate the data to see if RE testing would also pass. RE analysis results were marginal.
- Radiated Emission testing (RE01, RE02) was then performed on the RBSP CT Slice BB enclosed in a Box. This test passed. Recommendation is to use the DC/DC converter with Shielded wire on the power harness. Harness will provide the following: All cables will receive an overall shield of Neptape (Aluminum) wrap on the bundles. We will use shielded twisted pair for this application to add more shielding and isolation within the bundle. M27500-26SC2S23.
- Waiver will be submitted for approval.

Power Distribution Unit (PDU)

PDU Command/Telemetry BB

Solar Probe Plus
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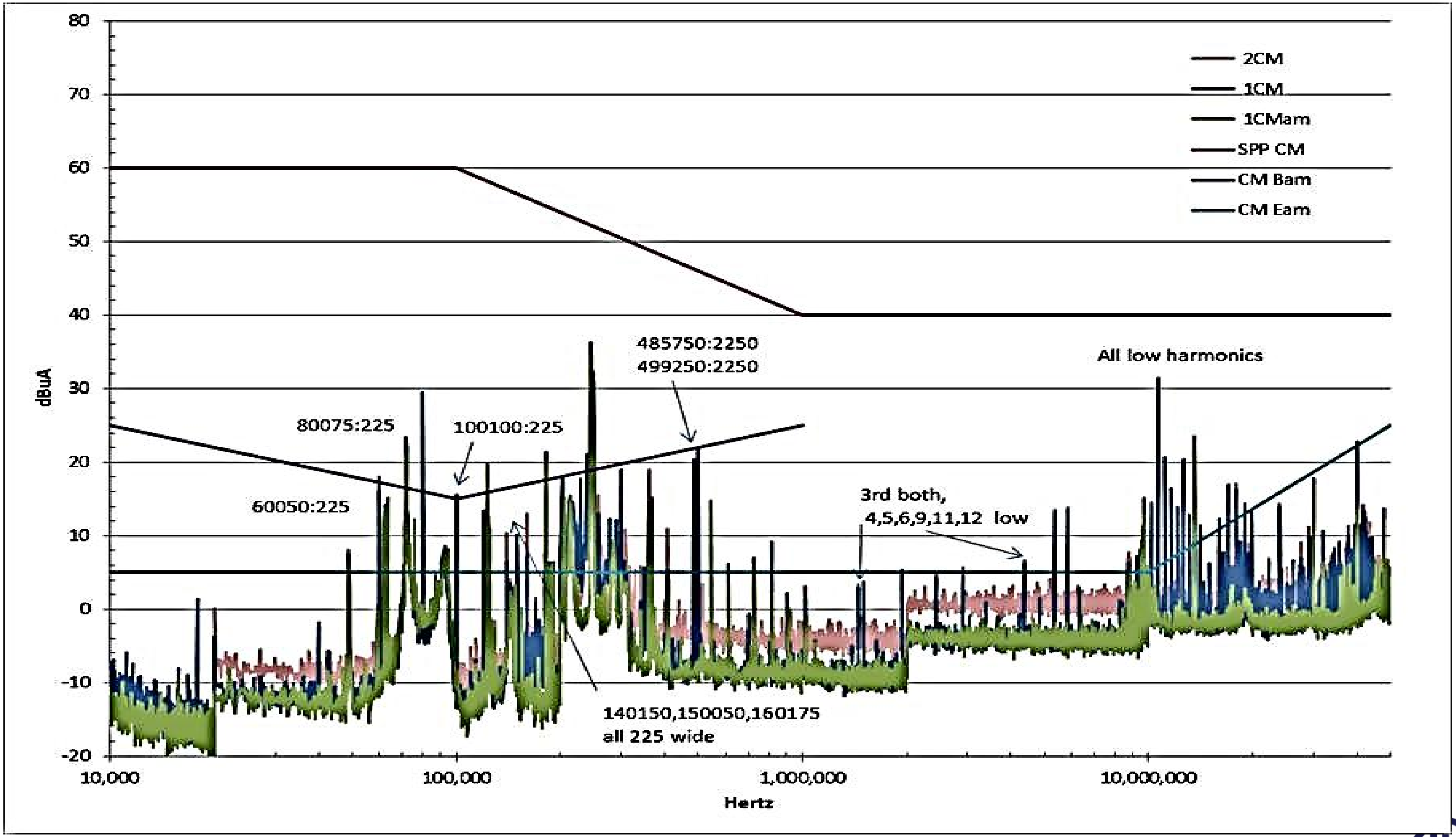
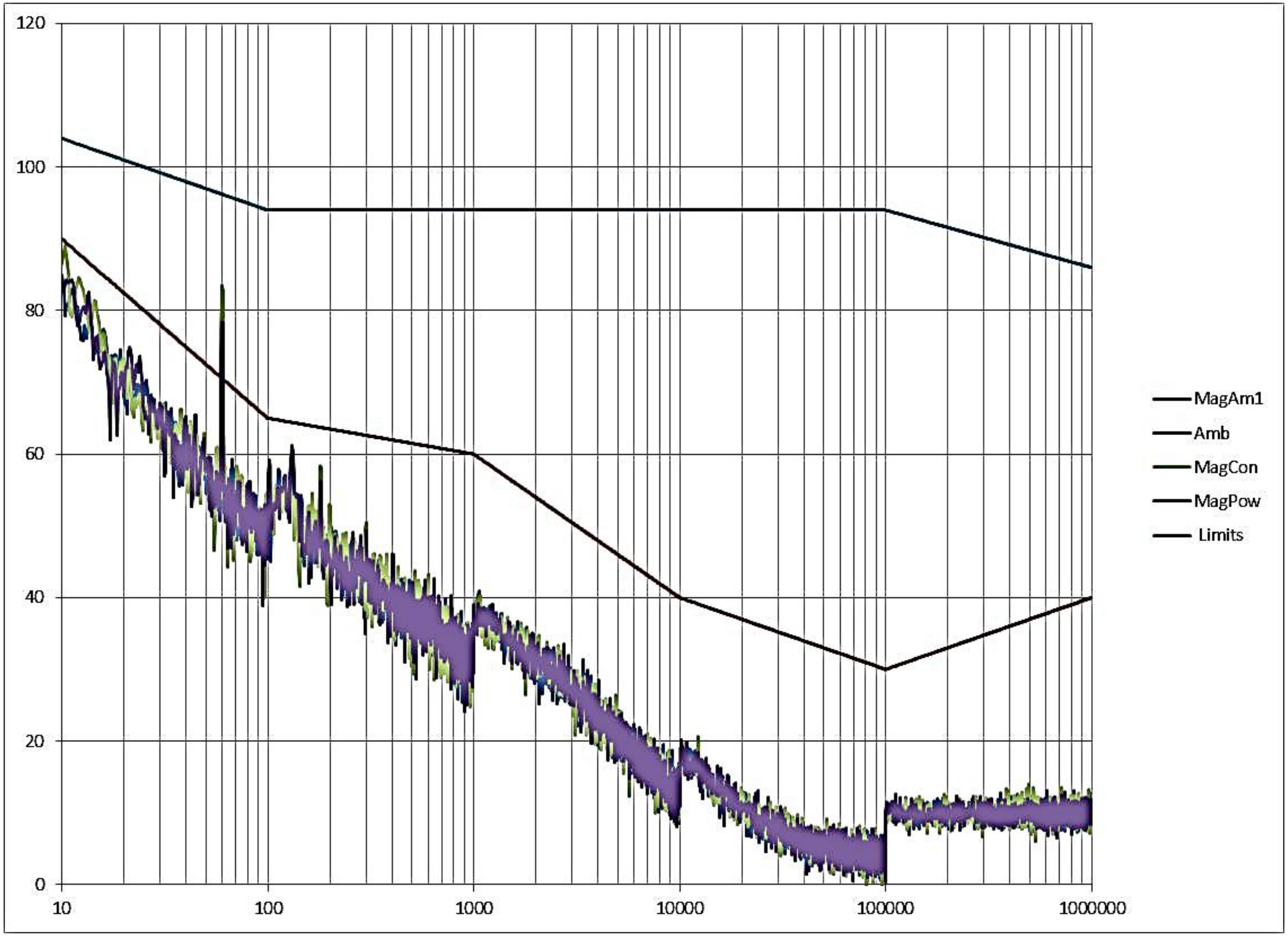


APL

Magnetic Emissions – RE-01

PDU Command/Telemetry BB



No measurable noise, only the 60 Hz ambient breaks the allowed ambient level

Electric Emissions – RE-02

PDU Command/Telemetry BB

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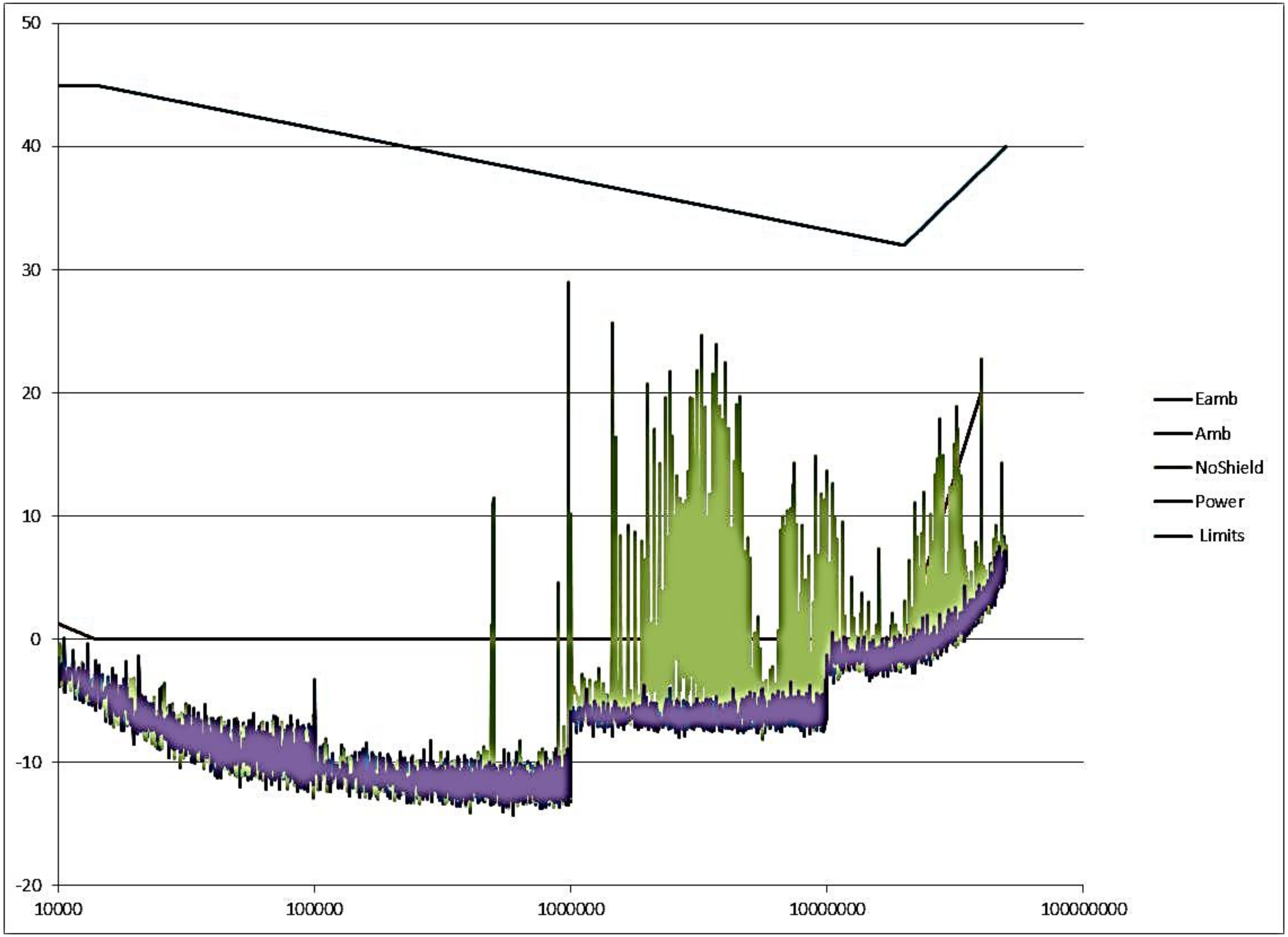
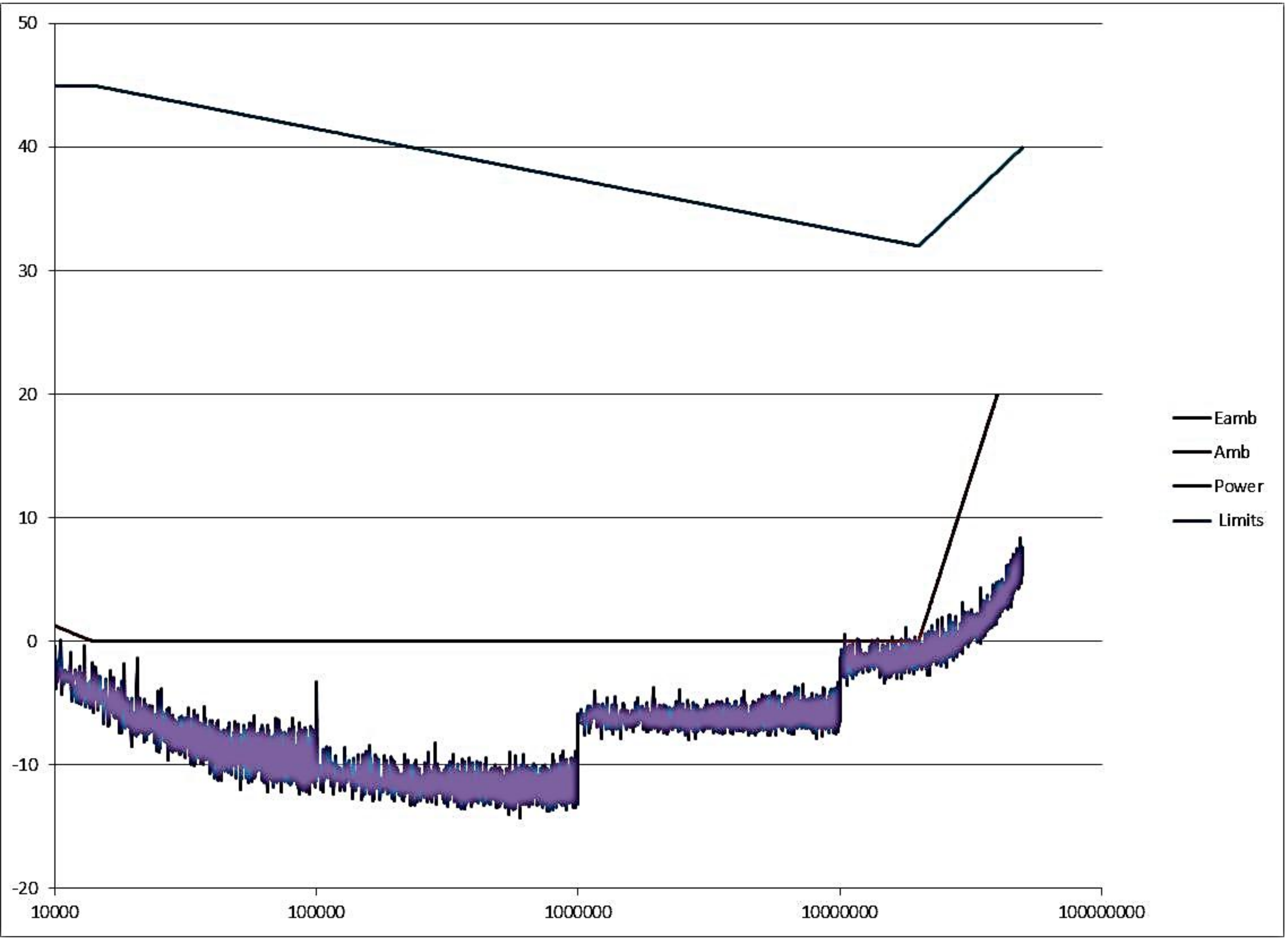


Unshielded Cable results clearly show the harmonic emissions from the power supply and other board noise

RE-02 Final

PDU Command/Telemetry BB



No Measurable noise with shielded cable. Power Supply Passes Ambient level requirement.

PASS

Solar Probe Plus

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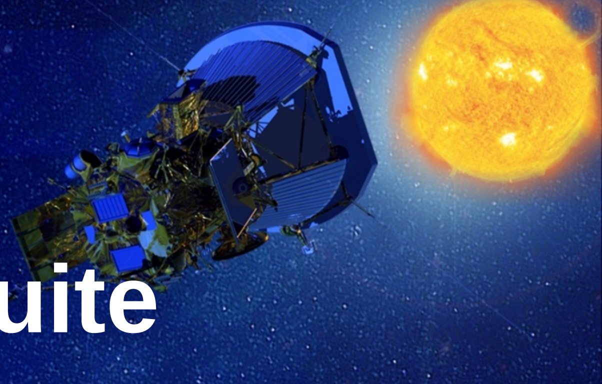

The FIELDS Instrument Suite

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13 – 16 January 2014

Boulder

UNH NEW HAMPSHIRE

l'Observatoire de Paris

cnrs

UNIVERSITY OF MARYLAND

APL The Johns Hopkins University APPLIED PHYSICS LABORATORY

Smithsonian Astrophysical Observatory

Agenda

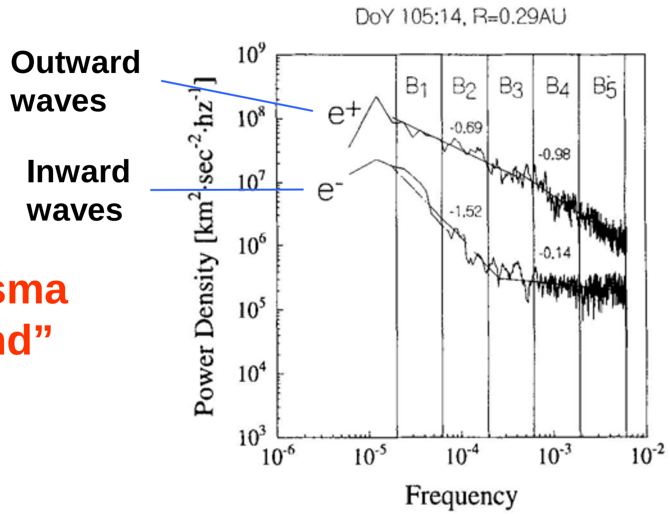
- **Science Overview**
- **Team Organization**
- **Instrument Overview**
- **Changes Since SRMDR**
- **System Description**
- **Assembly and I&T Description**
- **Verification**
- **Development Status**
- **Science Operations Center**
- **Risk**
- **Review Action Item Status**

FIELDS Science Overview

FIELDS Measurements are key for all three SPP L1 Requirements

1. "Trace the flow of energy that heats and accelerates the solar corona and solar wind"

FIELDS will measure:
1. Alfven and compressive waves; Poynting (energy) flux
2. Turbulent cascade and dissipation
3. Magnetic reconnection and collisionless shocks
4. Velocity-space (expansion) instabilities
5. Signatures of ambipolar/IP potential



2. "Determine the structure and dynamics of the plasma and magnetic fields at the sources of the solar wind"

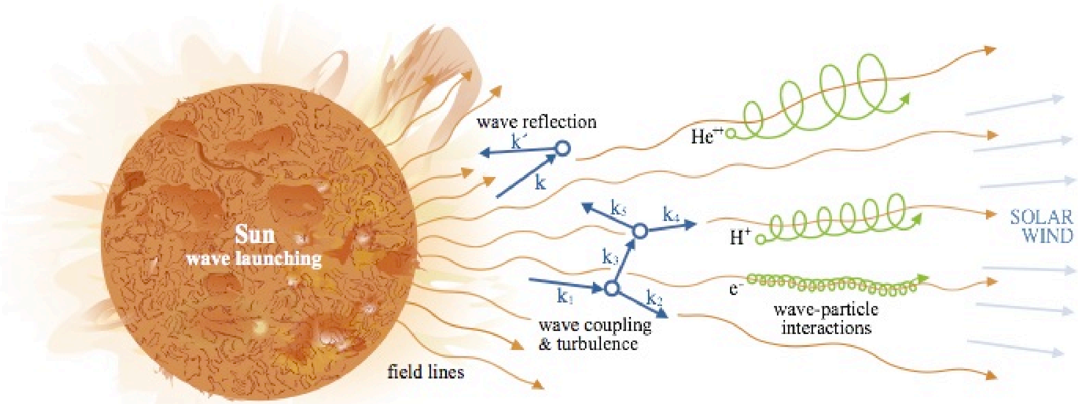
FIELDS will measure:
1. Magnetic field polarity and flux tube structure
2. Reconnection current sheets
3. Statistics of (Parker) nano-/micro-flares
4. Streamer belt latitudinal extent
5. The plasma density to ~1-2% accuracy over the science orbit
6. The core electron temperature to ~5-10% accuracy over the science orbit

3. "Explore mechanisms that accelerate and transport energetic particles"

FIELDS will measure:
1. Interplanetary shock structure
2. Type II and type III radio bursts
3. Solar wind magnetic reconnection
4. Stochastic (turbulent) acceleration

FIELDS Science Overview

Solar Probe Plus
A NASA Mission to Touch the Sun

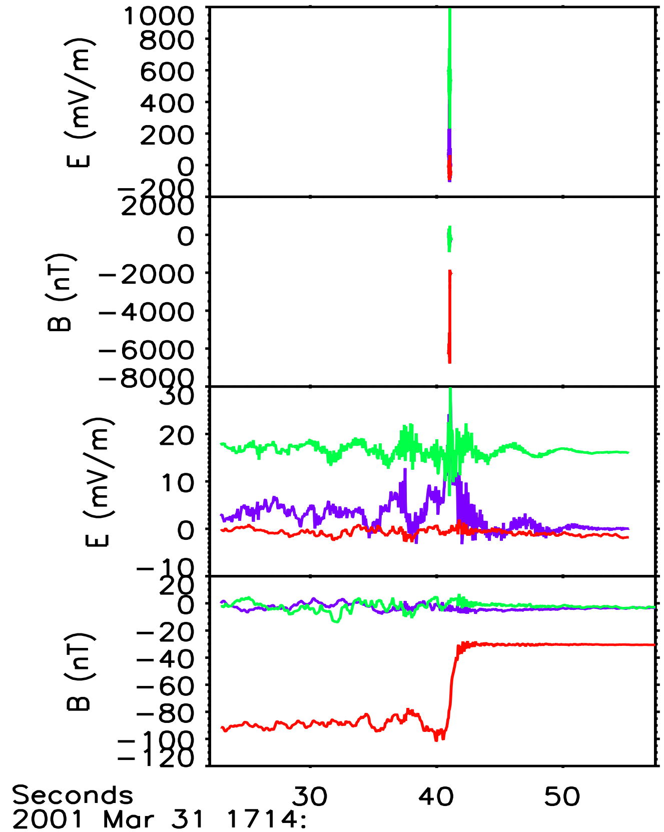


The SPP/FIELDS experiment will measure directly:

1. **DC/Low Frequency Electric Fields**
2. **DC/Low Frequency Magnetic Fields**
3. **Plasma wave (E and B) waveforms, spectra, cross-spectra**
4. **Spacecraft floating potential**
5. **Solar and interplanetary radio (e/m) emissions**
6. **Quasi-thermal noise spectrum**

…and by analysis:

1. **Perpendicular electron velocity and its spectrum**
2. ***Very* accurate electron density and temperature**
3. **Rapid (~kHz) density fluctuations and spectrum**
4. **Voltage signatures of interplanetary dust**



SPP/FIELDS will see very large electric and magnetic fields and compressions: ~1+ V and ~1000+ nT at strong shocks

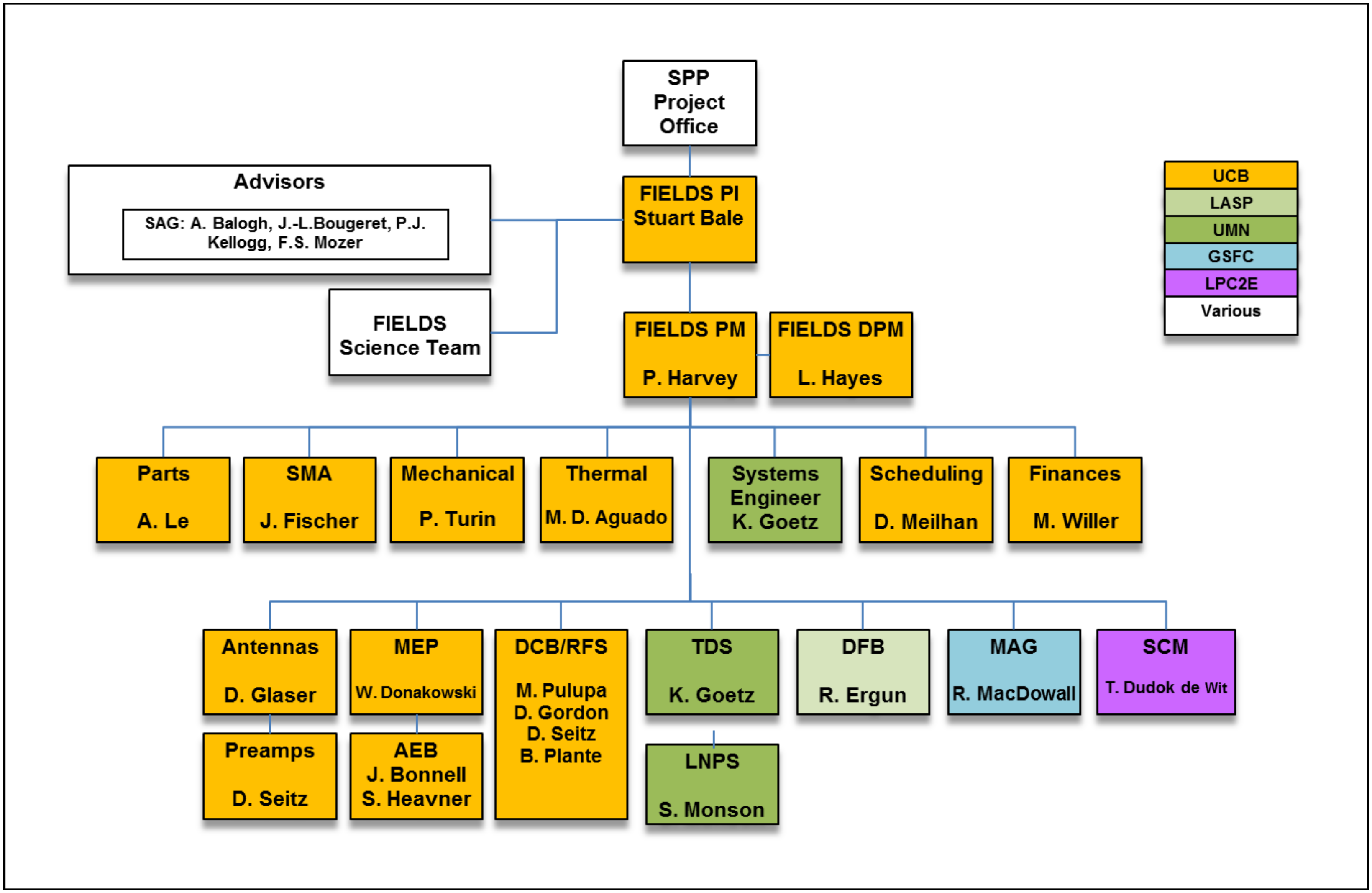
Drivers for FIELDS

FIELDS makes *rapid* measurements of *intense* fields

Parameters		~10 R_s Typical	55 R_s Typical	1 AU Typical
Magnetic Field	$\lvert B_0 \rvert \sim \delta B$	2000 nT	70 nT	6 nT
Elecric Field	$\lvert E \rvert \sim v_{sw} B_0$	100 mV/m	30 mV/m	3 mV/m
Density	$n_e \sim \delta n_e$	7000 cm^{-3}	120 cm^{-3}	7 cm^{-3}
Electron Temperature	T_e	85 eV	25 eV	8 eV
Solar Wind Speed	v_{sw}	210 km/s	400 km/s	450 km/s
Alfven Speed	v_A	500 km/s	125 km/s	45 km/s
Plasma Frequency	f_{pe}	750 kHz	100 kHz	24 kHz
Electron Gyrofrequency	f_{ce}	60 kHz	2 kHz	160 Hz
Proton Gyrofrequency	f_{ci}	32 Hz	1 Hz	0.1 Hz
Convected Debye Scale	v_{sw}/λ_D	250 kHz (4 μs)	125 kHz (8 μs)	45 kHz (22 μs)
Convected Electron Inertial Length	$v_{sw}/(c/\omega_{pe})$	3.5 kHz (0.3 ms)	825 Hz (1.2 ms)	180 Hz (5.5 ms)
Convected Ion Inertial Length	$v_{sw}/(c/\omega_{pi})$	75 Hz (13 ms)	20 Hz (50 ms)	4 Hz (250 ms)
Convected Ion Gyroradius	v_{sw}/ρ_i	300 Hz (3 ms)	35 Hz (30 ms)	5 Hz (200 ms)
DC/LF Electric Fluctuations	$\delta E_A \sim v_A\, \delta B_A$	1 V/m	10 mV/m	1 mV/m
Kinetic Electric Fluctuations	δE_L	1 V/m	70 mV/m	10 mV/m

- **High cadence sampling**
- **Burst memory system**
- **Floating voltage preamps**
- **Large dynamic range**

FIELDS Team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FIELDS PI Stuart Bale
Advisors
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FIELDS Science Team
FIELDS PM P. Harvey
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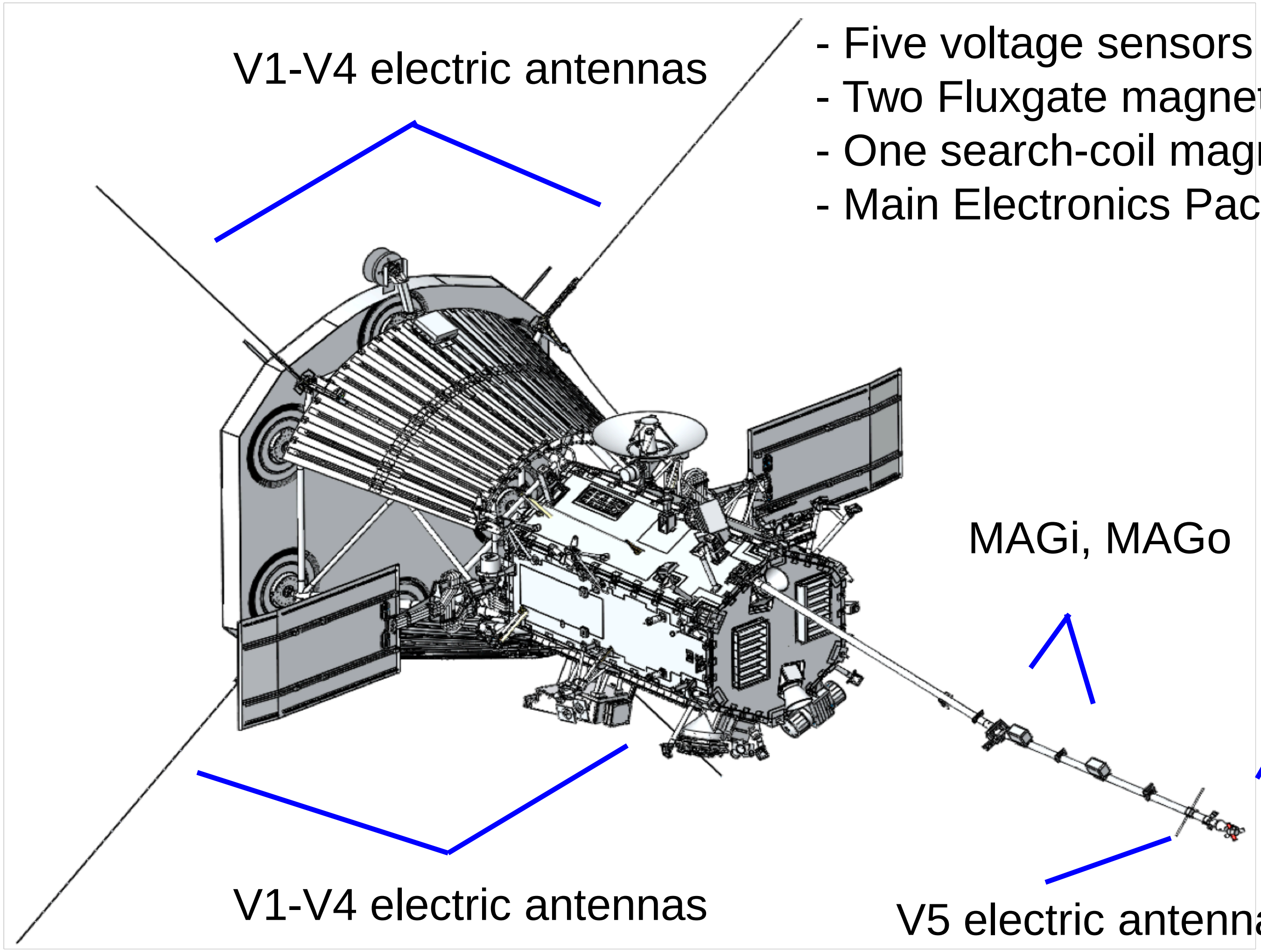
Scheduling D. Meilhan
Finances M. Willer
Antennas D. Glaser
Preamps D. Seitz
MEP W. Donakowski
AEB J. Bonnell S. Heavner
DCB/RFS M. Pulupa D. Gordon D. Seitz B. Plante
TDS K. Goetz
LNPS S. Monson
DFB R. Ergun
MAG R. MacDowall
SCM T. Dudok de Wit

The FIELDS Sensors

- Five voltage sensors
- Two Fluxgate magnetometers
- One search-coil magnetometer
- Main Electronics Package



FIELDS Block Diagram

Two Sides

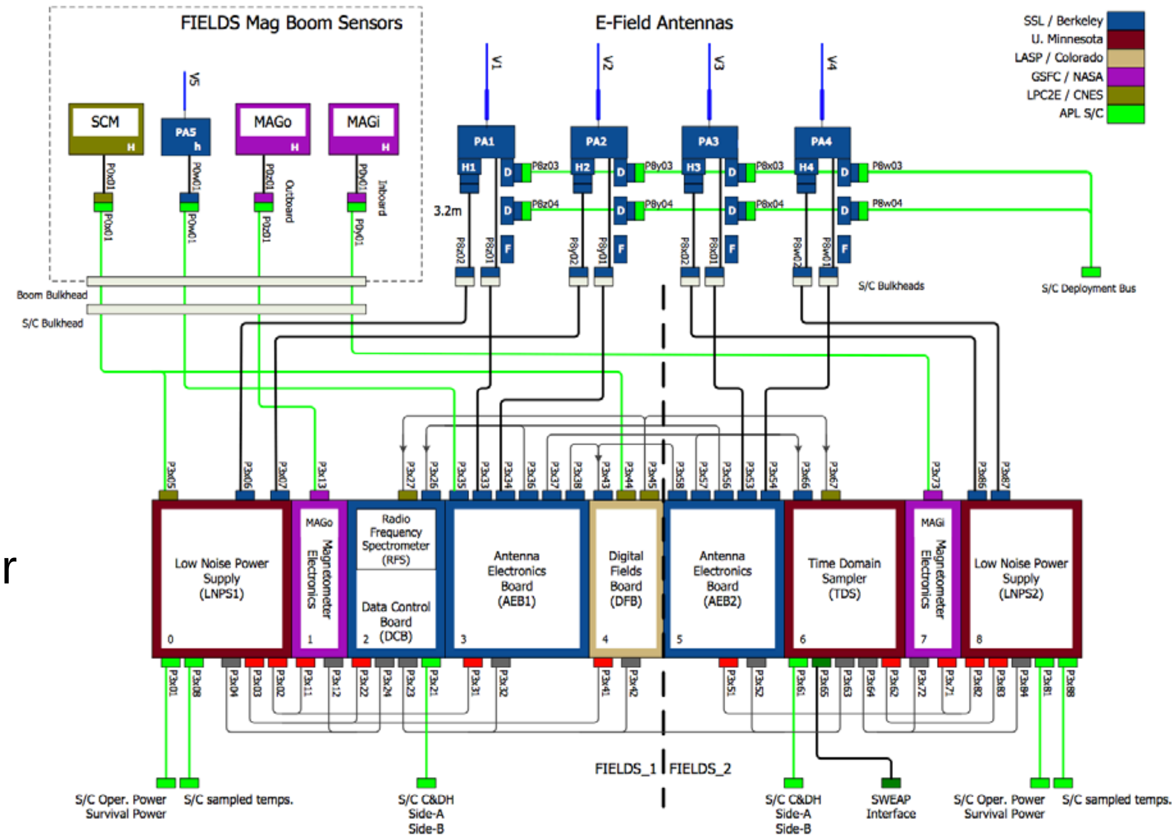
- Each has Spacecraft I/F
- Each has Magnetometer
- Each has Antenna Elect.
- Each has Power Supply

FIELDS1 also has

- Radio Freq Spect./DCB
- Digital Fields Board
- SCM Calib Control
- Absolute Time Sequencer
- TDS I/F

FIELDS2 also has

- Time Domain Sampler
- DCB I/F
- SWEAP I/F



Technical Changes Since SRR/MDR

Change since SRR/MDR	Reason for Change	Impact on Resources
TNR/HFR from Meudon replaced by a new UCB all-digital RFS	CNES budget shortfall	Negligible
FIELDS Clocks – synchronized to power supply	Improves science data and simplifies noise reduction	None
Added V5 Sensor	Meet Level 1 Requirement	Small mass & power impact
Redesigned FIELDS into two FIELDS1 and FIELDS2 to enhance fault tolerance	Improves reliability, fault tolerance Requested by APL	Mass, power, complexity, cost Added AEB, LNPS, S/C Interfaces
Added Calibration Signal from DFB to SCM	Provide accurate calibration capability	Increased: power and mass some, and added FPGA processing
Changed from discrete ADCs to SIDECAR ASIC	Power, mass, volume constraints, and radiation tolerance	Decreased: power, mass and volume, Increased: radiation tolerance

System Description
FIELDS Level-1

- **MRD requirements flow to FIELDS**
  - **Mission Success is 7 of 9 measurements**
  - **FIELDS is responsible for 4 of these measurements**

Baseline

Req.	Measurement	Dynamic Range	Cadence	Bandwidth
4.1.1.3	Magnetic Field	140dB	100k vectors/s	DC - 50kHz
4.1.1.4	Electric Field	140dB	2M vectors/s	DC - 1MHz
4.1.1.5	Plasma Waves	140dB	1 spectrum/s	~5Hz - 1MHz
4.1.1.6	QTN/Radio	100dB for QTN 80dB for radio	1 spectrum/4s QTN 1 spectrum/16s radio	10-2,500kHz QTN 1-16MHz radio

Threshold

Req.	Measurement	Dynamic Range	Cadence	Bandwidth
4.1.2.3	Magnetic Field	125dB	256 vectors/s	DC - 128Hz
4.1.2.4	Electric Field	125dB	256 vectors/s	DC - 128Hz
4.1.2.5	Plasma Waves	90dB	1 spectrum/10s	~5Hz - 50kHz
4.1.2.6	QTN/Radio	70dB for QTN 70dB for radio	1 spectrum/32s QTN 1 spectrum/32s radio	10-2,500kHz QTN 1-16MHz radio

Requirements FIELDS Level-2

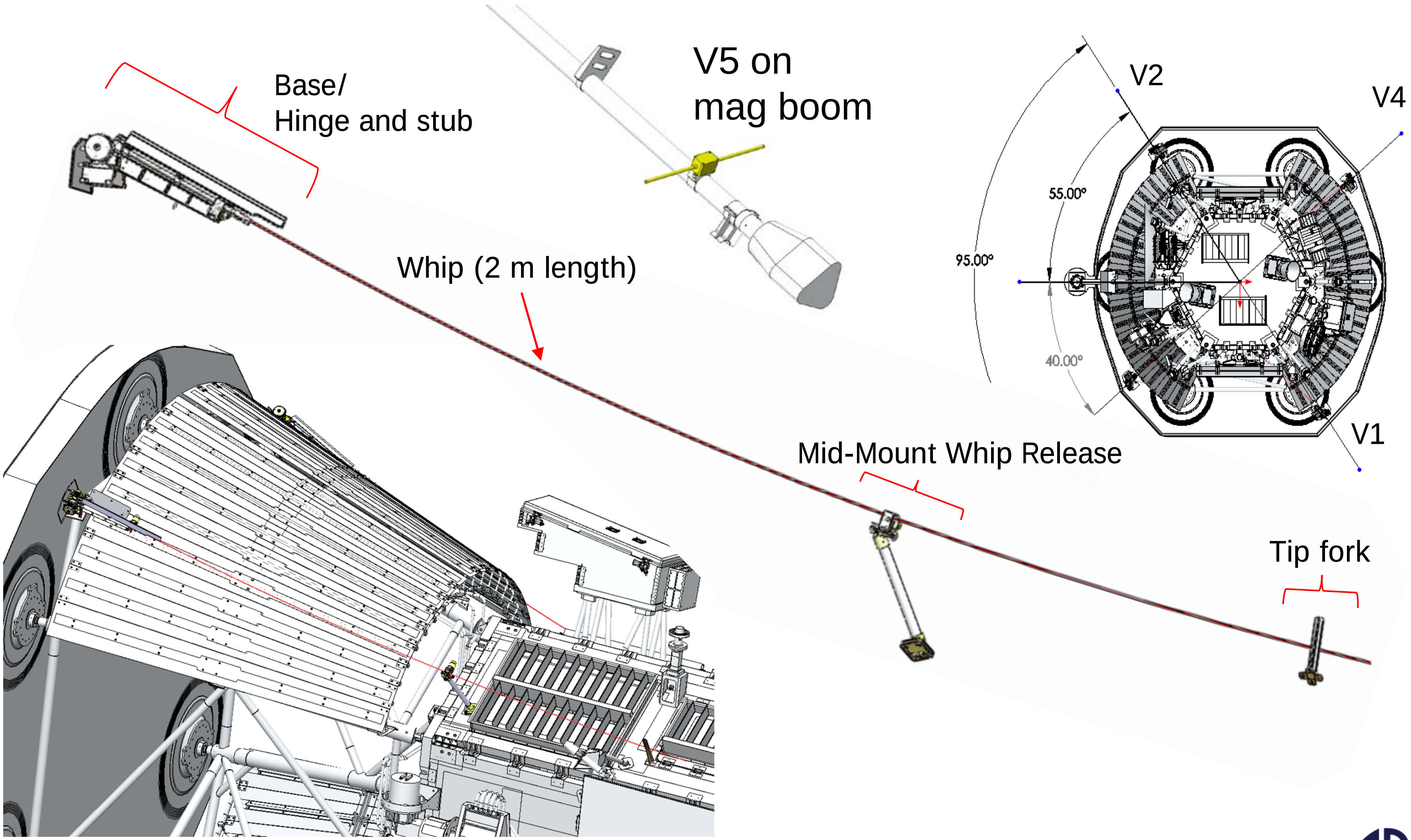
FIELDS Science Measurement Requirements						
ID	Requirement Title		Baseline	Threshold	Current	
MRD-89	FIELDS: DC Magnetic Field	-- dynamic range:	140 dB	125 dB	140 dB	✔
		-- cadence:	100k vectors/sec	256 vectors/sec	150k vectors/sec	
		-- bandwidth:	DC – 50 kHz	DC – 128 Hz	DC – 75 kHz	
MRD-99	FIELDS: DC Electric Field	-- dynamic range:	140 dB	125 dB	140 dB	✔
		-- cadence:	2M vectors/sec	256 vectors/sec	2M vectors/sec	
		-- bandwidth:	DC – 1 MHz	DC – 128 Hz	DC – 1 MHz	
MRD-103	FIELDS: Plasma Waves	-- dynamic range:	140 dB	90 dB	140 dB	✔
		-- cadence:	1 spectrum/sec	1 spectrum/10sec	1 spectrum/sec	
		-- bandwidth:	5 Hz – 1 MHz	5 Hz – 50 kHz	5 Hz – ~2 MHz	
MRD-107	FIELDS: Quasi-Thermal Noise	-- dynamic range:	100 dB	70 dB	100 dB	✔
		-- cadence:	1 spectrum / 4 sec	1 spectrum / 32 sec	1 spectrum / 4 sec	
		-- bandwidth:	10 – 2500 kHz	10 – 2500 kHz	10 – 2500 kHz	
MRD-108	FIELDS: Radio Emissions	-- dynamic range:	80 dB	70 dB	80 dB	✔
		-- cadence:	1 spectrum / 16 sec	1 spectrum / 32 sec	1 spectrum / 16 sec	
		-- bandwidth:	1 – 16 MHz	1 – 16 MHz	1 – 19.2 MHz	

System Description Driving Requirements

FIELDS Driving Requirements

PAY-37	**Measurement: Magnetic Field MAG**
PAY-38	**Measurement: Magnetic Field SCM & Plasma Waves**
PAY-170	**Measurement: Electric Field & Plasma Waves**
PAY-172	**Measurement: Plasma Waves (AC Magnetic Field)**
PAY-174	**Measurement: Plasma Waves (Magnetic Field Power Spectra)**
PAY-272	**Measurement: Plasma Waves (Electric Field Power Spectra)**
PAY-175	**Measurement: Electric Field QTN Spectroscopy**
PAY-176	**Measurement: Electric Field Radio Emissions**
PAY-105	**Payload: FIELDS Burst Mode**
PAY-113	**Timekeeping: FIELDS Time Knowledge Accuracy**
PAY-100	Payload: Minimum Perihelion Hours
PAY-101	Payload: Mission Length
PAY-104	Payload: Risk Category (single fault tolerant)
PAY-109	Payload: Burst Mode Management
PAY-112	Payload: Flight Software Modification
PAY-277	Compliance: FIELDS to SWEAP ICD (FIELDS)
PAY-279	Compliance: FIELDS to Spacecraft ICD
PAY-276	Compliance: General Instrument Specification
PAY-283	Compliance: MOC to SOC ICD
PAY-140	Compliance: EMECP
PAY-141	Compliance: EDTRD
PAY-148	Compliance: CCP

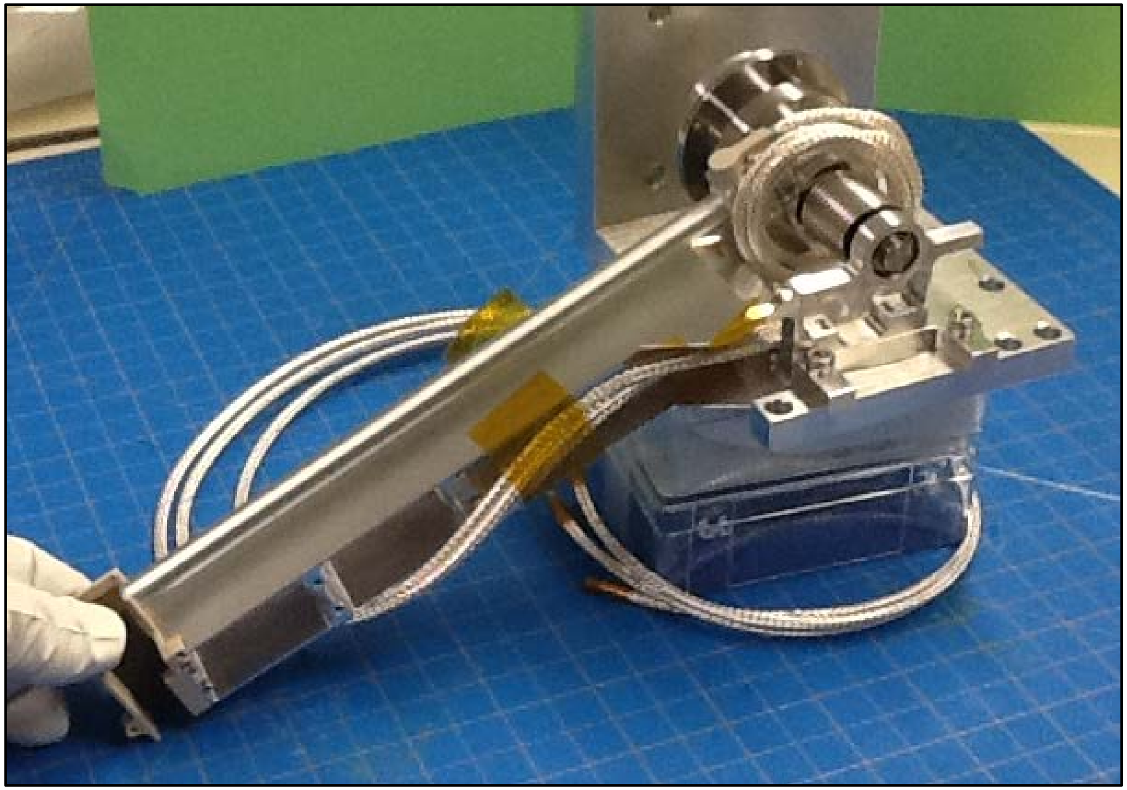
System Description
V1-V5 Antenna Design



System Description
Antenna Status

Successful Tests

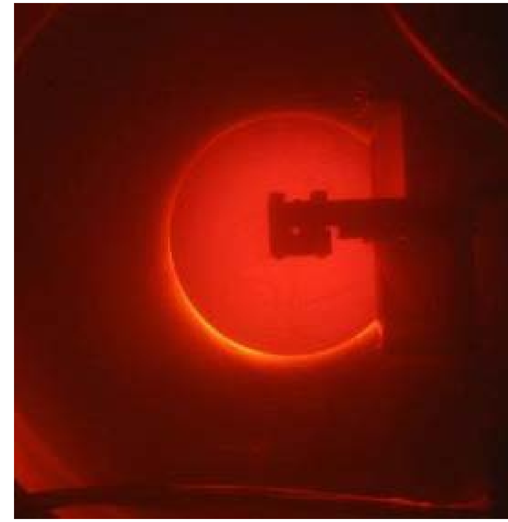
- Deployment Test at Room Temp. and 1 Atm
  - 6 seconds duration
  - Torque Margin > 4
  - Torque Margin with KO spring >7
- TVAC Torque vs. temp Test of Fly Weight Brake
- Hot and Cold TVAC Deploy Test
- Hot and Cold TVAC Torque Margin Test
- Vibration Test
- Capacitance Test

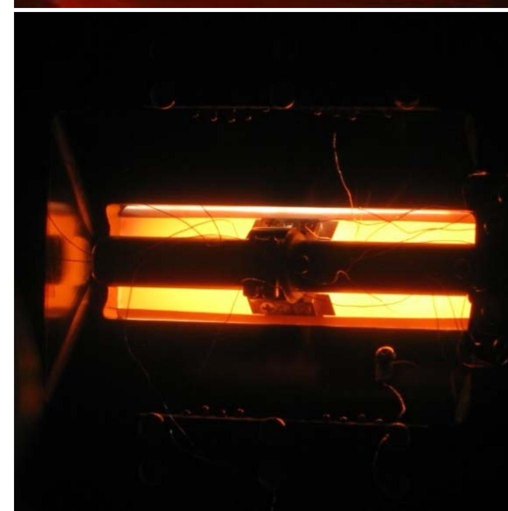


System Description
TRL6 Testing

1. **Basic material testing complete**
   - **Outgassing – within acceptable levels**
   - **Optical properties obtained for modeling**
     - **Surface "randomization" developed for BRDF**
   - **Thermal conductivity and resistance of metals and insulators: using SAO, SRI values**
2. **Thermal distortion testing complete**
   - **Within allowance in alignment budget**
3. **Testing of Thermal Test Models (TTMs):**
   - **Testing performed at PROMES and in a furnace**
   - **Thermal model correlated to 1303°C (max predict)**
   - **Materials issues uncovered and rectified**
     - **Using all refractory materials in hot section**
   - **Final furnace test verified the material change and electrical behavior (conductivity and isolation).**

➢ ***TRL-6 Achieved***





System Description
Fluxgate Magnetometer

Main Components

- Inboard and Outboard Magnetometers
- Redundant Magnetometer electronics boards in MEP

Performance

- Dynamic Range: 65,000 nT
- Ranges : 4 (1024, 4096, 16384, 65536 nT)
- Vector Accuracy (typ): < 0.1% +/- 0.5 nT
- Offset Stability (typ): +/- 0.2 nT / year
- Alignment Accuracy: < 0.1 degree
- Alignment Knowledge: < 0.1 degree
- Noise (typ): $3x10^{-4}$ nT/sqrt(Hz)
- Sampling Rate: 256 samples/0.874 sec

Heritage: 79 fluxgates flown since 1966

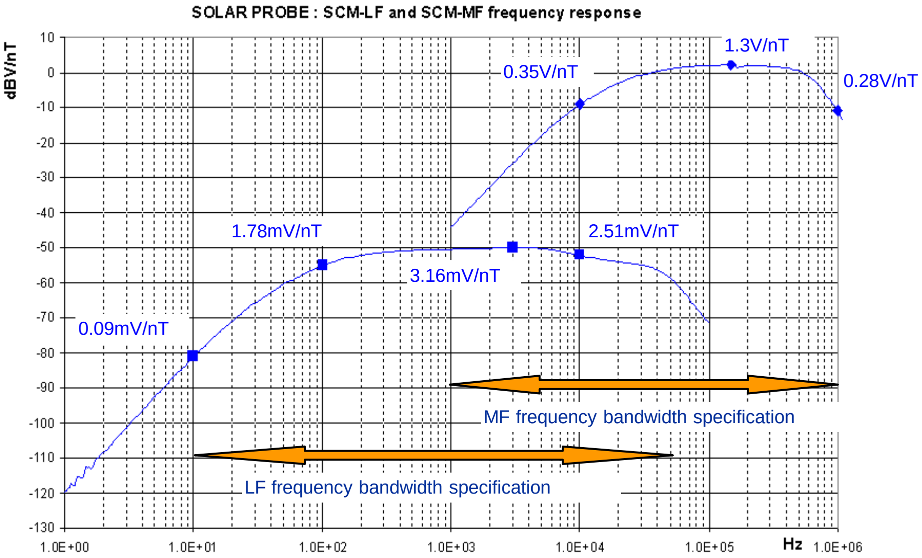
System Description
Search Coil Magnetometer

Main Components

- 2 single-band antennas (10 Hz-50 kHz range)
- 1 double-band antenna (10 Hz-50 kHz & 1 kHz-1 MHz)
- 4-channel miniaturized preamplifier inside sensor foot

Electrical Interfaces

- LF (X, Y, Z) and MF (X) signal outputs
- Calibration signal
- Heater power
- 2 Temp Sensors for Thermal Control
- 1 Temp Sensor for Telemetry



Specifications

- Electrical Power : 270 mW
- Vibration: 25 grms
- Shock: 2000 g
- Operational Temp: -50 to +80 C
- Survival Temp: -60 to +100 C

In development for Solar Orbiter
Being delivered for Taranis

System Description
Preamps & Antenna Electronics

Solar Probe Plus
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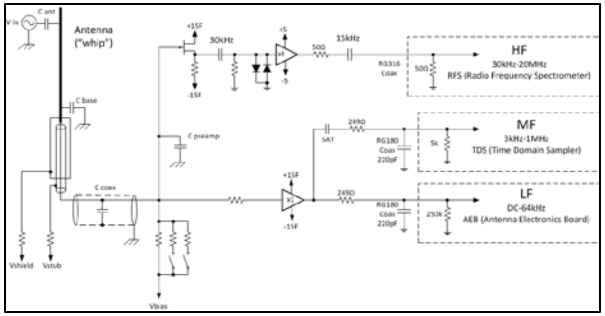
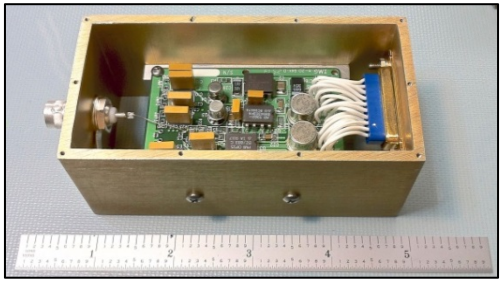
Preamps

- Low Input capacitance: 25pF
- High bandwidth output: > 50MHz
- Low Noise: 3nV/√Hz
- Mid & Low bandwidth out: > 5MHz
- Low Power : 190mW

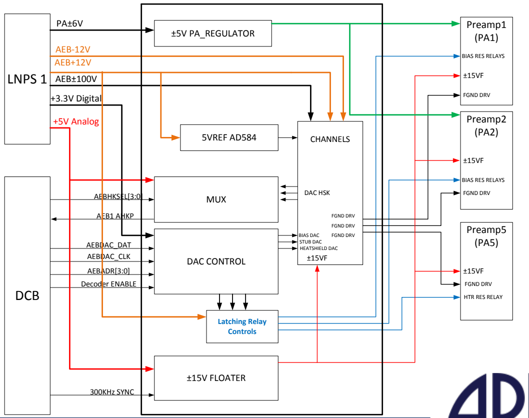
Antenna Electronics Board (AEB)

- AEB1 controls V1,V2 and V5
- AEB2 controls V3, V4
- Delivers BIAS, STUB, HEATSHIELD and +/-15V (Floating) for each antenna
- Controls Preamp Bias Resistor network.
- Provides V5 Heater power, monitors temperature





AEB 1 BLOCK DIAGRAM

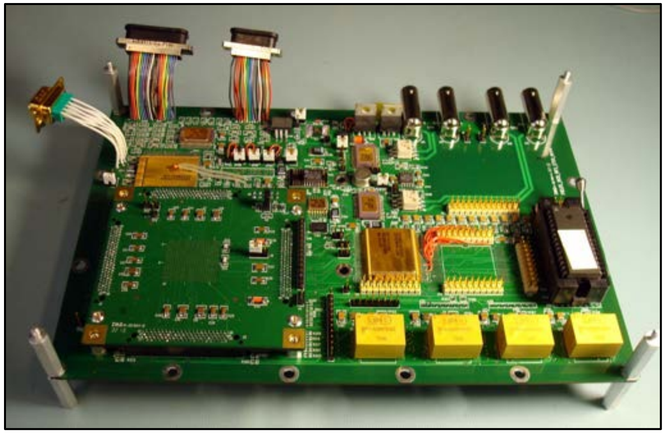


System Description

Data Controller Board and Radio Frequency Spectrometer

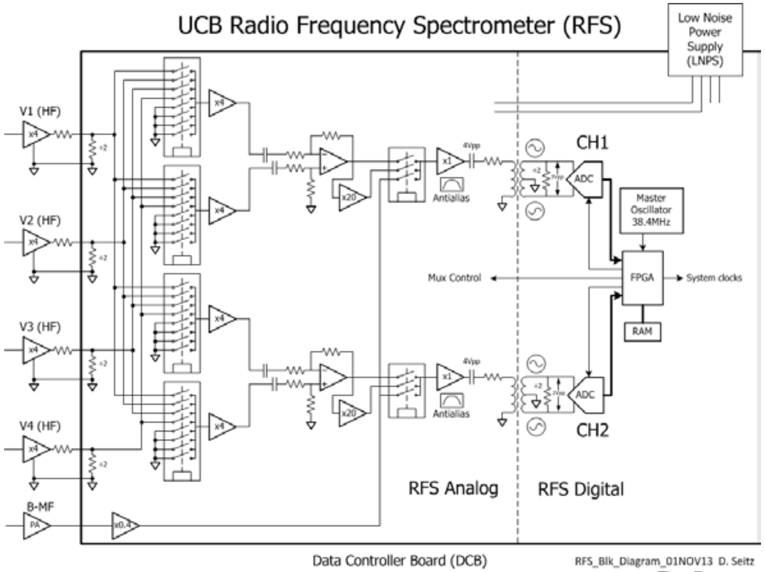
DCB Main Features

- RTAX-4000 FPGA daughter board with Coldfire processor at 38.4 MHz
- Controls AEB, RFS, MAG, DFB, TDS, and LNPS
- Processes MAG, DFB, RFS Survey Data
- Records/Dumps DFB & TDS Data using 32GB Memory
- Provides Master Clock for FIELDS Synchronization
- Provides 24 analog housekeeping channels



RFS Main Features

- Receives V1-V4, SCM MF signals
- Digitizes at 38.4 and 3.84 MHz using SRAM
- Produces High and Low Frequency Spectra, Cross Spectra, Phase and Coherence Survey Data
- Uses Rad-hard 12-bit 50 Msps A/D converters
- 2 identical channels each with High/Low gain
- Selection of 2 Differential or Single-Ended signals
- Has Low Noise: <4nV/√Hz from 30kHz to 16MHz



System Description
Digital Fields Board

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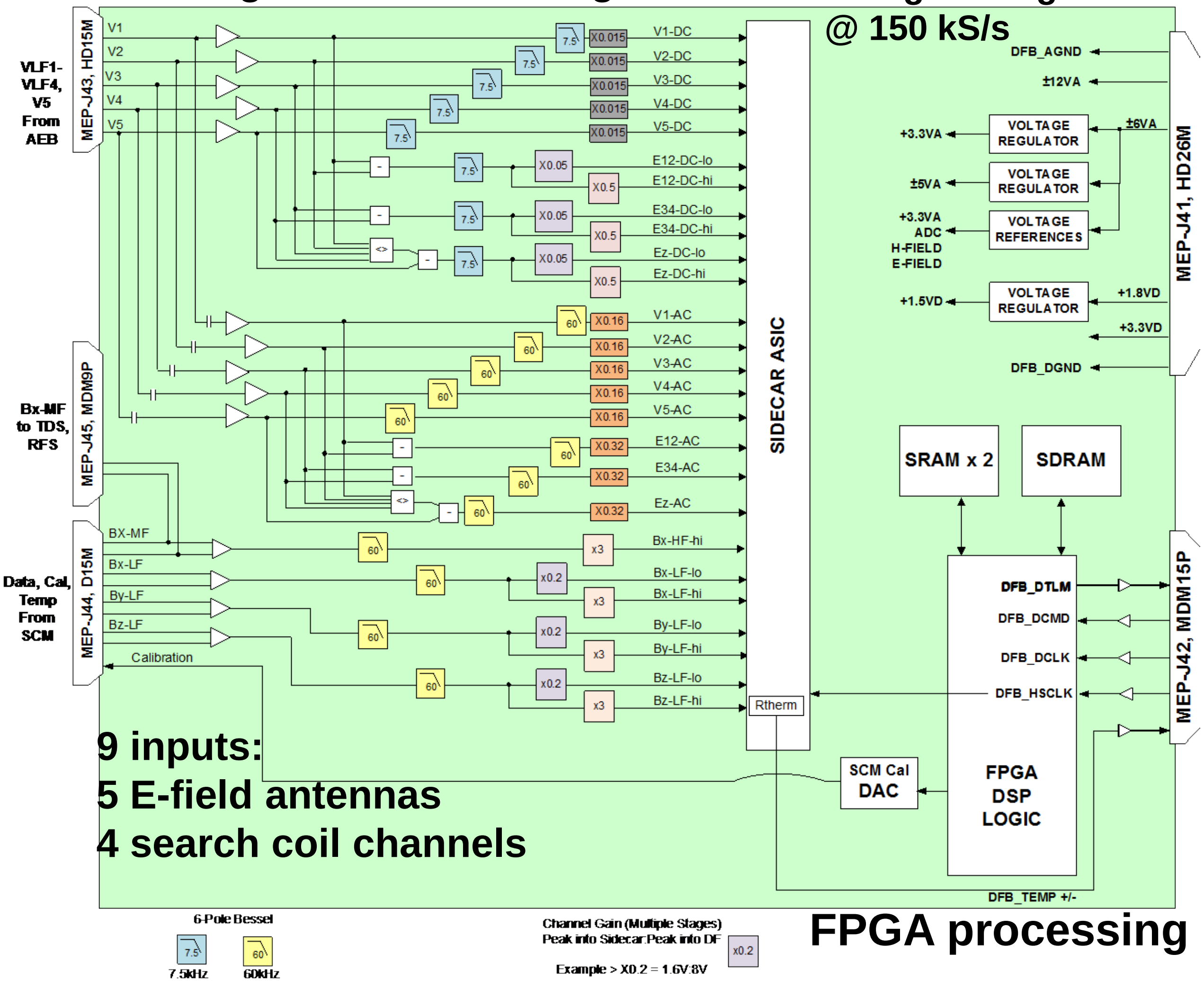
Analog Filters / Gain stages

26 signals digitized @ 150 kS/s



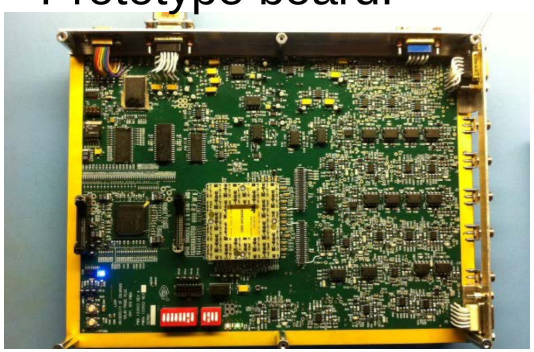
9 inputs:
5 E-field antennas
4 search coil channels

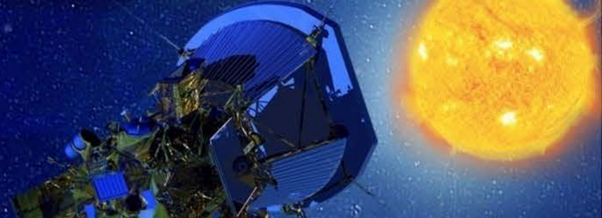
FPGA processing

Generates time domain and spectral domain data products (DC – 75kHz)

Implementation includes:
- Programmable gain states
- Burst memory
- Flexible configurations
- Search coil cal. signal
- Low mass, low power ADC

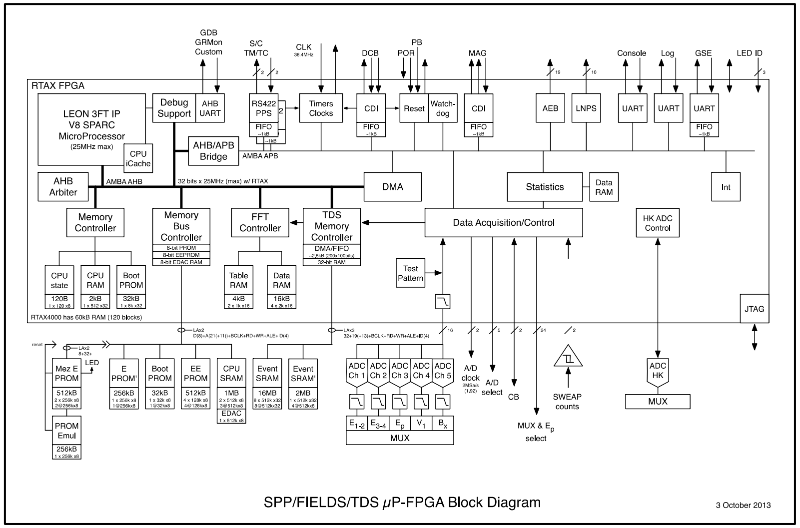
Prototype board:

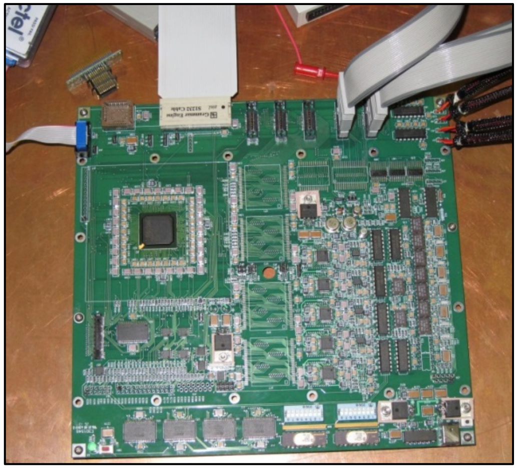




System Description
TDS Data Acquisition System

- **Centers on RTAX4000 FPGA daughter board with LEON-3 processor**
- **Records impulsive events (waveforms)**
- **Event data gathered by 16-bit ADCs at ~2MSa/s**
- **Simultaneous acquisition of SWEAP particle counts**
- **Event data stored directly into 16 MB event memory**
- **Event scoring, best events telemetered**
- **Interfaces: S/C, DCB, MAG, SWEAP, AEB, LNPS**
- **Telemetry: 10,000 b/s programmable**
- **Similar to: STEREO**

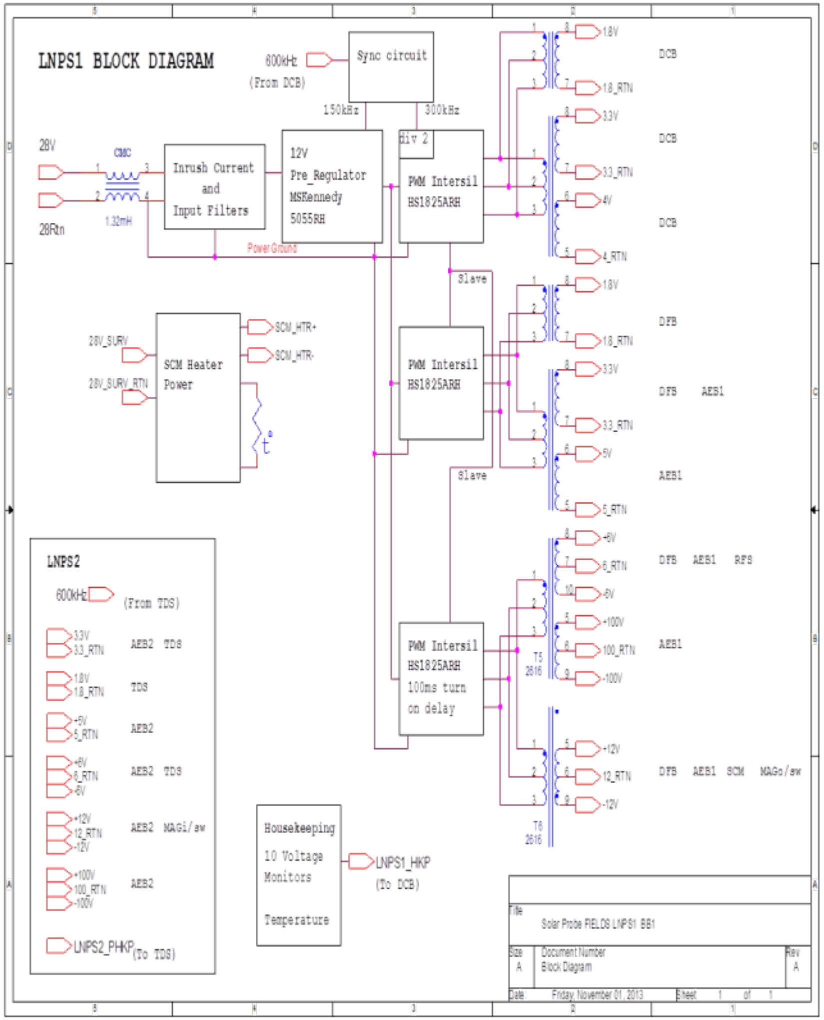




System Description
Low Noise Power Supply

Solar Probe Plus
A NASA Mission to Touch the Sun

- Input from : 22 to 35 VDC
- Temp range : -25C to +65C
  - Prime mission runs at 55ºC
- Sync : 150 kHz
- Output: DC voltage supplies
  - 1.8V, 3.3V, 4V, 5V, ±6V, ±12V
  - ±100V (with 100ms delay)
- Total Power:
  - 9W for LNPS1
  - 5W for LNPS2
  - Loads increase with temperature
- Monitors: 10 Voltages, 2 Temps
- Controls: SCM heater (in LNPS1)
- Similar to: STEREO



APL

System Description Resources

Mass

- **Detailed estimates of all MEP boards**
- **Harnessing included from MEP to Sensors**

Component	Mass (kg)		
	CBE	Cont. %	NTE
MEP	7.99	15%	9.19
V1/2/3/4	3.30	15%	3.80
SCM sensor	0.52	15%	0.60
MAG sensors (2)	0.93	15%	1.07
V5 sensor	0.06	15%	0.07
Harnessing	3.55	15%	4.08
Blankets	0.73	15%	0.84
Total	17.08	15%	**19.65**

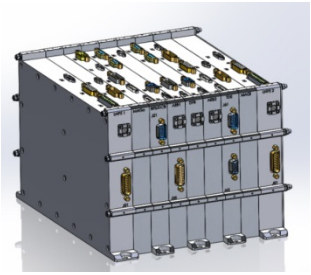
Power

- **MEP Power is ample at room temperature**
- **MEP Power at maximum temp is limiting factor**
- **Operational heater power has good margins**
  - **Improved heating to MAG sensors**

Case	Power (W)		
	CBE	Cont. %	NTE
Operational (<.25AU)	22.77	17%	26.65
Operational Heaters (<.25AU)	3.99	15%	4.59
Survival Heaters	9.37	15%	10.78

Telemetry

- **Survey data – 15Gb/perihelion**
- **Select data saved in internal Flash Memory**
- **Selected data played back during cruise – 5Gb/perihelion**



Assembly, I&T Description
Flight I&T Flow

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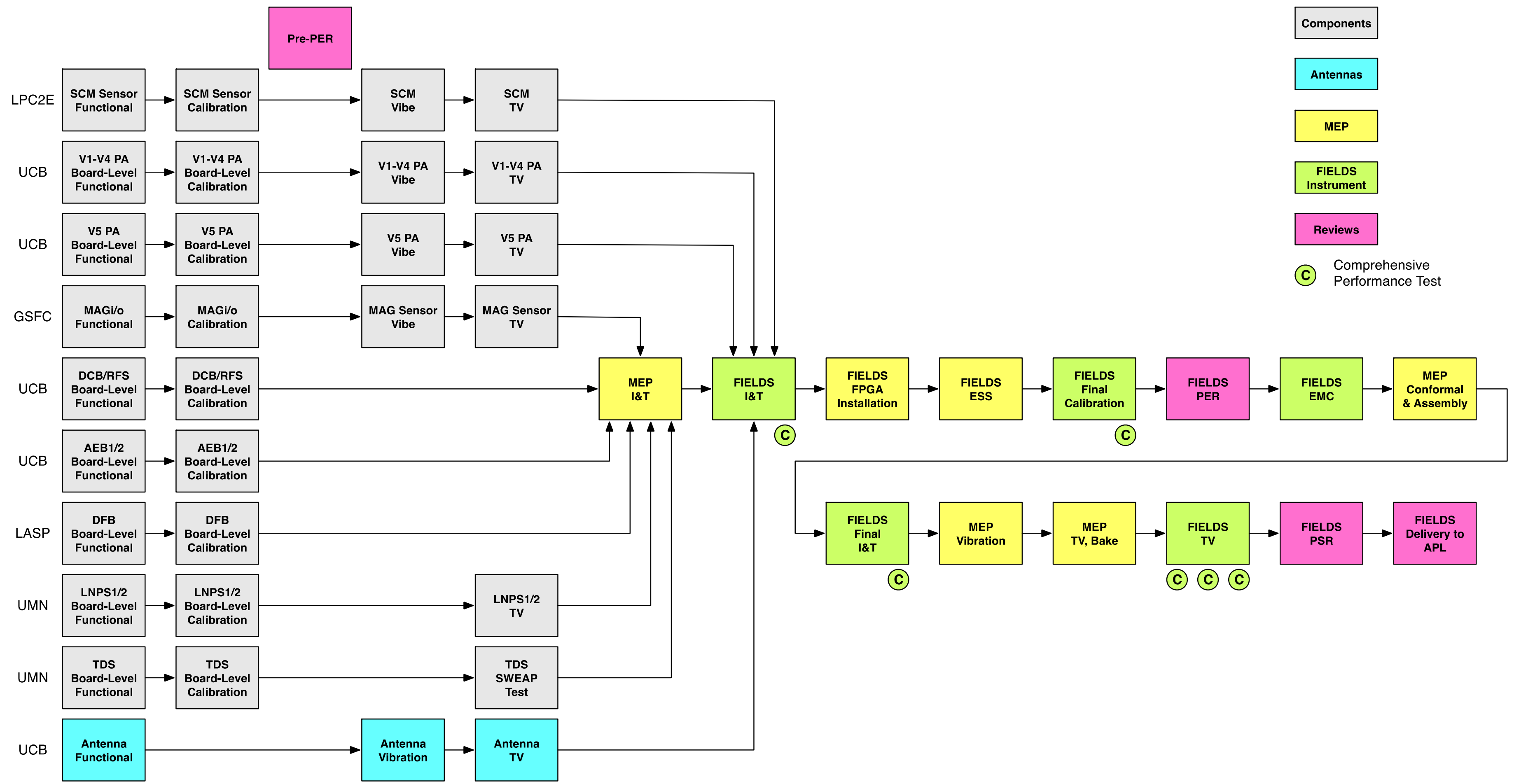


SPP/FIELDS FM I&T Flow

Assembly, I&T Description
Environmental Test Matrix

HARDWARE				MECHANICAL												ELECTRICAL					THERMAL CONTAM					OTHER	
COMPONENT (ITEM)	QUANTITY	SUPPLIER	TEST LOCATION	ALIGNMENT	MODAL SURVEY	STATIC LOAD	RANDOM VIBRATION	SINE VIBRATION	ACOUSTIC	PROOF TEST	CLAMP BAND SHOCK	VENTING/PRESS. PROFILE	MASS PROPERTIES	MECH Fn - DEPLOY	LIFE TEST	INTERFACE VERIFICATION	CONDUCTED EMISSIONS	CONDUCTED SUSCEPTIBI	RADIATED EMISSIONS	RADIATED SUSCEPTIBILIT	THERMAL VACUUM (# CYC	THERMAL BALANCE	ESC AND GROUNDING	DC MAGNETICS	BAKEOUT	RADIATION	FAILURE FREE HOURS
Instrument	2	UCB	UCB													T6	T7	T7	T7	T7	8		T9		T12		100
V1-V4 Preamps	4	UCB	UCB		T1	A1	T3	T3				A2	M1								8		T9	M2		T10	
V1-V4 Antennas	4	UCB	UCB		T1	T2	T3	T3					M1	T4		T6					8	T8	T9	M2			
V5 Sensor	1	UCB	UCB		T1	T2	T3	T3				A2	M1			T6					8		T9	M2		T10	
MAG Sensor	2	GSFC	GSFC		T1		T3	T3				A2	M1			T6					8					T10	
SCM Sensor	1	LPC2E	LPC2E		T1		T3	T3				A2	M1			T6					8					T10	
MEP	1	UCB	UCB		T1	A1	T3	T3				A2	M1			T6							T9	M2		T10	
Harness	1	UCB	UCB			T2							M1										T9	M2	T11		

A1: Yield of 2 x limit load, Ultimate at 2.6 x limit load
A2: 1 sq.in. vent area per cu.ft.

T1: 0.25g to 0.5g, 5 Hz to 2000 Hz
T2: Cable assy's undergo static load
T3: ETU tested to Qual, FLT to Acceptance
T4: Deploy @ temp extremes in TV
T6: ICD Compliance prior to I&T
T7: Per EDTRD
T8: Thermal Balance on one unit
T9: Grounding & ESC compliance prior to I&T
T10: Total Dose and SEU testing at part level
T11: 60C for 40 hrs prior to TV w/payload
T12: Verification w/TQCM at TV

M1: Mass, CG and MOIs measured
M2: DC Magnetics measured prior to I&T

Assembly, I&T Description
Thermal

- **Testing will be performed at +/-10 °C from predicted except:**
  - **Whip/shield will be tested +100 °C from predicted**
  - **Preamps will be tested -5 °C because they are heater controlled**
  - **MEP will be tested +/-10 °C from SC surface temperature prediction (predict shown is the box temp.)**
- **Testing temperatures will also be flight allowable**

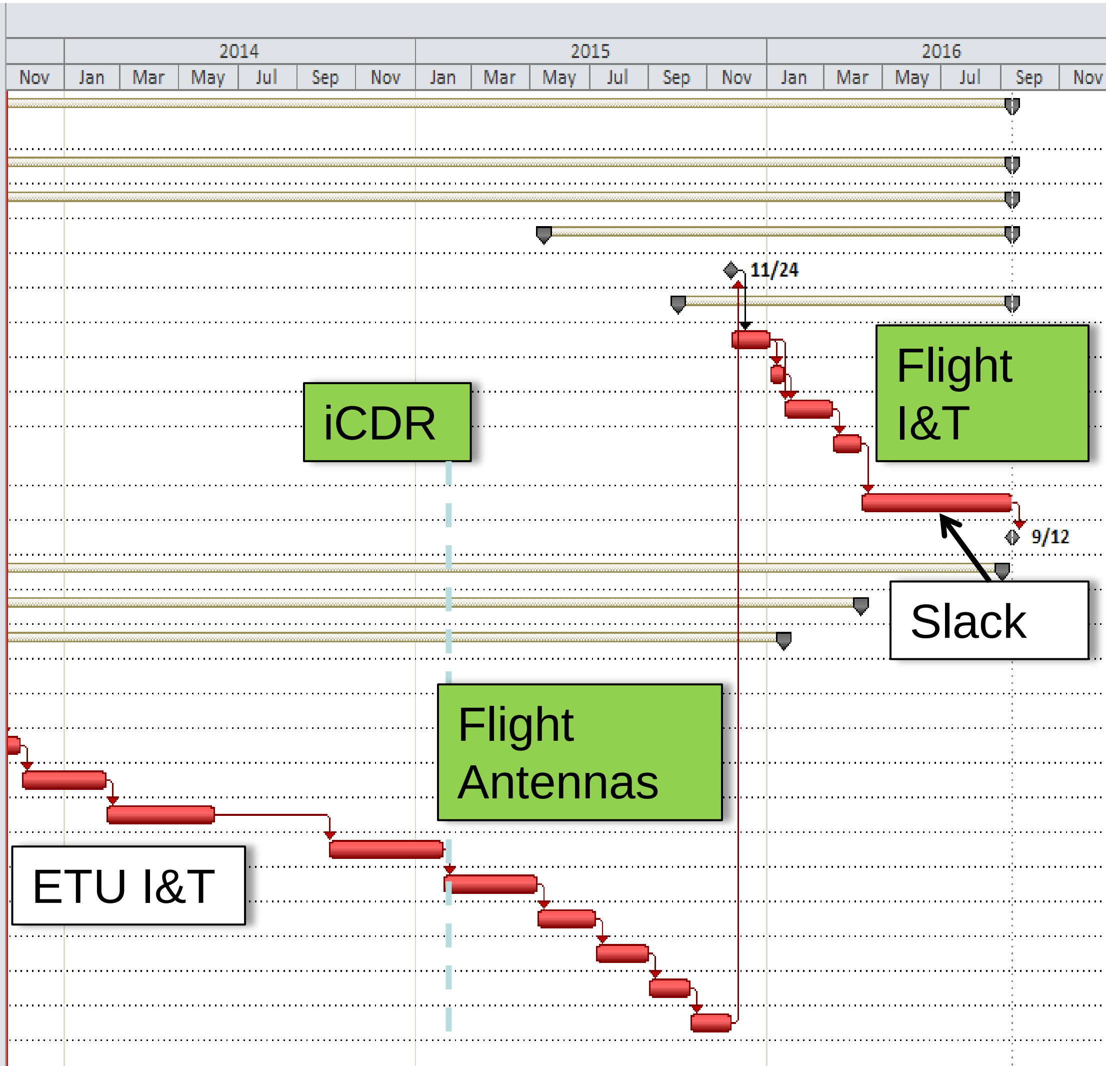
		Cold Survival Test/Allow (°C)	Cold Survival Predict (°C)	Cold Op. Test/Allow (°C)	Cold Op. Predict (°C)	Hot Op. Predict (°C)	Hot Op. Test/Allow (°C)	Hot Survival Predict (°C)	Hot Survival Test/Allow (°C)
Whip/Shield		-150	-135.6	25	38.7	1302	1405	1302	1405
Preamp V1-V4*		-60	-52.5	-60	-52.5	49.4	65	65.6	80
Hinge		-140	-127.0	-70	-59.0	30.6	45	208	215
Pin-Pullers	Pre-Open	-130	-118.3	-80	-68.6	35.4	50	62.4	75
	Post-Open	-130	-77.2	-	-	-	-	104.8	115
MEP		-30	-20	-25	-7.2	72.7	65	60	70
Preamp V5		-230	-216.7	-190	-177.5	4.3	40	60.2	75

Verification

- **Calibration**
  - **Co-I hardware institutions will deliver fully calibrated sub-assemblies**
  - **Calibration points will be verified at later points in I&T**
- **Mechanism Testing**
  - **Antenna mechanisms can be tested independently of electronics**
  - **Full functional testing – Vibration – TV**
- **Thermal Testing**
  - **1 survival and 6 operational thermal vacuum cycles – at minimum**
  - **Components with extreme environmental requirements tested at component level**
- **Contamination**
  - **Only contamination sensitivity is the antenna surfaces**
  - **No purge requirements**
- **EMC/ESC/MAG**
  - **Power supply conversion frequencies must be carefully controlled**
  - **Limited radiated and conducted noise**
  - **Electrostatics – S/C exterior an equipotential surface**
  - **Spacecraft must be magnetically clean**
  - **STEREO and RBSP are good models**

Development Status
Schedule Critical Path

	Task Name	Start	Finish
1	Solar Probe Plus Mission Schedule (See TSSD-21298 Letter)	7/2/08	9/12/16
15	Instruments	11/14/11	9/12/16
16	FIELDS	11/14/11	9/12/16
103	FIELDS FLT	5/14/15	9/12/16
112	ANT FLT Delivered	11/24/15	11/24/15
116	I&T FLT	10/2/15	9/12/16
118	FUNCTIONAL TESTING	11/25/15	1/4/16
119	iPER Package Preparation	1/5/16	1/19/16
120	QUAL TESTING	1/20/16	3/9/16
121	FIELDS Acceptance Package Preparation (iPSR Presentation)	3/10/16	4/7/16
122	Schedule Reserve	4/8/16	9/12/16
123	FIELDS Instrument Delivery to APL	9/12/16	9/12/16
124	FIELDS Links	1/5/12	9/1/16
125	System Dates v. 04/05/2013	2/11/13	4/8/16
228	ANT Milestones v. 10/03/2013	10/1/12	1/19/16
232	ANT BB Fab & Assy	5/21/13	10/9/13
233	ANT BB Testing	10/3/13	10/23/13
234	ANT ETU Design Drawings	10/24/13	11/15/13
235	ANT ETU Fab & Assy	11/18/13	2/13/14
236	ANT ETU Testing	2/14/14	6/6/14
237	ANT FLT Design Drawings	10/3/14	1/29/15
238	ANT FLT Fab	1/30/15	5/7/15
239	ANT FLT1 Assembly & Test	5/8/15	7/6/15
240	ANT FLT2 Assembly & Test	7/7/15	8/31/15
241	ANT FLT3 Assembly & Test	9/1/15	10/13/15
242	ANT FLT4 Assembly & Test	10/14/15	11/24/15



FIELDS Instrument Risks Status

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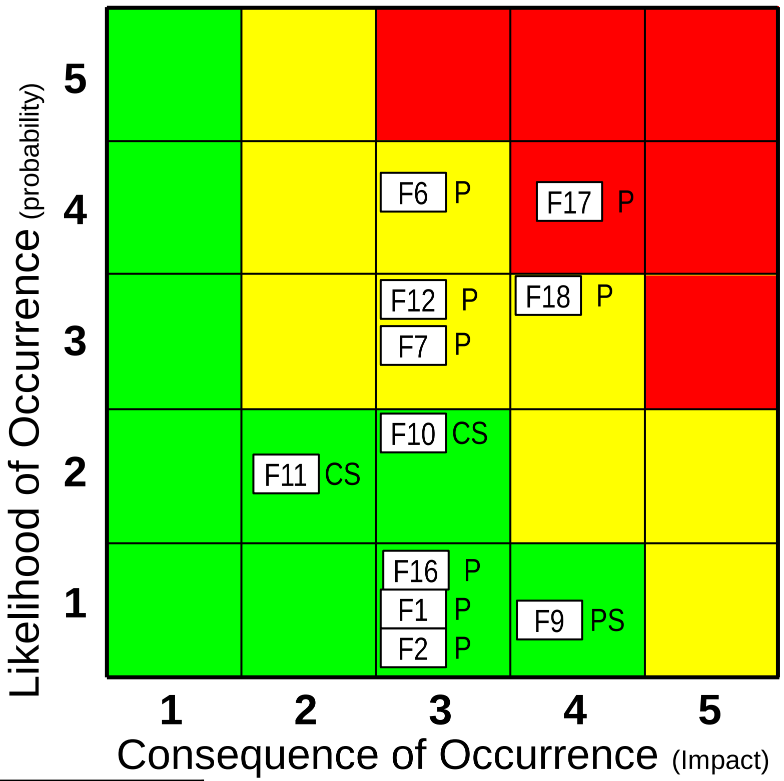

P = Performance
C = Cost
S = Schedule
M = Mass

High **Medium** **Low** (Criticality)

ID	TITLE	P	I	Crit	Retire At
F17	Inboard/Outboard MAG Sensor Interference	4	4	H	Instrument CDR (01/15)
F12	Magnetic Cleanliness	3	3	M	Mission I&T (~8/16)
F7	ElectroStatic Contamination	3	3	M	Mission I&T (~8/16)
F18	Antenna Thermal Environment	3	4	M	Instrument CDR (01/15)
F6	Magnetic Sensor Interference	4	3	M	ETU I&T (~8/14)
F16	MEP Thermal Environment	1	3	L	Parts confirmed at MEP Thermal Vac (11/14)
F9	Magnetic Sensor Qualification	1	4	L	MAG Thm Test by I-CDR (~1/15)
F10	Antenna Qualification	2	3	L	Ant. Qual (11/13)
F11	SCM dependence on Solar Orbiter	2	2	L	SO FLT SCM Complete
F1	S/C Conducted and Radiated Noise Contamination	1	3	L	Mission I&T (~8/16)
F2	Plasma Wake Effects	1	3	L	Mission CDR (~3/15)

Mitigation Plans in Place for All FIELDS Risks

Evaluation Date: 12/13/13

Science Operations Center Operations, Requirements

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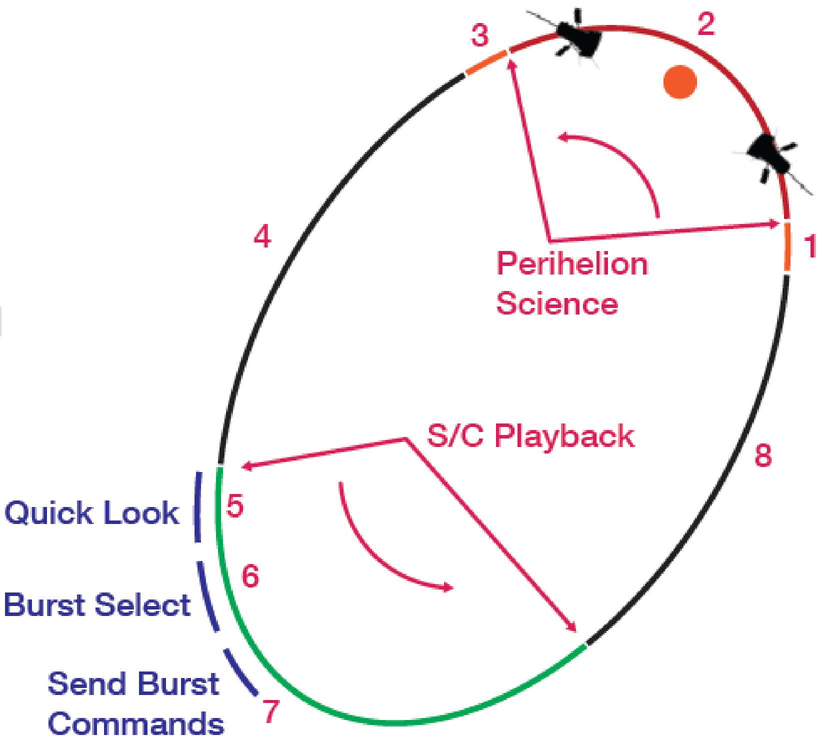
- Each encounter, the FIELDS SOC must coordinate several time sensitive activities:
  - Immediate processing of first data received/production of quick look plots
    - Requires smooth and rapid automated operation for producing useful data products
  - “Aphelion” science team meeting to select periods of interest for downlink of burst data
    - Requires appropriate facilities and tools for coordinated decision making
  - Uplink of burst playback commands and commands for next perihelion
    - Requires efficient command communication between Science and Ops teams



1. Calibration
2. High rate science
3. Calibration
4. Cruise
5. Data processing: Quick Look plots produced and distributed
6. FIELDS team convenes to select periods of interest for burst data
7. Command uplink / telemetry downlink
8. Cruise

Science Operations Center Block Diagram

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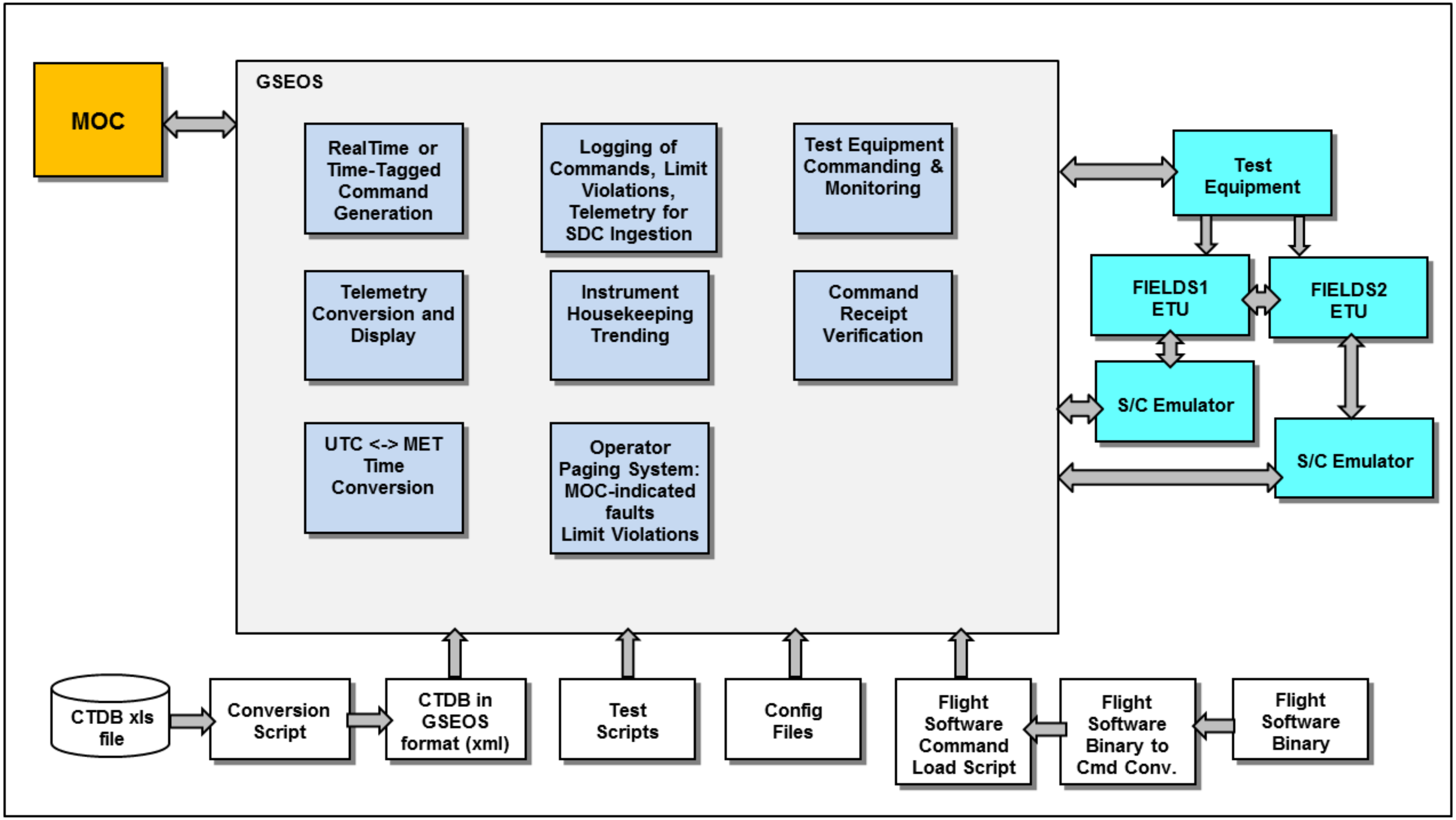


APL

Science Operations Center Data Products

Level	Description	Time to Availability	Users
L0	Raw telemetry produced by SPP MOC. Possibly 24-hour, ApID-separated, sorted, cleaned. PTP and SSR binary files.	Files retrieved from MOC as soon as available. Processing time: < 6 hours after receipt time T_0	FIELDS SOC Archives
L1	Uncompressed and decommutated L0 + Time-tagged waveform and spectral data in telemetry and engineering units [V, dBs, nT] in spacecraft coordinate system. Data affinity groups. ISTP-compliant CDFs (one per subsystem per day)..	Automated processing as soon as L0 files are available. Processing time scale: T_0 + ~1 day.	FIELDS SOC FIELDS team Archives
L2	L1 + Time-tagged waveform and spectral data in fully calibrated physical units [V, mV/m, nT, $(V/m)^2/Hz$, nT^2/Hz] in spacecraft and heliophysical coordinate systems. ISTP-compliant CDFs. Quick Look and daily/orbital summary plots.	Automated processing as soon as L1 files are available. Validated internally by FIELDS team and served via FIELDS SOC. Processing time scale T_0 + ~2 days	FIELDS SOC FIELDS team SPP science team Science community Public Archives Web access tools Other end users (archives, Virtual Observatories, etc.)
L3	L2 + VxB removal for DC E-field measurement, offsets and corrections with data quality flags. Plasma density. Spacecraft potential. Merged B. ISTP-compliant CDFs. Science data plots.	Requires V from SWEAP, full orbit's worth of survey data, and inspection by FIELDS team for quality determination. Processing time scale: T_0 + 1 orbit	
L4	Event lists (shocks, current sheets, radio bursts, stream interaction regions) with time tags and derived parameters.	Event lists will be maintained continuously and updated. Time scale: T_0 + 1 orbit	

Review Action Item Status

Review	Date	Result	# Reviewers	#RFAs/Rec's	# Open	# Closed	Concurred
I-PDR	Nov 13-14,2013	PASS	60	20 / 26	20 / 26	0 / 0	0 / 0
Peer Reviews							
DCB-RFS Board	Oct 25,2013	PASS	18	12	7	5	n/a
DCB FPGA	Oct 25,2013	PASS	18	2	0	2	n/a
DCB FSW	Oct 25,2013	PASS	18	2	1	1	n/a
AEB Board	Oct 24,2013	PASS	20	6	3	3	n/a
Preamps	Oct 24,2013	PASS	20	7	5	2	n/a
DFB Board	Nov 4-5, 2013	PASS	12	3	2	1	n/a
DFB FPGA	Nov 4-5, 2013	PASS	9	2	2	0	n/a
DFB ASIC	Nov 4-5, 2013	PASS	9	1	1	0	n/a
TDS Board	Oct 25,2013	PASS	18	3	0	3	n/a
TDS FPGA	Oct 25,2013	PASS	18	7	1	6	n/a
TDS FSW	Oct 25,2013	PASS	18	2	2	0	n/a
LNPS Board	Oct 24,2013	PASS	20	8	1	7	n/a
SCM Sensors	Sep 6,2013	PASS	17	24	19	5	n/a
MEP Chassis	Jul 17,2013	PASS	15	13	13	0	n/a
Antenna System	May 21,2013	PASS	10	21	12	9	n/a
V5 System	Jul 17,2013	PASS	15	19	16	3	n/a
MAG System	Oct 29,2013	PASS	6	15	6	9	n/a

Summary

- **FIELDS is on cost and schedule**
- **FIELDS has achieved TRL-6**
- **FIELDS has passed its Instrument PDR**
- **There are no “show stoppers”**
- **FIELDS is ready for Phase C**

Backup

Backup
Design Trades

Trade #	Description	Result
1	Discrete ADC vs. SIDECAR ASIC	SIDECAR ASIC implemented to save mass, power, volume
2	Use two RTAX2000 or a single RTAX4000 for DCB/RFS	RTAX 4000 implementation is lower power and lower mass.
3	Build a copy of TNR/HFR or build a new design (mostly digital)	Go digital. Using SETI technology developed at UCB
4	Use 150 KHZ Synchronization or try analog filtering	Heritage analog systems cannot filter power supply noise at this level. No quantifiable issue with the frequency change
5	Selection of 9 system changes to increase FIELDS robustness with a variety of mass and power impacts.	Selected System #6 as the most effective configuration with the least impact on mass and power.

Design Trades to be Completed

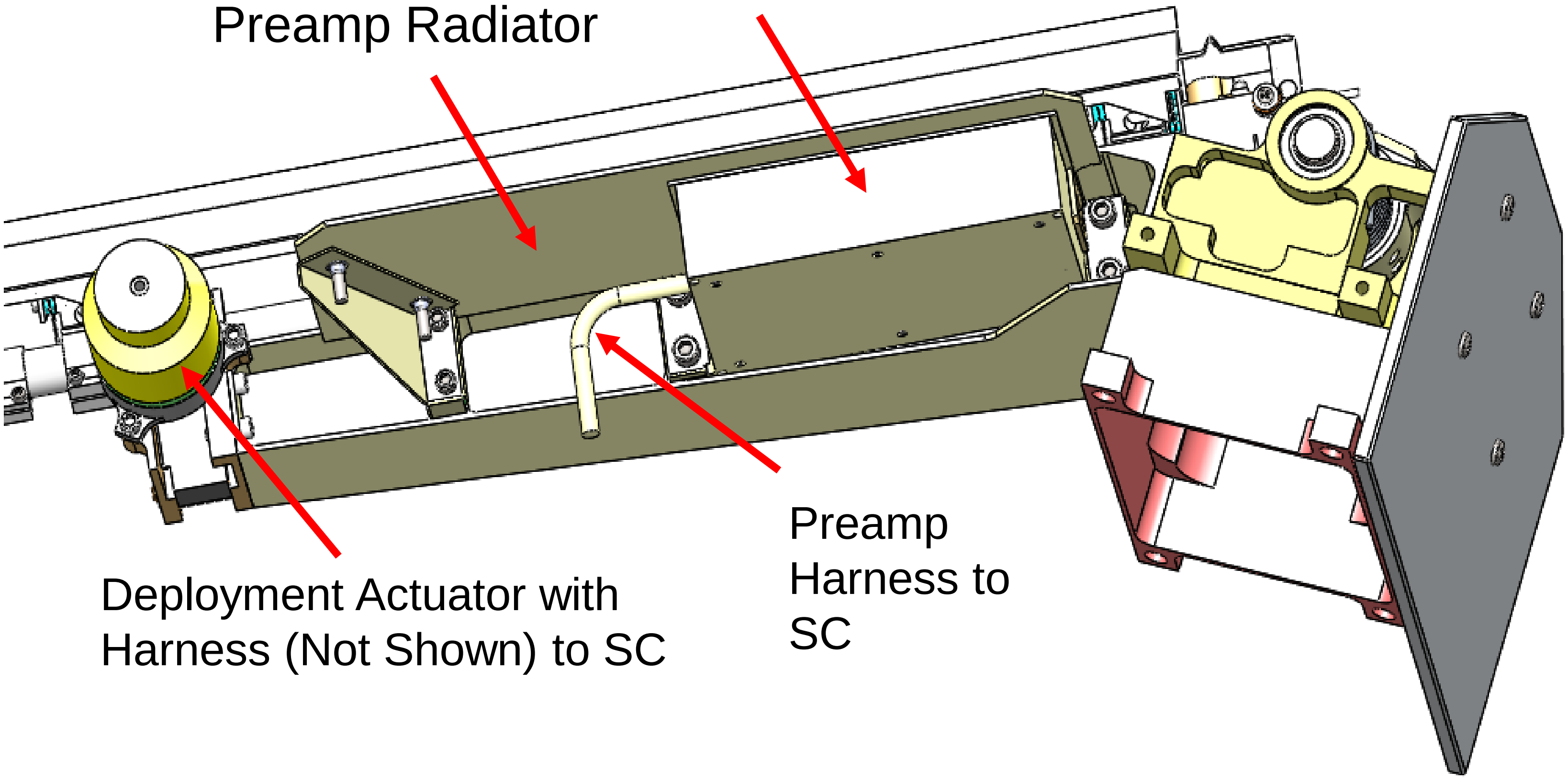
Trade	Description	Expected
1	SCM Cal Signal	ETU Integration Complete (Nov '14)
2	Order of the MAG and SCM sensors on the MAG Boom	iCDR

Backup Analyses

Analyses Completed		
Analysis#	**Description**	**Result**
1	Limited Life Items Analysis	No Limited Life Items in FIELDS
2	FIELDS FMEA	Delivered
3	MEP FEA	Delivered
4	Antenna FEA	Delivered
5	MEP Thermal	Delivered
6	Antenna Thermal	Delivered
7	V5 Thermal	Delivered
8	MAG Sensor Thermal	Delivered
9	SCM FMEA	Delivered

Analyses to be Completed		
Analysis#	**Description**	**Expected**
1	PCB deflection at MEP frequency modes	Mass model vibration test and model coorelation to support structural design
2	Signal Integrity on FPGA Daughter Board	RFA concern wrt # of gnd and power pins, recommend increasing gnding and pwr scheme on main PCB and leave DB as is
3	SCM Sensor Thermal	In progress

System Description
Preamps



System Description
Antenna Structural Analysis

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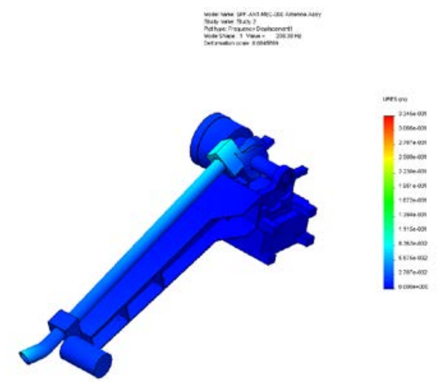
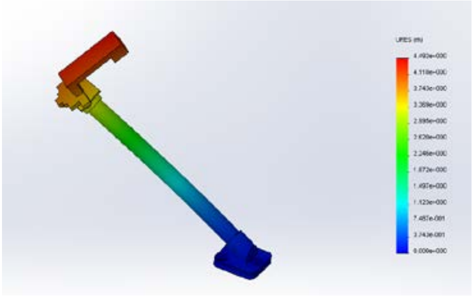
Base:

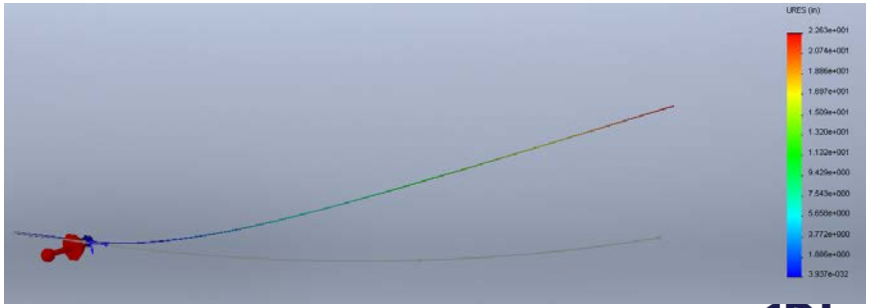
- **1st Mode Predict: 208 Hz**
- **Per 20 G_{RMS} from EDTRD with 36 G Notching (with APL Concurrence)**
  - **Max Stress Margin = 0.48**



- **Mid-Cage:**
- **1st Mode Predict: 130 Hz**
  - Max Stress Margin = 0.14 (Requirement > 0)



- **Whip:**
- **1st Mode predict: 5 Hz**
  - Breadboard Vibration Test ~6 Hz
  - Strength Margin 0.54 (Requirement > 0)

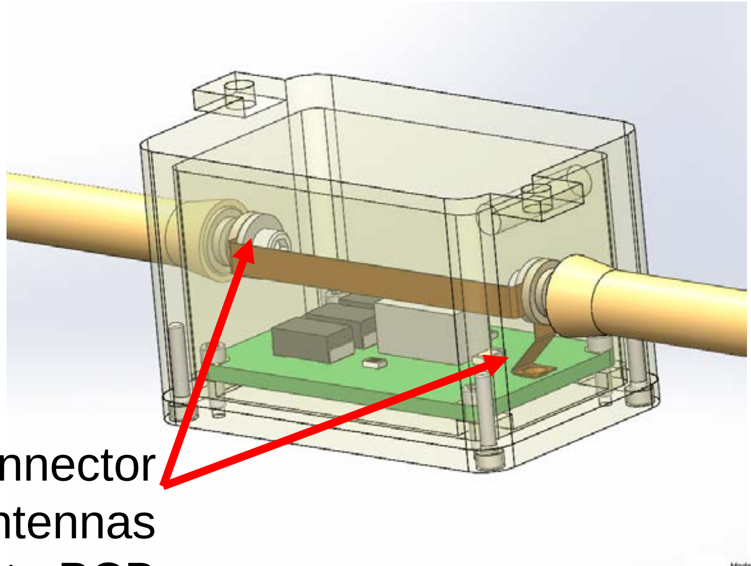


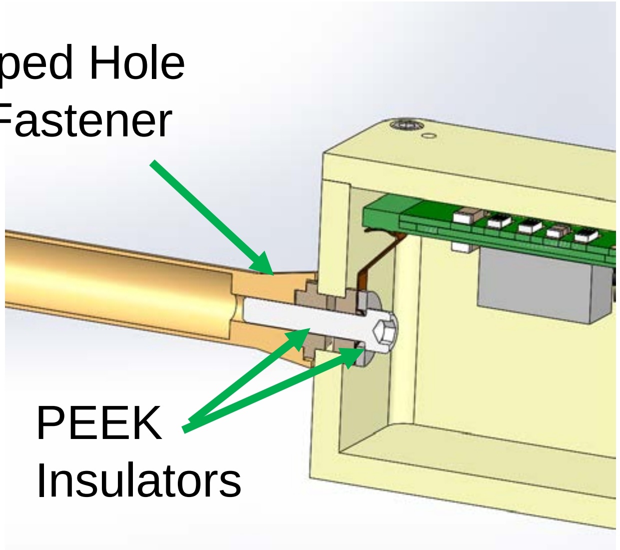
System Description
Margins Table

Item	Figure of Merit	Requirement
Whip Cage Release Spring Force Margin	0.57	> 0
Deployment Spring Torque Margin	> 4	> 0
Deployed Antenna Pointing Budget	±1.2°	±2.0°*
Antenna Hinge/Stub Assembly 1st Mode	>100 Hz	> 100 Hz
Antenna Hinge/Stub Strength Margin	0.48	> 0
Monopod 1st Mode	129 Hz min	> 100 Hz
Monopod Strength Margin	0.14	> 0
Stowed Whip 1st Mode	6 Hz	5-6 Hz*
Whip Strength Margin	0.54	> 0
Niobium-C103 Temperature (Shield, Whip)	1315°C	< 1500°C
Moly-TZM Temperature (Clamps)	650°C	>> 1000°C

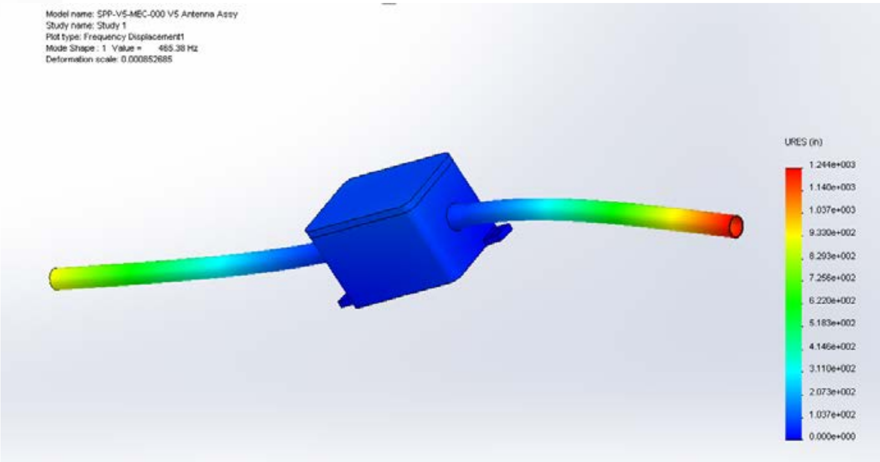
*Level 5 Instrument Team Requirement

System Description V5 Antenna



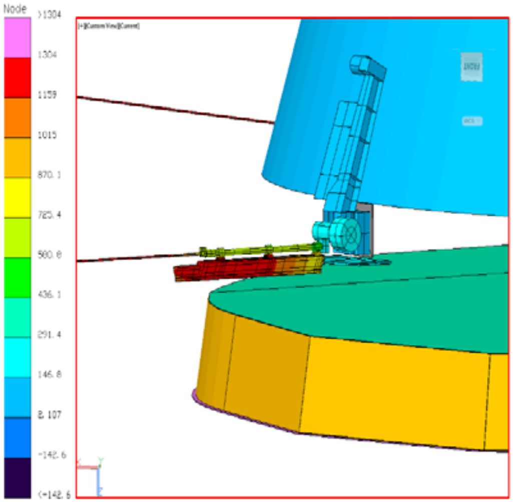


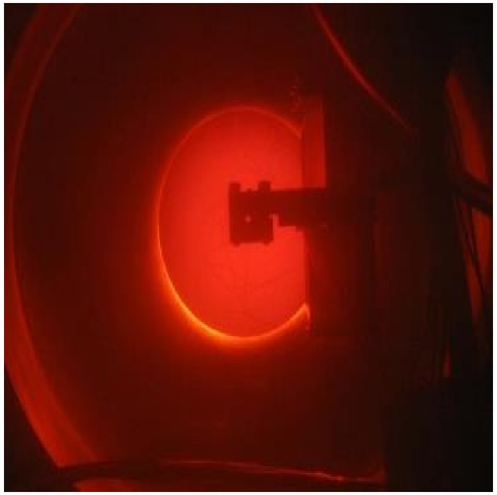
- 1^{st} Mode > 400 Hz
- No boom environment yet. Based on EDTRD panel mount,
  - Max Stress Margin: 0.74 (Requirement >0)



FIELDS Antenna/MEP Thermal Design

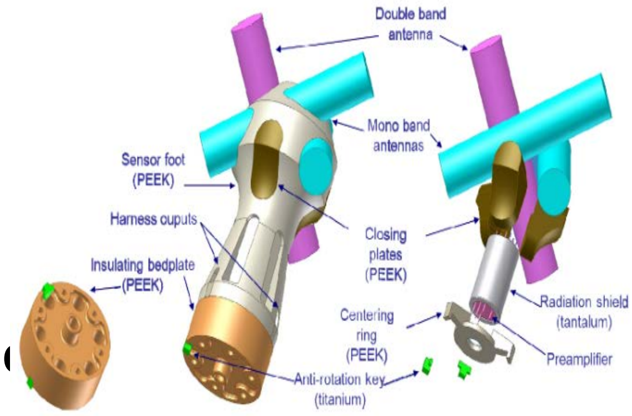
- **V1-V4**
  - **High temperature metals used: Nb C103, Molybdenum TZM on Whip and shield**
  - **Shield shape optimized to reduce maximum temperature**
  - **Sapphire and alumina thermal and electrical insulators**
  - **Thermal isolated from spacecraft by Ti spacer**
  - **Preamps MLI blanketed one side, protects from TPS heat. Radiator with electrically conductive white paint (Z93).**
  - **Small shield with high temperature MLI blanket to protect hinge mechanism from TPS heat**
  - **Preamps have heaters for pre-science cases of 2.3 W**
  - **Testing performed at flight temperatures for model correlation**
  - **Current heat flux transfer to SC radiators 335W**
- **V5**
  - **Preamp located at the MAG-boom will be isolated with Ultem spacers.**
  - **MLI blanket used to retain heat**
  - **Cold temperatures will be tested at cold helium**
- **MEP**
  - **Outer surface painted with black (Z307) electrically conductive paint**
  - **Box placed inside the spacecraft thermally coupled with wet mount and 10 #8 bolts**

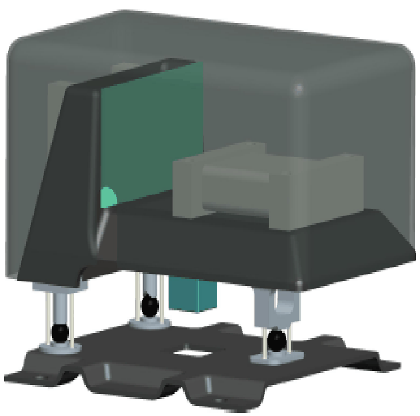




FIELDS SCM/MAG Thermal Design

- **SCM**
  - **MLI Blanket covering the SCM**
  - **Isolated from boom (peek bedplate)**
  - **Harness wrapped inside MLI to reduce heat loss**
  - **Heater of 0.8 W placed inside near electroni for improved efficiency**
- **MAG**
  - **MLI blanket covering the entire MAG**
  - **Ti-6Al-4V Kinematic mounts with SiN spheres to isolate from boom**
  - **Shielded twisted pair (STP) 26 AWG wires for heaters (to reduce heat leak)**
  - **G10 Spacers to isolate mounting plate from boom**
  - **DC heaters of 1.7 W, 30% loss due to inefficiency**





Risk Impact Classification

ank	Impact	Safety (NPG 8715.3)	Mission Performance	Project Execution
5	**Very High**	**I Catastrophic** - A condition that may cause death or permanently disabling injury, facility destruction on the ground, or loss of crew, major systems, or vehicle during the mission.	**Total Loss of Mission –** (Minimum mission success criteria is not achievable)	**Technical** – Threatens ability to meet minimum mission success criteria, estimates exceed established margins (mass, power, volume) **Cost** – Greater than 10% increase over that allocated and/or exceeds available reserves **Schedule** – Major impact to critical path and cannot meet major milestone.
4	**High**	**II Critical** - A condition that may cause severe injury or occupational illness, or major property damage to facilities, systems, equipment, or flight hardware.	**Loss of Science -** (Major impact to full success criteria, minimum success criteria is achievable)	**Technical** –Threatens established margins **Cost** – Between 7% and 10% increase over that allocated, and/or threatens to reduce reserves below prudent levels **Schedule** – Significant impact to critical path, and cannot meet established lower-level milestone. Level 2 milestone slip of > 1 month, or Project critical path impacted.
3	**Moderate**	**III Moderate** - A condition that may cause minor injury or occupational illness, or minor property damage to facilities, systems, equipment, or flight hardware.	**Degraded Mission -** (Does Not Meet Full Success Criteria, Meets Minimum Success Criteria with margin)	**Technical** –Can handle within established margins. **Cost** – Between 5% and 7% increase over that allocated, and can be handled within available reserves. **Schedule** – Moderate impact to critical path, but can handle within schedule reserve, no impact to milestones. Level 2 milestone slip of < 1 month.
2	**Low**	**IV Negligible** - A condition that could cause the need for minor first aid treatment though would not adversely affect personal safety or health. A condition that subjects facilities, equipment, or flight hardware to more than normal wear and tear.	**Not Used**	**Technical** –Can handle within established margins. **Cost** – Between 2% and 5% increase over that allocated, and can be handled within available reserves. **Schedule** – Minor schedule impact, but can handle within schedule reserve; no impact to critical path. Some additional activities may be required.
1	**Very Low**	**Negligible or No Impact**	**Loss of Non-Critical Function -** (Loss or Degradation of Redundancy)	**Technical** – No impact on margins. **Cost** – Less that 2% increase over that allocated, and can be handled within available reserves. **Schedule** – Minimal or no impact to schedule, no impact to schedule reserve; no impact to critical path.

FIELDS
Risk Likelihood Evaluation

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Rank	Likelihood	Safety	Mission Performance	Project Execution
5	Very High	$P_{SE} > 10^{-1}$	$P_T > 50\%$	$P_{CS} > 75\%$
4	High	$10^{-2} < P_{SE} \leq 10^{-1}$	$25\% < P_T \leq 50\%$	$50\% < P_{CS} \leq 75\%$
3	Moderate	$10^{-3} < P_{SE} \leq 10^{-2}$	$15\% < P_T \leq 25\%$	$25\% < P_{CS} \leq 50\%$
2	Low	$10^{-6} < P_{SE} \leq 10^{-3}$	$2\% < P_T \leq 15\%$	$10\% < P_{CS} \leq 25\%$
1	Very Low	$P_{SE} \leq 10^{-6}$	$0.1\% < P_T \leq 2\%$	$P_{CS} \leq 10\%$

Risk Type	Description
Safety	Potential problem that includes the potential for personnel injury and/or damage to hardware/facilities. The Safety related risks documented in hazard analyses are entered into the Project RM process to ensure that the Project has access to all the risks to mission success.
Mission Performance	Potential problem that includes the potential for impact to Flight/Ground segments during operations (i.e., "end products" performing their desired functions in their operational environments). This aspect of risk addresses the potential of not meeting mission requirements, possibly resulting in degraded science or total loss of mission. Reliability analyses are key to identifying Mission Performance risks.
Project Execution	Potential problem that includes the potential for impact to development activities or the ability to deliver the required product within the allocated budget, schedule and technical resources. This aspect of risk addresses programmatic risk related to delivering a fully functioning observatory to the launch site, on time, and within budget.

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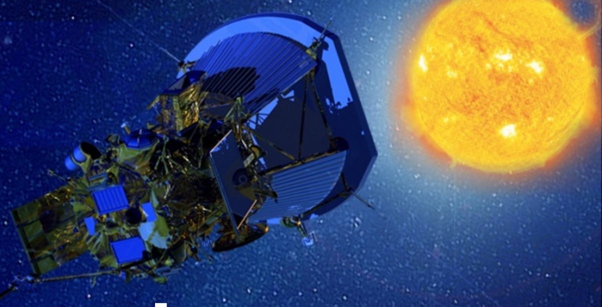

Solar Wind Electrons Alphas and Protons (SWEAP) Investigation

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University of Michigan / Smithsonian Astrophysical Observatory

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13 – 16 January 2014

The Johns Hopkins University
APPLIED PHYSICS LABORATORY

Agenda

- Science Overview
- Team Organization
- Instrument Overview
- Changes Since SRMDR
- System Description
- Assembly and I&T Description
- Verification
- Development Status
- Science Operations Center
- Risk
- Review Action Item Status

Science Overview

SWEAP Measurements

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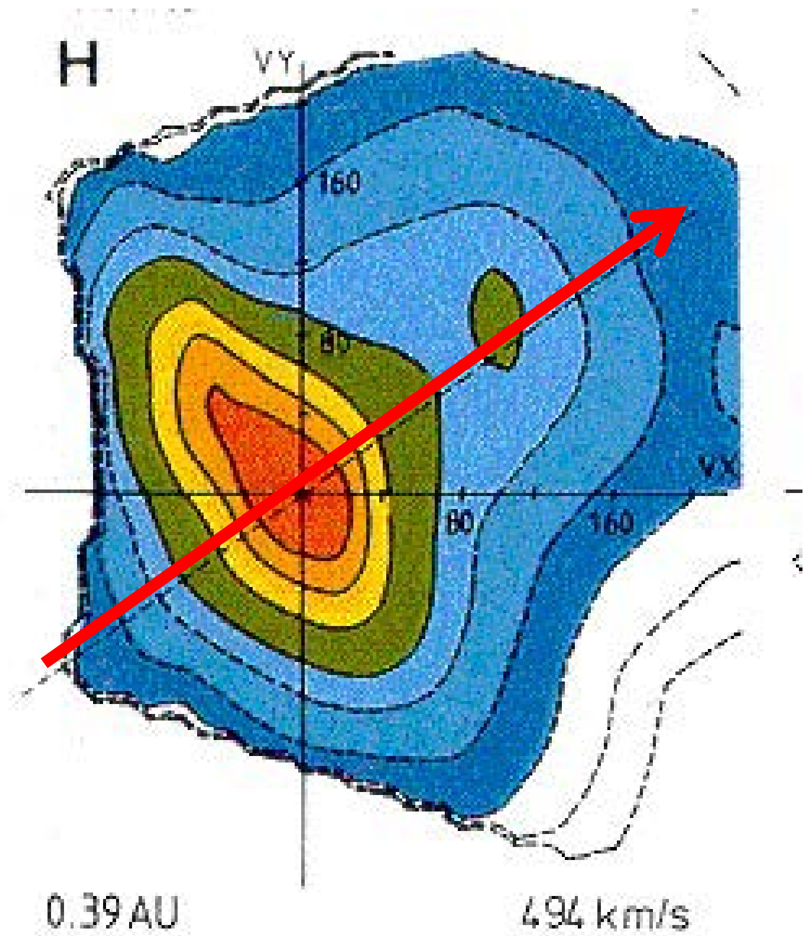
- **SWEAP measures velocity distribution functions of the H+ (protons), He2+ (alphas), and electrons that constitute the bulk of the coronal and solar wind plasma. These measurements are used to address all three SPP objectives**
- **The distribution function is used to determine velocity (speed and direction), density, and temperature of the solar wind.**
- **Why not just fly an anemometer and a weather vane?**
- **Because the solar wind is not in equilibrium - Relative densities change, species have different velocities, different temperatures, and temperature can be hard to define**
- **A SWEAP measurement is a map of the number of electrons, alphas, and protons as a function of direction and energy**



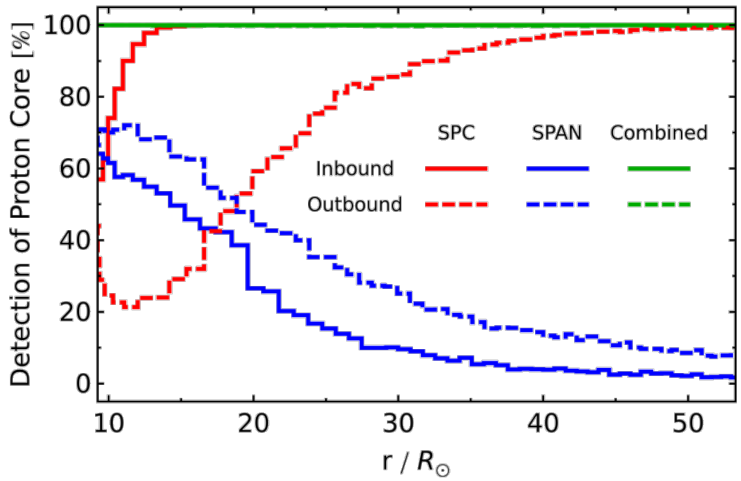
Primary Measurement Requirements

Mission L1/L2 Requirements Met by SWEAP

Parameter	Requirement	Justification
MRD-93 "The mission shall measure thermal ions, as follows"		
Field of View	Nadir and ram directions	Supersonic ion flow
Energy range*	10 eV – 20 keV	Known speed range
Energy resolution	< 20%	Temperature
Angular resolution*	10° x 25°	Flow angles and beams
Measurement cadence	1 Hz	Ion gyro-scale scale close to Sun
Mass/Charge (m/q) resolution*	D(m/q)/(m/q) < 25%	Hot H^+ and He^{2+} will overlap in energy near Sun
MRD-94 "The mission shall measure thermal electrons, as follows"		
Field of view	> 75% of the sky	Subsonic electron flow, beams
Energy range*	5 eV – 20 keV	Known speed/temperatures
Energy resolution	< 20%	Resolve temperature/beams
Angular resolution*	10 deg x 10 deg	Electron beams
Measurement cadence	1 Hz	< 200 km resolution on Sun, at ion gyro-scale close to Sun

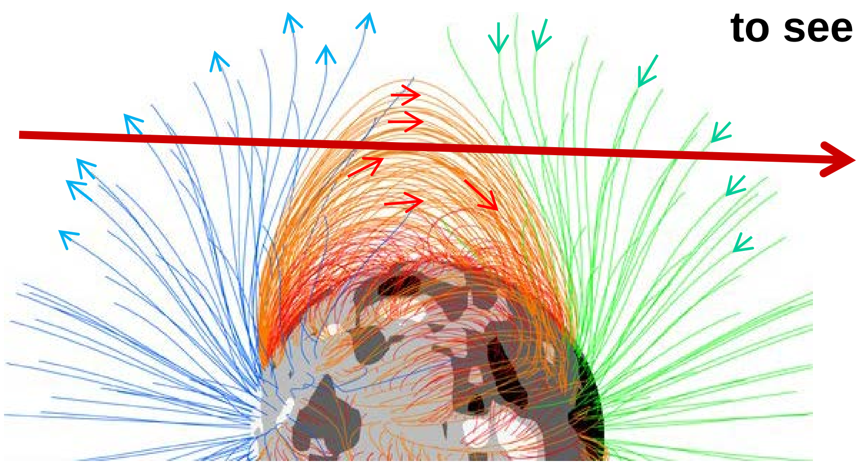
* not required in all directions

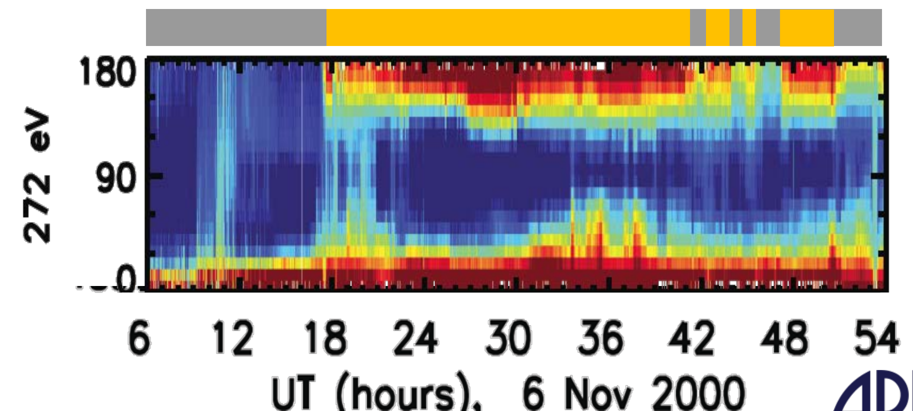
Drivers for SWEAP



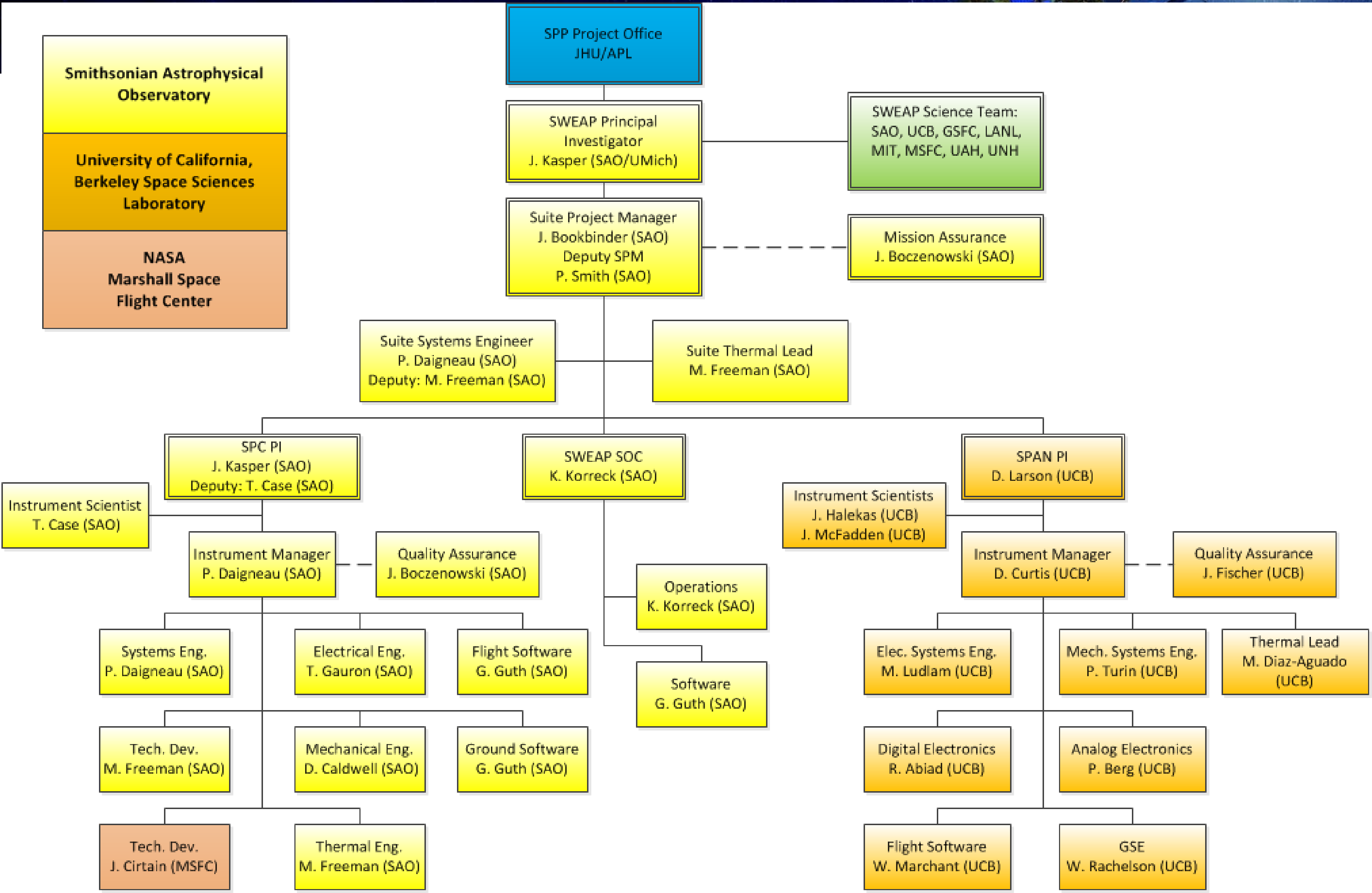
Ion instruments have to both view nadir and ram directions in order to see supersonic solar wind ion flow through an encounter

Electron instruments view as much of sky as possible to see subsonic electrons and energetic electron beams





SWEAP Team



Smithsonian Astrophysical Observatory
University of California, Berkeley Space Sciences Laboratory
NASA Marshall Space Flight Center
SPP Project Office JHU/APL
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Suite Thermal Lead M. Freeman (SAO)
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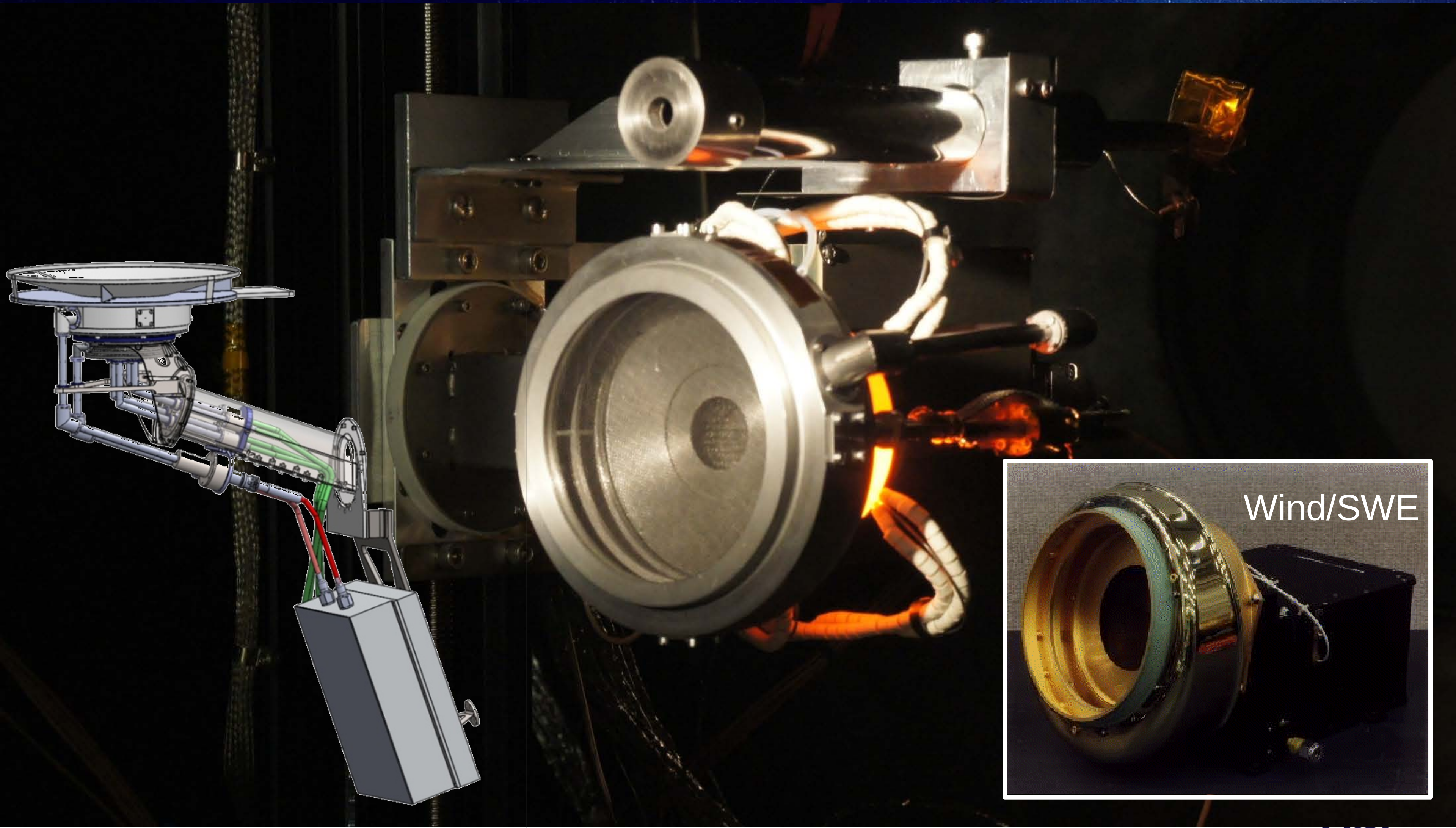
Analog Electronics P. Berg (UCB)
Flight Software W. Marchant (UCB)
GSE W. Rachelson (UCB)

The Solar Probe Cup (SPC)

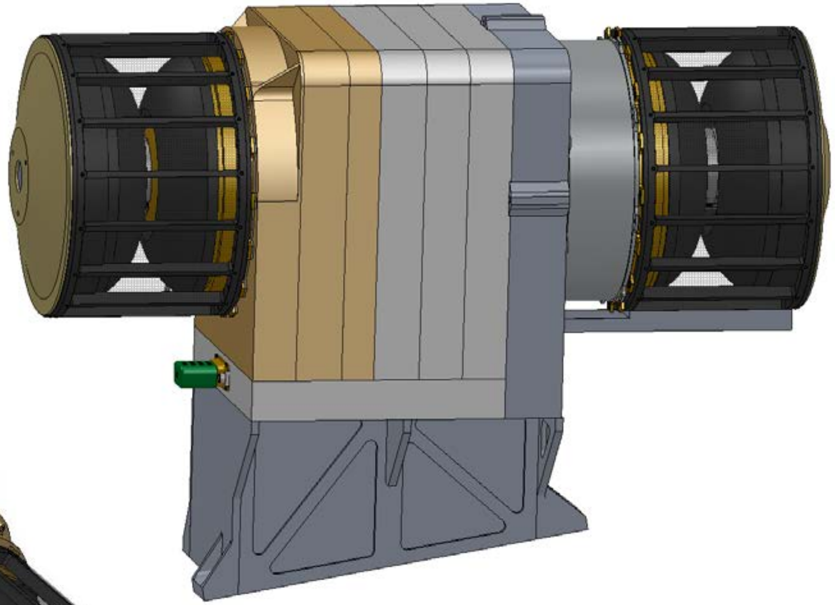
Nadir viewing ion/electron Faraday Cup

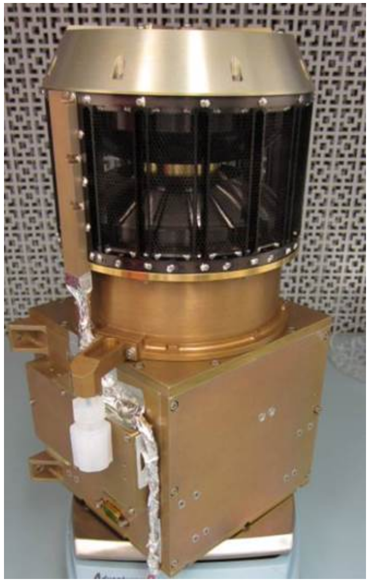


The Solar Probe Analyzers (SPAN)

Ion/Electron Electrostatic Analyzers

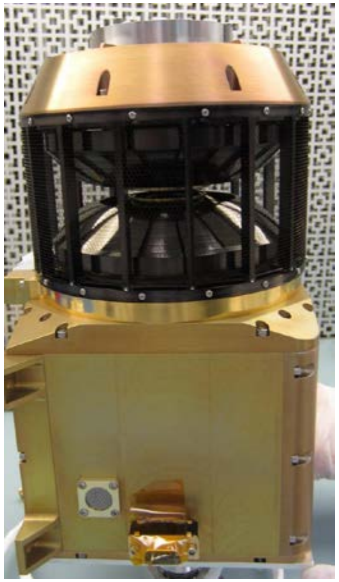
SPAN A+ (electrons and ions)

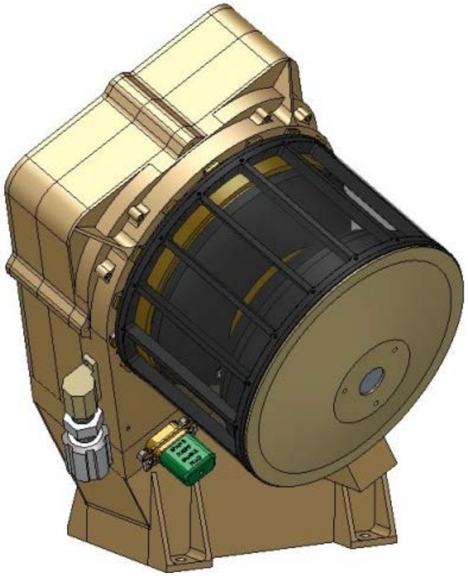




MAVEN STATIC

MAVEN SWIA

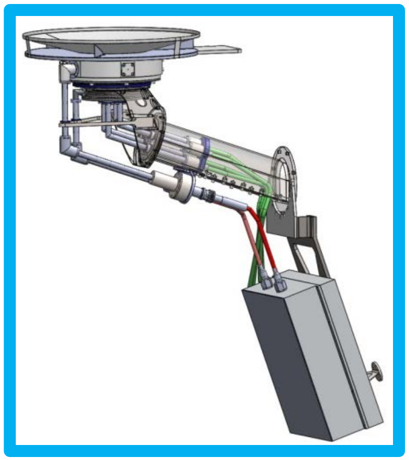


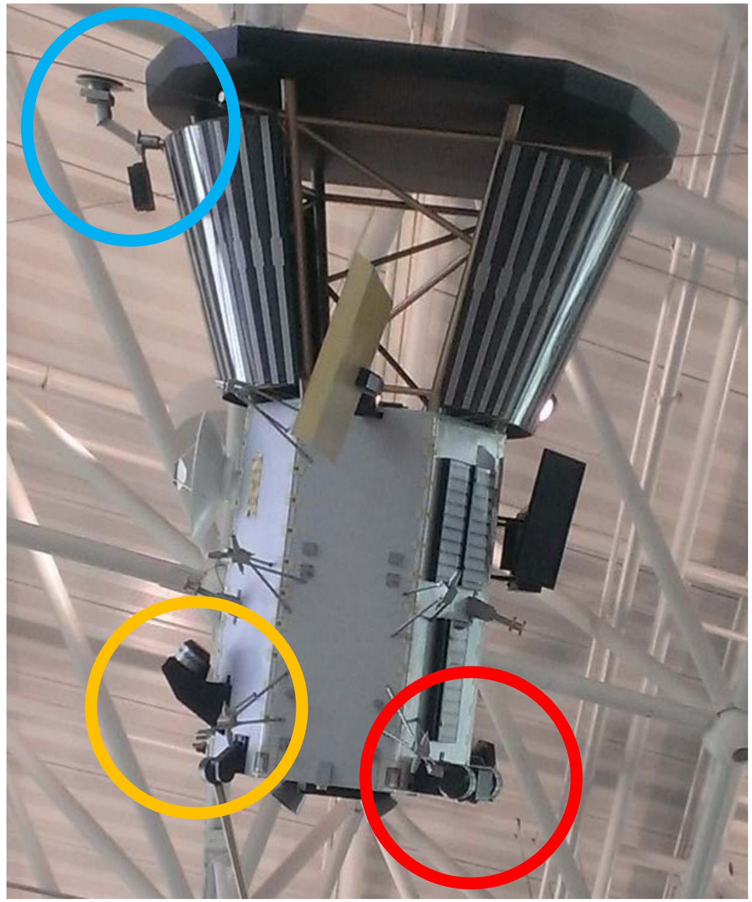


SPAN B (electrons)

SWEAP on Solar Probe Plus

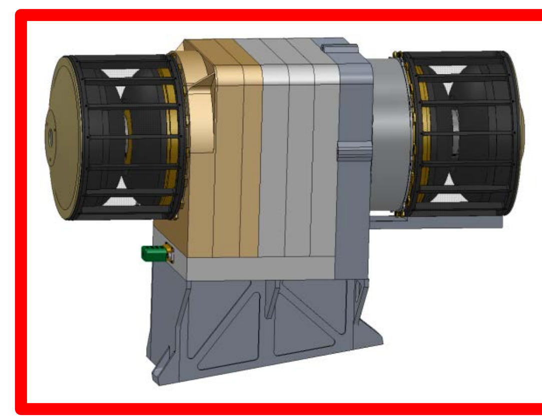
Nadir-viewing SPC looks directly at the Sun

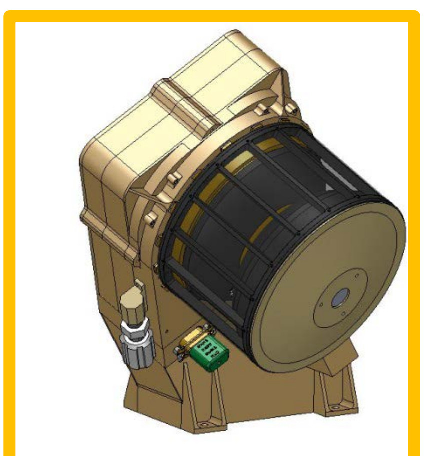




SWEAP Electronics Module (SWEM) is inside spacecraft bus

SPAN-A+ on ram side looks "ahead" of spacecraft motion





SPAN-B on anti-ram side looks "behind" spacecraft motion

SWEAP Functional Block Diagram

Interfaces defined and understood

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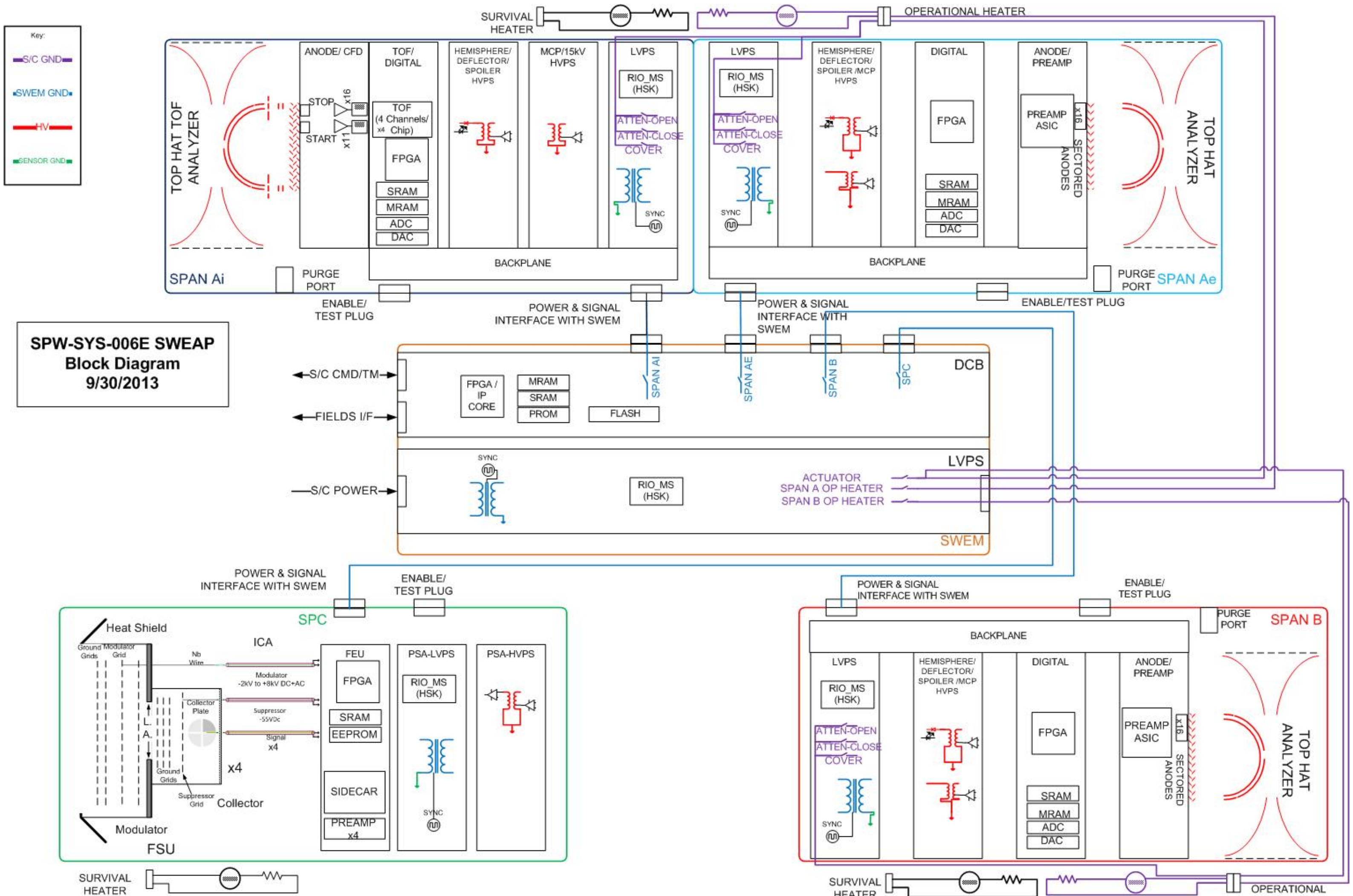

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Technical changes since SRR/MCR

Change since SRMDR	Reason for Change	Impact on Resources
SPC heat shield changed to Niobium 2-panel assembly	Simpler fab, lower cost, contamination-free design	Slight mass increase
SPC electronics relocated from SWEM to Sensor base	Lower power, lower radiated emissions, better sensitivity	Power decrease, slight mass decrease
SWEM Reconfigured from 4-PWA to 2-PWA box	PSA & FEU relocation allows smaller electronics assembly	Mass decrease, volume reduction
SPAN-A and B mechanical bracket designs simplified	Easier accommodation on SPP bus, simpler interfaces	Moderate mass savings
Synchronize to 19.20 MHz FIELDS Clock	Reduce RFI, maintain science at high frequency	Power increase
SPAN Operational Heater Power Added	Maintain SPAN-A+ and SPAN-B temperatures within 0.25 AU at closest pass	Heater power increase within 0.25 AU
SPAN AE and B uses LPP provided EASIC preamp	Resource reduction, performance maintenance	Saves power, mass

L3/L4 Requirements

Flow from and meet L1/L2 requirements

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	Parameter	Requirement	SPC	SPAN-A i+	SPAN-A/B e-
Ions	Field of View	Nadir and ram directions	28° half width cone nadir	180°x30° in ram(1)	
	Energy range*	10 eV – 20 keV	150 eV – 6 keV(2)	10 eV – 20 keV	
	Energy resolution	< 20%	< 20%	< 20%	
	Angular resolution*	10° x 25°	10°	10°x25°	
	Cadence	1 Hz	1 Hz	1 Hz	
	(m/q) resolution+	< 25%		< 25%	
Electrons	Field of view	> 75% of the sky	28° half width cone nadir		200°x90° each > 75%(3)
	Energy range*	5 eV – 20 keV	100 eV – 1.5 keV		5 eV – 20 keV
	Energy resolution	< 20%	< 20%		< 20%
	Angular resolution*	10° x 10°	10°		10°x10° (4)
	Cadence	1 Hz	1 Hz		1 Hz

*not required in all directions; +only required in ram direction (1) For e/q < 4 keV/q; (2) 1 keV below 15 R_s, 4 keV below 20 R_s; (3) For e- < 4 keV; (4) within 30° nadir for SPAN-A, within 15° ecliptic SPAN-B

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Requirements flow is captured

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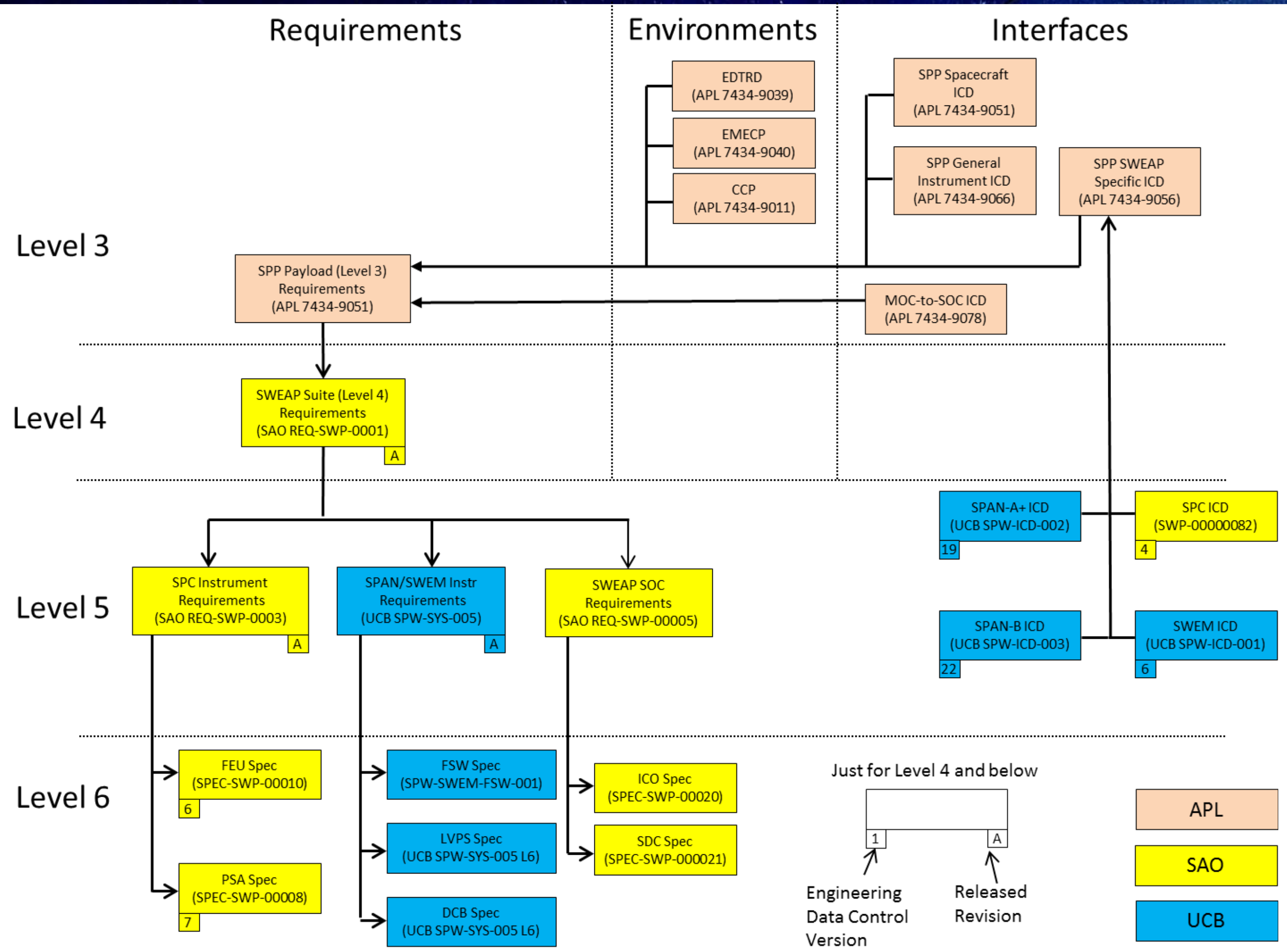

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SWEAP External Interfaces

- Interface Control Documents with S/C
  - General Instrument ICD – 7434-9066
  - SWEAP Specific ICD – 7434-9056
  - Spacecraft Mechanical ICD – 7434-0011
- Electrical Interfaces:
  - LVDS UART I/F with S/C – redundant interface. 115.2kBaud CMD, 345.6kBaud TM
  - Operational Power I/F with S/C – single service. 24V-35V
  - Survival Power I/F with S/C – single service to SPAN A, SPAN B and separate service for SPC (shared with WISPR). 24V-35V
- Mechanical Interfaces:
  - SWEM and SPANs are bus mounted.
  - SPC is TSA mounted.
- Thermal Interfaces:
  - SWEM coupled to S/C. SPANs and SPC isolated.
- Interface with FIELDS instrument
  - SPF_MEP_105_SWEAP_ICD Rev C
  - Electrical interface is LVDS CDI (UCB protocol).

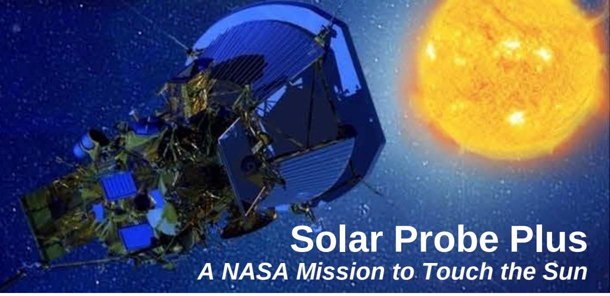
Resource Allocation Status

L3-to-L4 Resource Flow: APL 7434-9051 PAY-280 (SWEAP-to-SC ICD) → REQ-SWP-0001 SWP-808 (Technical Resource NTEs)

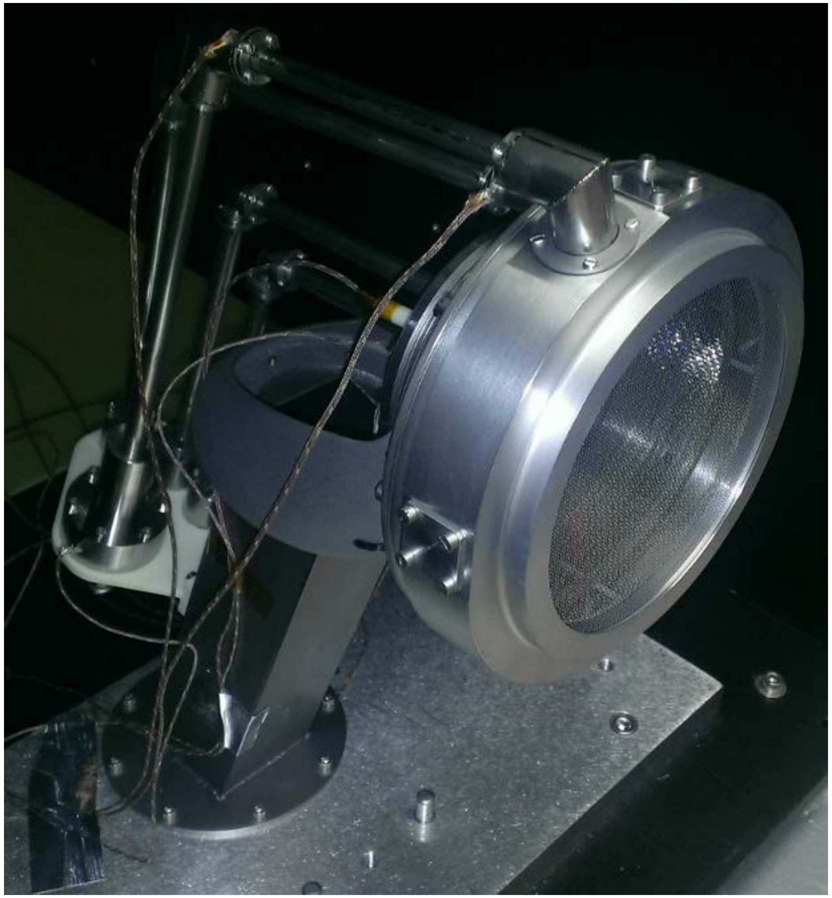
Resource	Type	Allocation	Current Best Estimate	Reserve Status
Mass	NTE	17.76 kg	14.64 kg	+21.3% Reserve
Average Power (Inside 0.25 AU)	NTE	21.0 W	16.93 W	+24.0% Reserve
Survival Heater Power	NTE	12.5 W	10.5 W	+19.0% Reserve
Data Rate/Volume	CBE	20 Gb/orb	19.96 Gb/orb	+0.2% Reserve (APL carries additional 30% telemetry reserve)

CBE – Current Best Estimate: No contingency/reserve included

SPC Technology Development
Passed TRL6 at SWEAP PDR



- **Development plan same as presentations to SRB at MCR, mid-Phase B briefing**
- **SPC Passed TRL-5 review on June 6, 2013, all subassemblies tested beyond expected environments, all material properties measured**
- **TRL-6 activities completed before SWEAP PDR**
  - **SPC prototype tested in reproduction of operating environment**
  - **Thermal/Photon - Strong thermal gradients induced within sensor due to light – spectrum of the light, angular size of the light, intensity and uniformity of the light all strongly effect instrument**
  - **Plasma - Ion and electron energies are similar to range seen at 1 AU, but currents and fluxes are stronger**



Pursued a redundant verification effort

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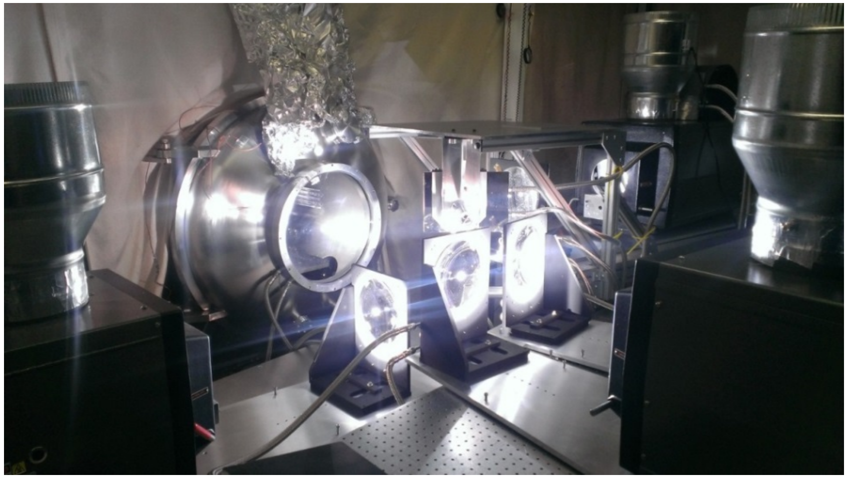
Factor	Solar Environment Simulator (SES)	Solar Wind Facility (SWF)
Location	Smithsonian Astrophysical Observatory	NASA Marshall Space Flight Center
Thermal	Light source makes high fidelity reproduction of sunlight, cooled shroud reproduces view of deep space	Resistance heaters bring the collector plates, cables, and electronics to their expected temperatures
Particles	Ion gun fixed angle	Ion and electron sources reproduce detailed solar wind ion and electron environment, rotation and translation stages
Exit Criteria for Demonstration	Performance verified as a function of incident light level – see next slide for details	Performance verified as a function of beam properties and sensor temperature – see next slide for details



Performance Requirements Have Been Met

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Level 1 Requirement	Measure	Energy Range	Energy Resolution	Field of View		Angular Resolution	Cadence
Level 1 Definition	Ions	10 eV – 20 keV (not in every direction)	Energy Resolution < 20%	Nadir and Ram direction		10 degrees	VDF at 1 Hz
Requirement for SPC TRL6	R1: Detect 15 pA in 31.25 ms	R2: Bias HV grid from 200 V to 6 KV	R3: Put sine wave on HV grid with amplitude < 20% of bias	R4: SPC has 30 degree half width FOV	R5: Thermal conditions within levels established by analytic models	R6: Flow angles at better than 1 degrees	R7: More than 32 measurements per second
Preferred Verification	V1A: Measure 15 pA ion beam produced by particle accelerator	V2A: Show modulator can block/admit 200 eV and 6 KeV protons	V3A: Use protons with different energies to show voltage window < 20%	V4A: Measure proton beam at edge of field of view	V5A: Expose closest approach sunlight, measure temperatures, verify	V6A: Measure proton beams at different angles or histogram measurements at one angle	V7: Verified by analysis if R1 and R2 are met
Backup Verification	V1B: Measure instrument noise level and verify below 15 pA	V2B: Measure DC voltage on HV modulator grid	V3B: Measure AC voltage on modulator grid	V4B: Verify by analysis of modulator and collector dimensions	V5B: Same test at a backup facility	V6B: Derive based on measured minimum noise levels	

SAO/SES (PROMES, ORNL) | MSFC Solar Wind Facility | Verification by Analysis

Suite I & T Flow

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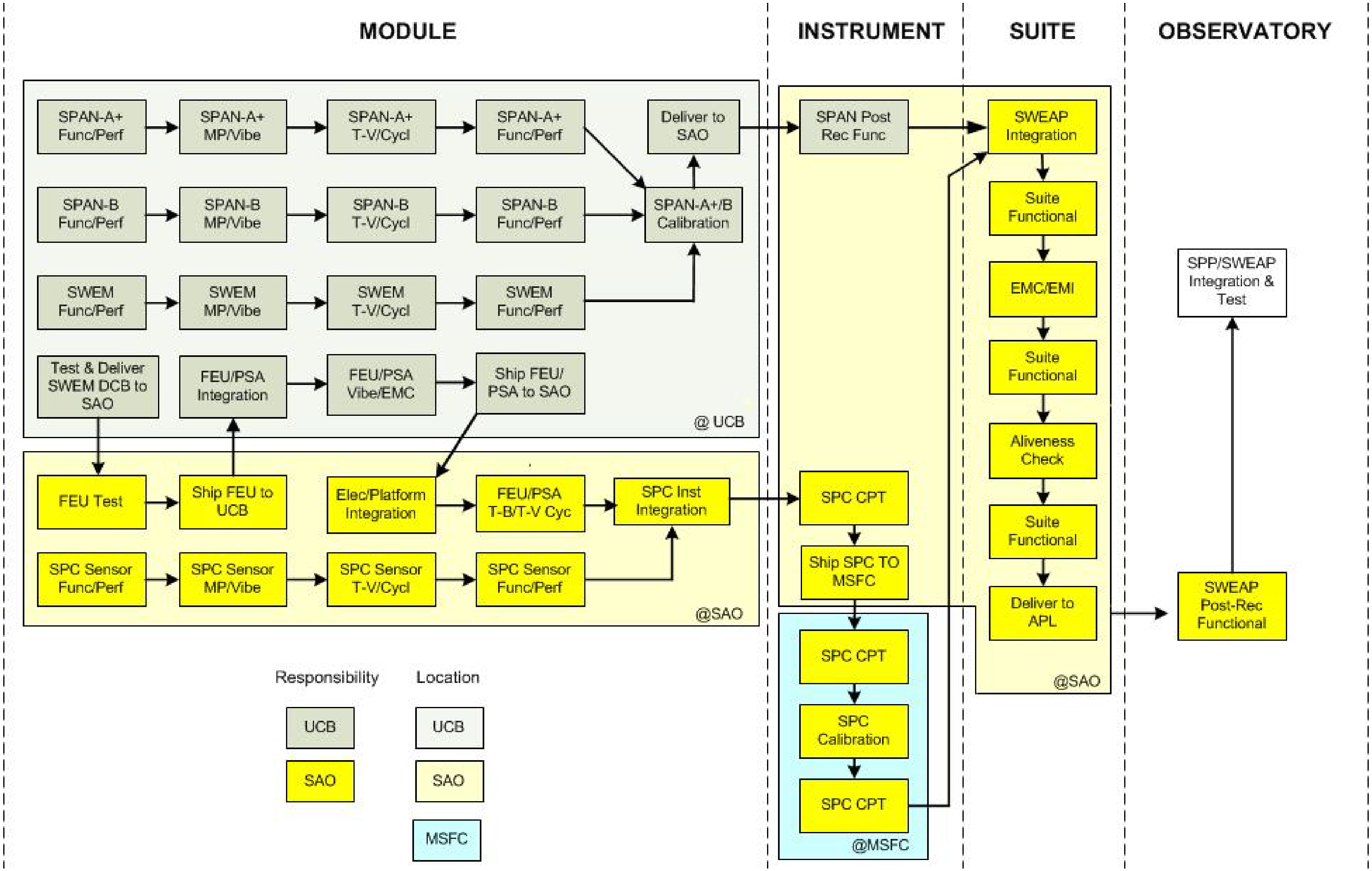

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SPC Verification Matrix

(SPAN, SWEM have corresponding matrices)

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HARDWARE			MECHANICAL										ELECTRICAL										THERMAL		CONTAM.			OTHER		
COMPONENT (ITEM)	QUANTITY	SUPPLIER	ALIGNMENT	MODAL SURVEY	QUASI-STATIC LOAD	RANDOM VIBRATION	SINE VIBRATION	ACOUSTIC	CLAMP BAND SHOCK	VENTING/PRESS. PROFILE	MASS PROPERTIES	SELF SHOCK		INTERFACE VERIFICATION	FIELDS INTERFACE TEST	BONDING AND ISOLATION	TURN ON/OFF TRANSIENTS	CONDUCTED EMISSIONS	CONDUCTED SUSCEPTIBILITY	RADIATED EMISSIONS	RADIATED SUSCEPTIBILITY	SELF COMPATIBILITY	THERMAL VACUUM (# CYCLES)	THERMAL BALANCE	ESC AND GROUNDING	DC MAGNETICS	BAKEOUT	RADIATION	DEEP DIELECTRIC DISCHARGE	FAILURE FREE HOURS
SAO QM SPC											A																			100
QM Sensor Module	1	SAO	A1	T		W		A			M1			T									Q2	A						
QM FSU w/Shield	1	SAO	A1	T		Q	Q	Q								T									T		T8		A	
QM Strut/Adapter/ICA	1	SAO	A1	T	Q1		Q							T											T		T			
QM Electronics Module	1	SAO		T		W		A			M1			T																
QM FEU/ETU PSA		SAO/UCB																					Q3	T			T	T6		
QM FEU w/FSU Cabling	1	SAO		T		Q	Q							T			T5	T5	T5						T		T	T6	A	
QM Electronics Platform	1	SAO		T	Q1		Q							T													T			
SPC FM SPC	1	SAO									A			T		T5								A	T					100
FM Sensor Module	1	SAO	A1	T		T1	T1	T1			M1			T									6+1	A			T			
FM FSU w/Shield	1	SAO	A1	T		W										T							T9				T8		A	
FM Strut/Adapter/ICA	1	SAO	A1	T										T													T			
FM Electronics Module	1	SAO		T		T1	T1	A			M1			T									6+1	T			T			
FM FEU/PSA	1	SAO/UCB				W								T										T			T			
FM FEU w/FSU Cabling	1	SAO		T		T	T							T4		T5	T5	T5									T	T6	A	
FM Electronics Platform	1	SAO		T										T													T			
PSA	1	UCB									M3			T4														T6	A	

(A)nalysis

A1: Tolerance stack-up analysis meets alignment allocation; int alignment via cube if not

(M)easurement

M1: Mass, CG measured, MOI analysis

M3: Mass measured only, COG and MOI analysis

(Q)ualification

Q1: Qual w/Simulators

Q2: SEP Accelerated Exposures, min 2 oper plus 1 survival cycle

Q3: w/FSU load simulator

(T)est/(W)orkmanship

T1: Per 7434-9039

T4: Safe to Mate & ICD compl before

T5: Full testing on FM

T6: Total Dose and SEE testing at part level

T8: no TQCM on Shield 1850 °C & FSU 1200 °C

T9: 1 survival + 6 operational cycles at reduced temp range; 50 °C/min trans rate

Suite Verification Matrix

HARDWARE			MECHANICAL										ELECTRICAL									THERMAL		CONTAM.			OTHER		
COMPONENT (ITEM)	QUANTITY	SUPPLIER	ALIGNMENT	MODAL SURVEY	QUASI-STATIC LOAD	RANDOM VIBRATION	SINE VIBRATION	ACOUSTIC	CLAMP BAND SHOCK	VENTING/PRESS. PROFILE	MASS PROPERTIES	SELF SHOCK	INTERFACE VERIFICATION	FIELDS INTERFACE TEST	BONDING AND ISOLATION	TURN ON/OFF TRANSIENTS	CONDUCTED EMISSIONS	CONDUCTED SUSCEPTIBILITY	RADIATED EMISSIONS	RADIATED SUSCEPTIBILITY	SELF COMPATIBILITY	THERMAL VACUUM (# CYCLES)	THERMAL BALANCE	ESC AND GROUNDING	DC MAGNETICS	BAKEOUT	RADIATION	DEEP DIELECTRIC DISCHARGE	FAILURE FREE HOURS
UCB SWEEP ETU	1	UCB		A							M1	T9	T4	T3	T5	T5	T5				T	1+1			M2				
UCB SWEAP FM	1	UCB											T4	T	T5	T5	T5				T	1		T		T8			100
SPAN A	1	UCB		T1	T2	T2	T2			A1	M1		T4									6+1	T	T	M2	T8			
SPAN AI	1	UCB	A									T9															T6	A	
SPAN AE	1	UCB	A									T9	T4											T			T6	A	
SPAN B	1	UCB	A	T1	T2	T2	T2			A1	M1	T9										6+1	T		M2	T8	T6	A	
SWEM	1	UCB		T1	T2	T2	T2			A1	M1		T4									6+1		T	M2	T8	T6	A	
SPC	1	SAO																											
PSA	1	UCB									M3																T6	A	
Instrument Harness	1	UCB									M3													T	M2	T7			
Instrument Suite	1	UCB/SAO													T5	T5	T5	T5	T5	T5	T5								
Instrument on S/C	1	UCB	A	T		T	T	T	T				T	T	T	T	T	T	T	T	T	T	T	T	T				

A1 Units follow design rule of 1 sq in vent area/ft^3 of volume
T1 Per 7434-9039
T2 Per 7434-9039 but test is done unpowered and no functional between axes
T3 FIELDS Interface test done with simulators, plus an ETU to ETU test, FM to FM test and finally on the spacecraft
T4 Safe-to-Mate and compliance to ICD prior to Integration
T5 Per 7434-9040, full testing on FM, CE testing on ETU
T6 Total Dose and SEE Testing at part level as needed
T7 60C for 48 hours prior to TV w/ integrated payload
T8 Contamination Verification w/ TQCM
T9 Self Shock test from Ti-Ni pin puller to open cover

M1 Mass, CG, MOI measured
M2 DC Magnetics measured prior to Instrument Payload integration
M3 Mass only measured, no CG or MOI
A Analysis
T Test
M Measurement

Summary Schedule
Critical path through SPC

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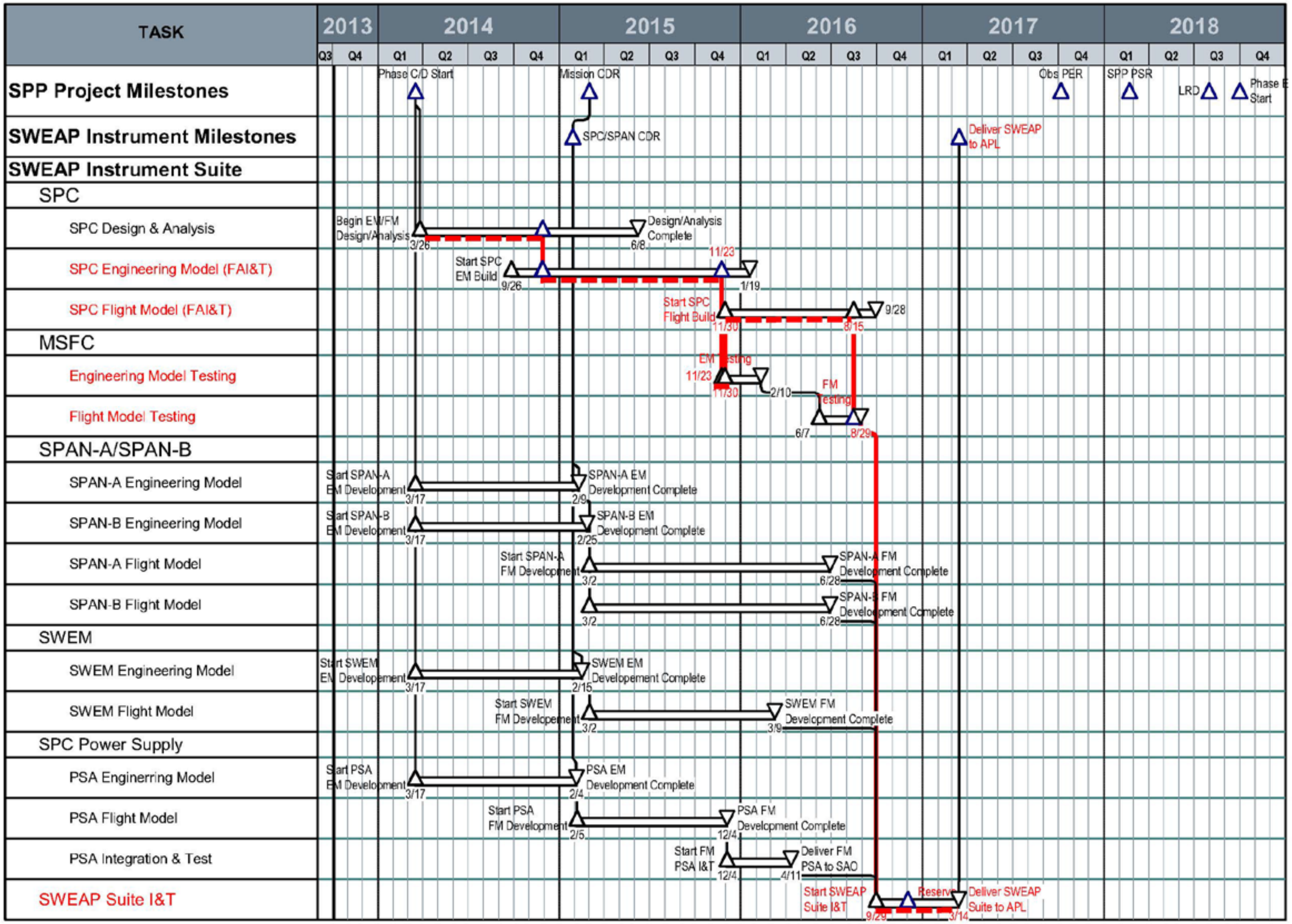

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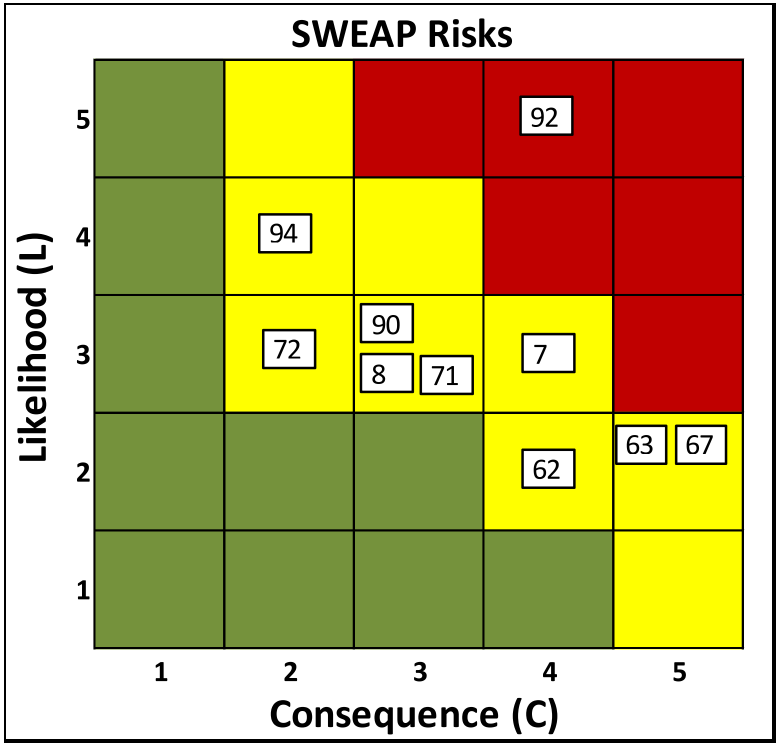
SWEAP Risk Status

5x5 Matrix and Top 10 Risks

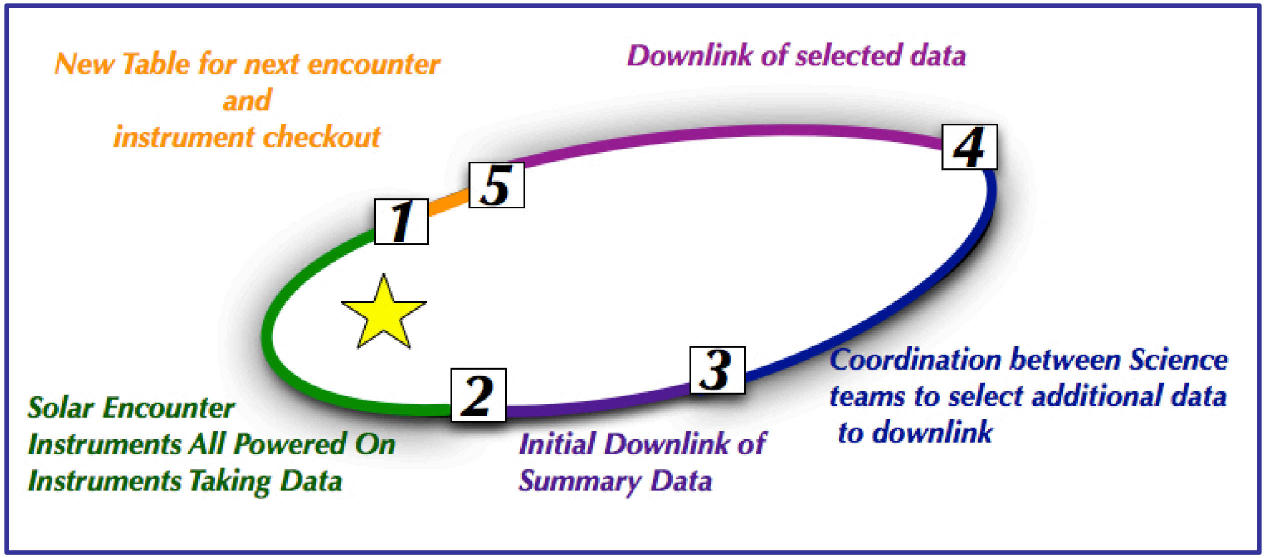


Mitigation plans in place for all Red & Yellow SWEAP risks

#	Title	Type	L	C	Score	Trend
92	White paint charging	T	5	4	20	
7	Survival heater allocation	T,S	3	4	12	
63	DCB failure/single string	T	2	5	10	
67	HV801 performance	T,S	2	5	10	
71	Vacuum furnace availability	S	3	3	9	
90	Personnel coverage	P	3	3	9	
8	Electrostatic cleanliness	T	3	3	9	
62	ICA DDD	T	2	4	8	
94	Parts cost growth	C	4	2	8	New
72	FEU SNR	T	3	2	6	

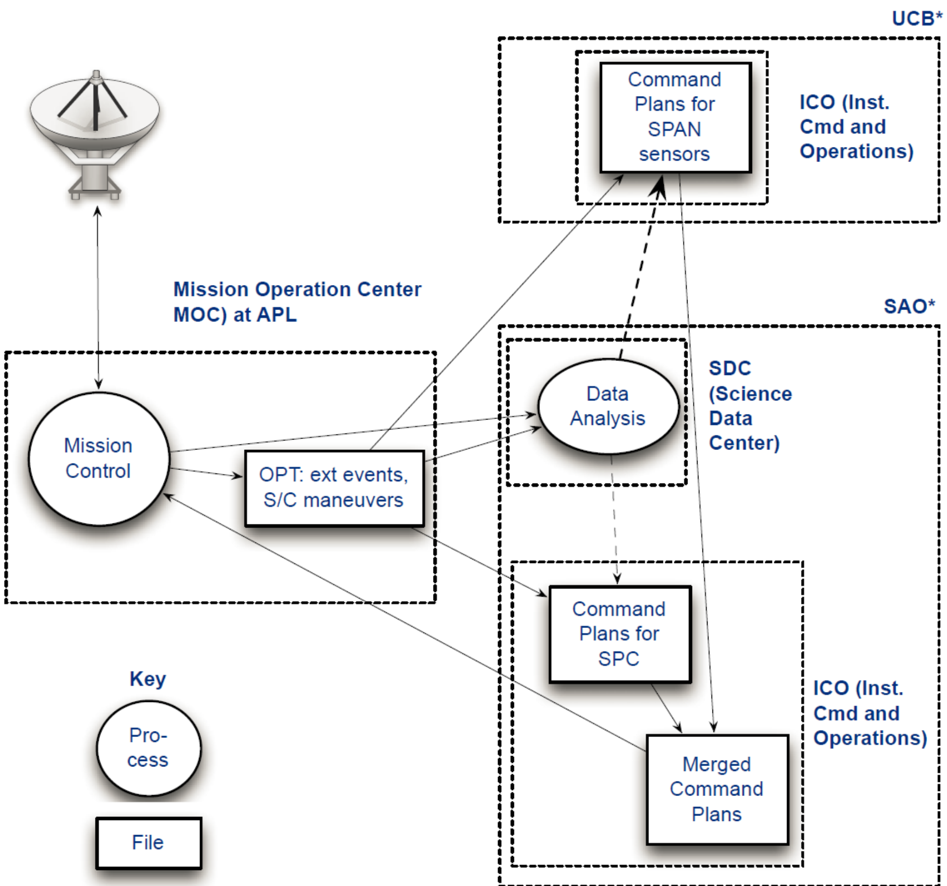
T = Technical Performance
C = Cost
S = Schedule
P = Programmatic

SWEAP Science Operations Center
Requirements and Overview

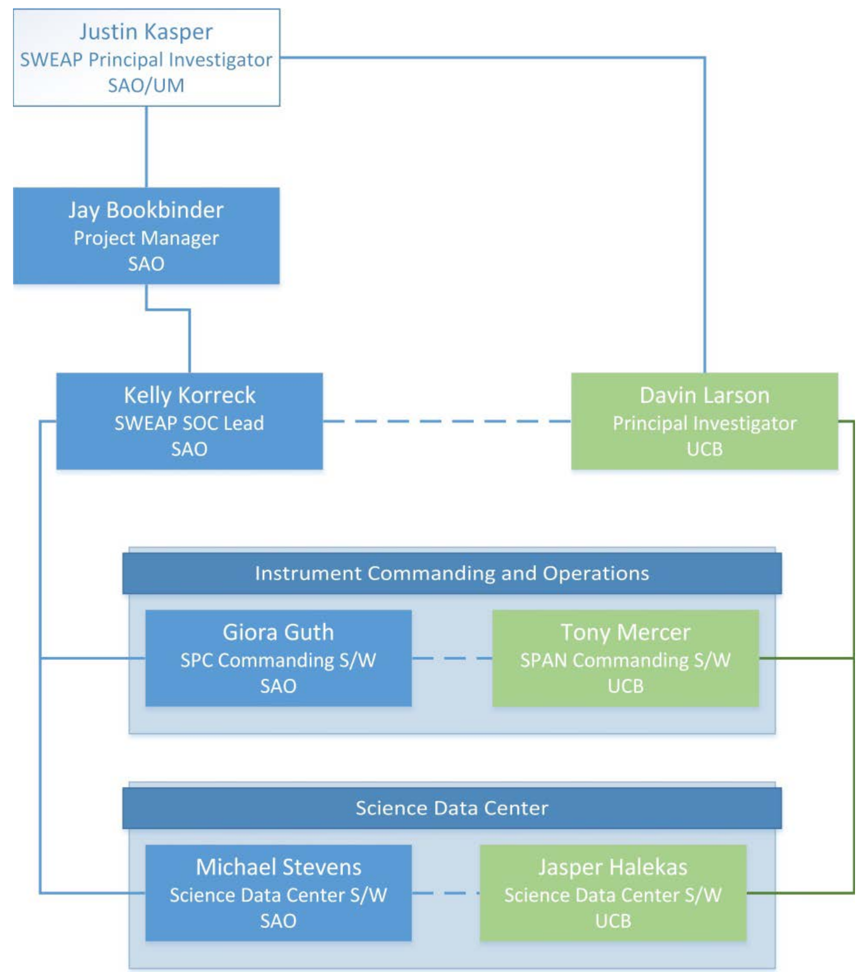


- **Requirements tracked in REQ-SWP-00005 “Specification for the SWEAP Science Operations Center”**
- **The SOC shall interface with the MOC and provide for rapid processing of survey data downloaded immediately following each encounter**
- **The SOC shall provide for the monitoring of instrument and suite health and status**
- **The SOC shall provide commanding to the MOC for download of selected data and operations during the next encounter**
- **The SOC shall process higher order data products and make them available to the public**

SWEAP SOC Organization



*UCB and SAO can act as ICO backups for each other



SWEAP Encounter

Data Products Summary

Data Product	Cadence [s] Nominal (Highest)
SPC	
Proton velocity, density, and temperature [Key parameters]	0.874 s (0.1 s)
Detailed fitted proton and alpha particle solar wind parameters [Anisotropies, secondary beam]	0.874 s (0.1 s)
Solar wind flow angle and flux variation	0.874 (0.0068 s)
Electron heat flux and flow angles	10 s (0.0068 s)
SPAN	
Full resolution ion and electron 3D Velocity distribution Functions (VDF)	56 second (0.437 s)
Ion and electron moments	0.437 seconds
Ion and electron energy spectra	0.437 seconds
Mass/charge spectra	7 minutes

SWEAP Review Request for Action (RFA) Status

Solar Probe Plus
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Review	Date	# RFA	# Open	# Closed	# Concurred
I-PDR	Oct ‘13	12			
SWEAP Mechanical, Thermal, Structural, Materials, Systems Peer Review	Sep ‘13	14			
SPC Instrument/FEU Peer Reviews	Sep ‘13	23			
SPAN/SWEM Mechanical/Thermal Peer Reviews	Sep ‘13	7			
SPAN/SWEM Power/Analog Peer Reviews	Sep ‘13	9			
SPC TRL-5 Review	June ‘13	0			
SPC Systems Requirements Review (SRR)	Dec ‘12	0			

Summary

- **SWEAP is on schedule**
- **Requirements and interfaces are understood and documented**
- **The SWEAP Solar Probe Cup has achieved TRL-6**
- **SWEAP passed Instrument PDR**
- **SWEAP is ready to proceed to Phase C activities!**

Solar Probe Plus

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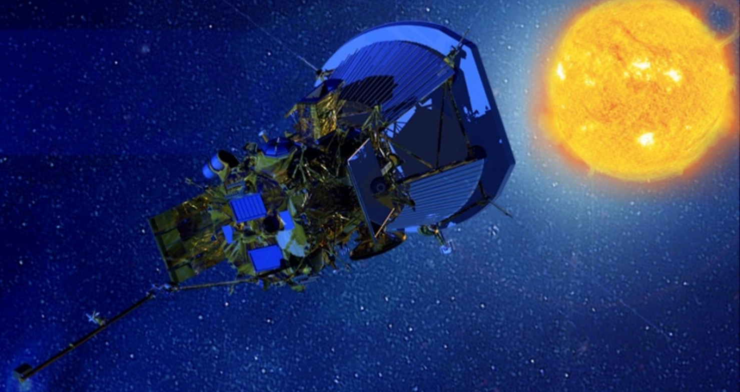

Backup Slides

The Johns Hopkins University
APPLIED PHYSICS LABORATORY

Representative Trade Studies

SWEAP performed approximately 30 trade studies in Phase B.

SWEAP Technical Trade Study List									
TS #	Phase B WBS	Trade	Purpose	Predicted Resource Impact		Technical Impact	Trigger Date	Status	Risk Item
				Δ Mass	Δ Pwr				
TS-21	5.2.1.1.1	Number of SPAN-A+ cover actuators (1 each for ion and electron)	Reliability vs. Ease of assembly, potential mass savings	neg.	-	No mass was saved by combining ion/electron covers. Reliability was reduced.	Phase A	**Implemented:** 2 covers for SPAN-A+ implemented. Design reflected in MDR slides.	
TS-28	5.2.2	Modulator/Collector Isolation Interface	Coupled Noise Minimization	+36g	N/A	M/C Coupling ↓, Resources ↑	Early Phase B (3/23/12)	**Implemented:** Single 3mm thk "wagon-wheel" sapphire isolated baselined	27
TS-29	5.2.7	HMB Location - SPP or adjacent FEU	SPC and HMB Performance	+100g	-TBD	Performance↑, Resources ?	Early Phase B (June '12)	**Implemented:** HMB adjuacent to FEU	N/A
TS-31	5.2.5	SPC FTS/Radiator Panel Reconfiguration	Reduce complexity and cost	+30g	N/A	Performance similar, Complexity↓, Cost ↓, Mass↓	6/1/2012	**Implemented:** Multi-panel Niobium shield	N/A
TS-32	5.2.3	SIDECAR ASIC vs. FPGA functionality	Performance vs. Resources	+20g	+200 mW	Performance↑, Resources ↓	Phase B (6/30/12)	**Recommended:** FPGA in FEU for data I/F & HV control, SIDECAR handles ADC, DSP	32

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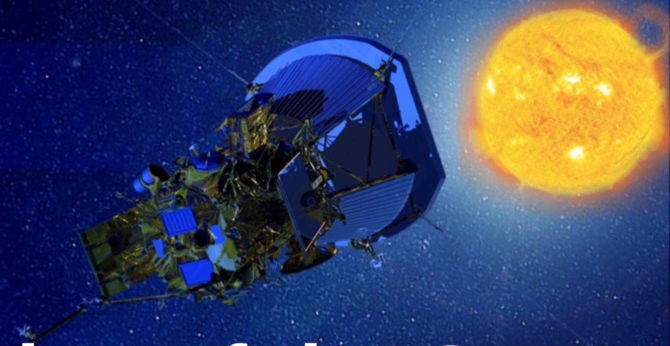


Integrated Science Investigation of the Sun Energetic Particles

Dave McComas, PI

Southwest Research Institute

dmccomas@swri.edu

13 – 16 January 2014

ISIS
Solar Probe Plus
Energetic Particles
NASA • GSFC • JPL • Caltech • SwRI • APL • UNH • U-Az • U-Del

APL
The Johns Hopkins University
APPLIED PHYSICS LABORATORY

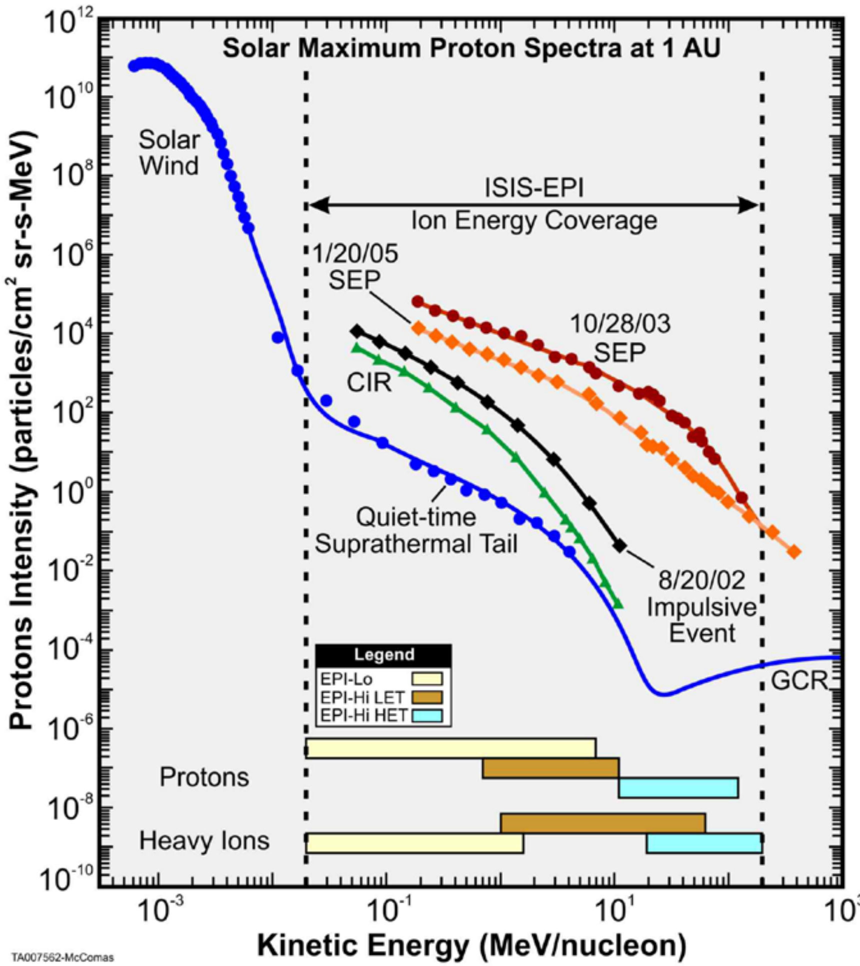
Agenda

- ISIS Science Objectives and Measurement Requirements
- Organization of the ISIS Team
- ISIS Overview
- Technology Development
- Changes since MDR
- Requirements Flow-Down
- Resource Summary
- Integration and Testing
- Verification
- Development Status
- Risk Summary
- ISIS Science Operations Center
- Action Items from Reviews
- Summary

ISIS Science Objectives

- **Explore mechanisms that accelerate and transport energetic particles**
  - **<u>Origin</u>: Determine the seed populations and physical conditions necessary for energetic particle acceleration**
  - **<u>Acceleration</u>: Determine the roles of shocks, reconnection, waves, and turbulence in accelerating energetic particles**
  - **<u>Transport</u>: Determine how energetic particles propagate from the corona out into the heliosphere**

Note: Includes coordinated analysis between ISIS and other SPP instruments of solar wind plasma, fields, and waves



ISIS-EPI also provides electron measurements from ~0.025 to 6 MeV

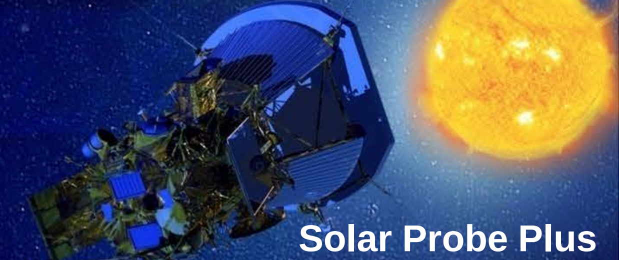
Primary Measurement Requirements

MRD Req't	Parameter	Required	Comment/Heritage
MRD-96a MRD-97a	Energy range	e^-: ≤ 0.05 to ≥ 3 MeV p^+/i: ≤ 0.05 to ≥ 50 MeV	Combined energy range of all sensors; small gaps in energy coverage are acceptable
MRD-96b MRD-97b	Energy binning	≥ 6 bins/decade	ΔE/E≤16%
MRD-96c MRD-97c	Highest cadence	e^-: ≤ 1s for selected high-statistics electron rates p^+/i: ≤ 5s for selected high-statistics ion rates	Additional rates at lower cadences, as appropriate for expected statistics and bit rate allocation
MRD-96d MRD-97d	Field of view	≥ π/2 ster coverage in both sunward and anti-sunward hemispheres, including coverage within 10 degrees of the nominal Parker spiral field direction at perihelion	Combined sky coverage of all sensors, some regions densely sampled rather than 100% covered
MRD-96e MRD-97e	Angular sectoring	e^-: ≤ 45 degree sectors p^+/i: ≤ 30 degree sectors	
MRD-97e	Composition	at least H, He, ^{3}He, C, O, Ne, Mg, Si, Fe	Measured species; not all measured under all conditions
MRD-98a	Max. intensity <1 MeV	≥ 10^6 particles/cm^2-sr-s	
MRD-98b	Max. intensity >1 MeV	≥ 5×10^5 particles/cm^2-sr-s	Highest intensities measured over restricted fields of view

Drivers for ISIS

- Field-of-View
  - As close as possible to Probe-Sun line while staying in umbra
  - Access to the direction of the Parker Spiral
  - Accept large variation in magnetic field direction
  - Measure anisotropies
- Wide Energy Range
  - Requires multiple instruments, sensors, and detectors
- Large Variation in Particle Intensities
  - Drive large dynamic range for the detectors

ISIS Team

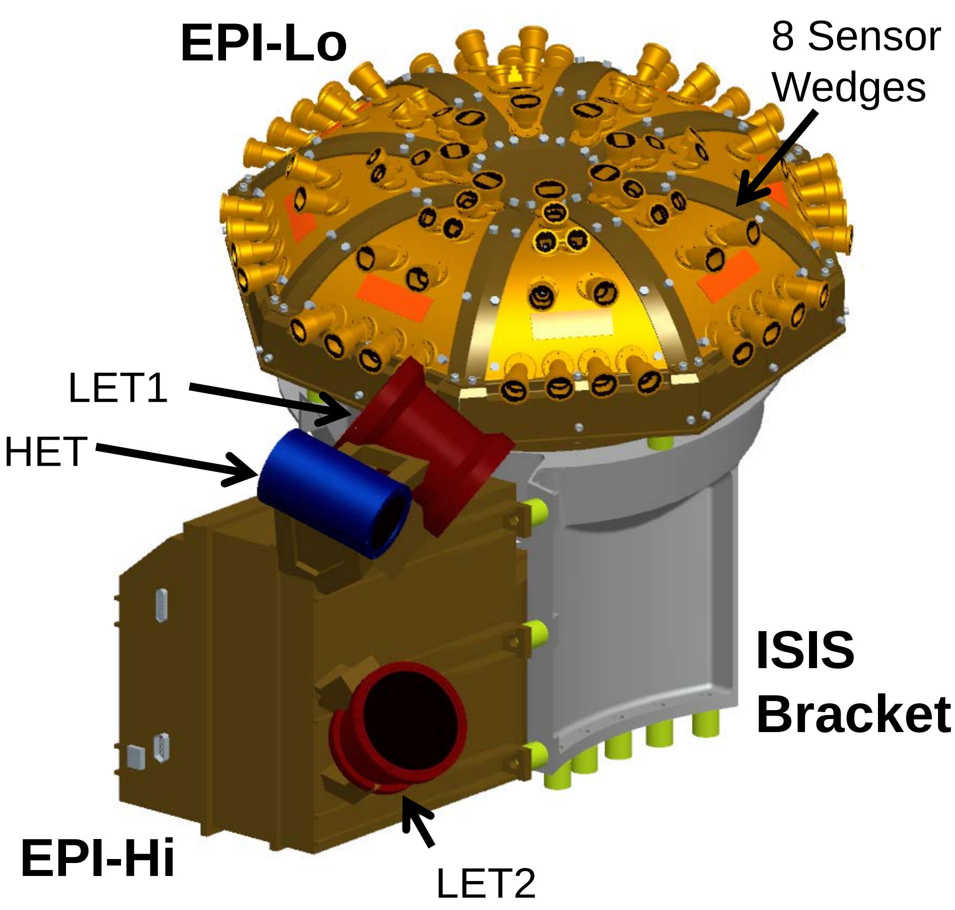


Solar Probe Plus
A NASA Mission to Touch the Sun

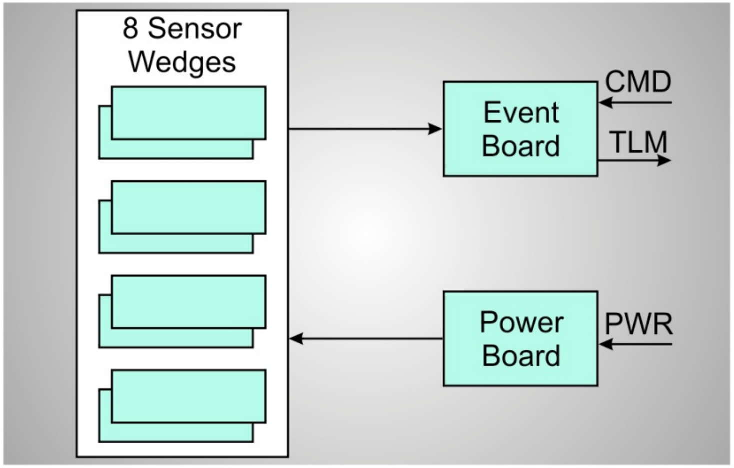
- SPP Project Office
  - **ISIS PI:** D. McComas (SwRI)
    ISIS Deputy PI: E. Christian (GSFC)
    - **ISIS Science Team** — APL, Caltech, GSFC, SwRI, U-Az, U-Del, UNH
    - **ISIS Project Manager** — S. Weidner (SwRI)
      - **ISIS Planning** — B. Birdwell (SwRI)
      - **ISIS Performance Assurance** — J. Gerhardus (SwRI), E. Edlund (SwRI)
      - **ISIS Systems Engineering** — J. Dickinson (SwRI), N. Angold (SwRI)
      - **ISIS Mechanical Engineering** — N. Alexander (SwRI)
      - **ISIS Parts Engineering** — J. Tumlinson (SwRI)
      - **ISIS Thermal Engineering** — G. Dirks (SwRI)
      - **EPI-Lo Lead Co-I:** R. McNutt (APL)
        EPI-Lo Deputy Co-I: M. Hill (APL)
        - **Instrument Scientist** — D. Mitchell (APL)
        - **Instrument Manager** — H. Seifert (APL)
          - **Systems Engineering** — R. Gurnee (APL)
          - **Quality Assurance** — J. Burgum (APL)
          - **Electrical** — R. Gurnee (APL)
          - **Mechanical** — S. Cooper (APL)
          - **Ground Software** — J. Vandegriff (APL)
          - **Flight Software** — J. Hayes (APL)
      - **ISIS SOC** — N. Schwadron (UNH)
        - **Software** — K. Fairchild (UNH)
        - **Operations** — S. Sherman (UNH)
      - **EPI-Hi Lead Co-I:** M. Wiedenbeck (JPL)
        - **Instrument Scientist** — D. Mewaldt (Caltech)
        - **Instrument Manager** — A. Cummings (Caltech)
          - **Systems Engineering** — R. Cook (Caltech)
            - **Mechanical Lead** — T. Rosenvinge (GSFC)
              - **Mechanical** — S. Shuman (GSFC)
          - **Quality Assurance** — B. Kecman (Caltech)
            - **Elec. Dev. & Test** — B. Kecman (Caltech)
              - **Elec. Engineering** — J. Burnham(Caltech)
          - **Calibration** — R. Mewaldt (Caltech)
            - **Flight & Ground Data Systems** — A. Davis (Caltech)
          - **Detector Dev.** — M. Wiedenbeck (JPL)

TA008484

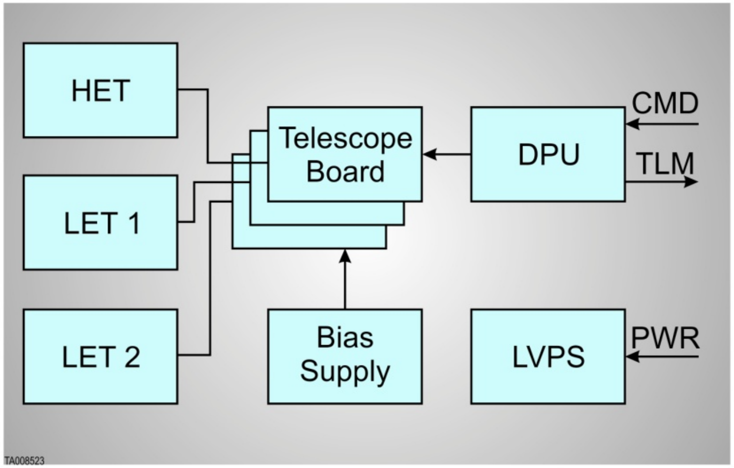
ISIS Overview



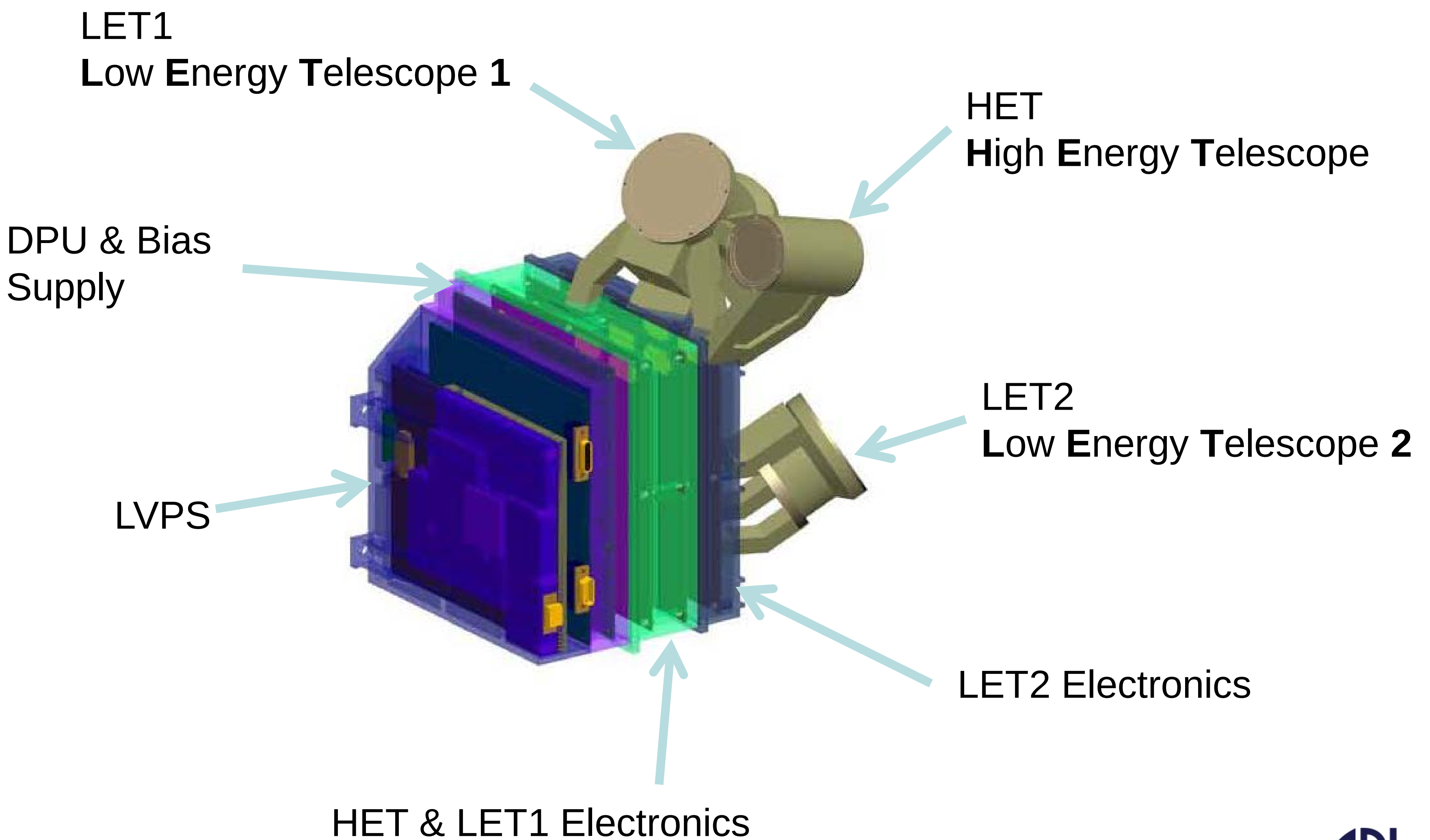
EPI-Lo



EPI-Hi

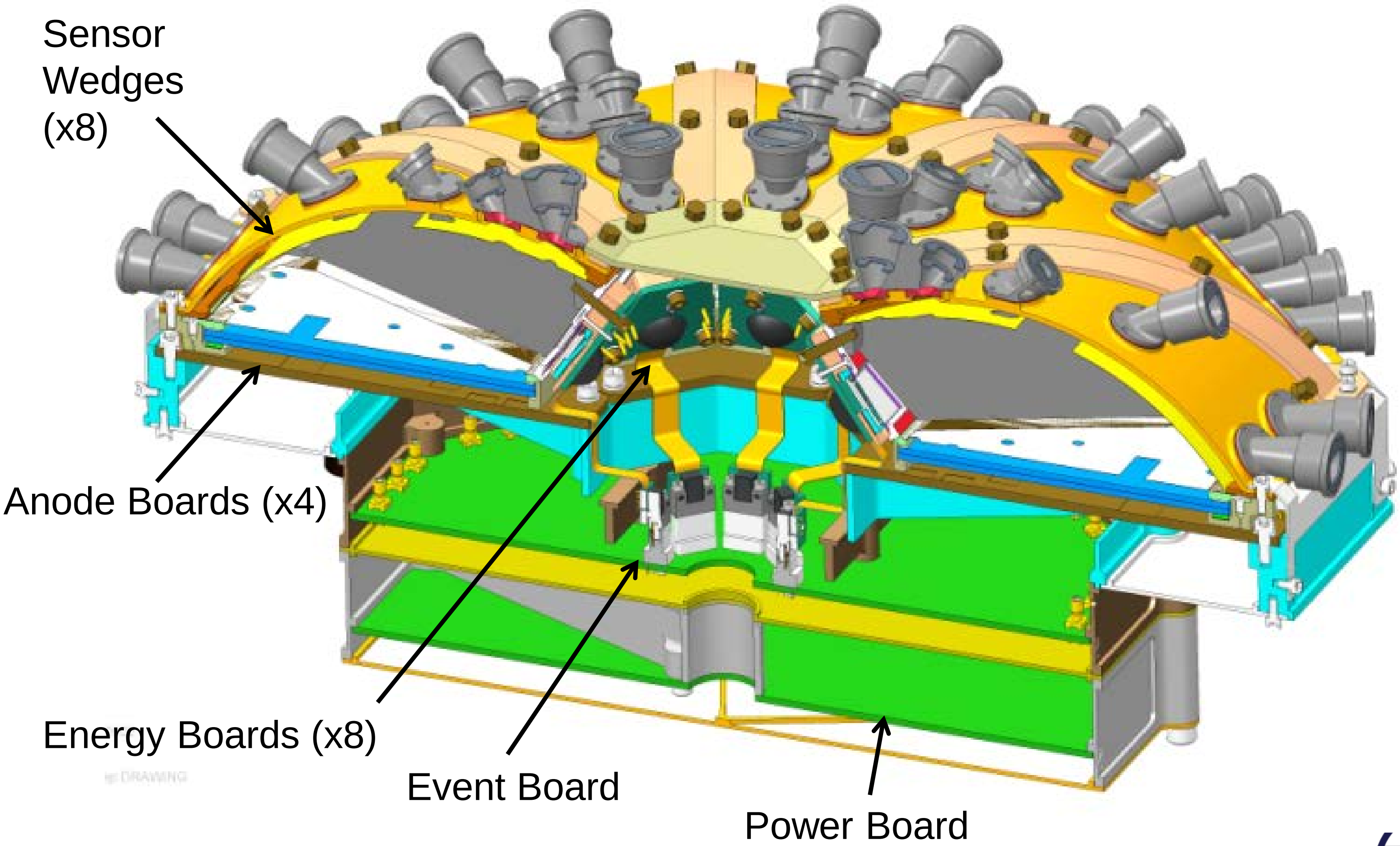


ISIS EPI-Hi Overview



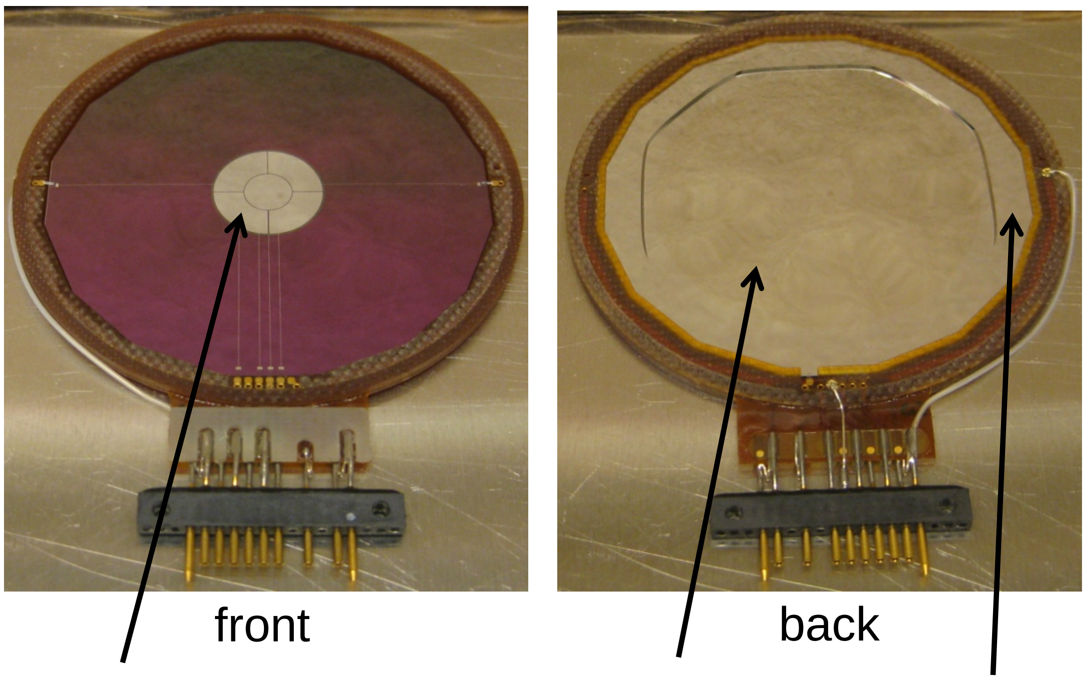
ISIS EPI-Lo Overview

Solar Probe Plus
A NASA Mission to Touch the Sun



EPI-Hi Technology Development

L0 Detector from Micron Semiconductor

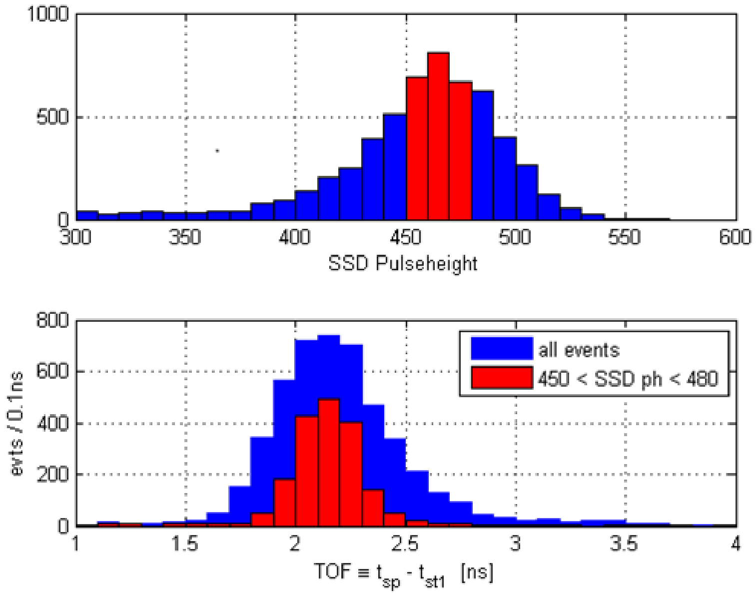


- Developed new approach to fabricate multi-element ion-implanted silicon solid-state detectors ~10 to 30 μm thick
- Acoustic tested to +8 dB over SPP level
- Radiation dose tested to 10 M-Rad
- Thermal Vacuum tests demonstrated stability
- Particle response:
  - Alpha particles from ^{244}Cm source
  - LBNL Accelerator beam of heavy ions
  - Demonstrated performance and uniformity requirements achieved
  - Survived all environments

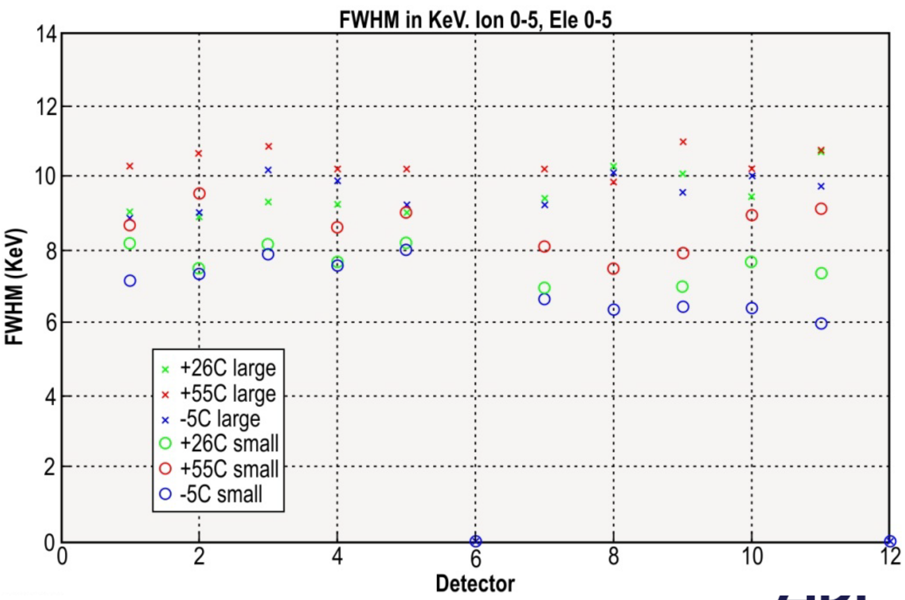
EPI-Lo Technology Development

- Species composition driven by two systems: energy system and timing system
  - Energy and TOF performance to meet ^{3}He / ^{4}He separation
  - ^{3}He, ^{4}He: 0.5 FWHM AMU
    for incoming energies between ≤0.2 MeV and ≥2.0MeV
- Validated that one anode covering two sensors has adequate timing performance
- Validated that SSD has adequate energy performance
- TOF-D and CFD-D ASIC performance meets requirements

TOF Performance Achieved

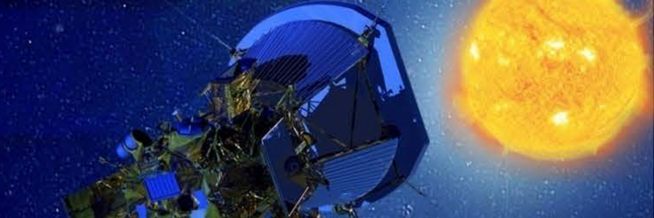


Energy Performance Achieved



Changes Since MDR

- **No changes to Science**
- **EPI-Lo electronics box reduced in diameter and fits inside the ISIS bracket**
- **Updated design for EPI-Hi electronics box**
- **ISIS bracket modified to accommodate the Ebox changes**
- **Mass increased as part of risk-reduction process run by the SPP spacecraft when the nominal orbit was modified**
- **Power and telemetry have held steady with some reductions in uncertainty**
- **Two small additions**
  - **EPI-Lo added an anti-coincidence detector**
  - **EPI-Hi added small “high-rate” pixels**
  - **Both of these use spare resources of existing electronics and provide large payoff for dynamic range**



Requirements Flow-Down

Status Key:
- Started
- Draft: Key Driving
- Draft: Complete
- Preliminary
- Baseline

Level 1

L1 Requirements For The SPP Mission
Appendix E to Living With a Star Program Plan

Level 2

Solar Probe Plus (SPP) Level 2 Mission Requirements Document (MRD)

Level 3

SPP Level 3 Payload Requirements Document (PAY)

EDTRD | EMECP | CCP | MPCP | PCP

SPP-ISIS ICD | GI ICD | MOC/SOC ICD

Level 4

SPP ISIS Level 4 Instrument Requirements Document (IRD)

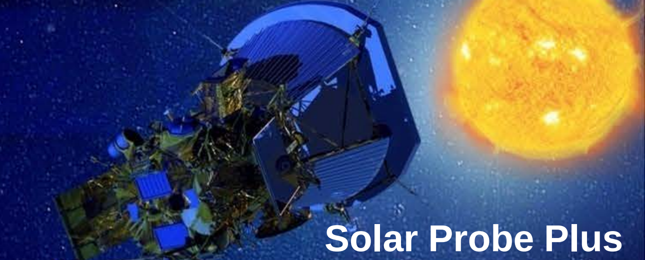
ISIS Meets L1/L2 Measurement Performance Requirements

Parameter	EPI-Lo Requirement	EPI-Hi Requirement
Ion Energies (MRD-97)	**50 keV/nucleon – 15,000 keV Total E** (PAY-80)	**1 MeV/nucleon – 50 MeV/nucleon** (PAY-203)
Ion Energy Resolution (MRD-97)	**6 bins / decade** (PAY-81)	**6 bins / decade** (PAY-205)
Ion Cadence (MRD-97)	**≤ 5 s** (PAY-82)	**≤ 5 s** (PAY-267)
Ion Angle resolution (MRD-97)	**$\leq 30^\circ$ sector width** (PAY-83)	**$\leq 30^\circ$ sector width** (PAY-206)
Ion Composition (MRD-97)	**H, He, ^{3}He, C, O, Ne, Mg, Si, Fe** (PAY-84, PAY-223)	**H, He, ^{3}He, C, O, Ne, Mg, Si, Fe** (PAY-268, PAY-224)
SEP Event Ions (MRD-97)	**Intensities up to 10^6 particles / cm^2-sr-s** (PAY-226)	**Up to 10% of upper limit proton spectrum from SPP EDTRD** (PAY-230)
Electron Energy Range (MRD-96)	**50 – 500 keV** (PAY-76)	**0.5 MeV to 3 MeV** (PAY-200)
Electron Energy Resolution (MRD-96)	**6 bins / decade** (PAY-77)	**6 bins / decade** (PAY-201)
Electron Cadence (MRD-96)	**≤ 1 s** (PAY-78)	**≤ 1 s** (PAY-202)
Electron Angular Resolution (MRD-96)	**$\leq 45^\circ$** (PAY-79)	**$\leq 45^\circ$** (PAY-266)
SEP Event Electrons (MRD-96)	**Intensities up to 10^6 particles / cm^2-sr-s** (PAY-85)	**Up to 10% of upper limit electron spectrum from SPP EDTRD** (PAY-228)

Engineering-Level Performance Requirements

- **Design description and top level specifications**
  - **Level 4 requirements (16105-ISIS-IRD-01) developed for EPI-Hi and EPI-Lo**
- **Electrical and thermal instrument and components performance requirements**
  - **Defined in SPP-ISIS Instrument ICD (7434-9058)**
- **Software architecture and design**
  - **Software Development Plans**
    - **EPI-Hi (16105-EPI-Hi_SDP-01)**
    - **EPI-Lo (7464-9003)**
  - **Software Requirements Documents**
    - **EPI-Hi (16105-EPI-Hi_SRD-01)**
    - **EPI-Lo (7464-9004)**
- **Mechanical design and analyses**
  - **Preliminary structural analyses completed for EPI-Hi, EPI-Lo, and the ISIS Bracket based on SPP EDTRD (7343-9039) requirements**

Mechanical and Electrical Interface Requirements



- **General Instrument ICD (7434-9066)**
  - **Overall interface between instruments and spacecraft**
  - **Includes requirements common to all instruments**
- **SPP-ISIS Instrument ICD (7434-9058)**
  - **ISIS-specific requirements**
    - **Command, Telemetry, Power, and Heater services**
    - **First circuit interfaces**
    - **ISIS method to mitigate fault propagation thru LVDS interface**
    - **APID's and definition of Critical Housekeeping packets**
    - **Ground straps, aperture covers, safe plugs, alignment features**
  - **ISIS MICD in appendix A**
- **ISIS Bracket MICD (161050001)**
  - **detailed interface requirements to EPI-Lo, EPI-Hi, and Spacecraft**
- **EPI-Hi LVPS Requirements Document (SPP-CIT-001.E)**
  - **Internal delivery from EPI-Lo team to EPI-Hi team**

ISIS Resources: Mass, Power, Telemetry

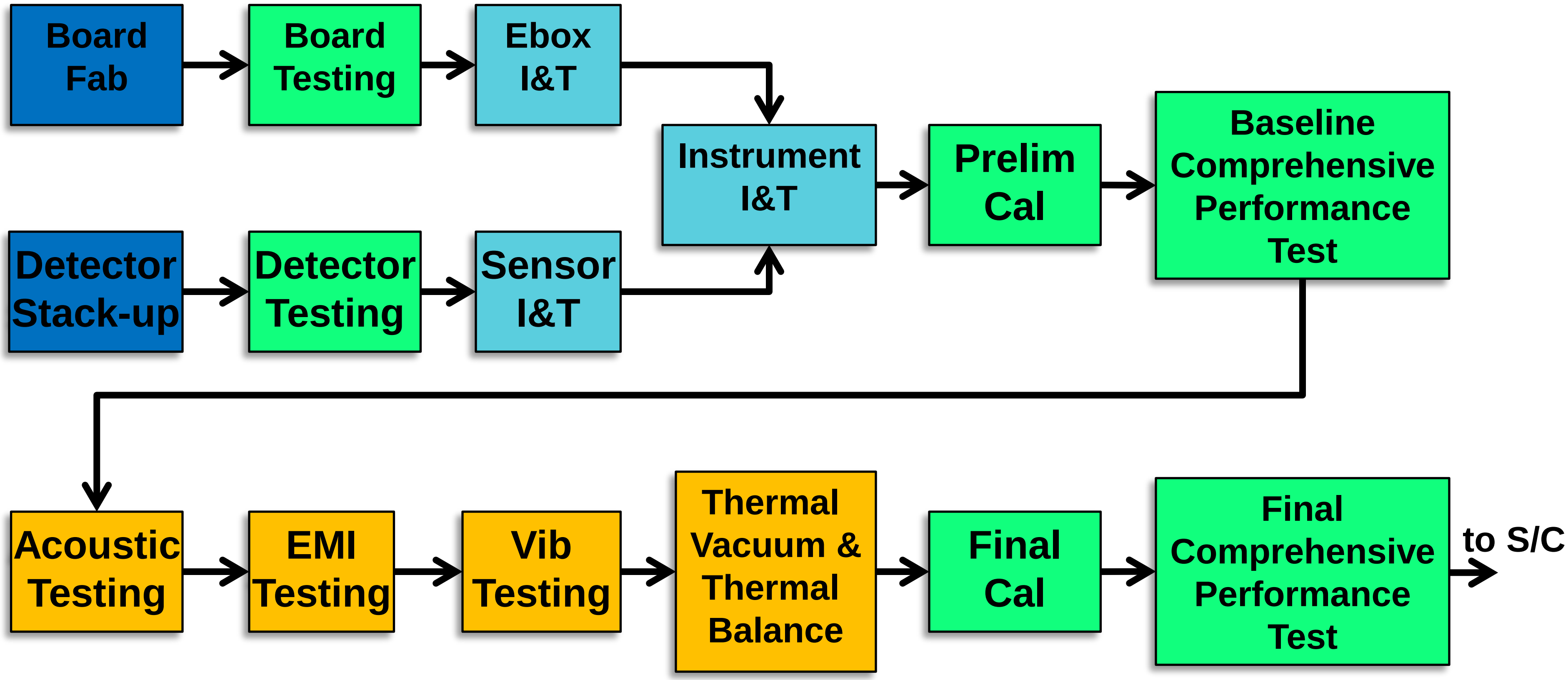
	EPI-Hi			EPI-Lo			ISIS Bracket			ISIS
	CBE	Contin. %	NTE	CBE	Contin.%	NTE	CBE	Contin. %	NTE	NTE
Mass [kg]	3.628	19.1%	4.32	3.435	16.0%	4.091	0.817	19.0%	0.972	9.383
Instrument Power [W]	5.81	14%	6.77	4.17	17%	5				11.77
Operational Heaters [W]	0.48	13%	0.55							0.55
Survival Heaters [W]	3.81	9%	4.18	2.45	5%	2.57				6.7

	EPI-Hi			EPI-Lo			ISIS
	Raw	Burst	Total	Raw	Burst	Total	Total
Uncompressed Data Volume [Gbit / orbit]	3.660	0.000	3.660	11.320	0.200	11.520	15.180
Compressed Data Volume (75%) [Gbit / orbit]	2.745	0.000	2.745	8.490	0.200	8.690	11.435
Packetized Data Volume (105%) [Gbit / orbit]	2.882	0.000	2.882	8.915	0.210	9.125	12.007

Data Volume Formula: 105%[75% * (EPI-Hi Raw + EPI-Lo Raw) + EPI-Hi Burst + EPI-Lo Burst]

ISIS
Assembly, Integration, and Test

- **EPI-Hi and EPI-Lo follow similar, but independent AI&T flows**



ISIS Requirements In Spacecraft I&T

- **ISIS plans to have > 300 operating hours before delivery to the spacecraft**
- **ISIS will supply Red-tag items**
  - **Safe plug for EPI-Lo air-safe operations**
  - **Aperture covers for EPI-Hi and EPI-Lo**
- **Continuous high-purity GN_2 purge required through T-0**
- **Simple alignment requirements (1 degree)**
  - **Alignment fiducials to be incorporated in MICD**
  - **Initial and final verification during SPP Spacecraft I&T**

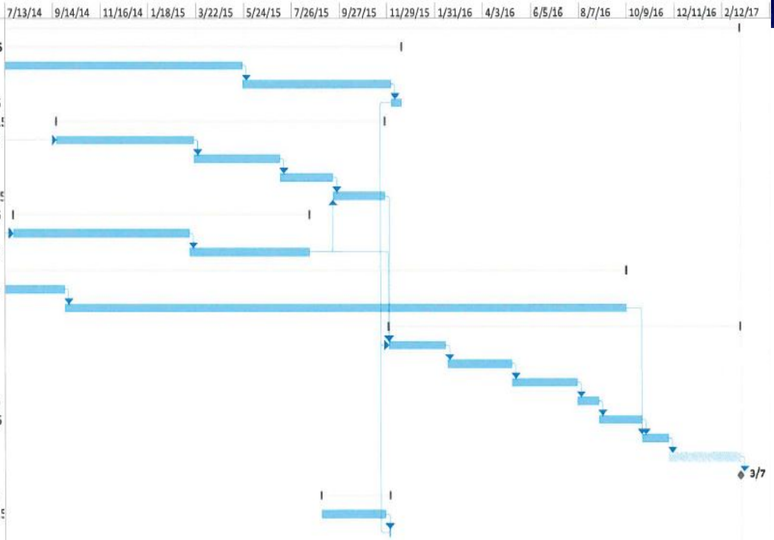
ISIS Verification Plans

- Verification Process
  - 91% of the verification items include Test for closure
  - Test procedures signed off by Systems Engineering to ensure complete coverage of requirements
  - Tests results reviewed by Systems Engineering and recorded in requirements verification spreadsheet
- Details of captured in the ISIS Verification Plan 16105-ISIS_VVP-01

Requirements	Method	Event
Mechanical:		
MICD	Inspection	FM Assembly and FM Delivery
Mass Properties	Inspection	FM Assembly
Acoustic	Test	EM and FM Acoustic Test
Pre- & Post- Vibe Survey	Test	FM Vibration Test
Sine Vibe	Test	FM Vibration Test
Random Vibe	Test	FM Vibration Test
Strength	Test	FM Vibration Test
Thermal Vacuum	Test	FM Thermal Vac Test
Thermal Balance	Test	FM Thermal Vac Test
Final Bakeout	Test	FM Thermal Vac Test
Electrical:		
Magnetic Field Testing	Test	FM Assembly and EM & FM EMI Test
EMI/EMC	Test	EM and FM EMI Test
Spacecraft Electrical Interface	Test	Comprehensive Performance Test
Software	Test	Software Acceptance Test
Measurement Performance:		
Energy Range	Test & Analysis	Calibration Test
Energy Binning	Test & Analysis	Calibration Test
Cadence and Rates	Test & Analysis	Calibration Test
Field of View	Test & Analysis	Calibration Test
Angular Sectoring	Test & Analysis	Calibration Test
Composition	Test & Analysis	Calibration Test
Intensities	Test & Analysis	Calibration Test

Development Status

ID	Task Name	Duration	Start	Finish
97	**EPI-Hi Flight Model**	**766 days**	**Thu 2/27/14**	**Tue 3/7/17**
98	**Detectors**	**395 days**	**Wed 5/28/14**	**Thu 12/17/15**
99	Flight Detector Process/Mount/Test	250 days	Wed 5/28/14	Thu 5/21/15
100	Detector Environmental Tests	135 days	Fri 5/22/15	Thu 12/3/15
101	Select FM Detectors for Flight Unit	10 days	Fri 12/4/15	Thu 12/17/15
102	**Electronics Module**	**301 days**	**Fri 9/19/14**	**Wed 11/25/15**
103	Electronics Boards Design Update/Modify	124 days	Fri 9/19/14	Wed 3/18/15
104	Electronics Boards Fab	79 days	Thu 3/19/15	Thu 7/9/15
105	Electronics Boards Test	49 days	Fri 7/10/15	Thu 9/17/15
106	Electronics Boards Integrate	49 days	Fri 9/18/15	Wed 11/25/15
107	**Mechanical**	**270 days**	**Thu 7/24/14**	**Mon 8/17/15**
108	Mechanical Design Update/Modify	160 days	Thu 7/24/14	Thu 3/12/15
109	Mechanical Fabrication	110 days	Fri 3/13/15	Mon 8/17/15
110	**Firmware/Software**	**664 days**	**Thu 2/27/14**	**Fri 10/7/16**
111	Firmware/Software Implementation	150 days	Thu 2/27/14	Mon 9/29/14
112	Firmware/Software Validation/Test	514 days	Tue 9/30/14	Fri 10/7/16
113	**EPI-Hi FM Unit Assy/Calibration/Test**	**322 days**	**Mon 11/30/15**	**Tue 3/7/17**
114	Assembly	53 days	Mon 11/30/15	Fri 2/12/16
115	Test	61 days	Mon 2/15/16	Mon 5/9/16
116	Calibration	60 days	Tue 5/10/16	Wed 8/3/16
117	Disassemble, Stake, Coat, Reassemble	20 days	Thu 8/4/16	Wed 8/31/16
118	Environmental Test	40 days	Thu 9/1/16	Thu 10/27/16
119	Final Calibration	23 days	Fri 10/28/16	Thu 12/1/16
120	ISIS Schedule Reserve (65 days)	65 days	Fri 12/2/16	Mon 3/6/17
121	Mandatory Ship Date	0 days	Tue 3/7/17	Tue 3/7/17
122	**ISIS FM Bracket Fabrication**	**62 days**	**Wed 9/2/15**	**Tue 12/1/15**
123	ISIS Bracket Fab (x2)	60 days	Wed 9/2/15	Wed 11/25/15
124	ISIS Bracket Delivery to FM Integration	2 days	Mon 11/30/15	Tue 12/1/15



ID	Task Name	Duration	Start	Finish
144	**EPI-Lo Flight Model**	**235 days**	**Wed 7/2/08**	**Tue 3/7/17**
145	**Sensor Module**	**291 days**	**Tue 9/2/14**	**Fri 10/23/15**
146	Sensor Design Update/Modify	104 days	Tue 9/2/14	Fri 1/30/15
147	Sensor Fab	99 days	Mon 2/2/15	Fri 6/19/15
148	Sensor Assembly	44 days	Mon 6/22/15	Fri 8/21/15
149	Sensor Test	44 days	Mon 8/24/15	Fri 10/23/15
150	**Electronics Module**	**291 days**	**Tue 9/2/14**	**Fri 10/23/15**
151	Electronics Boards Design Update/Modify	104 days	Tue 9/2/14	Fri 1/30/15
152	Electronics Boards Fab	99 days	Mon 2/2/15	Fri 6/19/15
153	Electronics Boards Test	44 days	Mon 6/22/15	Fri 8/21/15
154	Electronics Boards Integrate	44 days	Mon 8/24/15	Fri 10/23/15
155	**Mechanical**	**203 days**	**Tue 9/2/14**	**Fri 6/19/15**
156	Mechanical Design Update/Modify	104 days	Tue 9/2/14	Fri 1/30/15
157	Mechanical Fabrication	99 days	Mon 2/2/15	Fri 6/19/15
158	**Firmware/Software**	**664 days**	**Thu 2/27/14**	**Fri 10/7/16**
159	Firmware/Software Implementation	150 days	Thu 2/27/14	Mon 9/29/14
160	Firmware/Software Validation/Test	514 days	Tue 9/30/14	Fri 10/7/16
161	**EPI-Lo FM Unit Assy/Calibration/Test**	**345 days**	**Mon 10/26/15**	**Tue 3/7/17**
162	Assembly	45 days	Mon 10/26/15	Wed 12/30/15
163	Test	65 days	Thu 12/31/15	Thu 3/31/16
164	Calibration	60 days	Fri 4/1/16	Fri 6/24/16
165	Disassemble, Stake, Coat, Reassemble	20 days	Mon 6/27/16	Mon 7/25/16
166	Environmental Test	60 days	Tue 7/26/16	Tue 10/18/16
167	Final Calibration	30 days	Wed 10/19/16	Thu 12/1/16
168	ISIS Schedule Reserve (65 days)	65 days	Fri 12/2/16	Mon 3/6/17
169	Mandatory Ship Date	0 days	Tue 3/7/17	Tue 3/7/17
170	**ISIS FM Bracket Fabrication**	**62 days**	**Wed 9/2/15**	**Tue 12/1/15**
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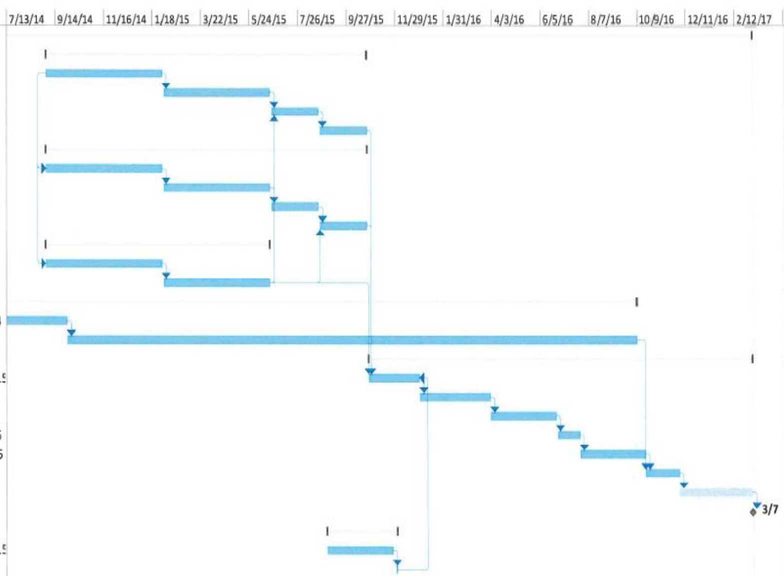

- **Large MS Project schedule maintained for ISIS**
  - **Most tasks 20 days or less**
  - **Every week, items put in a look-ahead-list and discussed on team telecon**
  - **Integrated with SPP master schedule each month**
- **Overall we have had good schedule performance through Phase B**
  - **Made adjustments where issues were found**
  - **Good performance in Pilot EVM program in Phase B**
- **ISIS Critical Path goes through EPI-Hi Mechanical development**
  - **Detectors => Telescopes => Assembly => Test**
- **65 days of Reserves in-line with guideline of month-per-year reserves to delivery**

Risk Summary

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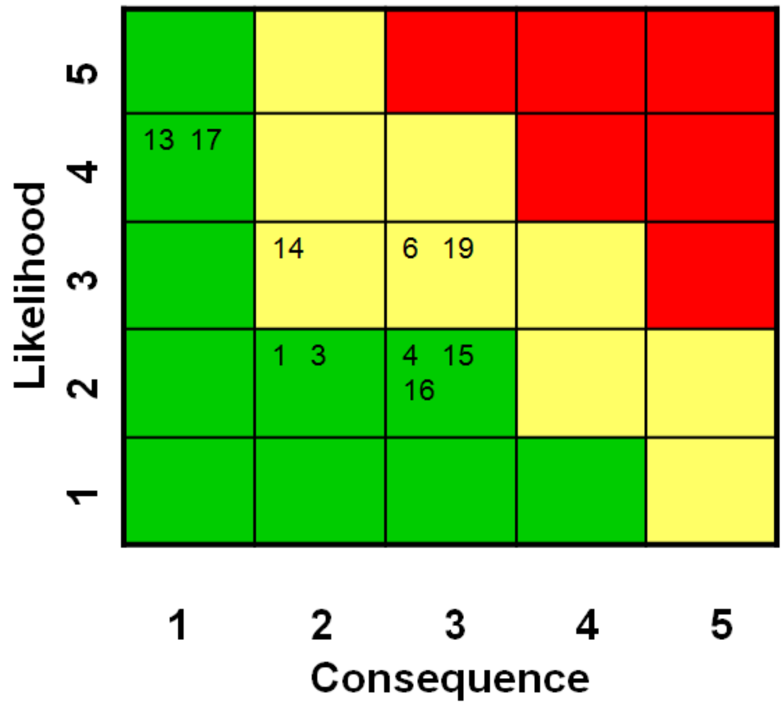

Rank	Trend	Risk ID	Approach	Risk Title
1	⇨	6	R	ISIS Vibration Levels
2	⇩	19	R	ISIS Increased Autonomy
3	⇨	14	R	ISIS Shock Testing
4	⇩	4	R	EPI-Lo Dust Impact Susceptibility
5	⇩	15	R	ISIS Increased Ground Software Demands Due to Autonomy
6	⇩	16	R	ISIS Increased Instrument FSW Demands Due to Autonomy
7	⇩	13	R	ISIS Time Tagged Commands
8	⇩	17	R	Configuring ISIS Based on Solar Distance
9	⇩	1	R	EPI-Hi Thin Detector Availability
10	⇩	3	R	EPI-Hi LET Thin Windows and Dust Impact Susceptibility

Criticality	L x C Trend	Approach
High	⇩ Decreasing (Improving)	M - Mitigate
Med	⇧ Increasing (Worsening)	W - Watch
Low	⇨ Unchanged	A - Accept
	☐ New Since Last Period	R - Research

ISIS SOC Driving Requirements

- **ISIS SOC Requirements flow down from L2 (MRD) and L3 (PAY) requirements documents**
- **Interface requirements captured in SPP MOC SOC ICD (7434-9078)**
- **Summary:**
  - **Public quick-look data 60 days after downlink (MRD-58, PAY-133)**
    - **6 months for first 3 orbits**
  - **Public science data 6 months after downlink (MRD-61, PAY-136)**
  - **Share science/engineering/ancillary data among teams (MRD-59, PAY-134)**
  - **At SOC, archive all telemetry, data, software and docs for mission + 1 year (MRD-64, PAY-138)**
  - **All SOC software + data to final, deep archive by 12 months after mission end (MRD-65, PAY-139)**
  - **SOC must have SPP project-approved security on computers (MRD-82)**
  - **SOC able to receive "remote SOC notification" of instrument fault conditions as detected by the spacecraft (MRD-72, PAY-152)**

ISIS SOC Design Description

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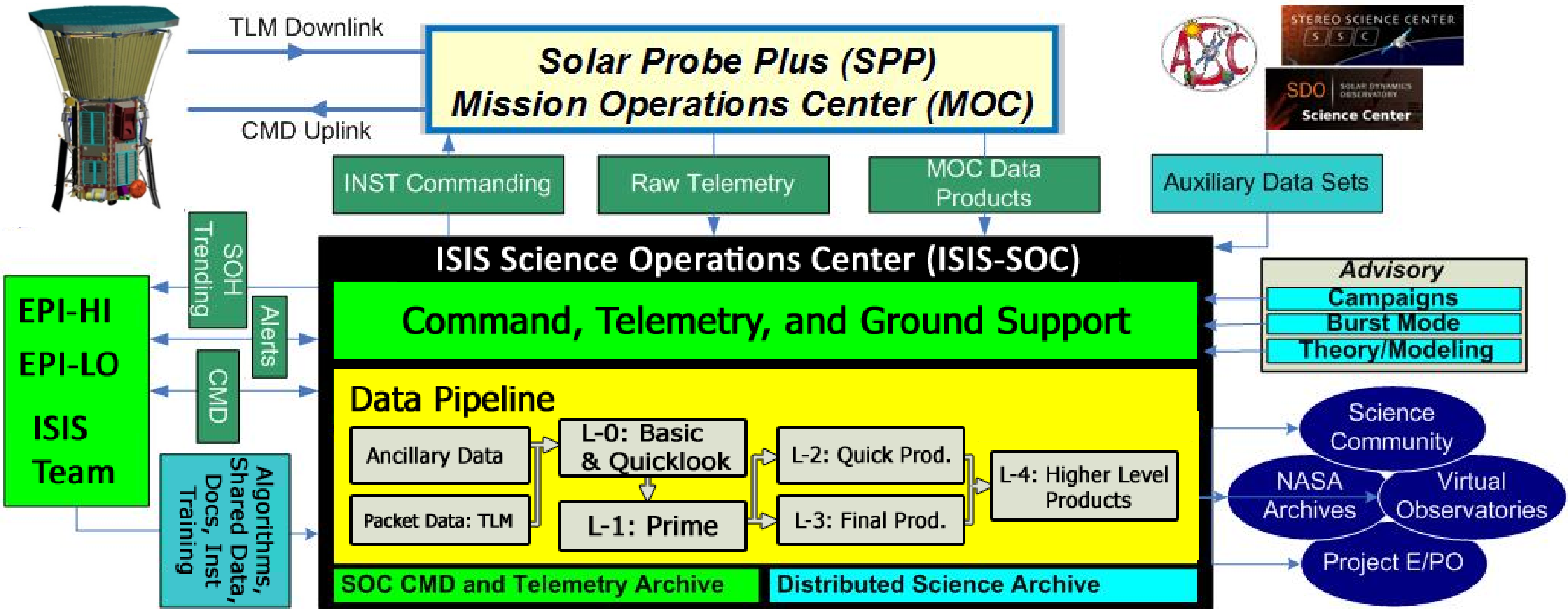


- **ISIS Science Operations Center manages commanding of EPI-Lo and EPI-Hi in coordination with instrument teams.**
- **University of New Hampshire (UNH) hosts ISIS SOC, staffed by small team responsible for day-to-day operations**
- **ISIS SOC utilizes similar architecture as IBEX Science Operations Center developed by N. Schwadron currently running at UNH**

ISIS SOC Operating Approach

- **Planning for instrument operations**
  - **Planning software**
    - **Automated routines and templates for initial planning**
    - **Interactions with ISIS SOC interfaces for finalization of planning**
  - **Develop rough plans three orbits ahead**
    - **Test command load**
  - **Develop definitive plans one orbit ahead**
    - **Final testing**
    - **Upload**
- **Commanding of EPI-Hi and EPI-Lo**
  - **“Flat-Sat” at UNH used to test command loads**
    - **Development of Flat-Sat will be Phase D work**
    - **Constraint Checking Modules**
  - **Standard Commanding performed via GSEOS at UNH SOC**
  - **Commissioning and Contingency response, commanding may optionally be done by EPI-Hi and EPI-Lo via GSEOS directly through MOC**

Review Action Item Summary

Review	Action Items	Open With Plan	Closed	Concurred
MDR	**0**	**0**	**0**	**0**
I-PDR	**16**	**2 ***	**14 ***	**13 ***

*** as of 1/06/2014**

Peer Review Action Items	Actions	Closed	Open
EPI-Lo TOF and CFD ASIC peer review	0	0	0
EPI-Lo Sensor Peer Review	12	12	0
EPI-Lo Anode Board Peer Review	6	6	0
EPI-Lo Sensor Peer Review	22	22	0
EPI-Lo LVPS, HVPS, Event Board Peer Review	11	11	0
EPI-Lo Energy Board Peer Review	4	4	0
EPI-Lo Software Peer Review	0	0	0
EPI-Hi ASIC Peer Review	0	0	0
EPI-Hi LVPS Board Peer Review	24	24	0
EPI-Hi DPU Board Peer Review	18	18	0
EPI-Hi HET/LET Telescope Boards Peer Review	9	9	0
EPI-Hi SSD Bias Supply Peer Review	13	13	0
EPI-Hi Mechanical Peer Review	14	14	0
EPI-Hi Flight Software Peer Review	6	6	0
PEER REVIEW TOTALS	**139**	**139**	**0**

Summary

- **ISIS passed Instrument PDR**

- **Team has performed well during Phase B**
  - **TRL6 achieved on technology developments**
  - **New design elements have been prototyped and tested**
  - **Requirements Defined**
    - **Baseline of ICDs and Requirements Documents**
  - **Detailed Preliminary Design completed**
    - **Schematics and mechanical designs Peer Reviewed**
  - **Preliminary analyses show good margins**

- **ISIS is on track to proceed into Phase C on schedule**

BACKUP SLIDES

ISIS Phase B Trade Studies

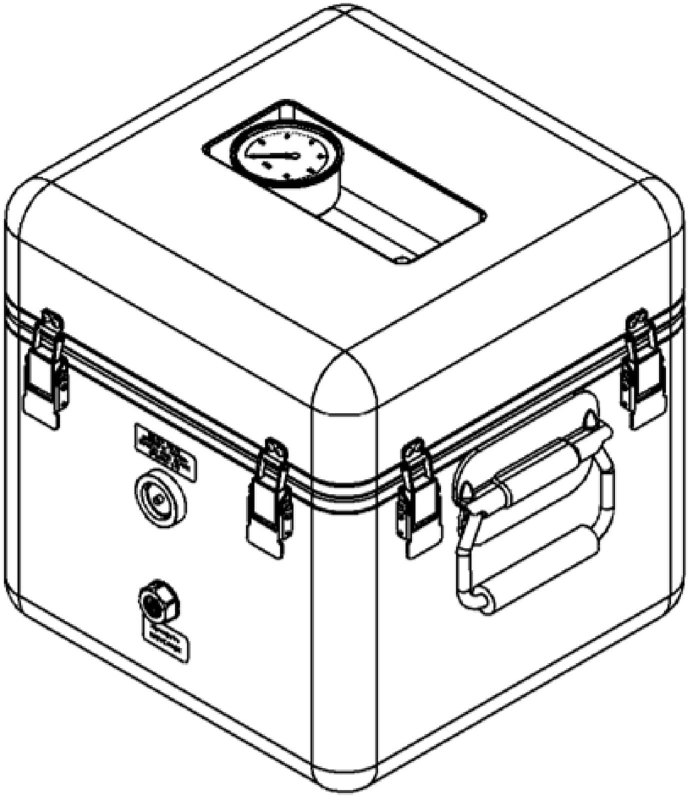
Trade	Description	Status	Closure Date
Hi: PHASIC Approach	Improve PHASIC TID: 1) Passive Shielding 2) RadHard respin of STEREO PHASIC by Aeroflex	EM Components fabricated, tested, and meet requirements	PDR (closed)
Hi: Thin Silicon Detectors	Process for making thin ion-implanted detectors that simultaneously meet all of the specifications for the EPI-Hi LET telescopes have not yet been demonstrated.	Thin detectors have been fabricated, tested, and meet requirements	PDR (closed)
Hi: Thin Windows	Because of the thin front detectors on the EPI-Hi LETs, it would be useful to make the windows at the LET apertures thinner than those used in heritage STEREO/LET instrument. (Note: Fall back to flight-proven 1/5 mil Kapton meets Level 1 Reqs)	Thin windows fabricated and tested at Heidelberg dust facility	PDR (closed)
Lo: RIO Chip	APL has developed an ASIC that performs housekeeping functions called the Remote IO (RIO) chip. Component may be useful as Housekeeping chip for ISIS (EPI-Hi and EPI-Lo).	EM Components fabricated, tested, and meet requirements	PDR (closed)
Lo: Wedge-to-TOF Chip Ratio	Time-of-Flight can be derived in several configurations of MCP wedges and TOF chips (start/stop inputs), i.e. 1 or 2 wedges with direct or daisy chained TOF chips. Minimizing mass without sacrificing measurement quality is the goal.	Quadrant approach implemented	MDR (closed)
Lo: ASIC Lot Selection	The use of new generation TOF/CFD timing chips and RIO housekeeping chips alleviates the availability concern due to depletion of existing flight stocks. However, new designs might not be available in time.	EM Components fabricated, tested, and meet requirements	PDR (closed)

Phase B Analyses

- **Thermal Analysis**
  - **Instrument Requirements (Temperature Limits) are Defined**
  - **Thermal Environments and Interfaces are Defined**
  - **Resources (Heater Power) have been Iterated and Baselined**
  - **Thermal Design Analyzed and Meets all Requirements in the Specified Environments within the Allocated Resources**
- **Mechanical Analyses**
  - **Finite Element Models completed for EPI-Hi, EPI-Lo, and Bracket**
  - **Modal Analysis performed and meets requirements**
  - **Stress Analysis performed and meets required margins of safety**
- **Failure Modes Effects Analysis**
  - **Supported SPP analysis efforts by providing Block-Diagram-Level FMEA**

GSE Top-Level Summary

- **GSEOS and Spacecraft Emulators provided by the SPP Project**
- **EPI-Lo has a HV air-safe plug**
  - **When installed HV is limited to air safe levels (hardware and software limited)**
  - **Plug will be permanently removed during final closeout**
- **Instrument covers**
  - **ISIS instruments will have red-tag covers to protect the apertures**
  - **Covers will be permanently removed during final closeout**
- **Environmental Test Fixtures**
  - **Thermal Vacuum Fixture**
  - **Vibration Plate Fixture**



Document Release Status: Project Requirements Documents

Project Requirements Document	Version	Date
NASA L1 Requirements For The SPP Mission Appendix E to Living With a Star Program Plan	Rev. -	9/6/2011
APL 7434-9047, Solar Probe Plus (SPP) Level 2 Mission Requirements Document (MRD)	Rev. C	8/30/2013
APL 7434-9051, SPP Level 3 Payload Requirements Document (PAY)	Rev. -	6/27/2013
APL 7434-9066, SPP General Instrument to Spacecraft ICD	Rev. -	10/3/2013
APL 7434-9058, SPP to ISIS ICD	Rev. -	10/30/2013
APL 7434-9078, SPP MOC to SOC ICD	Draft	PDR+60d
APL 7434-9039, SPP Environmental Design and Test Requirements Document	Rev. -	6/18/2013
APL 7434-9040, Electromagnetic Environment Control Plan (EMECP)	Rev. -	4/23/2013
APL 7434-9011, SPP Contamination Control Plan (CCP)	Rev. -	6/17/2013
APL 7434-9009, SPP Materials and Processes Control Plan (MPCP)	Rev -	6/11/2013
APL 7434-9001, SPP EEE Part Control Plan (PCP)	Rev. A	4/11/2013
Plus other Mission Assurance Documents		

Document Release Status: ISIS Documents

Number	Document	Released
16105-ISIS-IRD-01	ISIS Instrument Requirements Document	8/8/2013
16105-SPARES_PLAN-01	ISIS Spares Plan	10/15/2013
16105-EPI-Hi_SDP-01	EPI-Hi Software Development Plan	9/12/2013
16105-EPI-Lo_SDP-01	EPI-Lo Software Development Plan	9/6/2013
16105-SOC_SDP-01	SOC Software Development Plan	10/18/2013
16105-EPI-HI_SRD-01	EPI-Hi Software Requirements Document	8/8/2013
16105-EPI-Lo_SRD-01	EPI-Lo Software Requirements Document	8/8/2013
16105-ISIS_VVP-01	ISIS Verification and Validation Plan/Verification Matrix	10/8/2013
16105-ISIS_CMP-01	SwRI Configuration Management Plan	10/7/2013
16105-EPI-Hi_CMP-01	Caltech Configuration Management Plan	[In Review]
7464-9001	APL Configuration Management Plan (in PAIP)	10/3/2013
16105-ISIS_CRMP-01	ISIS Risk Management Plan	10/7/2013
16105-EPI-Hi_CCP-01	EPI-Hi Contamination Control Plan	[In Review]
7445-9023	EPI-Lo Contamination Control Plan	10/17/2013
16105-EPI-HI_FMEA-01	EPI-Hi Inputs to SC Interface FMEA	10/7/2013
16105-EPI-Lo_FMEA-01	EPI-Lo Inputs to SC Interface FMEA	9/6/2013

Document Release Status: ISIS Documents

Solar Probe Plus
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Number	Document	Released
16105-ISIS-IRD-01	ISIS Instrument Requirements Document	8/8/2013
16105-SPARES_PLAN-01	ISIS Spares Plan	10/15/2013
16105-EPI-Hi_SDP-01	EPI-Hi Software Development Plan	9/12/2013
16105-EPI-Lo_SDP-01	EPI-Lo Software Development Plan	9/6/2013
16105-SOC_SDP-01	SOC Software Development Plan	10/18/2013
16105-EPI-HI_SRD-01	EPI-Hi Software Requirements Document	8/8/2013
16105-EPI-Lo_SRD-01	EPI-Lo Software Requirements Document	8/8/2013
16105-ISIS_VVP-01	ISIS Verification and Validation Plan/Verification Matrix	10/8/2013
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16105-EPI-HI_FMEA-01	EPI-Hi Inputs to SC Interface FMEA	10/7/2013
16105-EPI-Lo_FMEA-01	EPI-Lo Inputs to SC Interface FMEA	9/6/2013

Other Documents ISIS has provided feedback on or input to

Solar Probe Plus
A NASA Mission to Touch the Sun

- **In addition to the Requirements documents, ISIS has provided feedback on the following documents/topics:**

ISIS Input to Project
Limited Life Items List
Missile System Pre-Safety Package (MSPSP) Inputs
Materials and Processes List
Long Lead-Time Items List
Common Buy Item List
Instrument Thermal Model Supporting Information
Structural Analysis Documentation and Models
Instrument Mechanical Models
List of Planned Reviews
Comments on MOC-SOC Software ICD
Response on SPP Contamination Control
Reliability Plan Review

ISIS Key Schedule Milestones

Solar Probe Plus
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Task Name	Q3 '13 – Q3 '18
Solar Probe Plus	
Mission Level Milestones	
Preliminary Design Review (PDR)	1/8
Critical Design Review (P-CDR)	3/4
System Integration Review (SIR)	6/3
Pre-Environmental Review (PER)	10/6
Pre-Ship Review (PSR)	2/22
Launch Readiness Review (LRR)	7/31
Mission Phases	
Phase B	
Phase C	
Phase D	
Phase E Start (Ends 9/1/25)	
Instruments	
ISIS Milestones	
ISIS PDR	11/5
ISIS CDR (13/14 January 2015)	1/13
EPI-Lo PER	2/5
EPI-Hi PER	2/8
EPI-Lo Mandatory Schedule Reserve (65 days)	
EPI-Hi Mandatory Schedule Reserve (65 days)	
EPI-Lo PSR	2/16
EPI-Hi PSR	2/17
EPI-Lo Mandatory Ship Date (3/08/17)	3/7
EPI-Hi Mandatory Ship Date (3/08/17)	3/7

Timeline columns: Q3 '13, Q1 '14, Q3 '14, Q1 '15, Q3 '15, Q1 '16, Q3 '16, Q1 '17, Q3 '17, Q1 '18, Q3 '18

ISIS Schedule: EPI-Hi FM

ID	Task Name	Duration	Start	Finish
97	**EPI-Hi Flight Model**	**766 days**	**Thu 2/27/14**	**Tue 3/7/17**
98	**Detectors**	**395 days**	**Wed 5/28/14**	**Thu 12/17/15**
99	Flight Detector Process/Mount/Test	250 days	Wed 5/28/14	Thu 5/21/15
100	Detector Environmental Tests	135 days	Fri 5/22/15	Thu 12/3/15
101	Select FM Detectors for Flight Unit	10 days	Fri 12/4/15	Thu 12/17/15
102	**Electronics Module**	**301 days**	**Fri 9/19/14**	**Wed 11/25/15**
103	Electronics Boards Design Update/Modify	124 days	Fri 9/19/14	Wed 3/18/15
104	Electronics Boards Fab	79 days	Thu 3/19/15	Thu 7/9/15
105	Electronics Boards Test	49 days	Fri 7/10/15	Thu 9/17/15
106	Electronics Boards Integrate	49 days	Fri 9/18/15	Wed 11/25/15
107	**Mechanical**	**270 days**	**Thu 7/24/14**	**Mon 8/17/15**
108	Mechanical Design Update/Modify	160 days	Thu 7/24/14	Thu 3/12/15
109	Mechanical Fabrication	110 days	Fri 3/13/15	Mon 8/17/15
110	**Firmware/Software**	**664 days**	**Thu 2/27/14**	**Fri 10/7/16**
111	Firmware/Software Implementation	150 days	Thu 2/27/14	Mon 9/29/14
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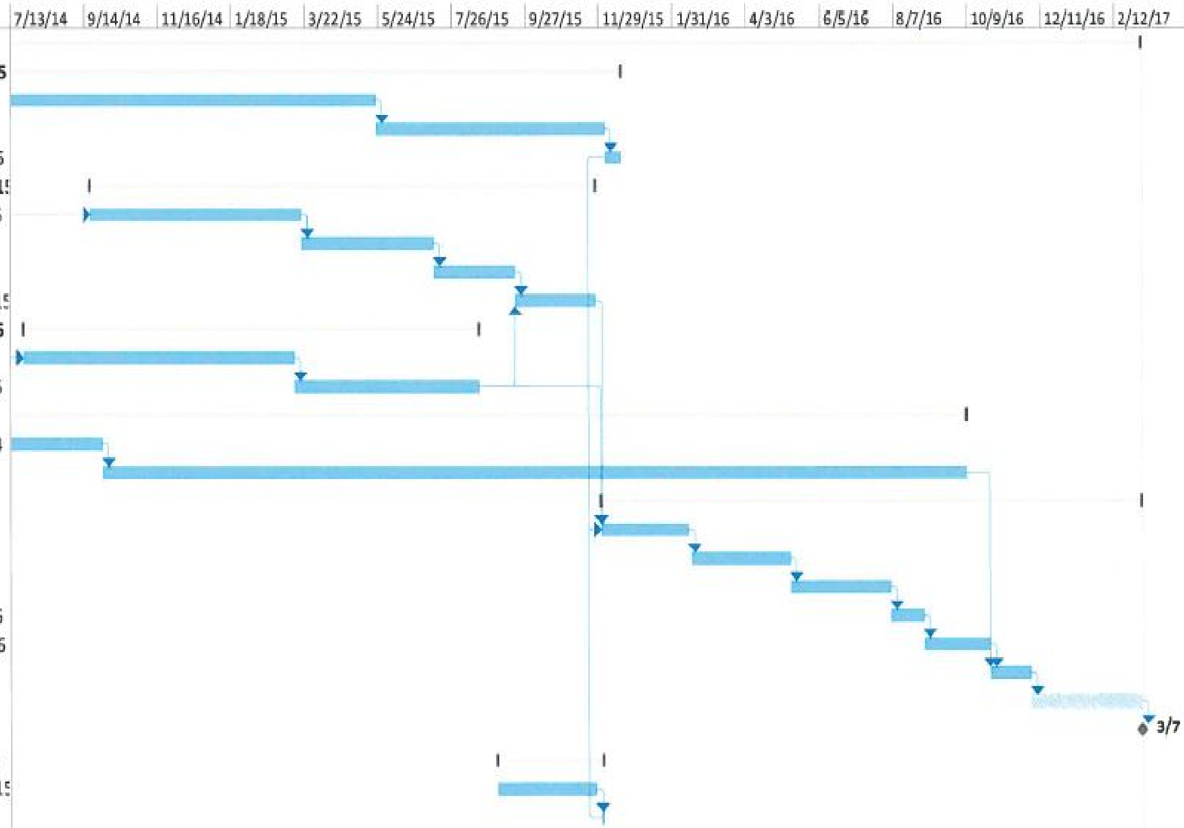

APL

ISIS Schedule: EPI-Lo FM and Bracket

ID	Task Name	Duration	Start	Finish
144	**EPI-Lo Flight Model**	**235 days**	**Wed 7/2/08**	**Tue 3/7/17**
145	**Sensor Module**	**291 days**	**Tue 9/2/14**	**Fri 10/23/15**
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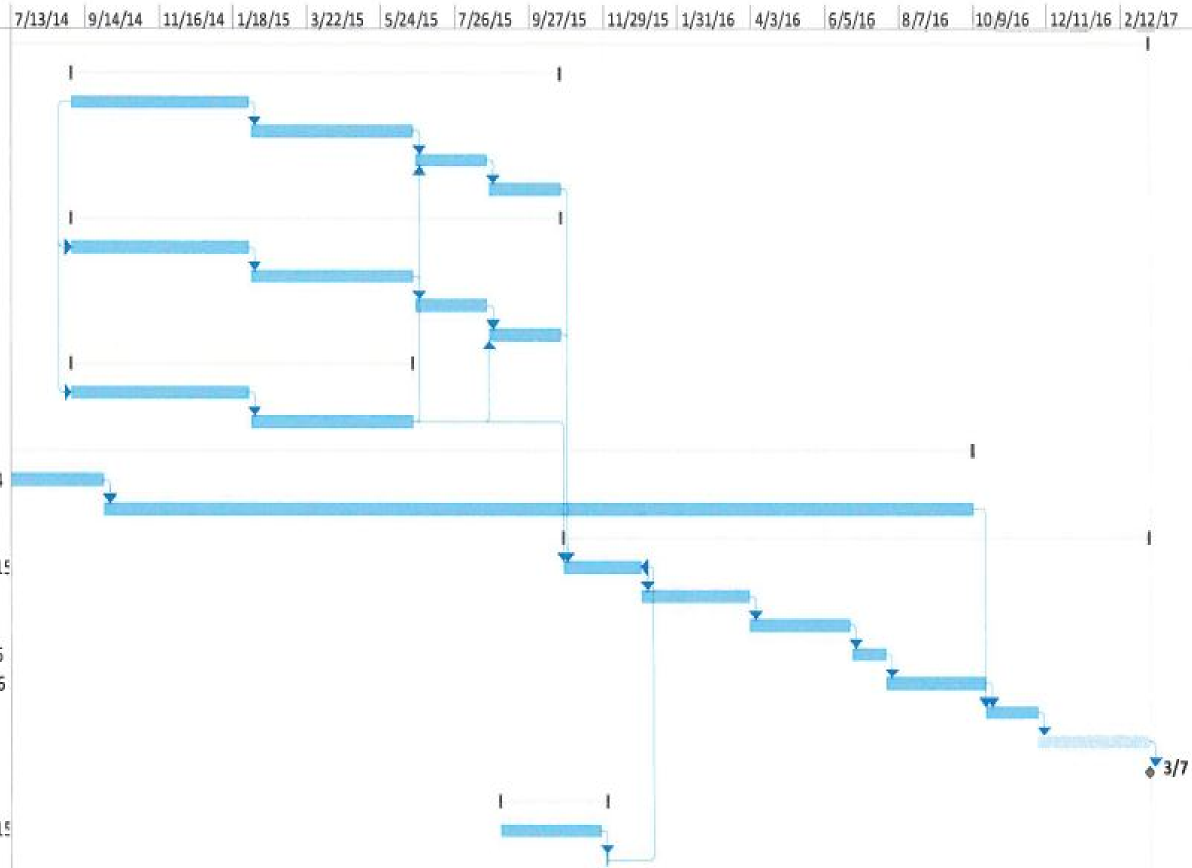
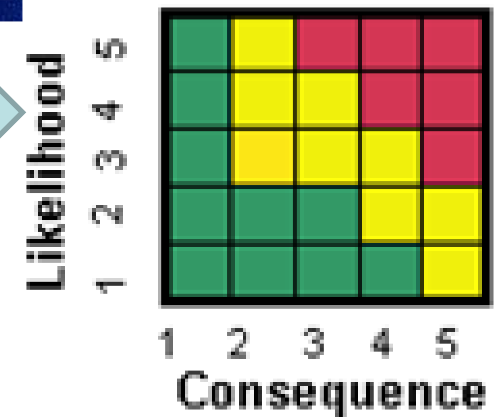


ISIS Risk Analysis Score Card

Likelihood Bins	Safety (likelihood of safety event occurrences)	Technical (Estimated likelihood of not meeting mission technical performance requirements)	Cost/schedule (Estimated likelihood of not meeting allocated Cost/Schedule requirements or margin)
5 Very High	($P_s > 10^{-1}$)	($P_T > 50\%$)	($P_{CS} > 75\%$)
4 High	($10^{-2} < P_s \le 10^{-1}$)	($25\% < P_T \le 50\%$)	($50\% < P_{CS} \le 75\%$)
3 Moderate	($10^{-3} < P_s \le 10^{-2}$)	($15\% < P_T \le 25\%$)	($25\% < P_{CS} \le 50\%$)
2 Low	($10^{-6} < P_s \le 10^{-3}$)	($2\% < P_T \le 15\%$)	($10\% < P_{CS} \le 25\%$)
1 Very Low	($P_s \le 10^{-6}$)	($0.1\% < P_T \le 2\%$)	($P_{CS} \le 10\%$)



LEVEL	Minimal (1)	Minor (2)	Medium (3)	Major (4)	Very High (5)
Safety	Negligible safety impact	Minor injury with no lost work time	Injury with lost work time	Severe injury	Death or permanent disabling injury
Technical	Negligible technical impact	Decrease in instrument capability/margin. But all instrument requirements met, or need for requirement definition or design/implementation workaround	Major loss of instrument capability	Loss of Instrument (EPI-Hi or EPI-Lo)	Loss of one or more Level-1 science requirements
Cost	ISIS Project cost overrun of less than 1% of allocated	ISIS Project cost overrun between 1% to 3% of allocated	ISIS Project cost overrun between 3% to 10% of allocated	ISIS Project cost overrun between 10% to 20% of allocated	ISIS Project cost overrun of greater than 20% of allocated
Schedule	Negligible schedule slip	Schedule slip not on critical path	Schedule slip affecting critical path but not launch or post-launch critical event	Schedule slip of 1 to 3 months	Schedule slip of greater than 3 months