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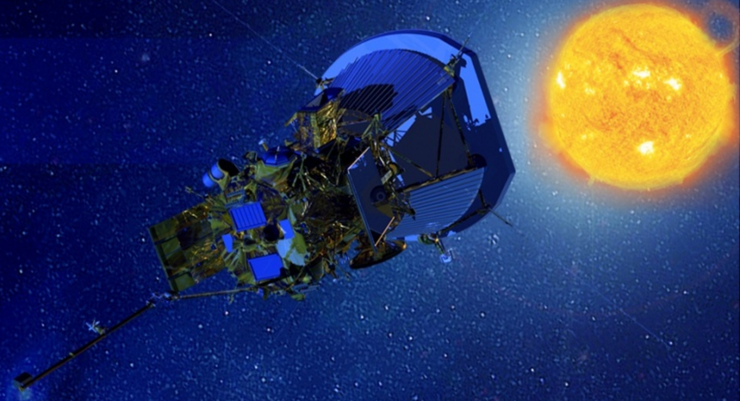

Spacecraft Electrical System Overview

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13 – 16 January 2014

APL
The Johns Hopkins University
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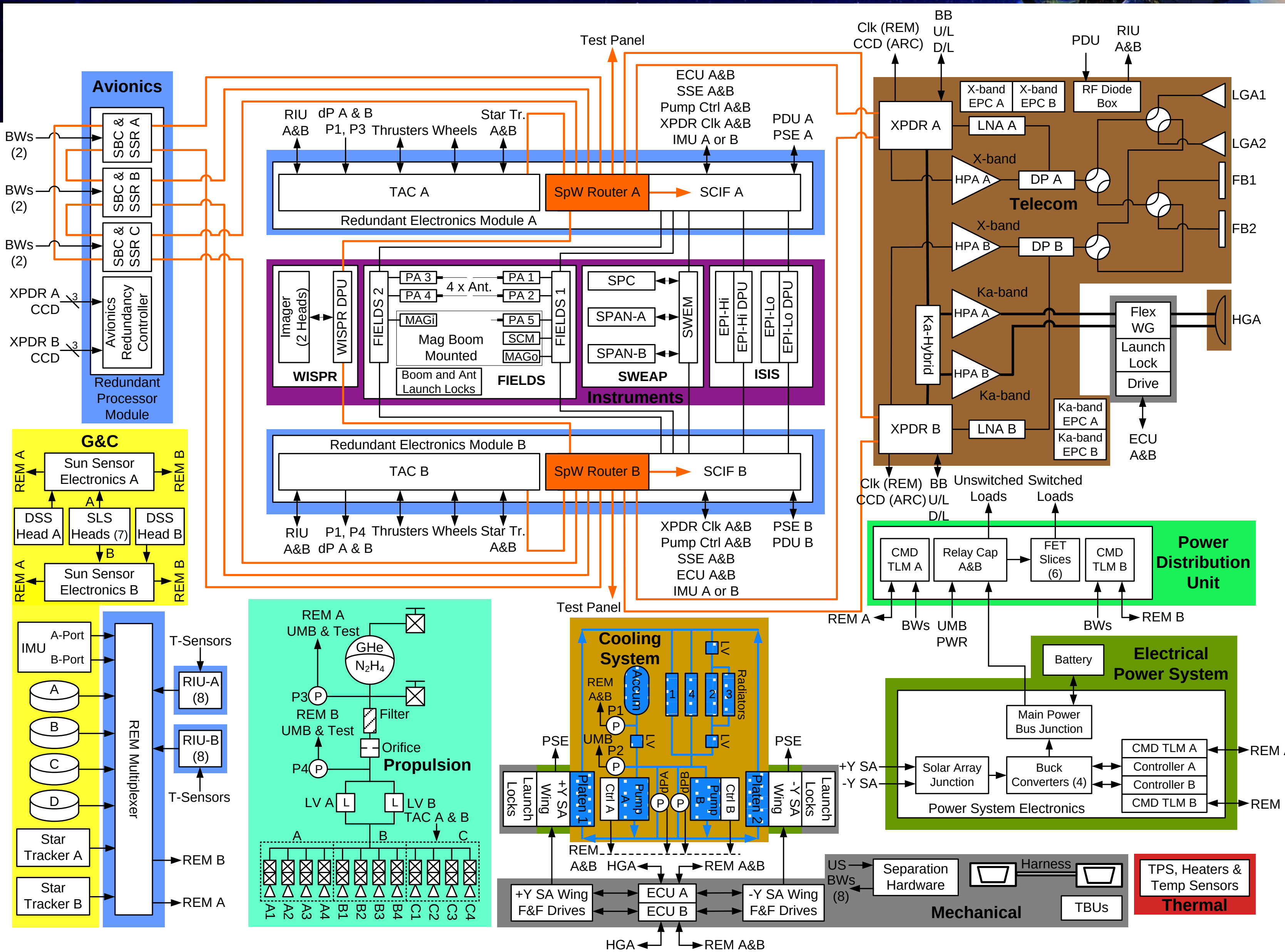
Outline

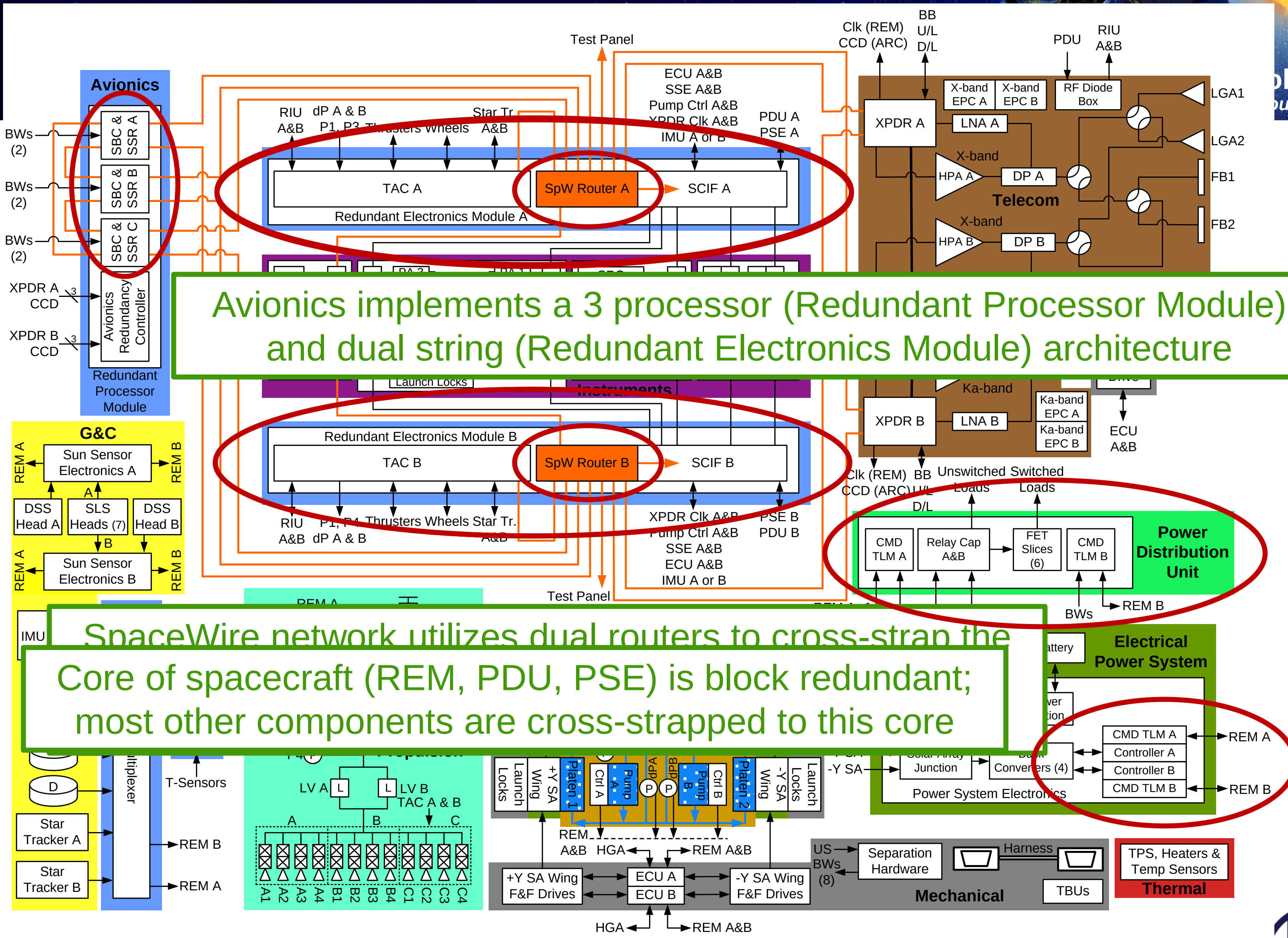
- Spacecraft block diagram overview and changes since SRR/MDR
- Summary of Phase B Level 2 electrical system trade studies
- FIELDS Antenna Deployment Options (Phase C trade study)
- Overview of Observatory timekeeping architecture and MET fault tolerance
- Overview of spacecraft electrical interfaces
- Approach to prevent fault propagation over LVDS interfaces
- Overview of spacecraft accommodations for nominal and fault testing
- Summary

Spacecraft Block Diagram



Spacecraft Block Diagram

Overview

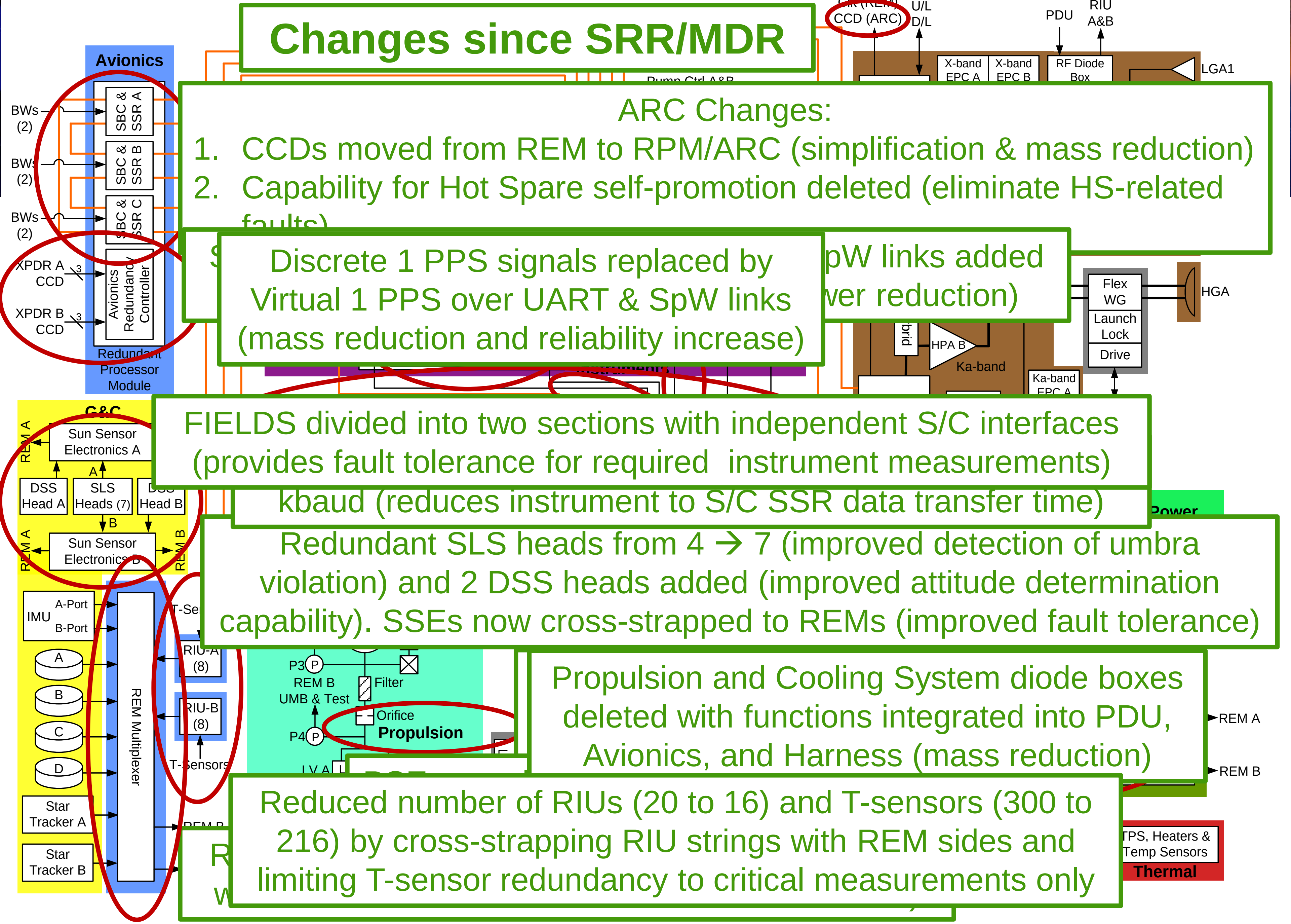


Avionics implements a 3 processor (Redundant Processor Module) and dual string (Redundant Electronics Module) architecture

SpaceWire network utilizes dual routers to cross-strap the

Core of spacecraft (REM, PDU, PSE) is block redundant; most other components are cross-strapped to this core

Changes since SRR/MDR



ARC Changes:
1. CCDs moved from REM to RPM/ARC (simplification & mass reduction)
2. Capability for Hot Spare self-promotion deleted (eliminate HS-related faults)

S... pW links added ...wer reduction)

Discrete 1 PPS signals replaced by Virtual 1 PPS over UART & SpW links (mass reduction and reliability increase)

FIELDS divided into two sections with independent S/C interfaces (provides fault tolerance for required instrument measurements)

kbaud (reduces instrument to S/C SSR data transfer time)

Redundant SLS heads from 4 → 7 (improved detection of umbra violation) and 2 DSS heads added (improved attitude determination capability). SSEs now cross-strapped to REMs (improved fault tolerance)

Propulsion and Cooling System diode boxes deleted with functions integrated into PDU, Avionics, and Harness (mass reduction)

Reduced number of RIUs (20 to 16) and T-sensors (300 to 216) by cross-strapping RIU strings with REM sides and limiting T-sensor redundancy to critical measurements only

R... w...)

Electrical System Trade Studies (Phase B – Closed)

Trade Study	Level	Result
1 PPS – retain or delete	2	Discrete 1 PPS deleted and replaced with virtual 1 PPS per 5 Hz UART protocol and SpW timecodes
Type and Location of Timekeeping Oscillator	2	Transponder EMXOs cross-strapped to and used by Avionics for timekeeping
S/C Data Interfaces: block or cross-strapped	2	Block redundant default, cross strapped as needed - minimize complexity/testing
Approach to redundant recording of instrument encounter data by spacecraft	2	Each single board computer includes an SSR. Data recorded on Prime then copied to Hot Spare. Approach maintains redundant recording while reducing mass and hardware complexity

Level 3 Electrical System Trade Studies in Backup

Phase C Trade Study: FIELDS Antenna Deployment Options

- **Background:**
  - **Each FIELDS antenna has a whip cage mechanism and a hinge release mechanism (8 pinpuller-based mechanisms total)**
- **Science Goal: individual deployment of each antenna hinge during FIELDS commissioning (whip cages can be simultaneously released)**
  - **Is individual release possible without driving system resources?**
  - **Since individual deployment is not a requirement would not add mass (PDU slice) if additional services needed for ind. deployment**
- **Currently 10 PDU services are allocated for individual deployment**
  - **4 for Whip cage release (possible to reduce to 2 once pinpuller resistance selected)**
  - **6 for Hinges (a PDU fault would result in 2 single + 1 pair-wise release); could reduce to as few as 2 for simultaneous release**

PDU has no unconstrained spare safety-inhibited services; if additional services become required may have to resort to pairwise or simultaneous antenna deployment (close by M-CDR)

Timekeeping System Architecture Introduction

- **The Timekeeping System provides time to instruments and some spacecraft subsystems that meets real-time and post-processed accuracy requirements**
- **The Observatory allocation for timekeeping maintains onboard time between ground contacts and distributes time to instruments and some spacecraft subsystems**
- **The Observatory Timekeeping System is distributed across multiple subsystems and instruments with an implementation that minimizes mass and power**
  - **Very little hardware exists solely for timekeeping (just a small number of signals in the spacecraft harness)**

Observatory Timekeeping Architecture

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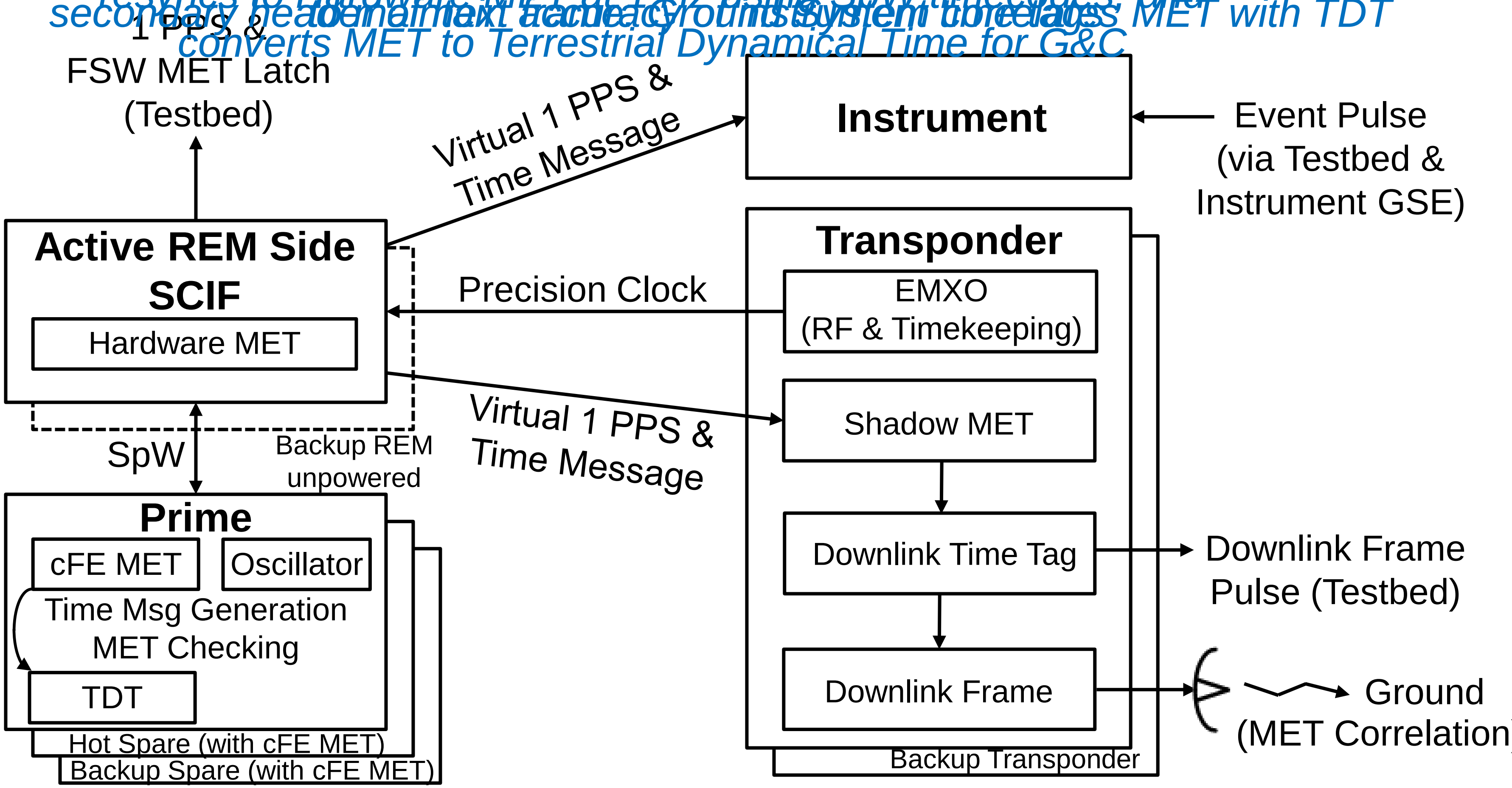
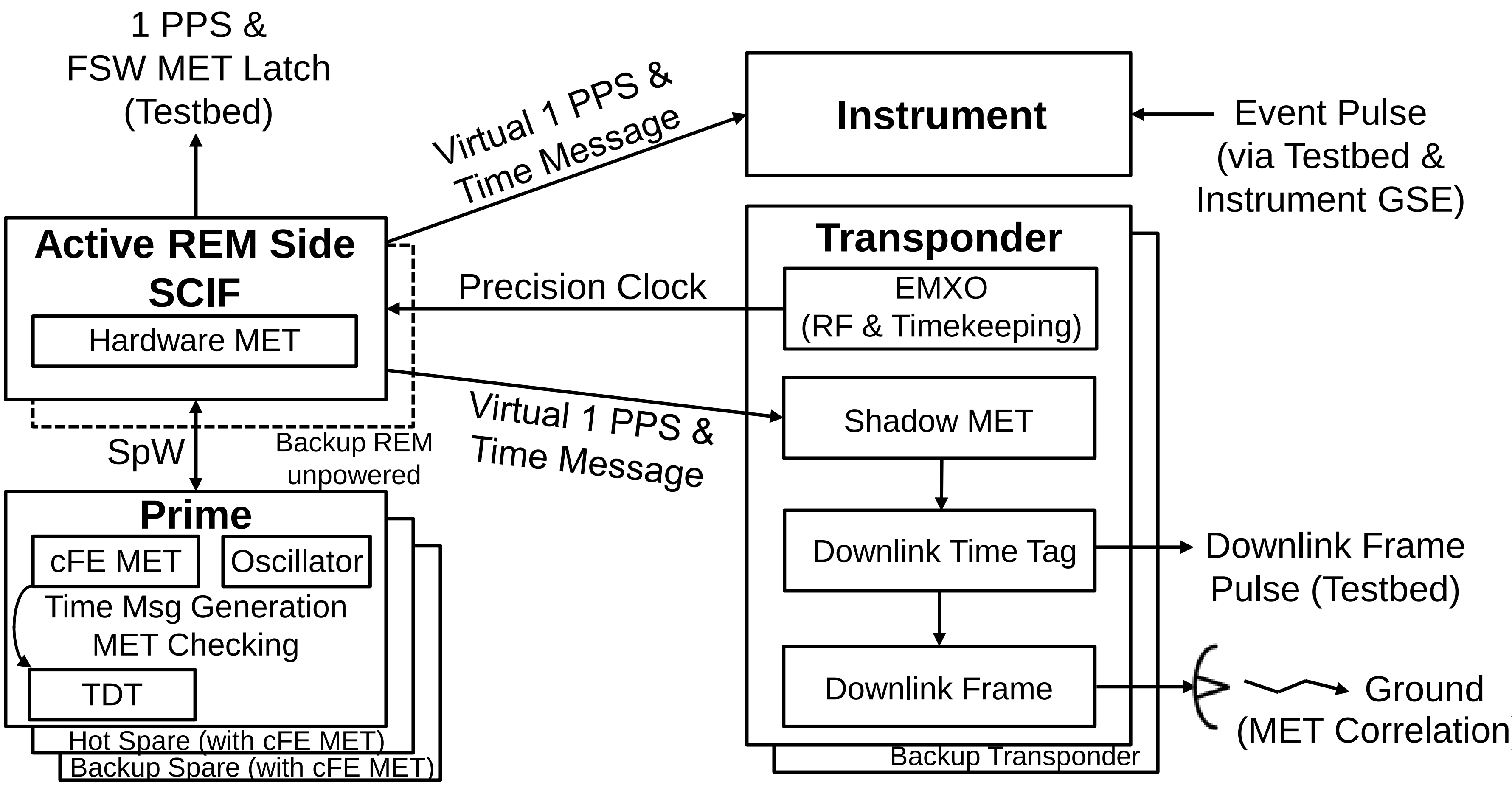
Prime FSW propagates cFE MET using SBC Oscillator, resyncs to Hardware MET at 1 Hz using SpW timecodes, and converts MET to Terrestrial Dynamical Time for G&C



Note – Precision Clock can be supplied to Active REM by either Transponder

Observatory Timekeeping Architecture



Overview of MET Fault Tolerance

- **MET/TDT is critical since used by G&C to determine target attitude**
- **Mission Elapsed Time (MET) is stored redundantly in 4 places during encounter:**
  - **MET is maintained in each of three processors as "cFE MET"**
    - **Each processor has a local oscillator used to maintain its own cFE MET**
  - **Hardware MET is maintained in the active (powered) REM/SCIF card**
- **Each processor resyncs its cFE MET to Hardware MET once per second but will flywheel using local oscillator if resync not possible or desirable**
- **If the SCIF fails and loses MET, the Prime processor can initialize MET in the backup SCIF with an accuracy of at least 20 milliseconds**
- **Even if the Prime processor corrupts SCIF MET and its own cFE MET, the Hot Spare processor will take over and correct the SCIF MET**
- **Combination of Avionics hardware and autonomy detects timekeeping oscillator frequency faults and autonomy will switch to the backup Precision Clock**

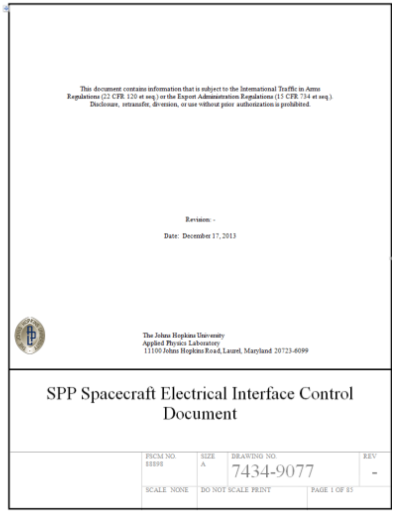
MET Fault Scenarios that have been addressed

(Covered in detail at FM peer review)

Fault #	MET Faults
1	Transient Loss of Time Code (1 PPS)
2	Transient Loss of Time Code (non-1 PPS)
3	SpW Transient failure - misread of MET or corrupted message
4	MET value in SCIF FPGA corrupted
5	Hard failure causing loss of EMXO Precision Clock to SCIF
6	MET oscillator frequency more than 150 ppm (TBR) out of spec
7	Any fault requiring REM side switch
8	Prime FSW executes erroneously and corrupts SCIF MET and cFE MET
9	Backup Spare Oscillator fails to a low or high frequency
10	Hot Spare Oscillator fails to a low or high frequency
11	Prime Oscillator fails to a low or high frequency

Spacecraft Electrical Interface Overview

- **Subsystem-to-subsystem and Spacecraft-to-GSE electrical interfaces documented in 7434-9077, Spacecraft Electrical ICD (currently in PLM for signoff)**
- **Spacecraft-to-instrument electrical interfaces documented in General and Specific Instrument ICDs**
- **LVDS interfaces extensively used since low noise and low power**
- **Instrument interfaces utilize an interface protocol that provides a virtual 1 PPS**



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Revision: -

Date: December 17, 2013

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SPP Spacecraft Electrical Interface Control Document

FSCM NO. 88898	SIZE A	DRAWING NO. 7434-9077	REV -
SCALE NONE	DO NOT SCALE PRINT	PAGE 1 OF 85	

- **Most spacecraft components utilize a 5 Hz protocol that accelerates detection of faults**
- **Interfaces to some G&C components (IMU, Star Tracker, Wheels) notional until formal selection made**
  - **Preliminary Avionics Thruster/Actuator Controller (TAC) slice design based on most probable component selection**
  - **G&C component selection scheduled to be made in time to incorporate final interfaces into TAC Engineering Model**

Prevention of fault propagation over LVDS Interfaces - Background

- **Aeroflex LVDS devices have good characteristics but they have some weaknesses that must be addressed to ensure there are no spacecraft single point faults (SPFs)**
  - **Example of a SPF: overvoltage in a component that is cross-strapped to REM A&B damages both REM sides via LVDS interfaces**
  - **LVDS ICs are not explicitly designed to prevent propagation of faults over LVDS interfaces**
- **Aeroflex does have some relevant information:**
  - **Aeroflex application note "Theory of Operation and VDD Fault Scenario for LVDS Products" documented testing that showed how faults can & cannot propagate over LVDS interfaces**
  - **Aeroflex Application note "Compatibility of 3.3V and 5.0V LVDS Drivers and Receivers" included a reliability assessment: "…**a 6.4V overvoltage … can occur for approximately 3 days and does not impact the 15 year mission life."

Prevention of fault propagation over LVDS Interfaces – Selected Approach

- **Approach to prevent propagation of faults over LVDS interfaces:**
  - **Limit the voltage applied to an LVDS device to < 6.4V even after a single fault**
  - **Telemetry must be available to flag an overvoltage condition so the "offending" component can be turned off**
  - **Implementations being documented in the Spacecraft Electrical ICD and Specific Instrument ICDs**
- **Reasons for this approach as opposed to limiting to less than max recommended LVDS voltage (3.6V):**
  - **Available data shows that limiting to 6.4V is "good enough"**
  - **Limiting to 6.4V can be simpler to implement**
  - **As the "limit" voltage approaches the operational voltage it is more likely that the protection mechanism itself can cause a failure**
- **Remaining task (underway)**
  - **APL analysis of the Aeroflex app note found gaps in testing; Aeroflex has been funded to perform additional tests to confirm the adequacy of the selected approach**

Spacecraft Accommodation of Nominal Closed Loop Testing

- **Spacecraft has been designed to be testable**
- **Testing approach has differences from previous APL spacecraft of similar complexity due to functional replacement of MIL-STD-1553 bus with a SpW network**
- **Key features that support nominal closed loop testing**
  - **<u>Actuators</u>: can operate in 1g environment (but without solar arrays mounted) and provide potentiometer feedback to FSW and autonomy**
  - **<u>G&C sensor data</u>: IMU & star trackers have test ports, SLS & DSS have stimulator heads**
  - **<u>Low latency actuator and ECU commands to testbed truth model</u>: SpW router table will be configured to duplicate packets with thruster, wheel, and ECU commands to testbed via SpW testport (this approach is functionally similar to a MIL-STD-1553 bus monitor)**
- **Spacecraft Safe/Arm Connector architecture and Test connector list in backup**

Spacecraft Accommodation of Fault Management Testing

- **Fault management testing requires injection of "fault" telemetry (in place of nominal telemetry) to trigger and verify fault responses**
- **Telemetry parameters required to trigger faults at the spacecraft level have been identified**
- **Several techniques are being used to inject fault telemetry:**
  - **SpW "override" of telemetry data in Avionics/REM telemetry buffers by testbed (via SpW test port)**
    - **Testbed overwrites data in telemetry buffers before they are read by Prime (example: Pump Electronics, Electronic Control Unit)**
  - **Testbed interception (via loopback connector) of UART telemetry data stream and replacement of selected bytes (example: PDU)**
  - **Simulated sensor (example: Voc/Isc cells simulated in Solar Array Simulator)**
  - **Component test ports (example: IMU & star trackers)**

Summary

- **During Phase B the spacecraft electrical system design has been refined to reduce mass while continuing to meet requirements**
- **Electrical interfaces are under configuration control in the Spacecraft Electrical ICD and Instrument ICDs**
- **Accommodations have been made for spacecraft nominal and fault management testing**
- **Spacecraft electrical system ready to proceed to Phase C**

Backup

System Electrical Trade Studies

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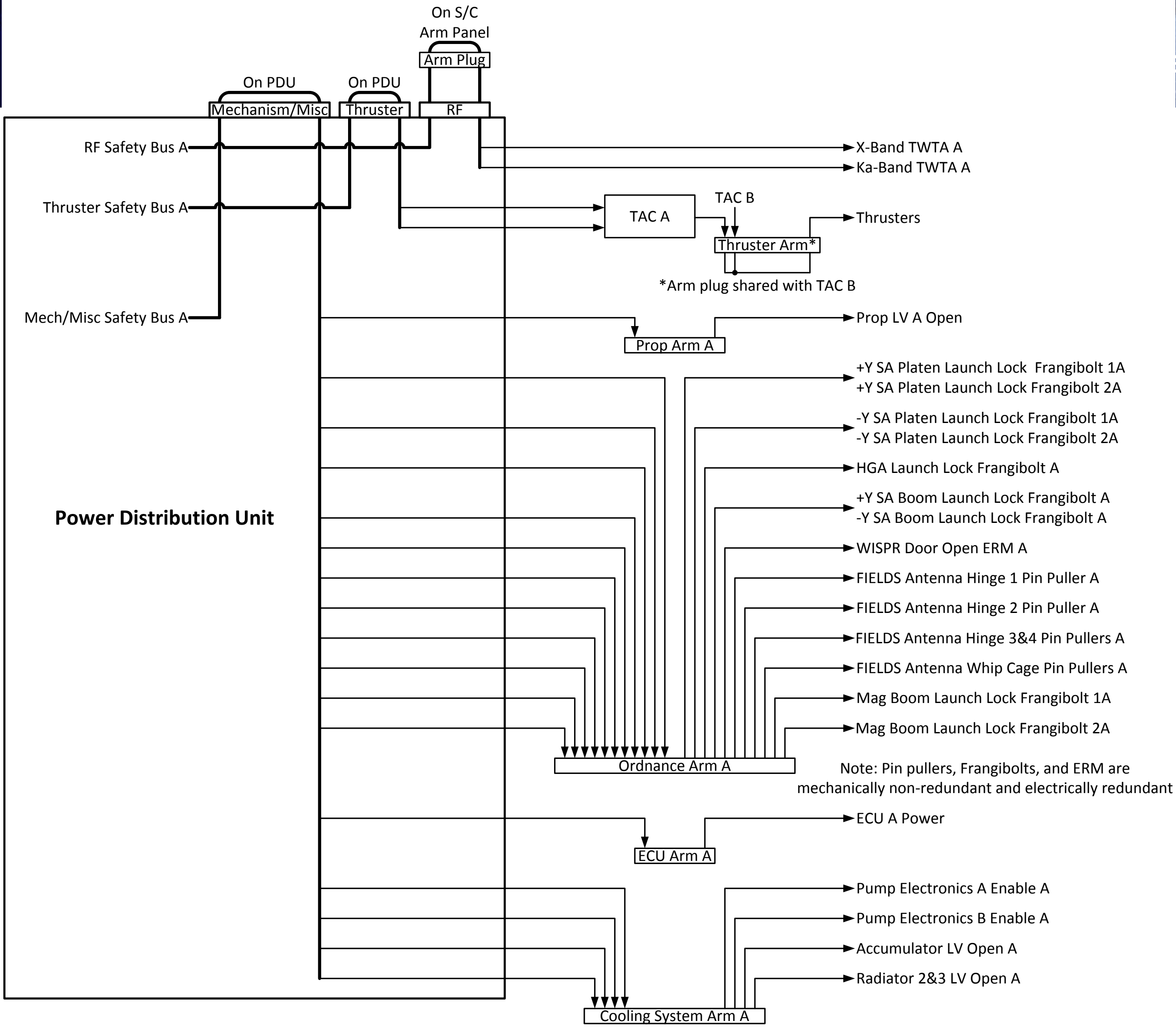
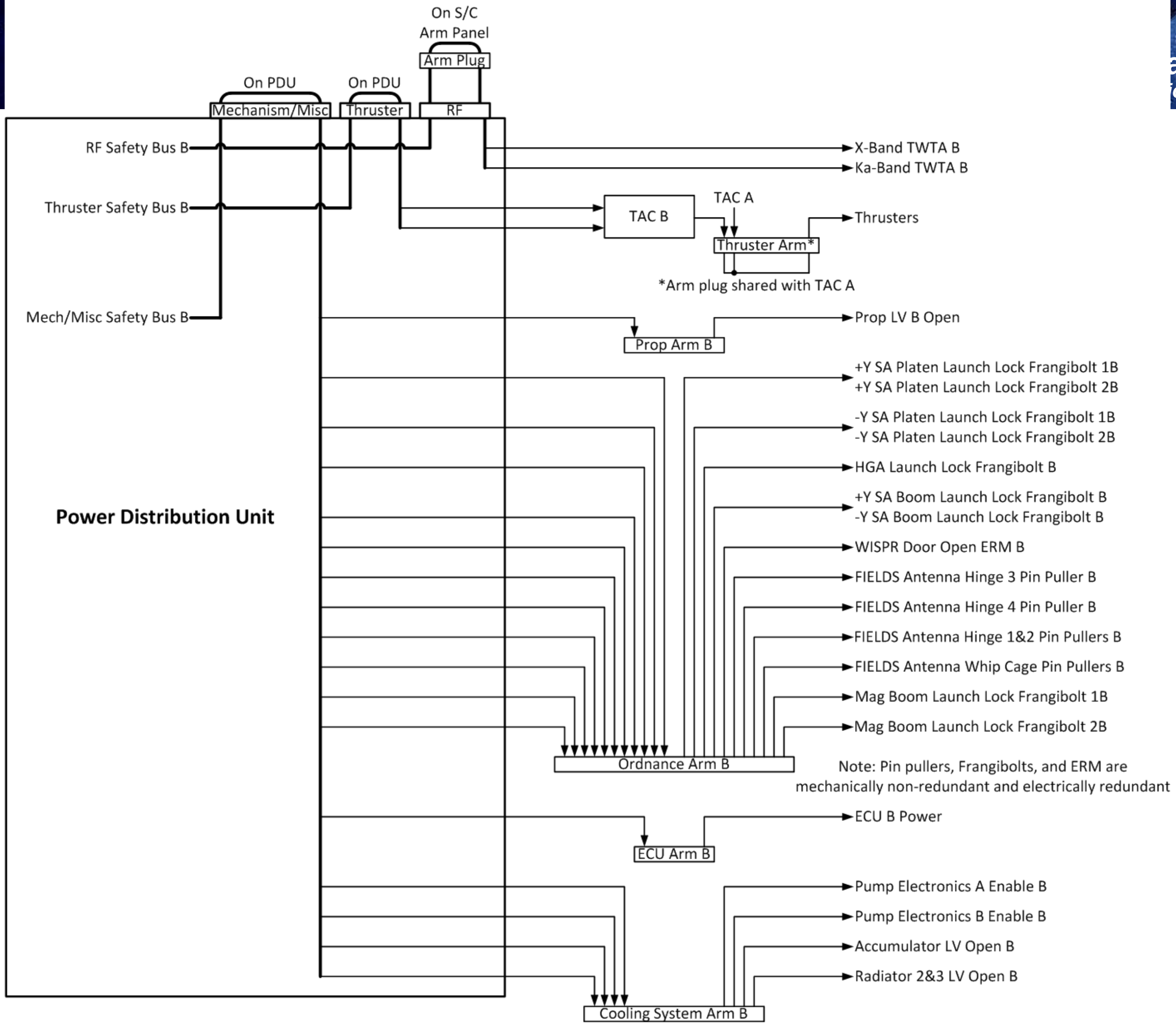
Trade Study	Level	Result
Heater configuration and redundancy	3	Spacecraft heaters redundant, instrument heaters non-redundant
Select method to eliminate LVDS interface fault propagation	3	Limit fault voltage to < 6.4V
Diode box configuration to accommodate propulsion, cooling and telecom	3	Propulsion and cooling system diode boxes eliminated
High Efficiency FIELDS FGM Survival Heater	3	FIELDS hardware heater controller used for operational and survival conditions
Temperature sensing mass reduction	3	T-sensors now cross-strapped with limited redundancy
Method selected to achieve clean prime processor switch	3	ARC timing accommodates uncertainties in processor logical switches
CCD Location		Moved from REM to ARC

Spacecraft Safe/Arm Connector Architecture (A-Side)



Spacecraft Safe/Arm Connector Architecture (B-Side)



Spacecraft Test Connectors (Preliminary)

Spacecraft Test Connectors
SSIRU A 1553 Test Connector A
SSIRU B 1553 Test Connector A
Star Tracker A Test Connector
Star Tracker B Test Connector
EPS Test Connector
Avionics, Transponder, and PDU Test Connector
Propulsion Test Plug

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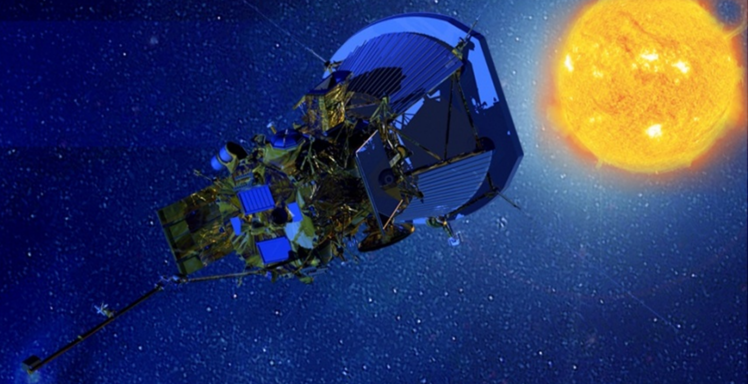

Avionics Subsystem

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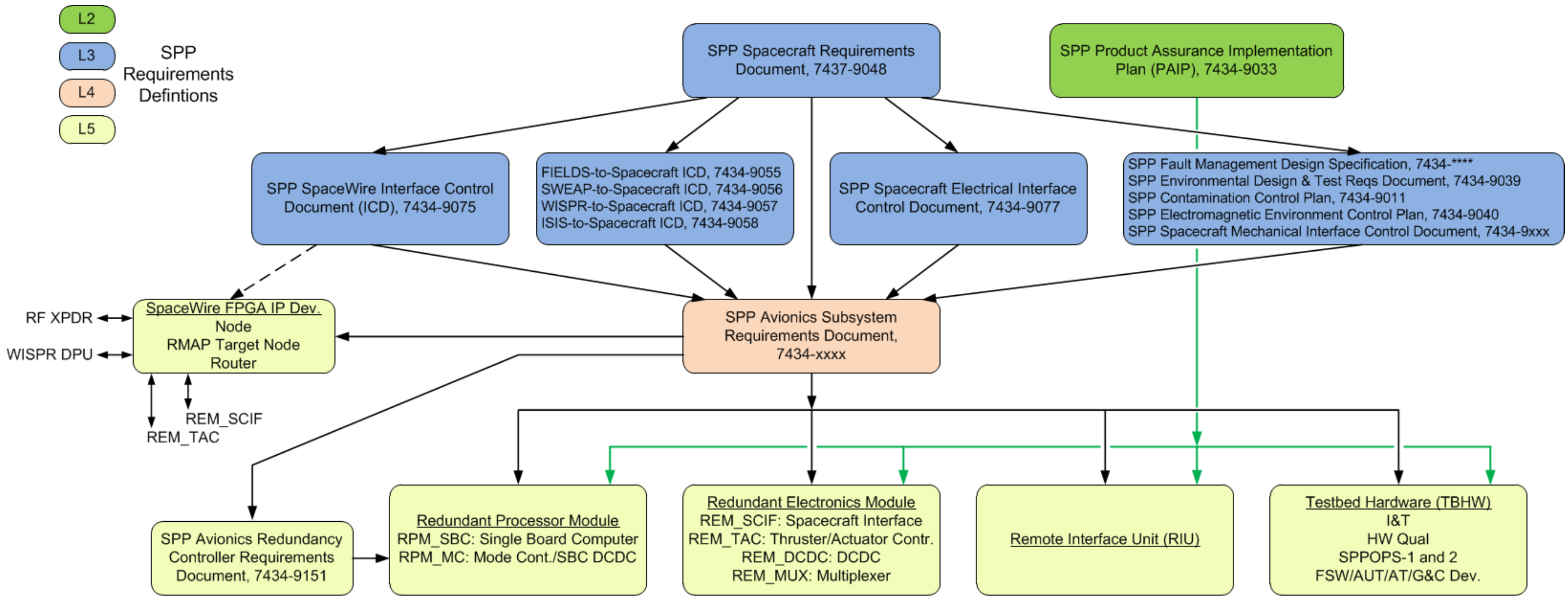
13 – 16 January 2014

The Johns Hopkins University
APPLIED PHYSICS LABORATORY

Agenda

- Driving Subsystem Requirements
  - General, Instrument Interfaces and Spacecraft Interfaces
- Design Description
  - Changes since Mission MDR
  - Mass and power resource allocation
  - Phase B Reviews
  - Subsystem Block Diagram
  - Subsystem Deliverables
  - RPM Design Information
  - REM Design Information
  - RPM and REM Packaging Design
  - RIU Design Information
- Verification Planning
- Backup

Avionics Requirements Flow-Down



Governing APL QMS Documents for the development of flight hardware:
C&DH, PDU & Power Subsystems Development Process, SD-QP-506
Electrical/Electronics Board and Box Dev. Process, SD-QP-774
Spacecraft FPGA Electronics Design and Development Process, SD-QP-775
Electrical Ground Support Equipment Development Standards, SD-QP-640
Electronic Packaging Process, SD-QP-514 (In Process)

Notes:
1. Spacecraft and Subsystem Requirements Flow-down and Verification are tracked in DOORS.

GKO 6/28/13

Driving Requirements, General

- **The Avionics Subsystem shall:**
  - be capable of simultaneous telemetry gathering, storing, downlinking, and real time commanding (AVI-25).
  - provide a single board computer capable of >=60 MIPS, 32 MBytes of user RAM, and 6 MBytes of nonvolatile memory (AVI-23).
  - be capable of storing >=208 Gbits (TBR) of data at EOL (AVI-36).
  - represent time with a Mission Elapsed Time (MET) that consists of a 32-bit unsigned integer seconds component called iMET, and a 16-bit subsecond or vernier called vMET which has a resolution of 20 microseconds (AVI-97).
  - have no single point failures except those on the spf list (AVI-78).
  - provide a critical command decoder (CCD) which is capable of executing commands independent of onboard software (AVI-24).
  - provide the capability to perform health checks on red. components (AVI-83).
  - assign the Avionics Single Board Computers' FSW to the logical states of Prime, Hot Spare, Backup Spare and Failed in accordance with the following figure: (Shown in later chart) (AVI-68).
  - accept PDU, REM and XPDR power switching commands from only the prime processor (AVI-81).

Driving Requirements, Instrument Interfaces

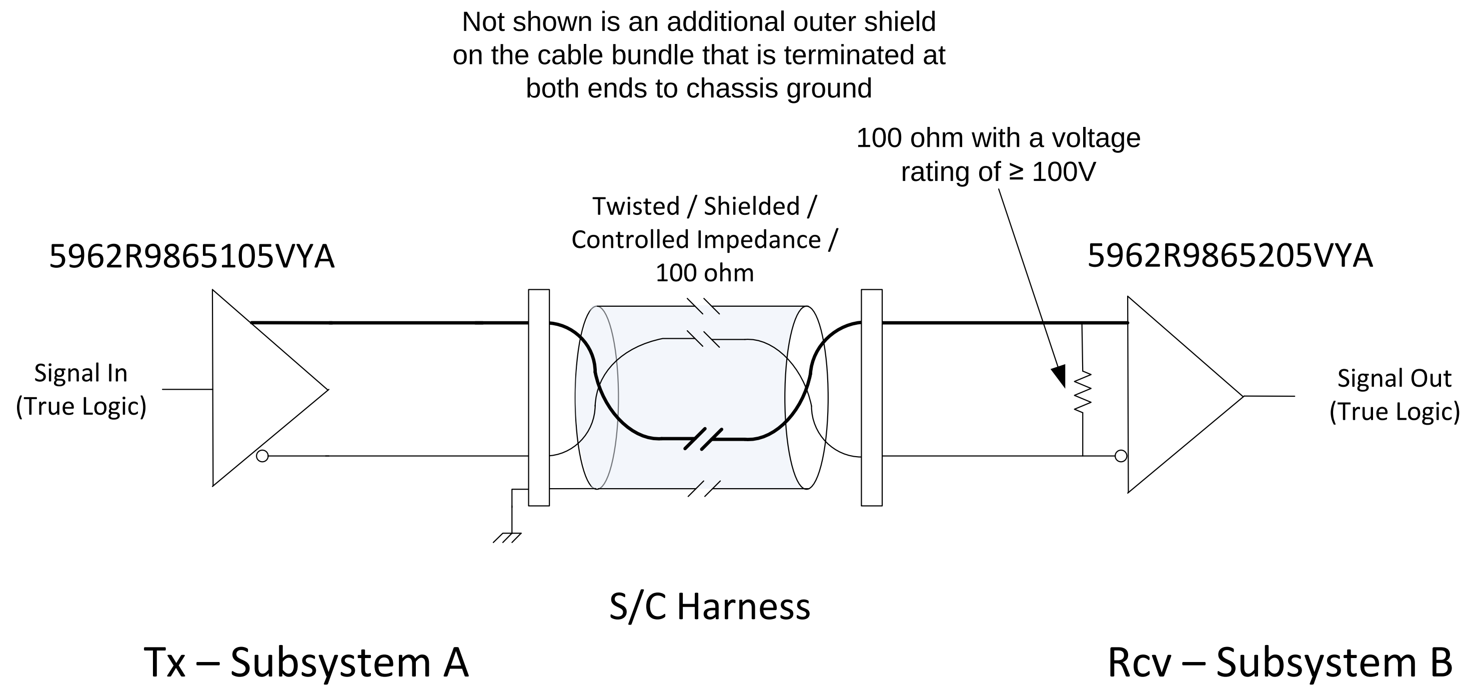
- **The Avionics Subsystem shall:**
  - be designed to accommodate the command and telemetry interfaces with the FIELDS/ISIS/SWEAP/WISPR investigation as specified in the ICDs, 7434-xxxx (AVI- 5, 6, 7, 8, 27, 28, 29, 30).
  - be capable of receiving simultaneous data, from all instruments or their DPUs (as applicable) in accordance with the Spacecraft to Instrument ICDs (AVI-44).
  - distribute a timing reference indication, virtual PPS encoded within the command UART, to the FIELDS/ISIS/SWEAP investigation within 10 usecs of SCIF MET rollover (AVI-104, 105, 106)
  - distribute a timing reference indication, SpaceWire time-codes, to the WISPR investigation within 10 usecs of SCIF MET rollover (AVI-107).

Driving Requirements, Spacecraft Interfaces

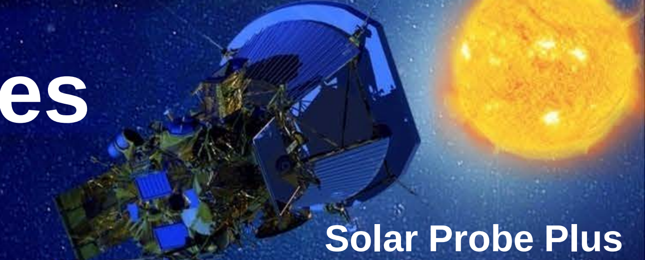
- **The Avionics Subsystem shall:**
  - be capable of signal isolation of cross-strapped components that do not support redundant interfaces (AVI-79).
  - provide cross-strapped interfaces with the G&C Reaction Wheels, IMUs and Star Trackers as spec. in the S/C Elec. ICD (AVI-136, 137, 138).
  - provide cross-strapped command and telemetry interfaces with the A and B Solar Limb Sensors (SLS), Electronic Control Units (ECU) and Pump Control Electronics as specified in the S/C Elec. ICD (AVI-19, 71, 124).
  - provide block-redundant command and telemetry interfaces with the A and B Power System Electronics (PSE) and Power Distribution Units (PDU) as specified in the S/C Elec. ICD (AVI-58, 67).
  - provide cross-strapped SpaceWire, CCD and Clock interfaces with the A and B Transponders (XPDR) as specified in the S/C Elec. ICD (AVI-20, 21, 139).
  - provide interfaces with Prop thrusters and pressure transducers (AVI-129)
  - monitor up to two-hundred and forty (240) spacecraft temperatures (AVI-60)
  - monitor CS Pxdcrs, discrete, analogs and breakwires (AVI-135, 131, 132, 110)

Driving Requirements, Spacecraft Electrical ICD

- **Conform to standard LVDS Interface; Pulse rejection filtering on UARTs (*any pulse 50 nanoseconds or less in duration is rejected)***
- **Instrument ICDs specify the standard LVDS interface with pulse rejection filtering on UARTs.**



Key Trade Results and Changes since Mission MDR



Change	Reason for Change	Impact on Resources
RPM from 7 slices to 6 (Consolidate SBC DCDCs w/MCs)	Mass reduction, distribute ARC on MCx3	~0.5 kgs mass savings Tight PWB area on MC Slice
Remove the SSRs from the REM, 8 slices to 6 (Bulk memory shifted to RPM SBC)	Mass reduction, reduced complexity	~1.2 kgs mass savings -2 Router SpW ports, -2 PDU Sw Svcs, Simplified REM DCDCs
Add REM MUX card for X-strapping of interfaces; REM 6 slices to 7	Simplify interface complexity w/physical isolation	~0.73 kgs mass increase
Added Inter-SBC SpW Interfaces	Reduce SpW network burden for redundant recording	~0.6W power increase
Added ARC pwr svcs for XPDR A&B	Requirement change	None
RIU Configuration Update: from block redundant 10-unit-strings to X-strap'd 8-unit-strings (20 units to 16)	Mass reduction	~0.4 kgs mass savings MUX relays to support X-strapping
SCIF/TAC Interface Swaps	Consolidate similar interfaces, improve LVDS CM offset	None
Propulsion Diode Box Deletion	Systems-level mass reduction	Thruster services require diode OR'ing and back EMF circuitry
UART Interface cmd and tlm to 5Hz	Reduce time for detection of time critical faults	Minimal FPGA impacts.

Resource Allocation: Mass

- **Subsystem mass liens are due to constrained PWB areas, detailed electrical design and approval of "baseline" parts, and completion of detailed structural analysis**

Avionics Subsystem Mass				
Component	Qty	CBE (kgs)	Margin	NTE (kgs)
RPM	1 Unit	5.26	10%	5.79
REM	1 Unit	5.36	10%	5.89
RIU	16 Units	1.09	8%	1.18
Avionics	**Total**	**11.71**	**9.9%**	**12.86**

Resource Allocation: Power

- **Subsystem power liens pending detailed electrical design and iterating estimates with BB, EM and FM actuals.**

Avionics Subsystem Power							
	CBE (Watts)				NTE (Watts)		
Component	Nominal (Cruise)	Encounter / RPM Checkout	REM Checkout	Margin	Nominal (Cruise)	Encounter / RPM Checkout	REM Checkout
RPM	13.9	18.9	14.6	15%	16.0	21.8	16.8
REM w/RIUs	13.3	13.3	25.5	15%	15.3	15.3	29.4
Avionics	**27.2**	**32.2**	**40.2**	**15%**	**31.3**	**37.1**	**46.2**

- Power Modes:
  - Nominal is RPM (Prime and HS) and one REM side with both RIU strings
  - Encounter/RPM Checkout RPM (Prime, HS, WS) and one REM side with both RIU strings
  - REM Checkout is RPM (Prime and HS) and both REM sides with both RIU strings

Phase B Review Summary

Name of Review	Date of Review	Assigned RFA #	Closed	Open	Past Due	Cmts
SPP RPM SBC Reqs and Schematic Peer Rev	8/17/2012	8	6	2	0	0
SPP RIO_MS ASIC EDR	2/19/2013	8	4	4	0	4
SPP RIO_MS ASIC Prototype Pre-Fab Walk-Through Summary	3/27/2013	2	2	0	0	2
SPP ARC Requirements Peer Review	4/10/2013	7	5	2	0	8
SPP SpaceWire FPGA IP Reqs Peer Review	7/9/2013	15	10	5	0	10
SPP Avionics Subsystem Reqs Peer Review	7/23/2013	18	15	3	0	15
SPP SCIF Board and FPGA Reqs Peer Review	7/24/2013	10	8	2	0	4
SPP TAC Board and FPGA Reqs Peer Review	9/26/13, 10/4/13	13	4	9	0	11
SPP Avionics Subsystem PDR Key Reviewers: C. Stevens (SRB/JPL), S. Battel (SRB), M. Fraeman (APL)	11/11/2013	11	0	11	0	8

Subsystem Block Diagram

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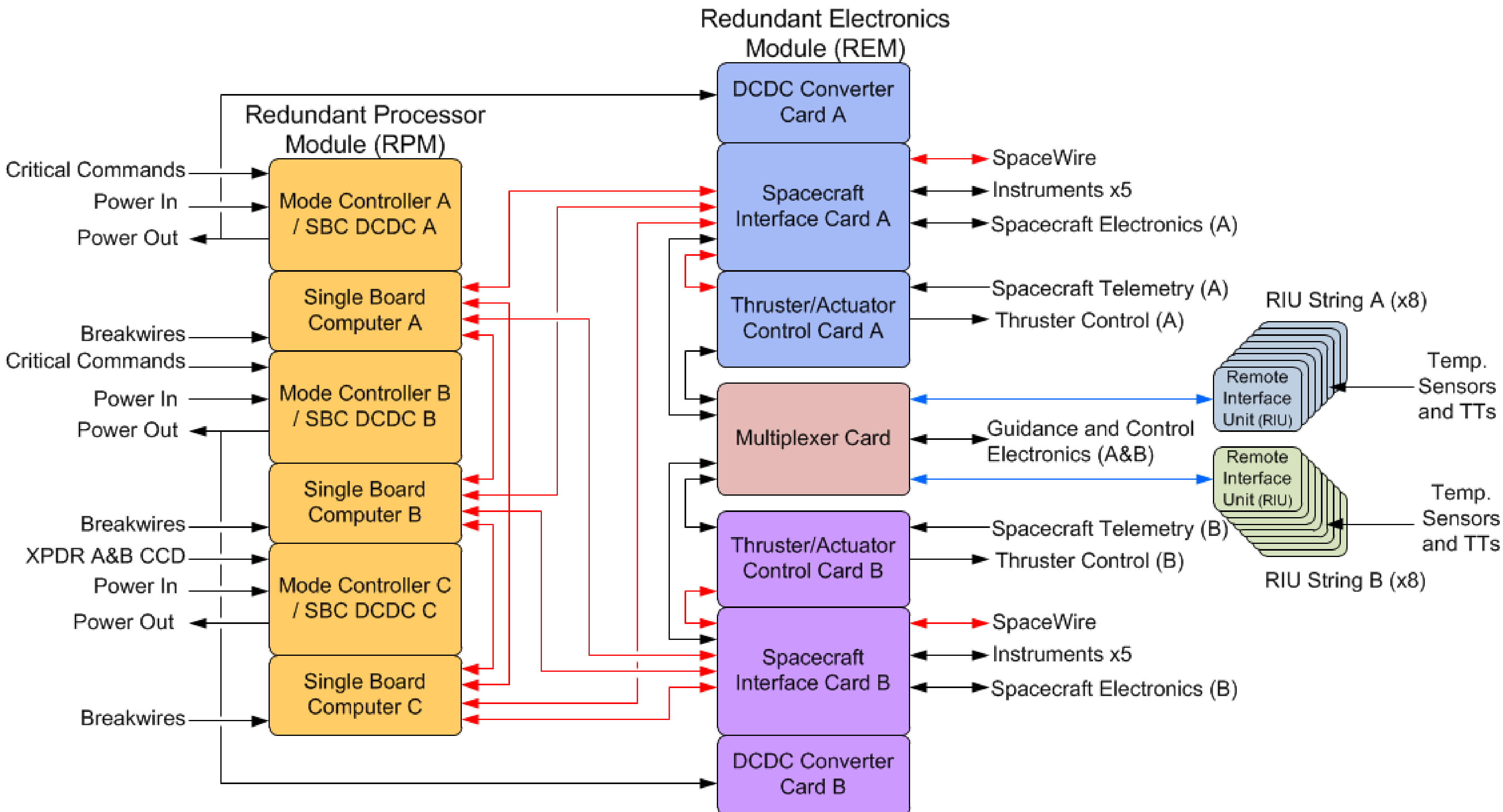

Subsystem Detailed Block Diagram

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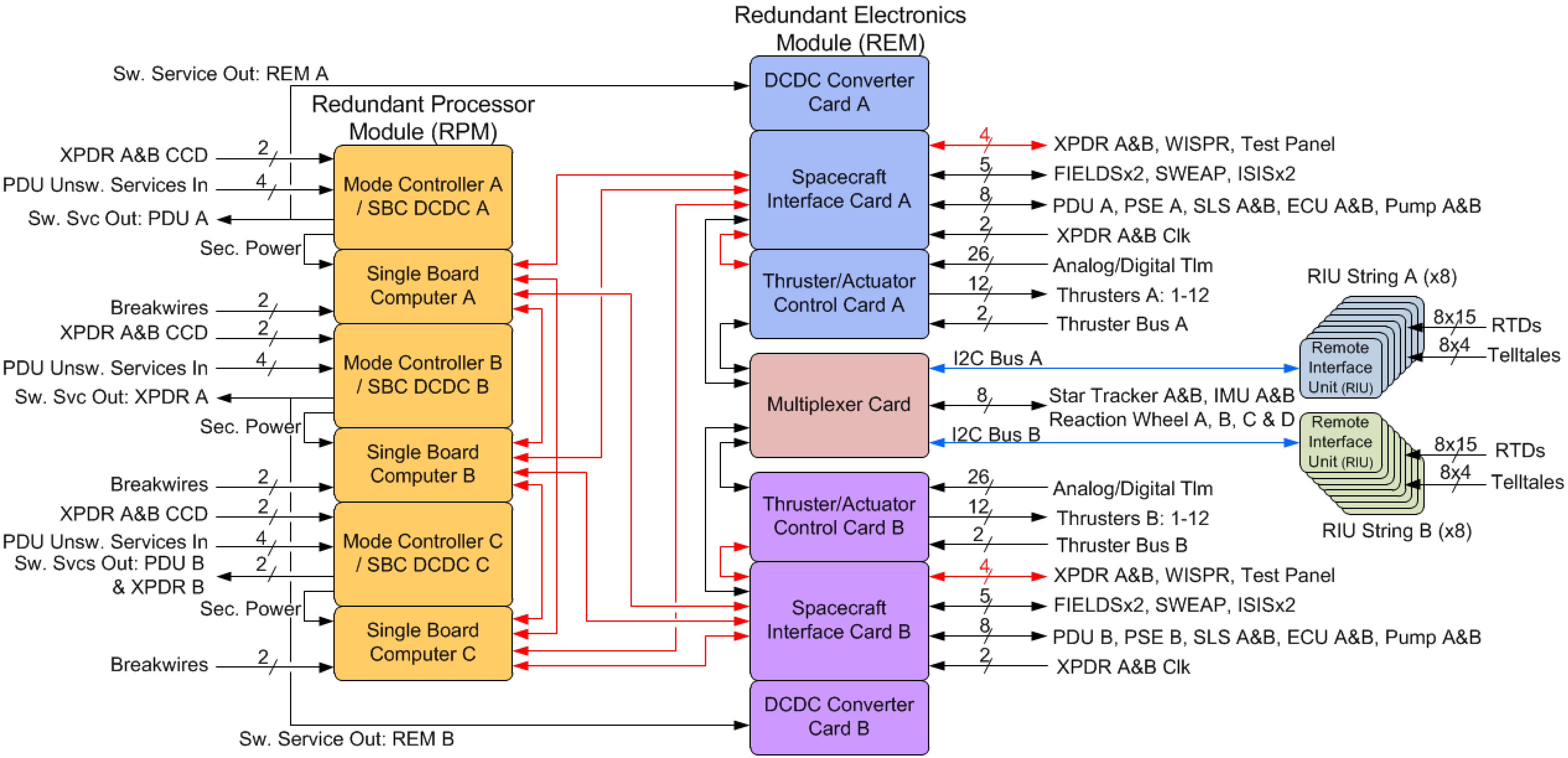

Avionics Subsystem Deliverables

- **Redundant Processor Module (3xSBC and 3xMode Controllers)**
  - **1 Flight Model (FM), 1 Eng. Model (EM), 6 Breadboards (BB)**
- **Redundant Elect. Module (2xDCDC, 2xSCIF, 2xTAC and 1x MUX)**
  - **1 FM, 1 EM, 4 Full and 2 Half BBs**
- **Remote Interface Units**
  - **16 FM, 3 EMs**
- **Testbed GSE Hardware**
  - **8 units (includes SPPOPS-1 and SPPOPS-2)**

- **Project sparing of flight HW is a complete kit for each slice type; additional part sparing will be identified as the design matures.**
- **BB - Breadboard model hardware is functionally equivalent to FM/EM with COTS parts and modified form and fit. BB RPM/REMs do not include DCDCs.**
- **EM - Engineering model hardware is pre-flight build with unscreened parts, no PWB coupons and limited manufacturing polymerics**

Redundant Processor Module Block Diagram

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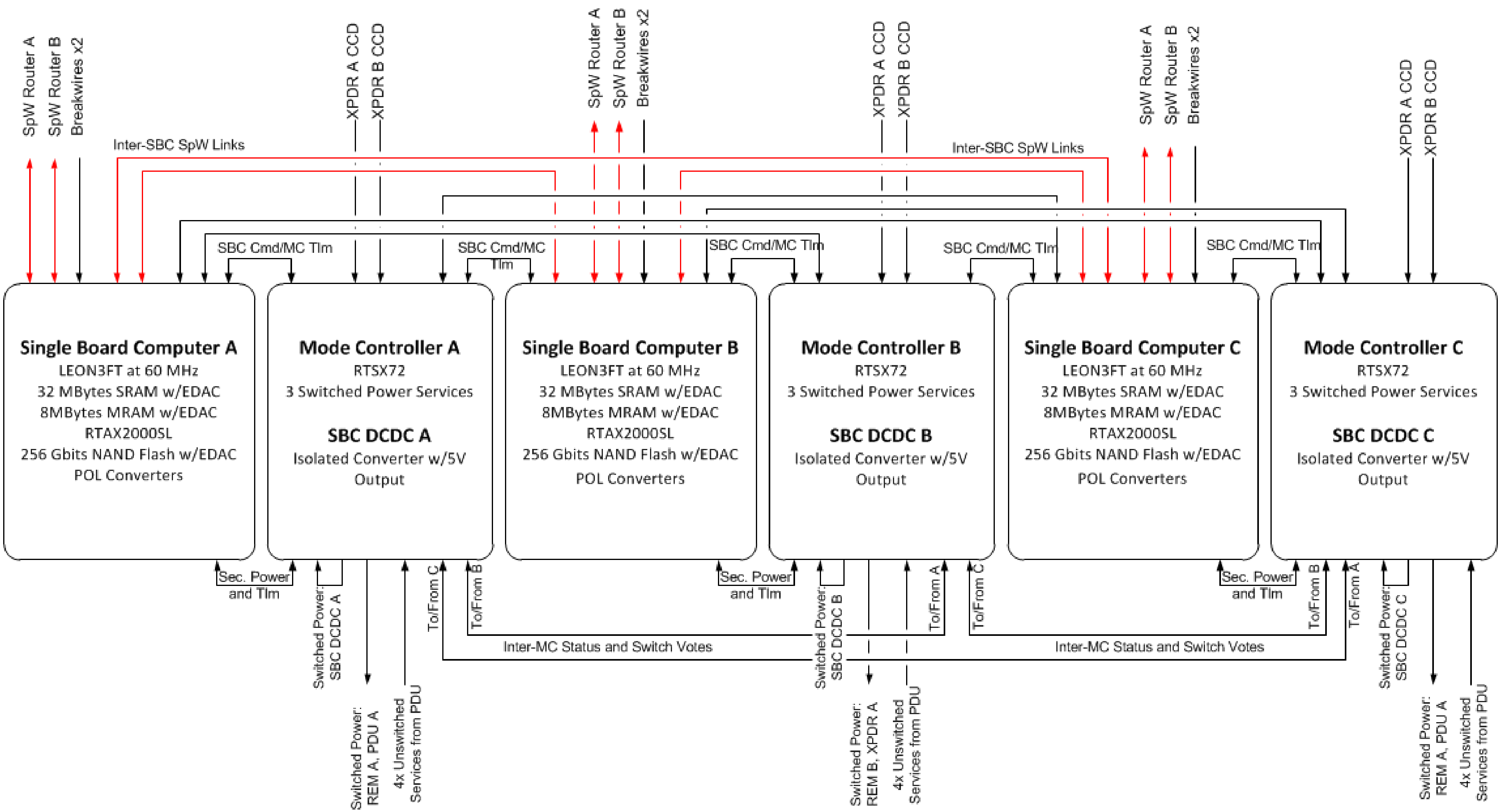

RPM Design (1 of 3)

- The RPM Single Board Computers (SBC) are 2 for 3 redundant:
  - Each SBC has SpW Links to the REM A&B Routers and the other two SBCs
  - 256 Gbits of non-volatile bulk memory on card.
  - Block Redundant Interfaces with the Breakwires
  - Command and telemetry interfaces with the three MCs.
  - Each SBC implements 2 of 3 voting of MC status (SBCs can assume all states):
    - SBC Physical location: A, B, or C
    - SBC Logic state: Prime (Pri), Hot Spare (HS), Backup Spare (BS), Failed (FAIL)
    - SBC FSW Application Select, NV Memory Write Enable and Reset
  - Notes: ▪ A processor reset is not considered a fault.
    - A failure of any SBC is not a mission ending fault.

RPM Design (2 of 3)

- **RPM Single Board Computer Design**
  - **Aeroflex UT699 (LEON3 FT), 5962R0822801QZA clocked at 60 MHz (datasheet max is 66 MHz). Up-screening to 80 MHz req'd for EEE-INST-002 derating to 60 MHz (or derate to 0.90 with waiver).**
    - **Open trade for the Aeroflex UT669E part with 100 MHz datasheet max clock as contingency for FSW processor margin. Vendor flight part testing to be completed on Mar2014 and APL proton testing will be needed.**
    - **Aeroflex Mar2014 date supports SBC EM development. BBs parts ordering is proceeding at risk.**
  - **2x Aeroflex 128 Mbit SRAM MCM UT8ER4M32. Working upset rate for SPP environment.**
  - **Aeroflex 64 Mbit NV Magnetorestrictive RAM UT8R8M8. Working upset rate for SPP environment.**
  - **8x Micron 32 Gbit SLC NAND Flash Memory MT29F32G08AFABAWP-IT:B. PEM part, SEE testing analysis in progress. 100K program/erase cycle endurance.**

RPM Design (3 of 3)

- **The RPM Avionics Redundancy Controller (ARC) is comprised of 2 for 3 redundant Mode Controllers (MC):**
  - **MCs are on PDU-unswitched-services with MC-current-limiting**
  - **MCs implement 2 of 3 voting of 9 switched power services with defined power states.**
  - **Each MC has a command and telemetry interface with the three SBCs and a status interface with the other two MCs**
  - **MCs monitor SBC Pri and HS health via acknowledge (ACK) timers**
  - **MCs maintain transition state history in SBC telemetry**
  - **MCs capable of resynchronization of processor logical states**
  - **Cross-strapped Interfaces with XDPR A&B CCDs**

  - **Note: A failure of any MC is not a mission ending fault**

RPM Single Board Computer Logical State Assignments

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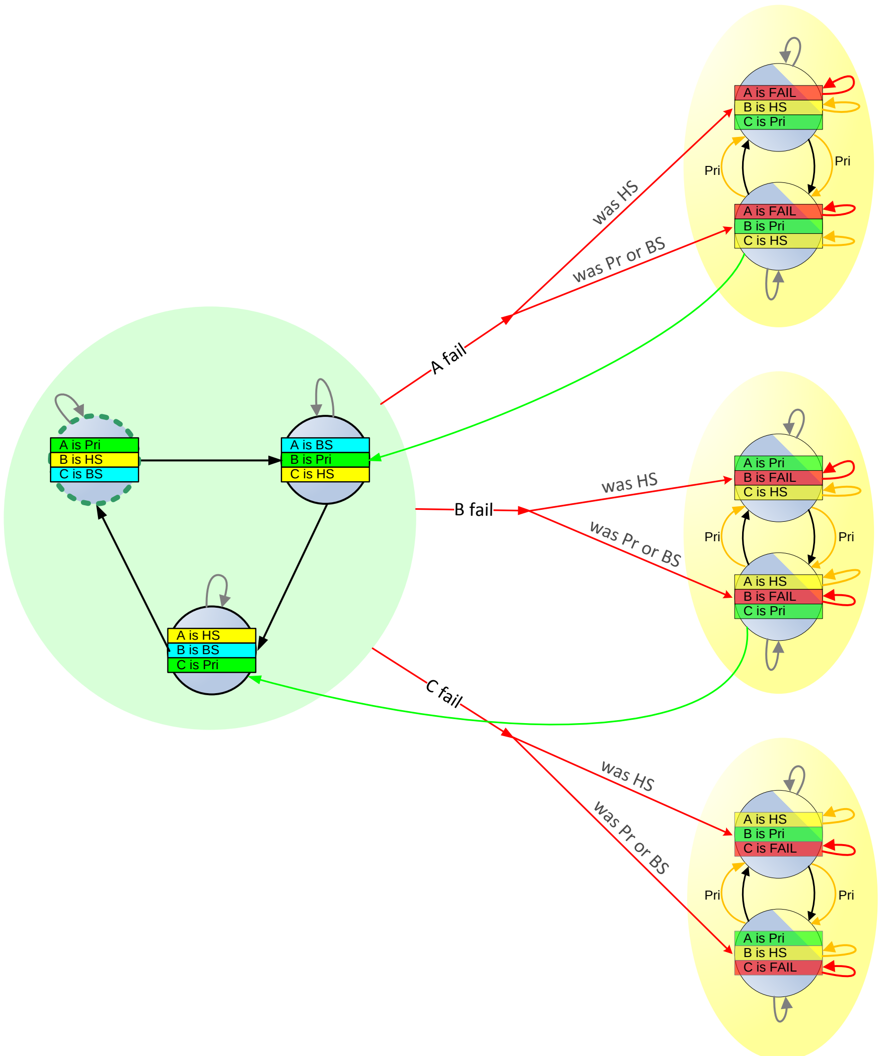
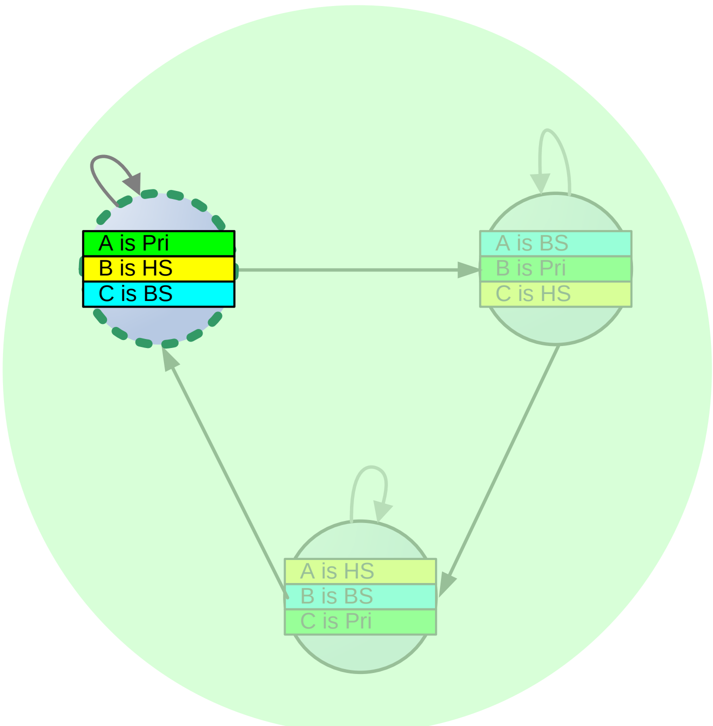


ARC Mode Controller-centric view:

- **9 valid combinations of SBC Logical States for the three processors**
- **Figure does not address MC resynchronization**
- **INV opcode demotion is only enforced after rotation wait period**
- **Processor power switch state tied in hardware to logical state.**
  - **Power on for BS (Off) to HS change is automatic in HW**

(red line)	Fail (by CCD CMD, INV opcode, or HS ACK)
(orange line)	Fail (by INV opcode, or HS ACK ONLY)
(green line)	Ground All OK (by CCD command)
(black line)	Demote (by Pri ACK [RST])
(loop arrow)	HS, BS, or FAIL Reset, no change
Pri	Prime, power = ON
HS	Hot Spare, power = SLEEP
BS	Encounter: Warm Spare, power = SLEEP Non-Encounter: Cold Spare power = OFF
(dashed circle)	Default power-on state

RPM SBC Logical State Default State



Fail (by CCD CMD, INV opcode, or HS ACK)

Fail (by INV opcode, or HS ACK ONLY)

Ground All OK (by CCD command)

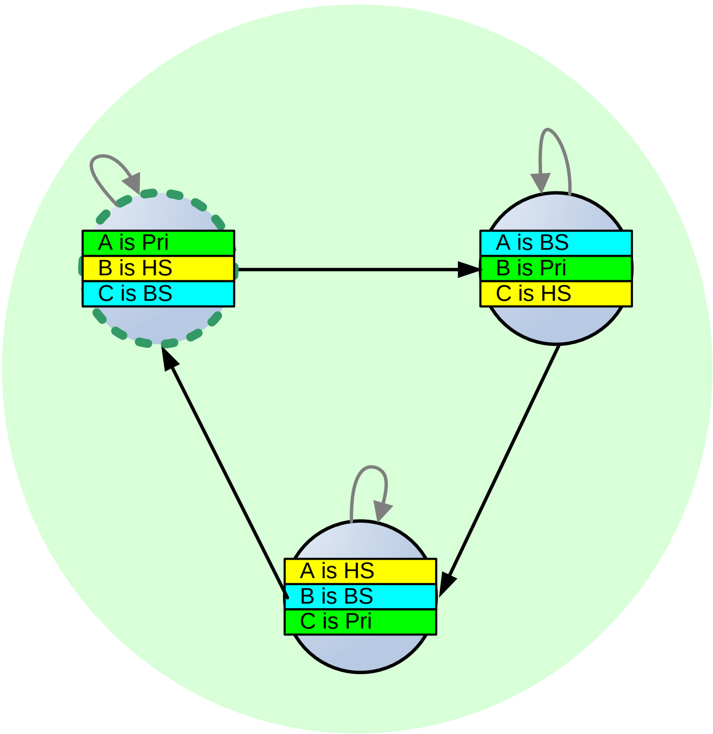
Demote (by Pri ACK [RST])

HS, BS, or FAIL Reset, no change

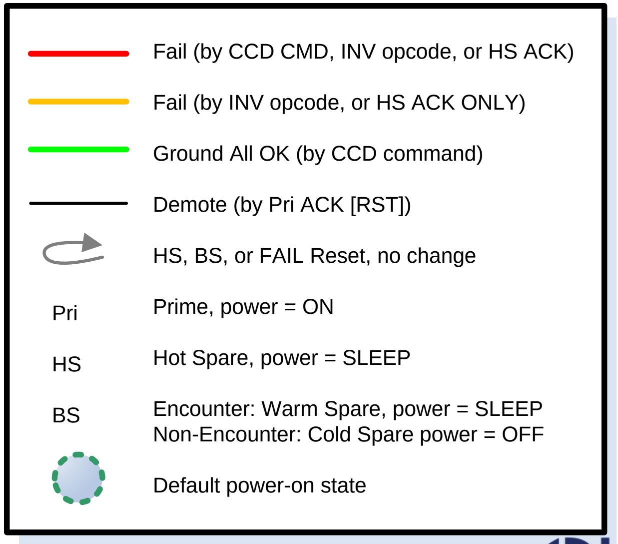
Pri	Prime, power = ON
HS	Hot Spare, power = SLEEP
BS	Encounter: Warm Spare, power = SLEEP Non-Encounter: Cold Spare power = OFF

Default power-on state

RPM SBC Logical State with Prime Acknowledge Timer Expirations

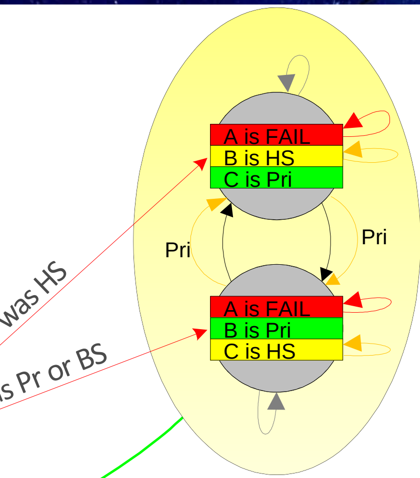


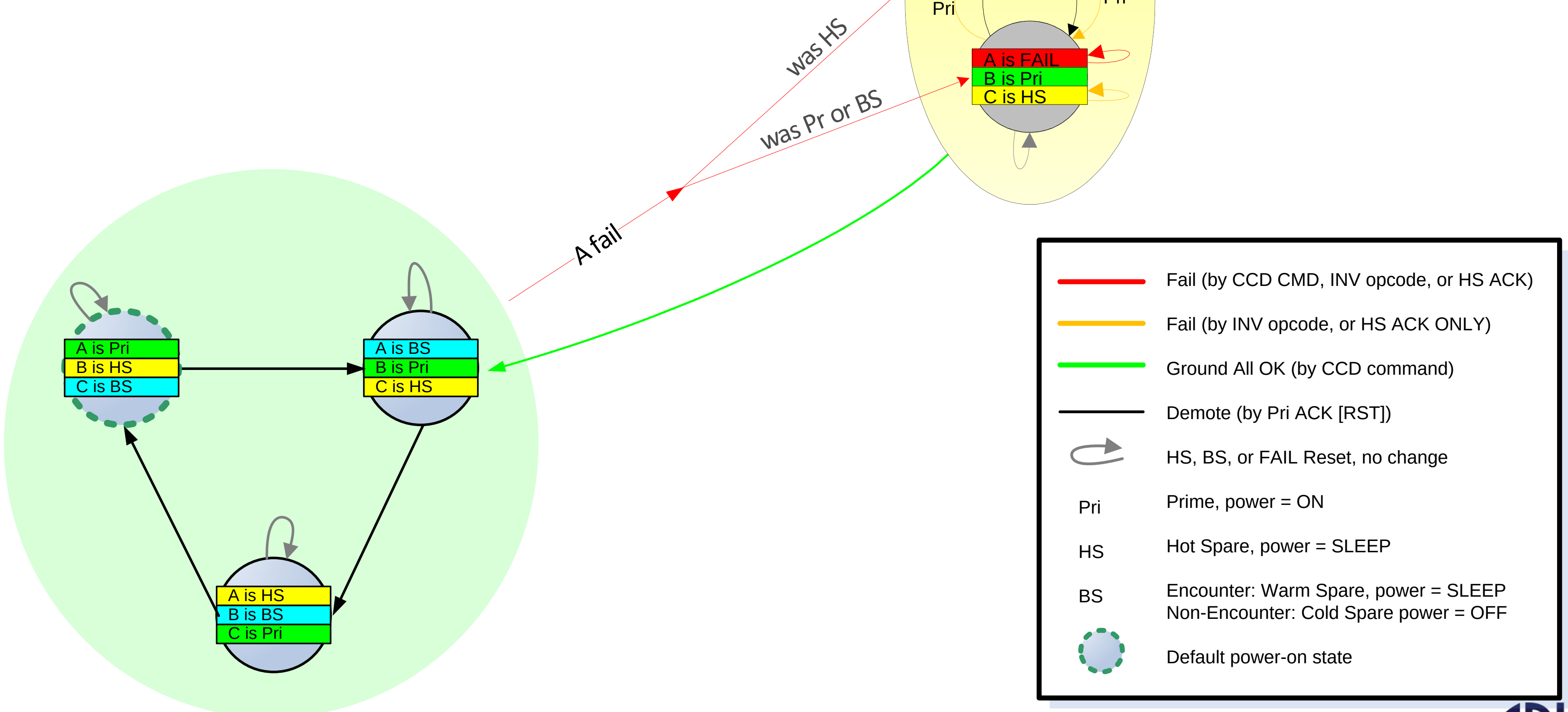
- Prime Ack Timer = 0.515 Seconds.
- A demoted Prime is Reset by the MCs.
- Prime Ack timer expiration is temporarily held off after SBC POR/Reset to limit continuous processor resets due to demoted Prime Reset.
- The Hot Spare Ack Timer will be 2x SBC Reboot Time.



RPM SBC Logical State with Failed SBC Scenario

- Only one SBC can be designated BS/FAIL; subsequent “Fail” criteria is ignored.
- CCD “All Okay” will only be accepted if the Failed SBC returns to the BS state.





RPM Mode Controller Hardware Critical Command Decoder

CCD CMD No.	Command
1	SBC A state set to Failed (SBC B and C to OK)
2	SBC B state set to Failed (SBC A and C to OK)
3	SBC C state set to Failed (SBC A and B to OK)
4	SBC A, B and C set to OK (no failed SBC)
5	SBC A FSW Application Select to Image A
6	SBC A FSW Application Select to Image B
7	SBC B FSW Application Select to Image A
8	SBC B FSW Application Select to Image B
9	SBC C FSW Application Select to Image A
10	SBC C FSW Application Select to Image B
11	Reset SBC A
12	Reset SBC B
13	Reset SBC C
14, 15, 16, 17	SBC A NV Memory Bank (1/2) Write Protect (Enable/Disable)
18, 19, 20, 21	SBC B NV Memory Bank (1/2) Write Protect (Enable/Disable)
22, 23, 24, 25	SBC C NV Memory Bank (1/2) Write Protect (Enable/Diable)
26	Data Field (command) Pass-through to SBCs
27	RPM MC Increment Command Counter

RPM Power Services

- **Power Inputs – 12 unswitched power services are provided by the PDU for the 3xMC, 3xSBC, 2xREM, 2xPDU, and 2xXPDR. The PDU provides fuses and current sense resistor and telemetry.**
- **Power Outputs**
  - **Each MC is powered directly from a PDU unswitched service.**
  - **The MCs triple vote the power state of the remaining switches:**
    - **SBC A*, B* and C*: Prime and Hot Spare are always powered; BS/FAIL power state commanded by Prime.**
    - **REM[1] A* and B: Power state commanded by Prime, One REM-side is always powered.**
    - **PDU[1] A* and B:Power state commanded by Prime, One PDU-side is always powered.**
    - **XPDR A* and B: Power state commanded by Prime, One XPDR is always powered.**

***Powered at Default;**

[1]REM and PDU power states required to be consistent for commanding and tlm.

Redundant Electronics Module Block Diagram

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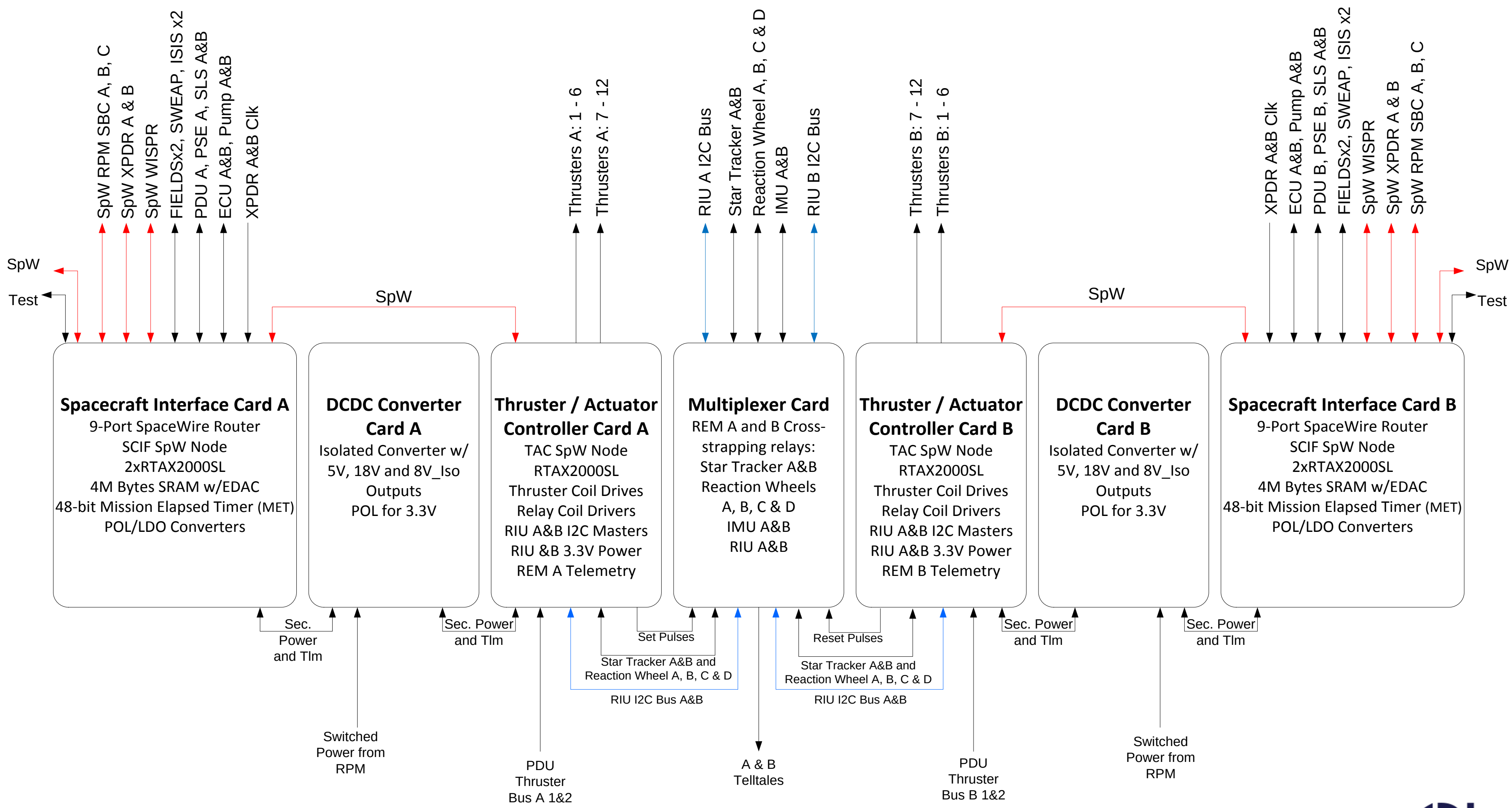


REM Design (1 of 2)

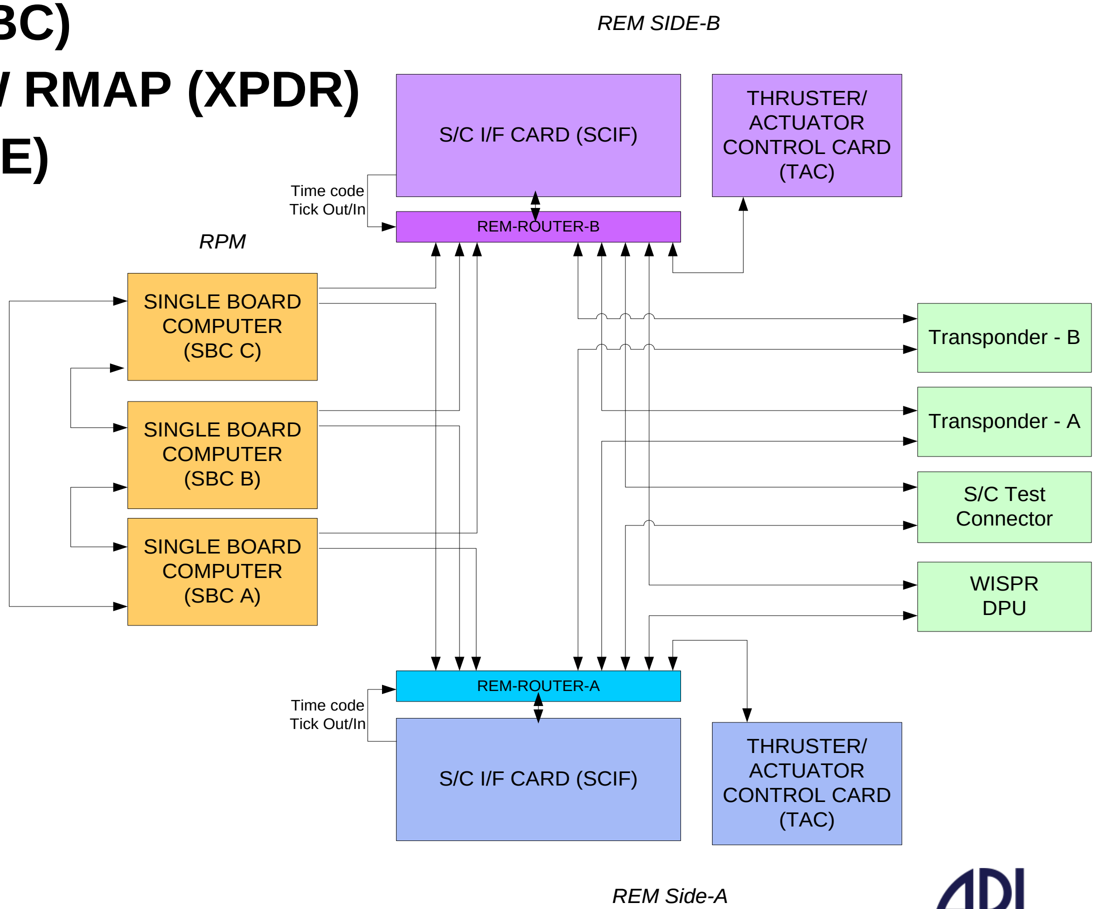
- **The REM SCIF/TAC/DCDC are A/B Block Redundant with a single MUX Card.**
  - **The MUX PWB is spacecraft single-point failure. Board design will be fault tolerant at the system level to any faulted signal, relay, connector or component.**
  - **Block Redundant Interfaces with PDU, PSE and Prop System Pressure Transducers**
  - **Cross-Strapped Interfaces with SBC A, B and C; Solar Limb Sensor A and B; Pump Controller A and B; ECU A and B; XPDR A and B; and Cooling System Pressure Transducers dPA and dPB**
  - **Relay-Isolated, Cross-Strapped Interfaces with RIU String A and B; Star Tracker A and B; IMU A and B; and Reaction Wheels A, B, C and D.**
  - **Cross-Strapped Internally Redundant Interface to Instruments, Thrusters and Cooling System Accumulator Pressure Transducer**
  - **Thruster coil drivers with individual thruster valve fault containment**

REM Design (2 of 2)

- XPDR A&B Clocks (10 MHz EMXO) are cross-strapped to each REM side.
- Interface conforms to the standard LVDS circuit.
- EMXO A, B or local SCIF oscillator is selected via SpW to feed S/C MET timing chain.
- MET is maintained as a 32-bit seconds and 16-bit sub-seconds with 20 usec resolution (sub-second counter is 0 to 49,999).
- MET sub-second rollover is the Spacecraft timing reference, Pulse Per Second (PPS).
- MET load is a protected command with defined a check-pattern required for validity.
- 50 Hz (20 msecs) minor frames are derived from the MET counters and are propagated via SpW time codes.
- SCIF supports EMXO fault detection.
  - Each XPDR Clock input feeds a FPGA counter from PPS to PPS+0.75 secs (counter based upon local board oscillator 10 MHz divide-down)
  - Counter results are available for FSW/AUT evaluation.

SpaceWire (1 of 2)

- **9-port Router (SCIF)**
- **RMAP Target Nodes (WISPR, SCIF and TAC)**
- **LEON3-based SpW Nodes (SBC)**
- **FPGA-based SpW Node w/SW RMAP (XPDR)**
- **Secondary Users (BB and GSE)**

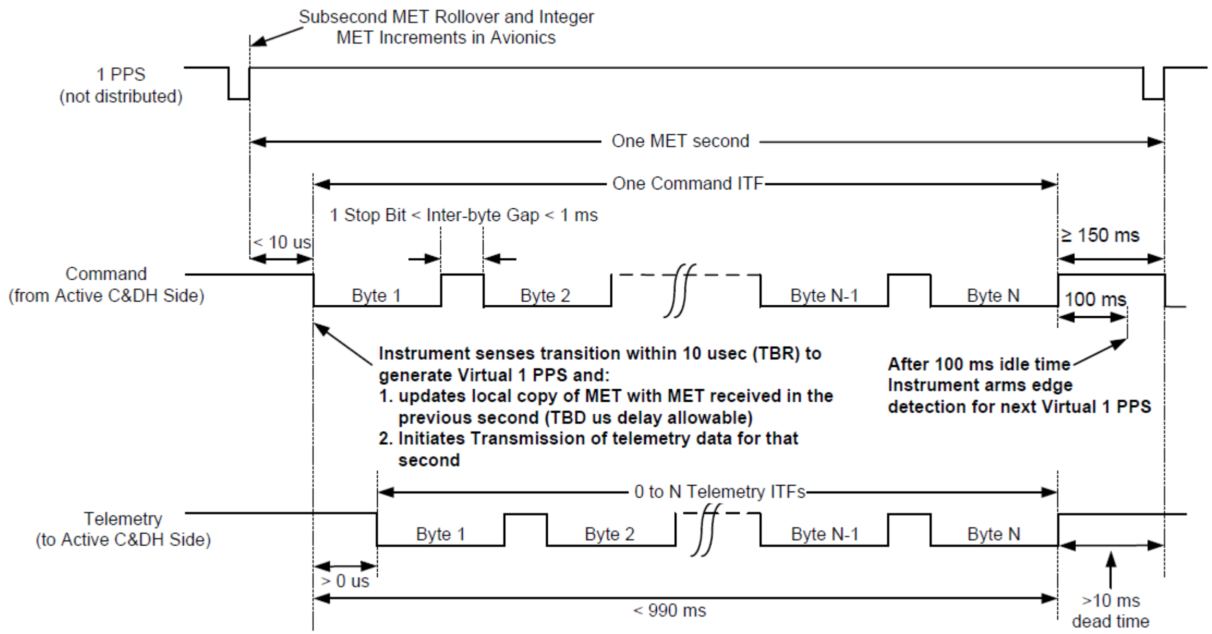


SpaceWire (2 of 2)

- **SpaceWire FPGA Development:**
  - **APL modified GSFC Intellectual Property (IP) to reduce FPGA resource usage and meet SPP requirements.**
  - **Clock recovery added to support use of generic LVDS Rcv ICs.**
  - **Test, error injection and debug support have been deleted.**
  - **Removed SpW Time code generation from nodes.**
  - **RMAP Event signaling, general purpose I/Os and bypass interfaces removed.**
  - **Router expanded from 4-ports to 9; support for expansion and back-end ports has been eliminated.**
  - **Test and verification effort includes providing a SpW VHDL testbench to the users.**
  - **Regular Users Group Meetings to cover design and verification.**
  - **Version control via Mercurial; Issue tracking in JIRA.**

Electrical UART Interfaces with Instruments

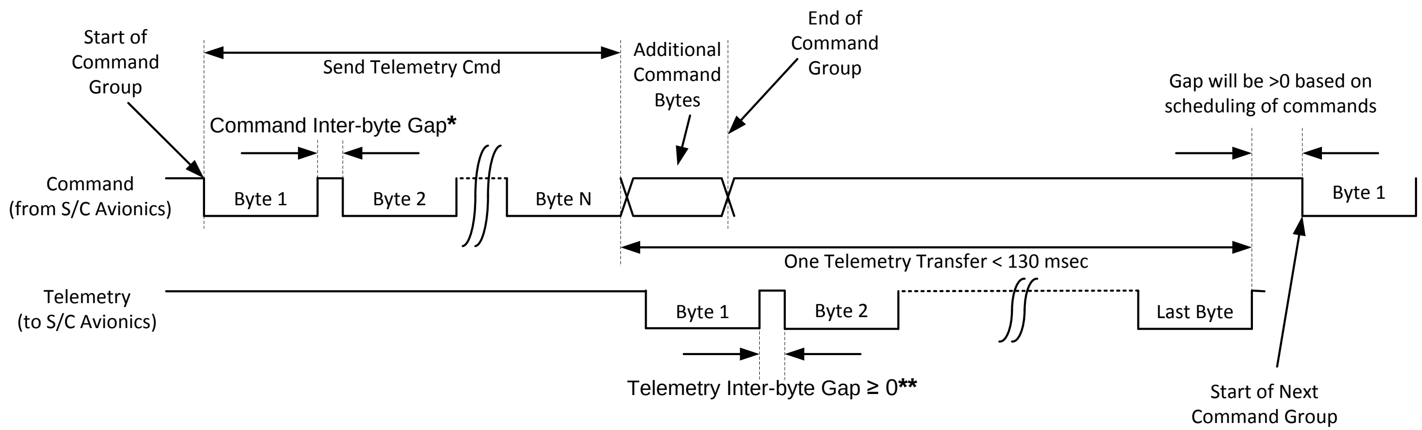
- **Each REM side is cross-strapped with each Instrument.**
  - **WISPR DPU is connected via SpaceWire Interfaces**
  - **FIELDS 1 and 2, SWEAP, EPI-Hi and EPI-Lo are connected via independent 1 Hz command and telemetry UARTs.**
    - **Command UARTs are 115.2 Kbaud and support 512B per second**
    - **Telemetry UARTs are either 345.6 KBaud (FIELDS 1 and SWEAP) or 115.2 KBaud (FIELDS 2, EPI-Hi and EPI-Lo) and support the links' data rate.**



Electrical UART Interfaces with S/C Components

- **Each REM side is cross-strapped with the SLS, Pump Controller and ECU**
- **Each REM side is block redundant with the PDU and PSE.**
- **Interfaces are via independent command and telemetry UARTs.**
  - **Command UARTs are 115.2 Kbaud and support 5 Hz transfers, except PSE which is 1 Hz double-buffered with virtual PPS encoded in the command protocol (PSE internally generates 5 Hz tlm).**
  - **Telemetry UARTs are either 115.2 KBaud (SLS, Pump, ECU, and PDU) or 345.6 KBaud (PSE) and support the links' data rate.**

*****Command Interbyte gap minimum is 0 (start bit of the next UART character can begin immediately after the stop bit of the previous UART character). Each group of 4 bytes (1-4, 5-8, etc.) has a maximum cumulative inter-byte gap of 1 ms.



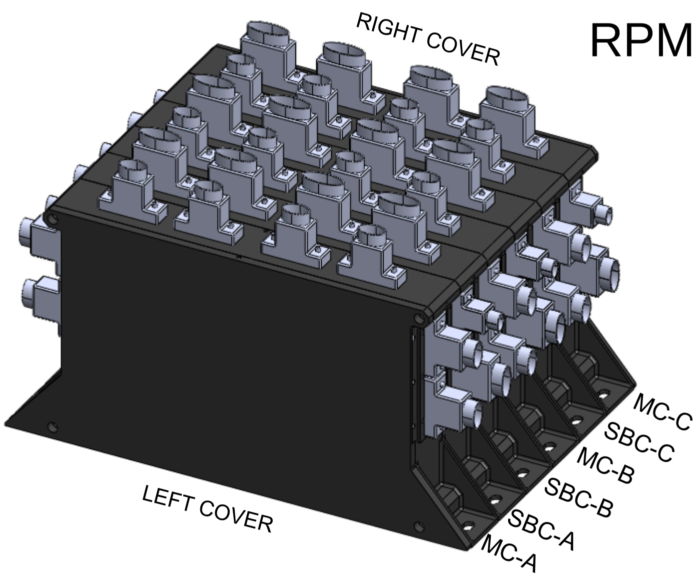
******Start bit of the next UART character can begin immediately after the stop bit of the previous UART character

Miscellaneous Interfaces

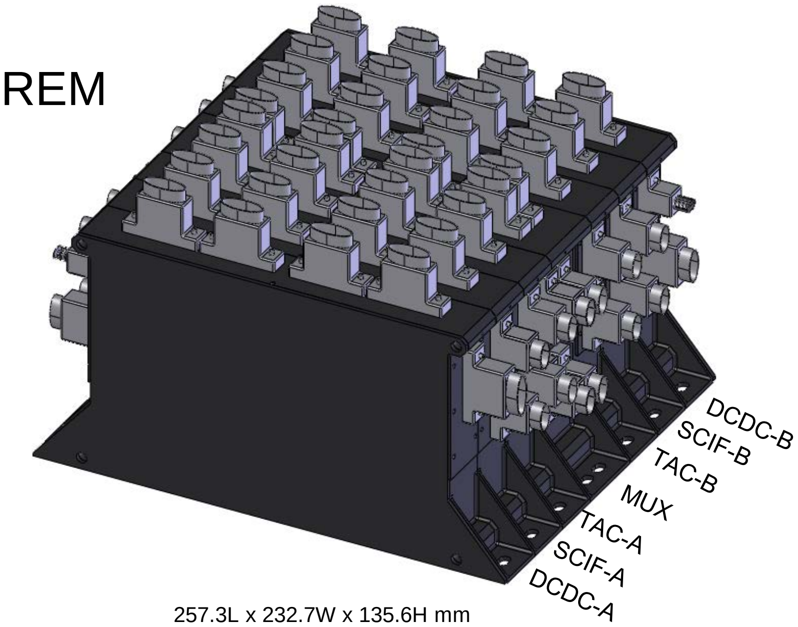
- **Interfaces to Reaction Wheels, IMU, and Star Trackers have been baselined for breadboard development and are pending contract awards post mission-PDR.**
- **Thrusters interface features:**
  - **Individual current-limiting and common low-side switch.**
  - **Diode OR'ing, kickback suppression and transient snubber circuitry.**
- **Pressure Transducer analogs, TWTA analogs and Bi-levels and 3.3V Monitors interfaces will be spec'd for maximum current imbalance to minimize current loops.**

Avionics Packaging Concept

- RPM is a six slice chassis / REM is a seven slice chassis
- Common PWB form factor of 190.5L x 127.0W x 2.4T (7.5L x 5.0W x 0.093T)
- Eight board mount, right-angle MDM connectors with additional I/O with pig-tailed connectors on the REM MUX.
- CCGA assembly process development with follow-on rework process development

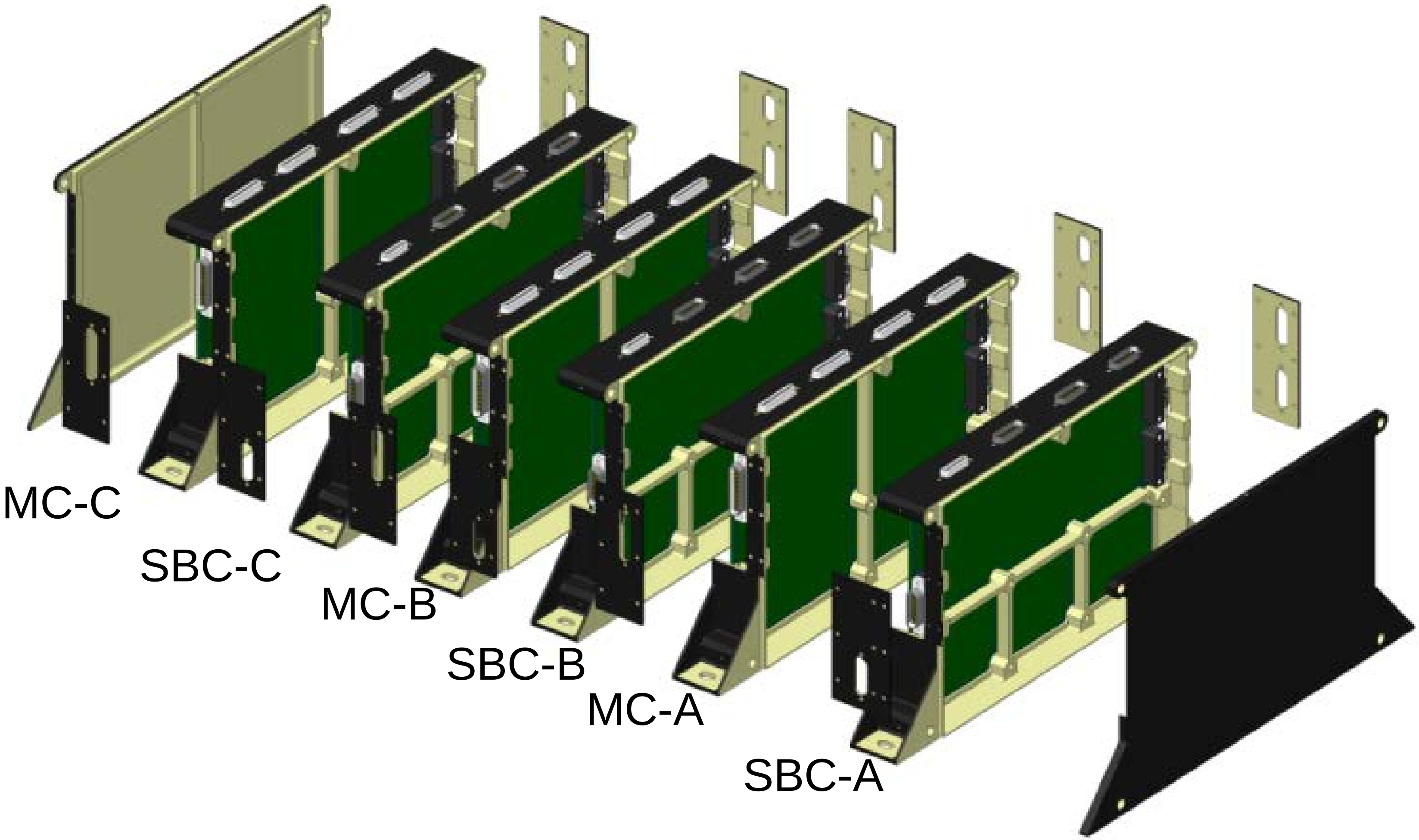


257.3L x 193.8W x 135.6H mm
(10.13L x 7.63W x 5.34H in)



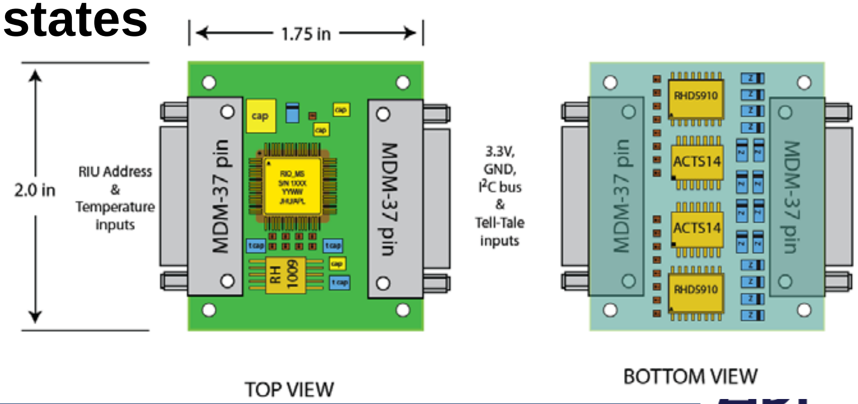
257.3L x 232.7W x 135.6H mm
(10.13L x 9.16W x 5.34H inches

RPM Packaging Design (RPM View)



Remote Interface Units (RIU) Design (1 of 2)

- RIU A and B strings with 8 RIUs each (16 RIUs total)
- Each RIU provides a regional sensor acquisition/digitization node
- Small, 4-wire, global harness (I2C and power/gnd), 15 temperature input channels, 1 calibration channel, and 4 digital telltale channels
- Each RIU can accommodate wide and narrow temperature range sensors with programmable I2C master capability.
  - Narrow Range: -100ºC to 100ºC (Minco S17624 RTD)
  - Wide Range: -175ºC to 200ºC (Lakeshore PT-103 RTD)
- TT: CS Radiator Upstream and Downstream TTs
- TT: CS Accumulator LV TT
- TT: RF Switches 1, 2, 3, and 4 A and B states
- TT: Prop LVs A and B states
- TT: I&T Loss of Vacuum Alarm



Remote Interface Units (RIU) Design (2 of 2)

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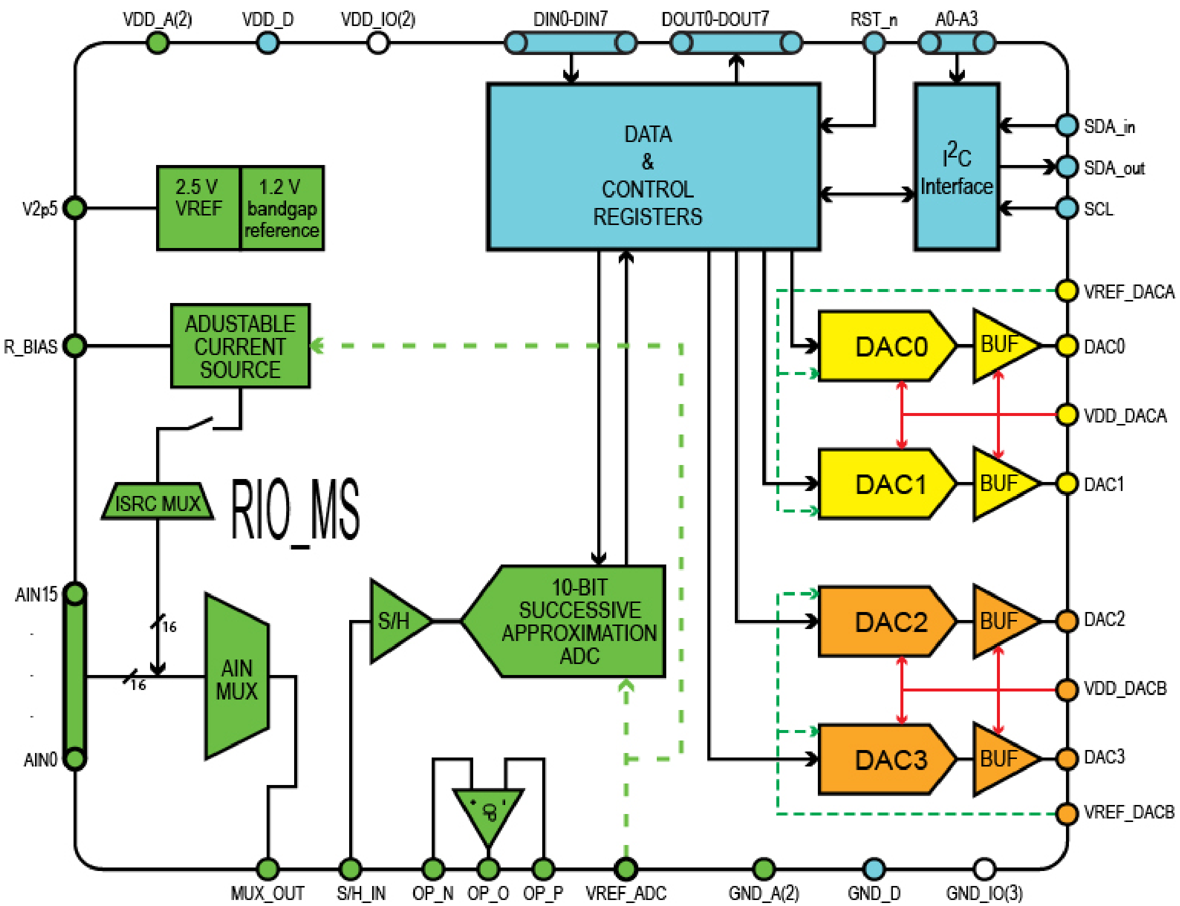
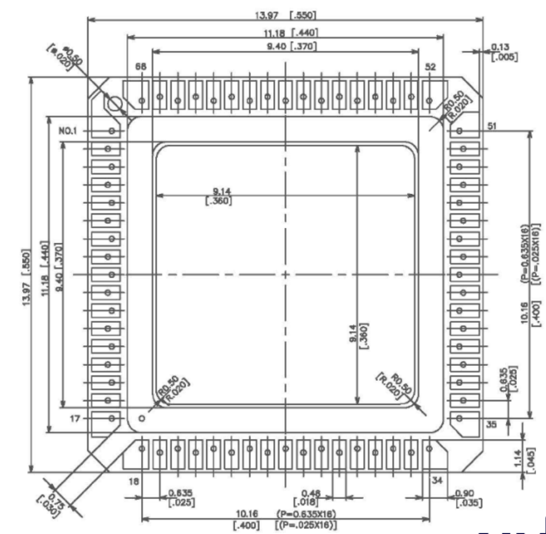


- APL Custom ASIC
- I2C Data Interface
- 16-ch analog voltage inputs
- 10-bit ADC, 0-VREF range
- Current stimulus for RTDs
- 8-bits of digital outputs
- 8-bits of digital inputs
- 4-ch 10-bit DAC (N/A for SPP)
- 68-pin CQFP (0.55” body size)



Test and Verification Support

- “Test As You Fly” philosophy
- Majority of requirements will be verified by Test using scripted, manual, and special tests.
  - Inspection and Analysis will be used to verify remaining requirements.
- Maximize test reuse between test levels: pre-flight (BB and EM) and flight board, box, and spacecraft.

- Design for Testability:
  - ARC power switching and processor logical states resynchronization functionality; and
  - LVDS Overvoltage Fault Propagation Testing.
- Design for Test Support:
  - Spacecraft SpaceWire Test Port; and
  - REM Timekeeping Verification Port.

Hardware and Test Flow

- **Test and Verification development during Breadboard PWB and FPGA development geared toward preparing for EM Testing:**
  - Verify feasibility of verification methods.
  - Verify requirements on the GSE are acceptable.
  - Develop preliminary test plans, procedures, test script outlines.
  - The bulk of script work takes place here.

- **EM Testing is a dress rehearsal for Flight HW**
  - Test and verification to be in place for the EM boards and boxes
  - Some verification by Analysis will take place here (MC primary power current limit, for example)

- **Test runs are for score on the flight HW**

- **First integrated subsystem testing occurs at Spacecraft**

Phase C Work Highlights

- **Complete Breadboard development.**
- **Produce Testbed quantities for BB RPMs and REMs.**
- **Deliver Testbeds.**
- **EM Board and FPGA design with EDRs.**
- **Test Script development.**
- **Hold Subsystem CDR.**

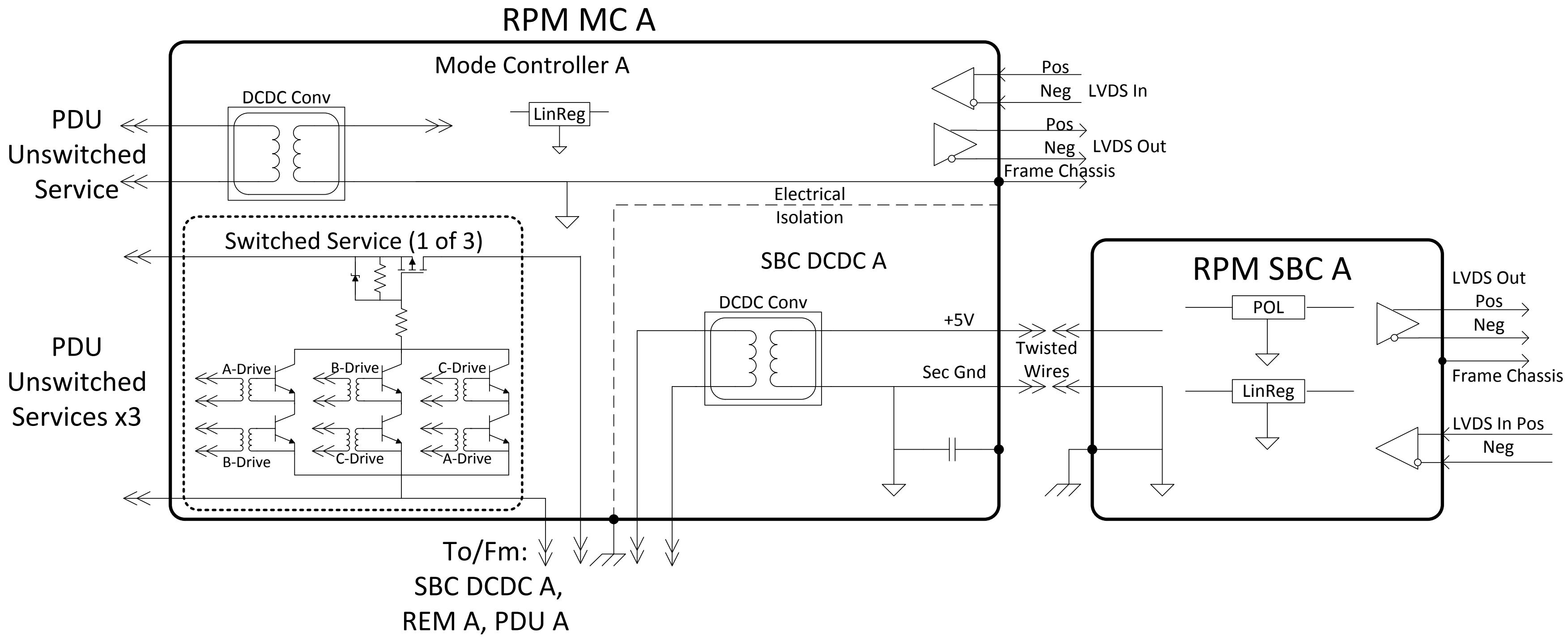
- **Avionics Subsystem is ready for Phase C.**

Backup Charts

- **Subsystem Risks**
- **Avionics PDR Action Items**
- **RPM Block Diagrams**
- **REM Block Diagrams**

RPM Grounding

- **Each SBC and MC-Mode Controller connects local secondary ground to its slice frame.**
- **The MC-SBC DCDC is grounded at the SBC.**



RPM B and C have identical grounding.

RPM SBC Block Diagram

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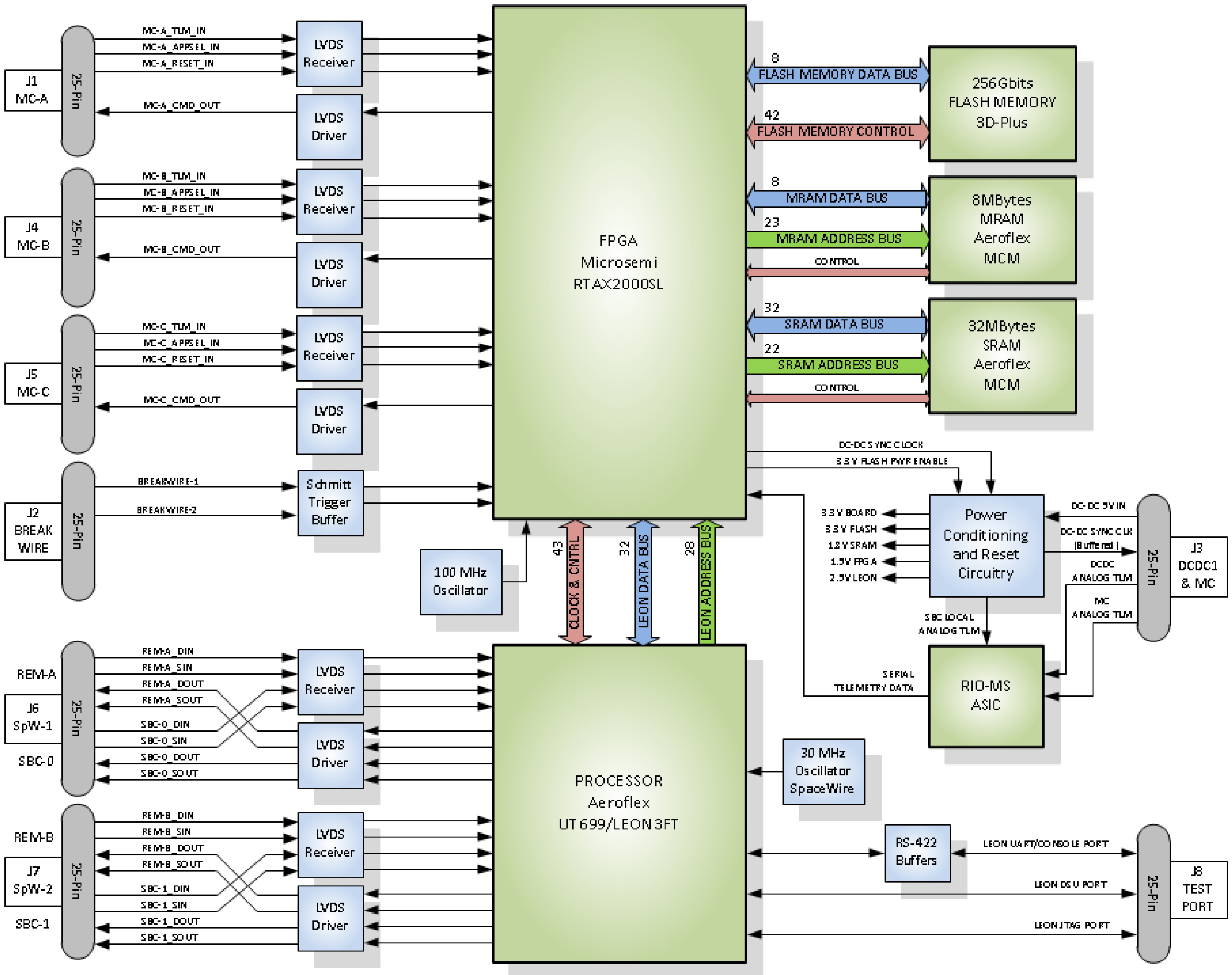


- **Aeroflex UT699FT at 60 MHz.**
- **32MBytes of SRAM with internal EDAC and HW scrubber.**
- **8MBytes of NV MRAM (LEON EDAC reduces the user to 6.4 MB).**
- **256Gbits of Flash Memory with FPGA EDAC, R/W Page Buffer and stack power control.**
- **RTAX2000SL FPGA: WDT, NV Protect, I2C with local RIO_MS, FPGA Boot Image selection and checksum verification.**
- **LEON3 DSU, JTAG and Console UART.**

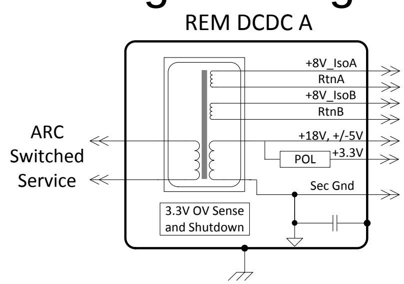
RPM MC Block Diagram

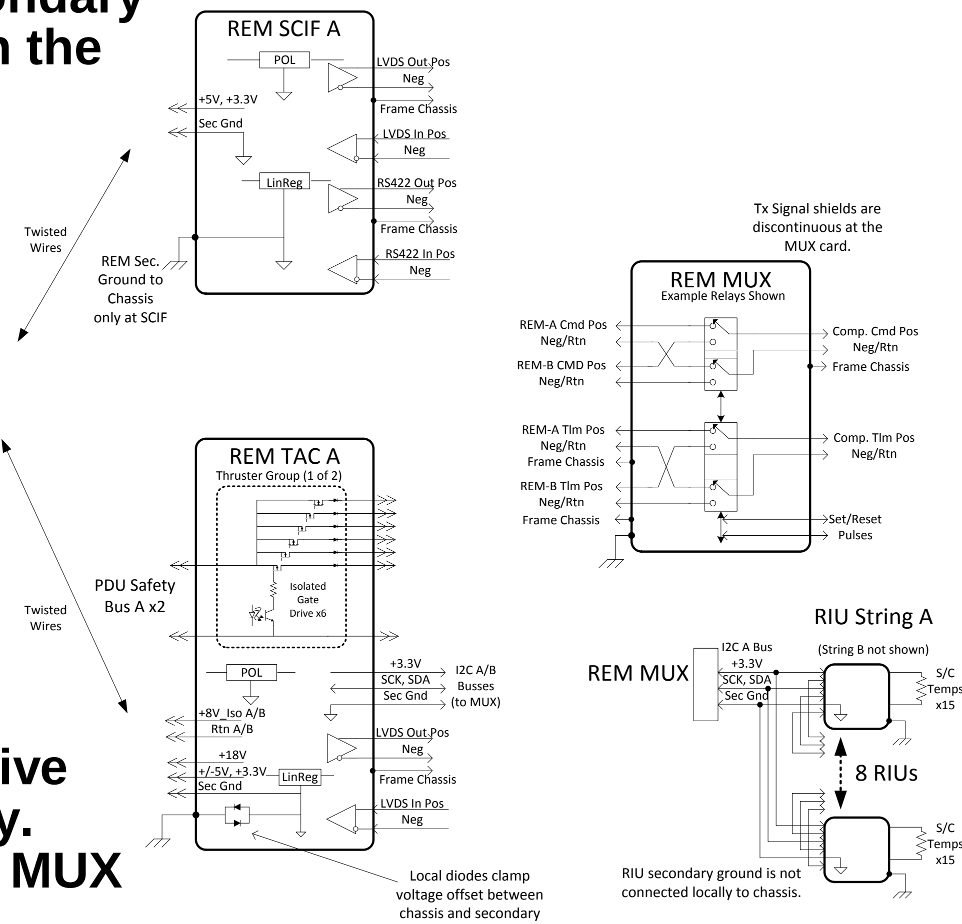
- Actel RTSX72SU-CQ208
  - ~70% Utilized
- Robust SBC Logical State FSM Implementation
  - FSM Timeouts
  - Transition History
  - Resynch by SBC CMD
- 3x Transformer Isolated Majority Voted FET Drive
- 3x 6Hz SBC UART CMD
- 2x XPDR UART CCD CMD
- 2x Remote MC Status
- 3x SBC Telemetry UART
- Harness Jumper for A/B/C Selection
- Dedicated current limited DC/DC Converter

REM Grounding

- **Each REM side connects local secondary ground to the S/C structure through the slice frame at the SCIF.**

REM B side has identical grounding.





- **The MUX card doesn't have any active circuitry and is not grounded locally. Tx shields are discontinuous at the MUX card.**

REM SCIF Block Diagram

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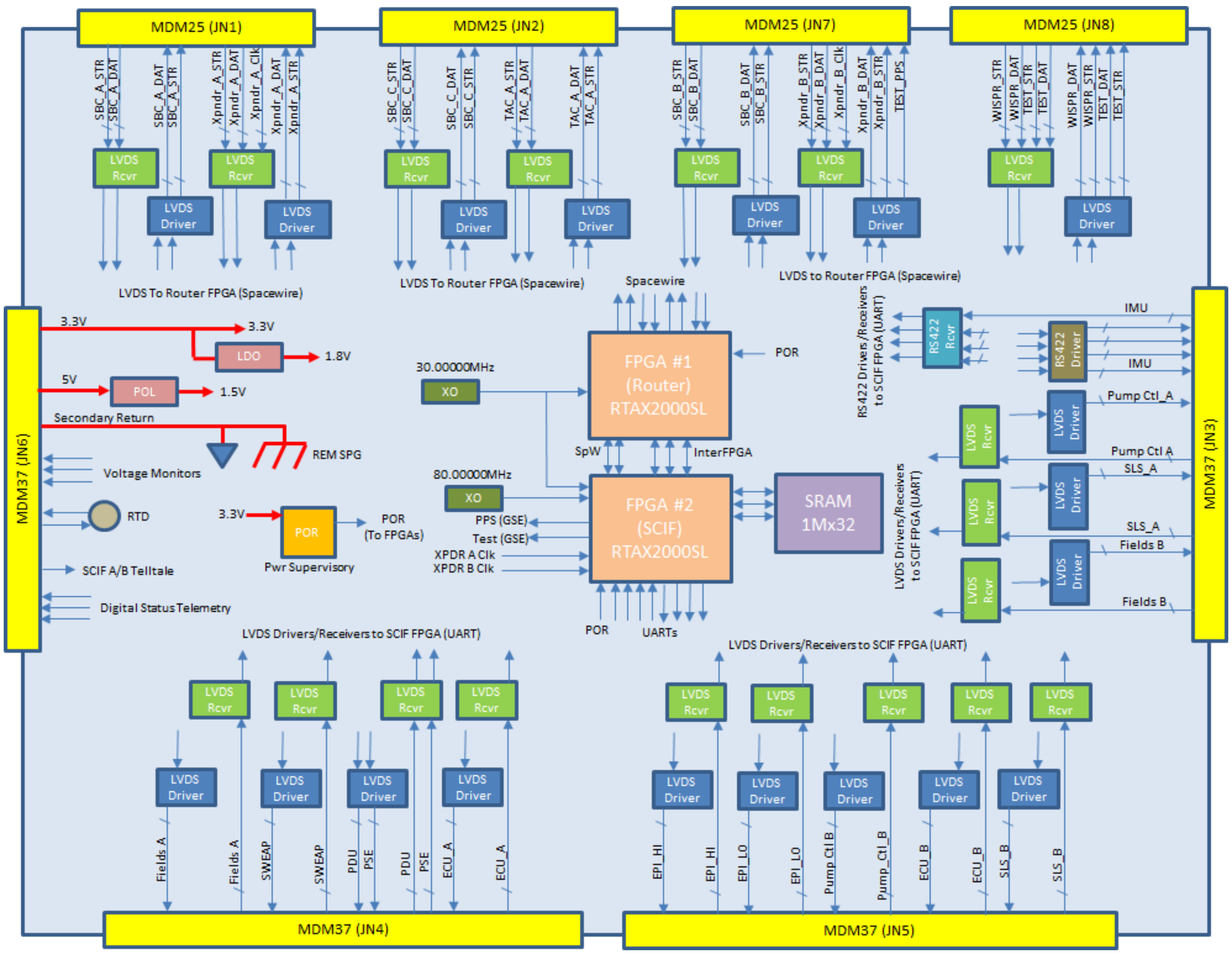

- **Two RTAX2000s: Router and SCIF SpW RMAP Node.**
- **Spacecraft MET**
- **Timekeeping verification interface: PPS and MET Latch**
- **4MBytes of SRAM with internal EDAC.**
- **Independent driver and receiver ICs per component.**
- **A/B TT**
- **On-card POR**
- **REM-side single point ground.**

REM TAC Block Diagram

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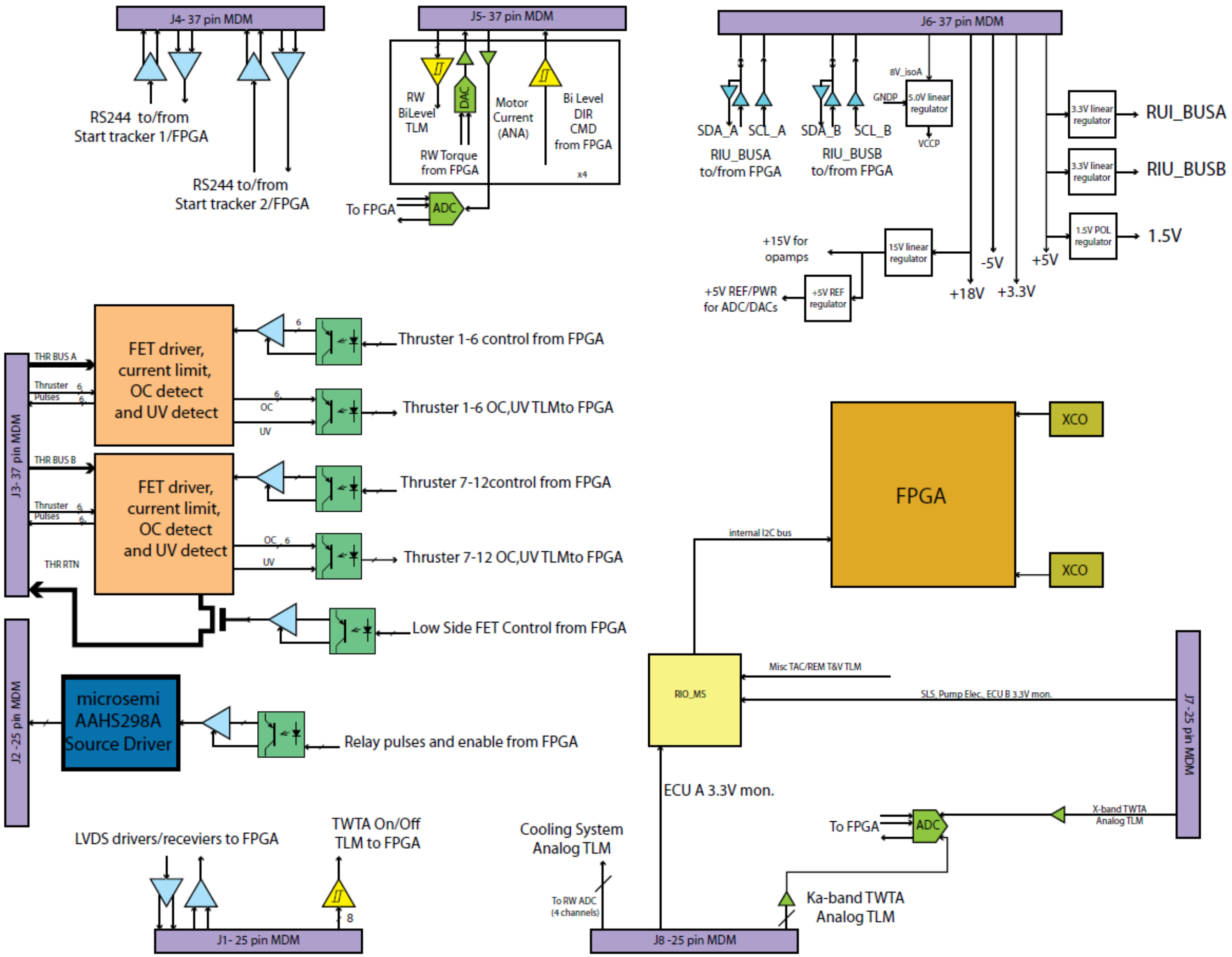

- **RTAX2000 with TAC SpW RMAP Node. Internal RAM for data storage.**
- **Multiple I2C masters (RIU A and B and on-card RIO_MS)**
- **Thruster current limit.**
- **MUX Relay coil drives.**
- **Opto-isolation on drive and tlm signals.**
- **Independent interface ICs per component.**
- **12-Bit ADCs.**
- **12-Bit DACs.**
- **A/B TT**
- **On-card POR**
- **PWB area study trade in progress.**

REM MUX Block Diagram

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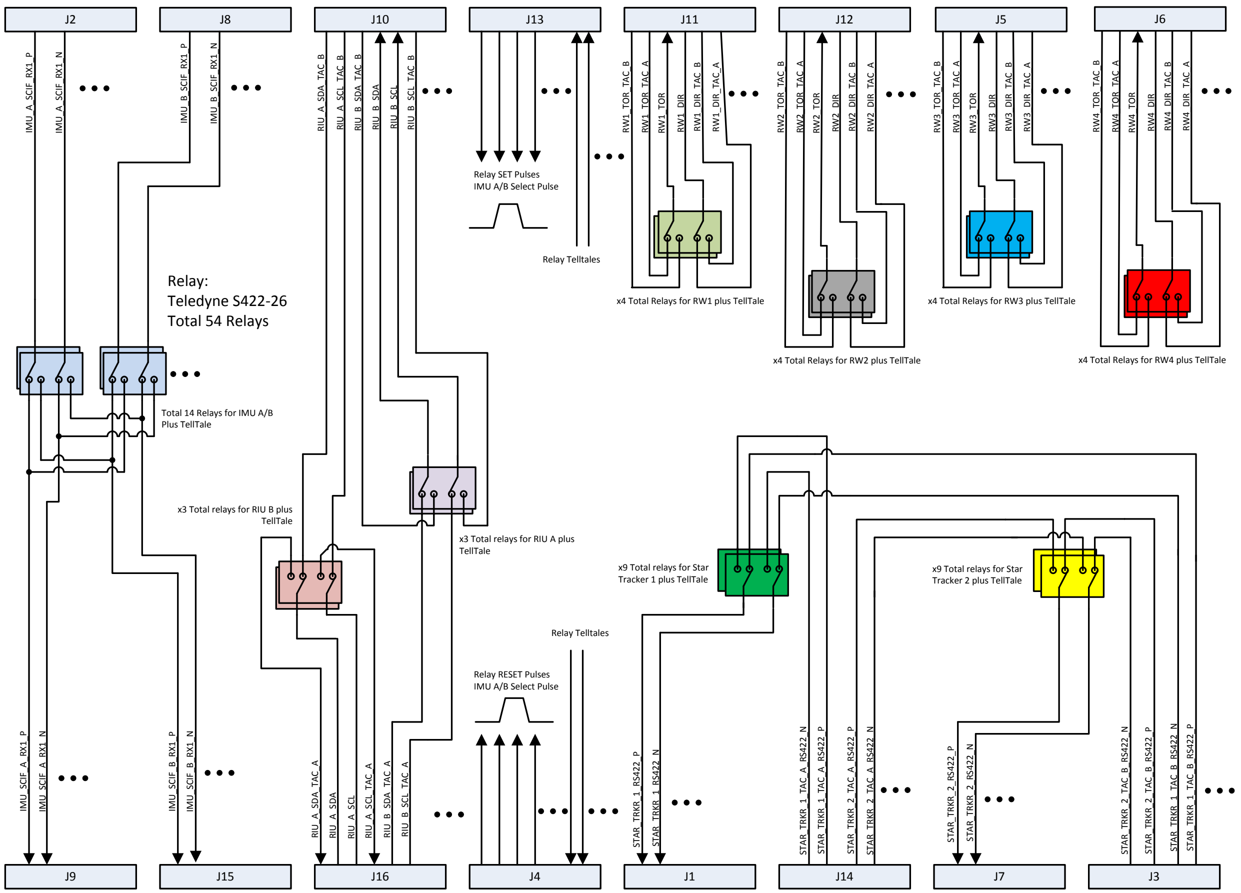

- **54 SMT DPDT Relays**
- **Relay Bank groupings for RW1, 2, 3 and 4; Star Tracker 1 and 2; RIU A and B; and IMU A/B.**
- **Relays per group:**
  - **4xRW – 4 relays each**
  - **2xSTR – 9 relays each**
  - **2xRIU – 3 relays each**
  - **1xIMU A/B – 14 relays**
- **A/B TT per group**

Solar Probe Plus

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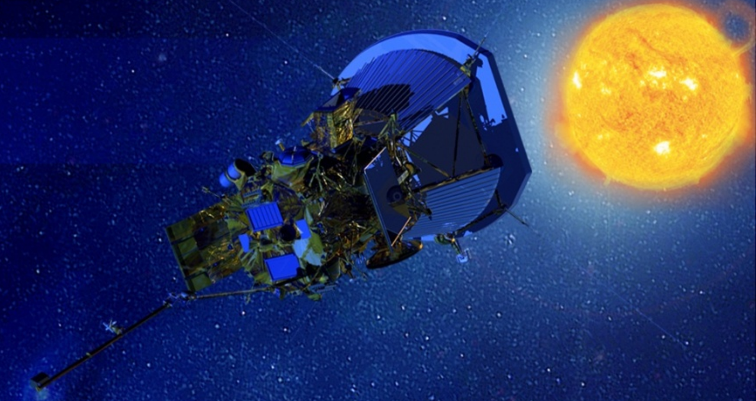

Power Distribution Unit Subsystem

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PDU Subsystem Lead

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13 – 16 January 2014

The Johns Hopkins University
APPLIED PHYSICS LABORATORY

PDU Agenda

- Driving Requirements
- Trade Studies
- Previous Review- Action Item Status
- Top Level Design Description and Specifications
    - Block Diagram
    - Power Estimate
- Packaging
    - Mass Estimate
- EGSE
- PDU EMI Test Results
- Verification and Testing
- Summary of Deliverables
- Phase C Work Plans
- Backup

Power Distribution Unit (PDU)

Driving Requirements

- **The PDU shall…**
  - Provide 150 switched/pulsed power services and 12 unswitched power services to the Spacecraft and Instrument loads
    - Implement fusing on all power services
    - Include three inhibits on safety-inhibited loads
  - Turn off/on switched loads via ground commands or on-board autonomy commands
    - Receive commands from the Avionics/REM via block redundant interfaces as defined in the SPP Spacecraft Electrical ICD
    - Transmit telemetry to the Avionics/REM via block redundant interfaces as defined in the SPP Spacecraft Electrical ICD
  - Implement inputs for Spacecraft Umbilical power and EPS power
  - Implement the Spacecraft Single Point Ground
  - Receive switched power from the Avionics/RPM/ARC for PDU Side A and Side B DC/DC converter power input
  - Be designed to be single fault tolerant
- **SPP PDU Subsystems Requirements Document, 7434-3900, has been entered into DOORS and PLM released on 10/21/13.**

Power Distribution Unit (PDU)

Trade Studies that Impact PDU

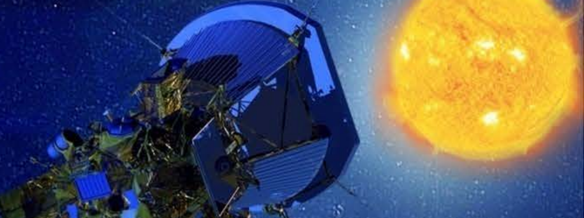
- **Jan 2013** **Power Distribution Mass Reduction Study**
  - New PDU FET Slice Design to reduce FET Slices from, 6 to 5, Saves 1.4 Kg, increases spare services
  - Aug 2013, Revert back to 6 FET Slice Design, reduces cost
- **Mar 2013** **Propulsion Diode Box Elimination Study (PDB)**
  - Incorporate Redundant Back-EMF circuits for inductive loads (latch valve coils) into PDU Subsystem. Eliminates PDB and reduces mass and cost from Propulsion Subsystem

Power Distribution Unit (PDU)

Previous Reviews – Action Item Status

- **Closure of Action Items from Previous Reviews**
  - **Pre-MDR PDU Subsystem Review, Aug 2011 – 2 of 2 Action Items Closed.**
  - **MDR Review, Oct 2011- None**
  - **Pre-PDR PDU Subsystem Review, Oct 29, 2013**
    - Review Board:
      - Thomas Kerslake (NASA-SRB Member)
      - Uno Carlson, Chair , APL (New Horizons Power/PDU Lead)
      - David Frankford, APL (RBSP FET Board Lead)
    - 23 Action Items (13 Recommendations)
      - 7 Completed
      - 7 Waiting Concurrence
    - Minutes and Actions Items are capture in SEE-13-093
    - Actions Items tracked in PIMS

SPP Spacecraft Block Diagram



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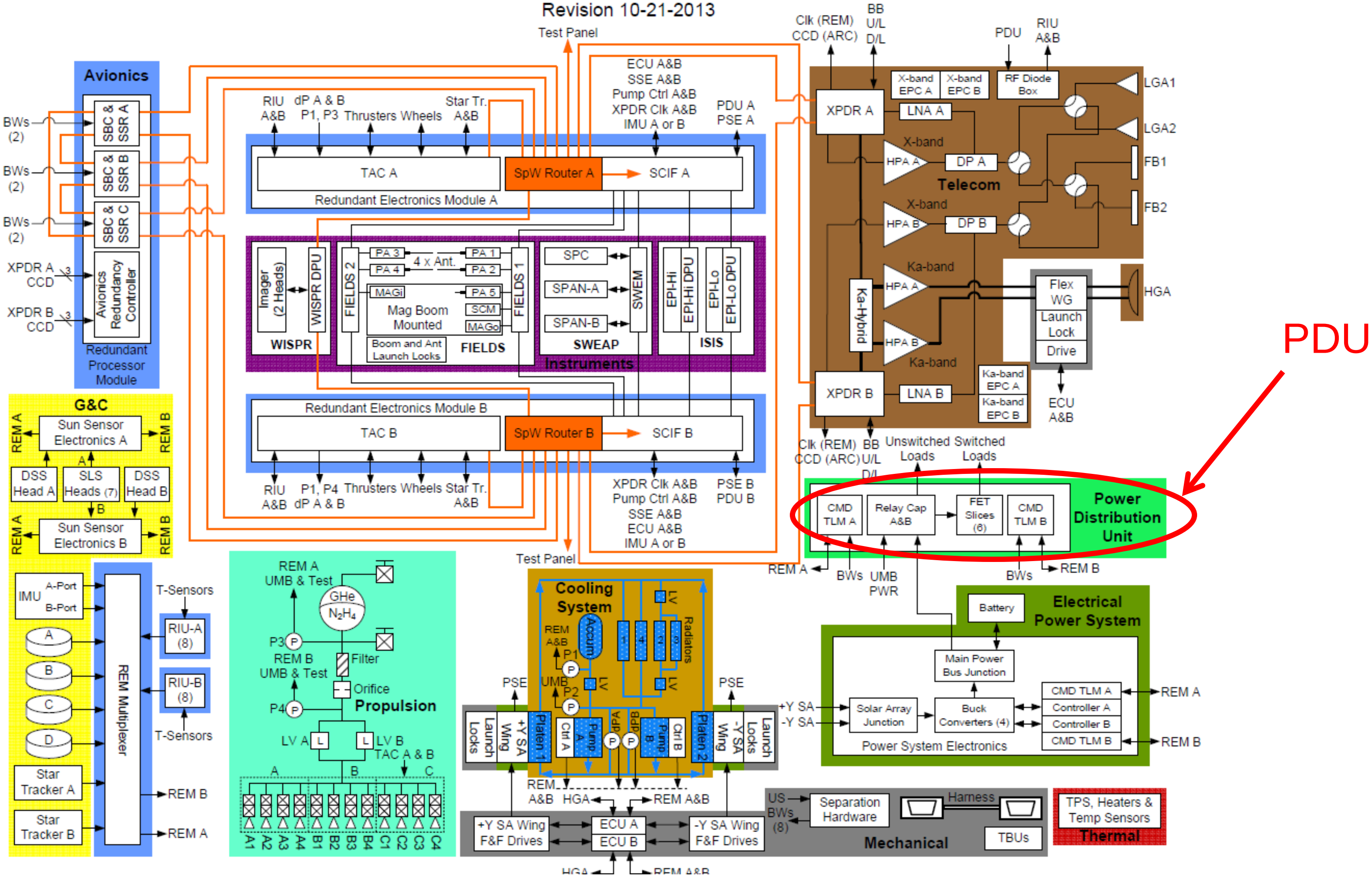
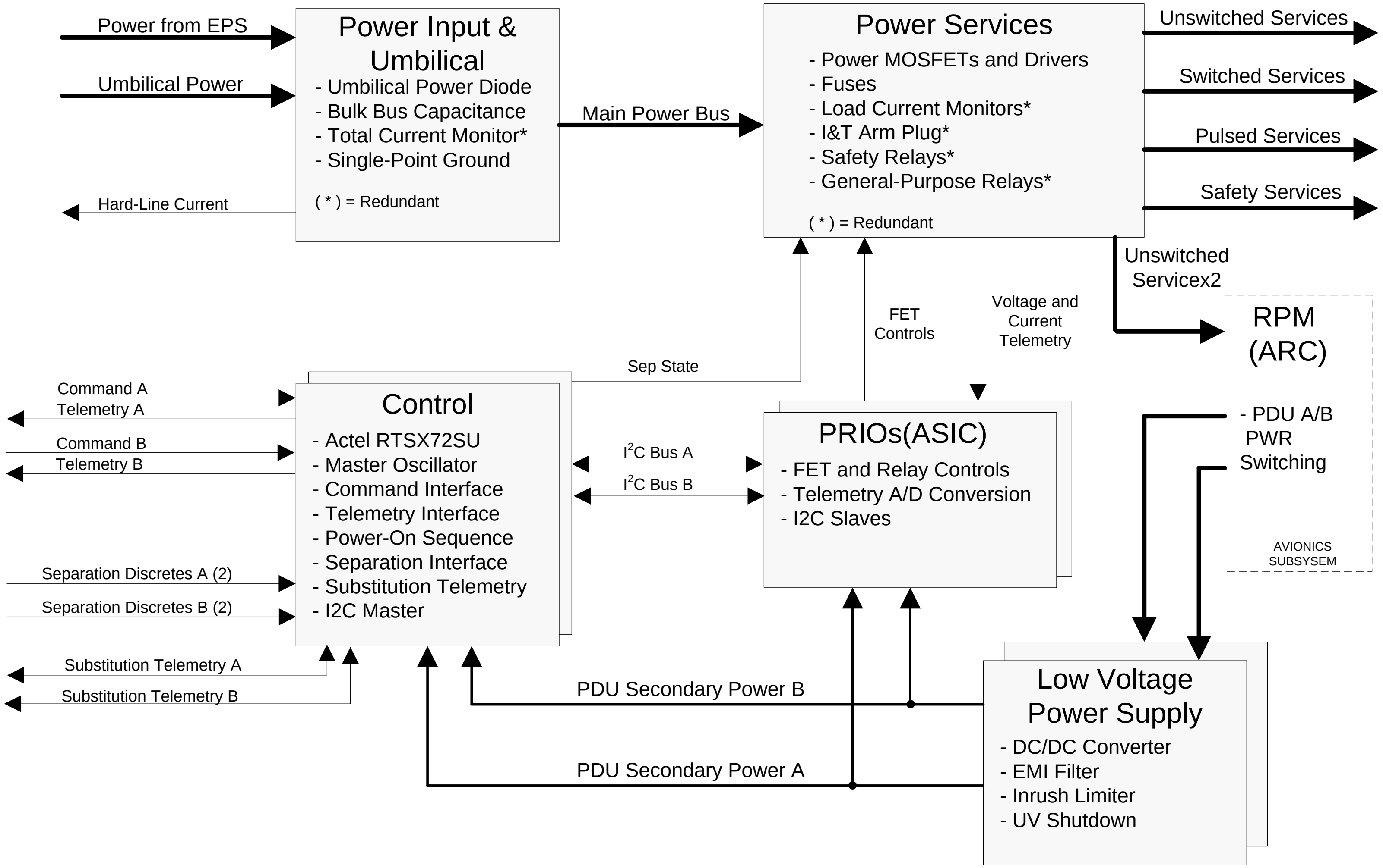
Solar Probe Plus Spacecraft Block Diagram

Revision 10-21-2013

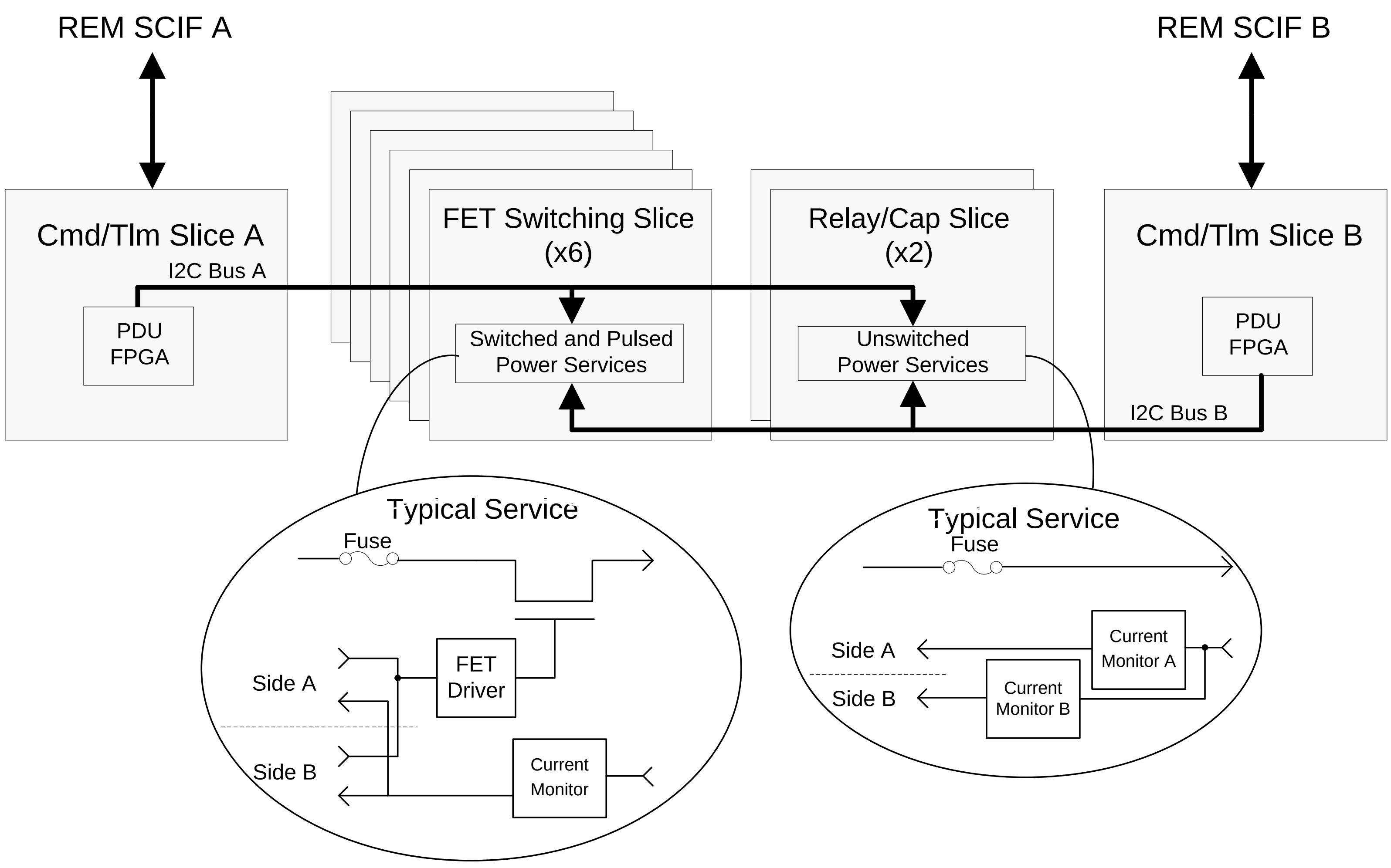


PDU Block Diagram



Power Distribution Unit (PDU)

Functional Block Diagram – Control Redundancy



PDU Top Level Design Description and Specifications

- **The SPP PDU uses a modified PDU that’s used on the Van Allen Probe/ Radiation Belts Storm Probe Mission (RBSP)**
  - Change from RBSP Non Redundant (6 slice design) to SPP Redundant Configuration (10 slice design)
    - Added 1 additional CT slice
    - Added 3 additional FET Slices
      - Slight changes to CT, RC and FET Slices – Add “B side Parts, BEMF Circuitry”
  - For RBSP, PDU was hardwired “ON”, only 1 side (No fuse)
  - For SPP, PDU Side A and Side B will be switched on by the AVIONICS/RPM/ARC (fused, unswitched power service provided from PDU to ARC)
    - PDU A ON, B OFF (Nominal)
    - PDU B ON, A OFF (Failure case)
    - PDU A/B ON (used for short periods of time during component switches)
      - Maintain power to pump and G&C sensors during Safe Mode global switch
      - Maintain power to all cross-strapped loads during REM switch (includes PDU switch)
    - ARC Fault Tolerant Logic precludes the PDU A/B OFF mode

PDU Top Level Design Description and Specifications

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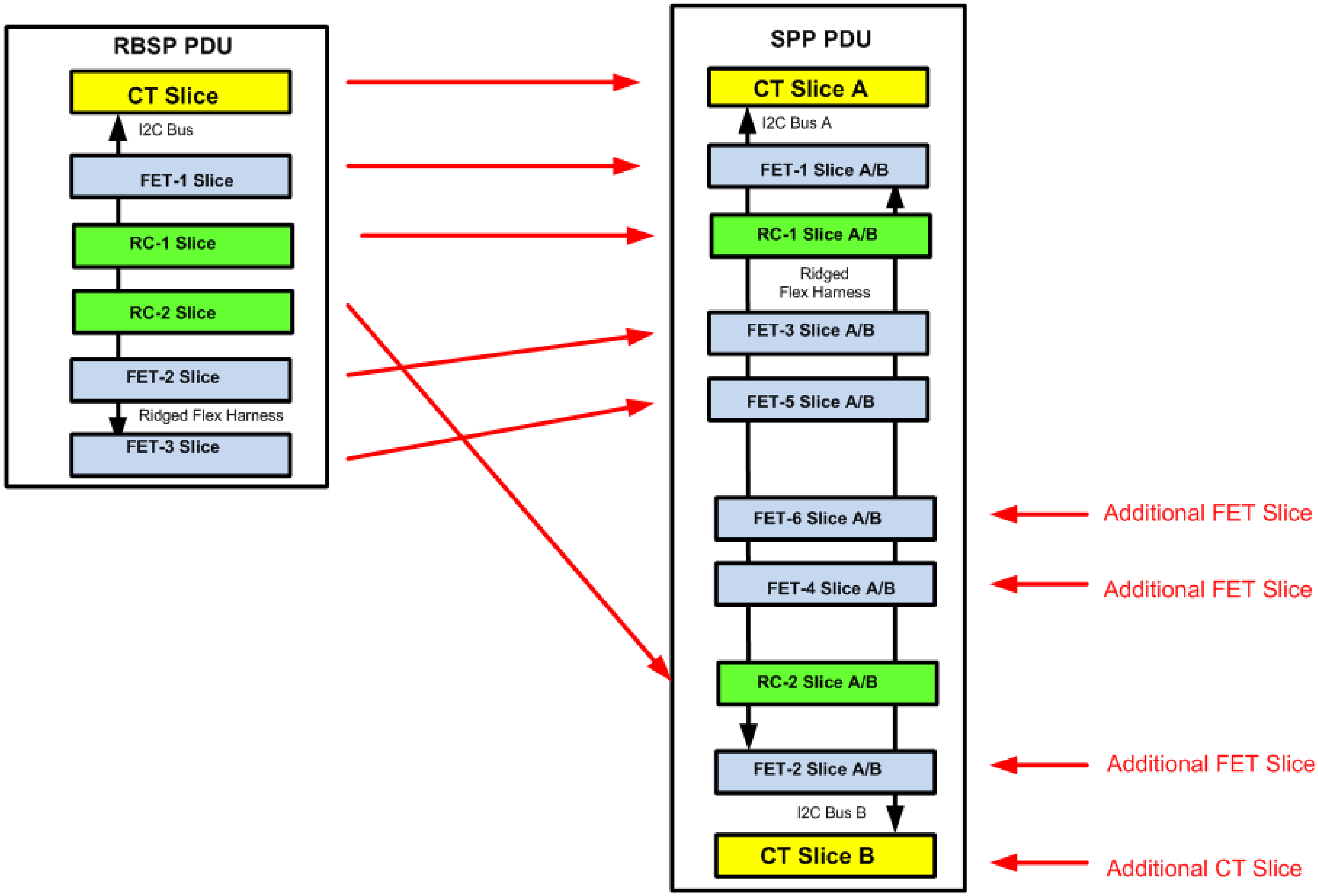


PDU Top Level Design Description and Specifications

- **Command and Telemetry Interface**
  - Receives commands and transmits telemetry from/to C&DH (UART 115.2 KBAUD)
    - LVDS Serial Digital I/F per SPP Spacecraft Electrical ICD
    - Performs command error checking, includes CRC error, UART Frame and parity error
    - Reports command rejection in telemetry, (error counters)
  - Accepts Commands(group of up to 10) at a rate of 5 Hz
  - Implements stored command sequences for PDU Power-On Reset (PRIO Initialization Only)
  - Provides all PDU telemetry upon request (from C&DH) at a rate of 5 Hz
    - Includes PDU Diagnostic Telemetry to allow autonomous mitigation of faults by the Fault Protection Subsystem
      - Includes individual load current telemetry for unswitched and switched loads
- **Test Interface**
  - Accommodates PDU telemetry substitution for SPP Mission Scenario Testing
    - PDU has a GSE port that can be used to “loopback” PDU telemetry
      - PDU routes its telemetry to the GSE Port
      - PDU transmits substituted telemetry (to REM) received from the GSE port
    - Telemetry substitution is transparent to CD&H

PDU Top Level Design Description and Specifications

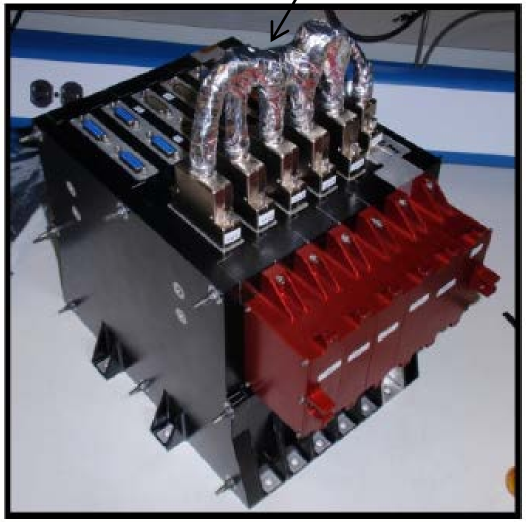
- **PDU Safety and Fault Protection**
  - Implements inhibits for safety-inhibited items
    - Thrusters, RF(Telecom TWTAs) and Mechanisms/Misc (Actuators)
  - Includes redundant Safety Buses for safety-critical loads
    - Safety Buses include in-line mechanical relays
      - Each relays controllable from either side of PDU, Side A or Side B, after separation of the spacecraft from the upper stage
      - Redundantly sense spacecraft-LV separation using two umbilical connector breakwires with 2-of-2 voting
  - Includes fusing for all loads
    - Lower-rated fuses would be used for all loads during I&T
  - Circuit breaker protection for switched loads
  - Includes latching relays (Common Relays) for storing bit states used by Fault Management Software (e.g., Safe Mode States)

PDU Top Level Design Description and Specifications

- **PDU Power Interface**
  - ➢ Receives unregulated bus power (22V to 35V) from EPS
  - ➢ Includes Bulk Bus Capacitance (2600uF) for bus stability
    - ➢ 1300uF per RC slice
  - ➢ Implements the Spacecraft Single-Point Ground
    - ➢ Provides Primary power return lines for connection to Spacecraft Chassis/Structure Ground
- **Umbilical Interface**
  - ➢ Accepts direct Spacecraft Umbilical Power input (with diode protection)
  - ➢ Provide total load current monitors to the Spacecraft Umbilical Port
  - ➢ Implement a hardline control interface to allow the PDU Safety Relays to be commanded to a safe state via the Spacecraft Umbilical when the spacecraft is unpowered

PDU Top Level Design Description and Specifications

- **Interslice Harness Interface**
  - PDU to PDU External Power Interface from RC slice outputs to FET Slice inputs
    - Purpose: Replaces an Internal Power Mother Board
    - Distributes the following types of Bus Power
      - Main Bus Power (unfused)
      - Safety Busses (fused)
        - RF (A and B)
        - Thruster (A and B)
        - Mechanisms/MISC (A and B)



RBSP PDU

PDU Top Level Design Description and Specifications

- **PDU Load Power Services** (SPP Configuration)
  - ➢ 150 Switched, Pulsed Power Services
    - All outputs are fused and have circuit breaker and current monitor capability
    - **66 Standard Switched Power Services**
      - Each switched service has a single high-side switch
      - 12 Outputs have Low Side Switch (Ground Closure)
      - 2 Outputs have blocking diode for Propulsion Pressure Transducer Interfaces
      - 1 Output has Redundant Back EMF circuitry to support Propulsion Latch valve interfaces
    - **72 Dedicated Pulsed Power Services (12 groups of 6)**
      - Each pulsed service group has dedicated high-side “arm” switches and shared low-side “fire” switches (1 of 2)
      - 6 Outputs have Redundant Back EMF circuitry to support Latch valve interfaces
    - **12 Flexible Power Services**
      - Can be configured as switched service or pulsed power services
      - Two outputs have option to share 1 Low Side Switch (Ground Closure)
  - ➢ 12 Unswitched Power Services
    - All outputs are fused and have current monitor capability

Power Distribution Unit (PDU)

PDU Power Services

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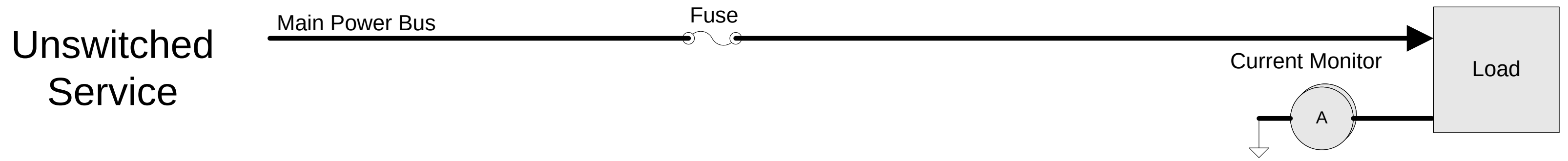
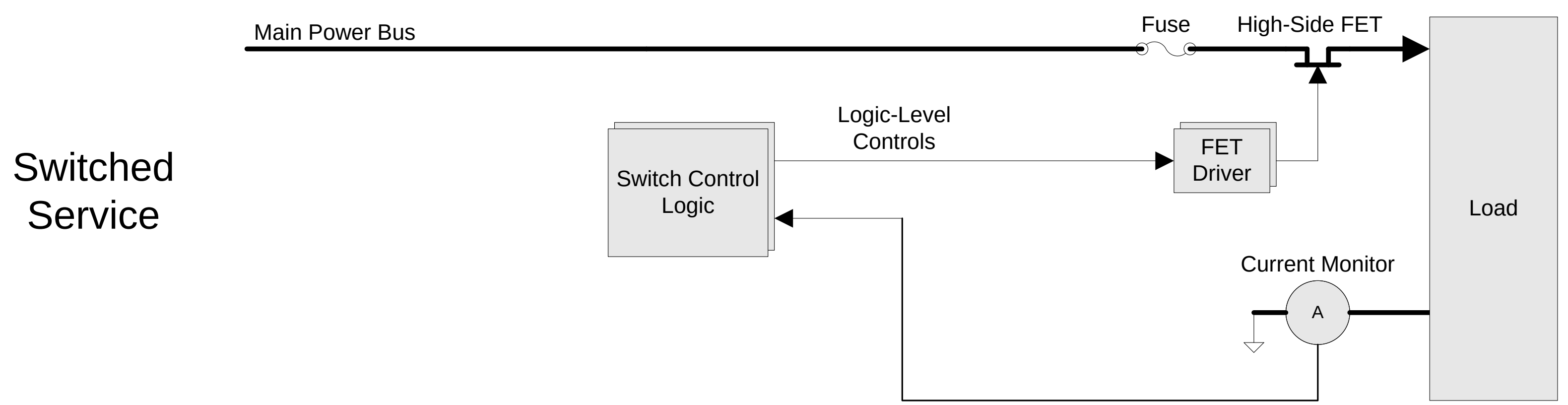
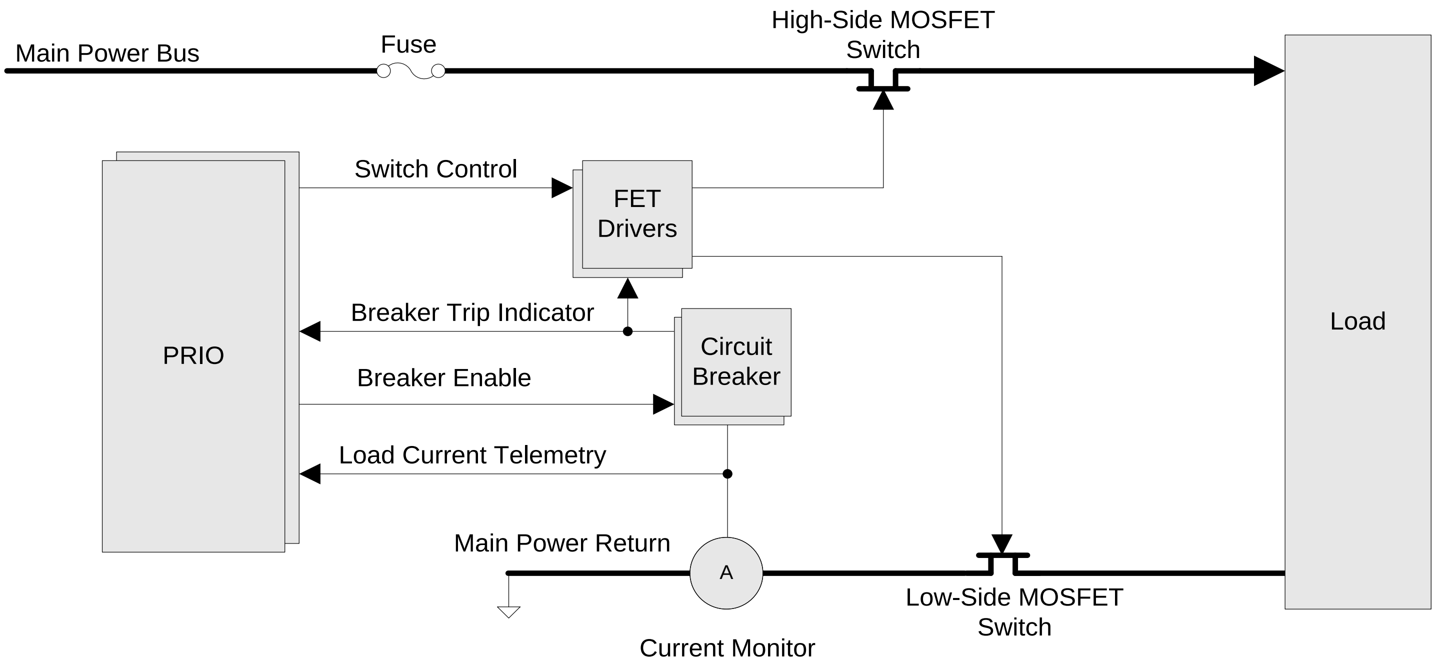




Power Distribution Unit (PDU)

PDU Power Services

Switched Service with Ground Closure and Circuit Breaker



Power Distribution Unit (PDU)

PDU Power Services

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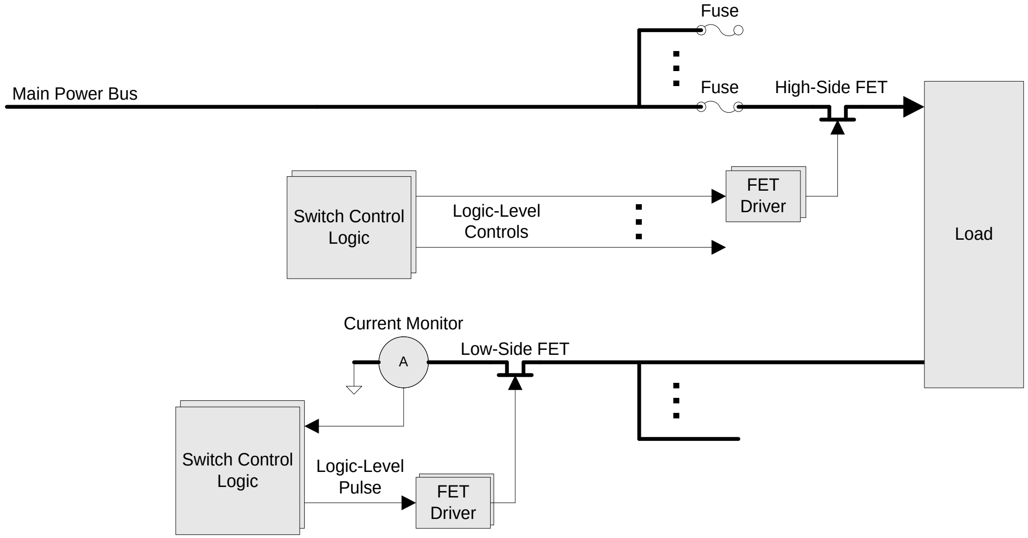
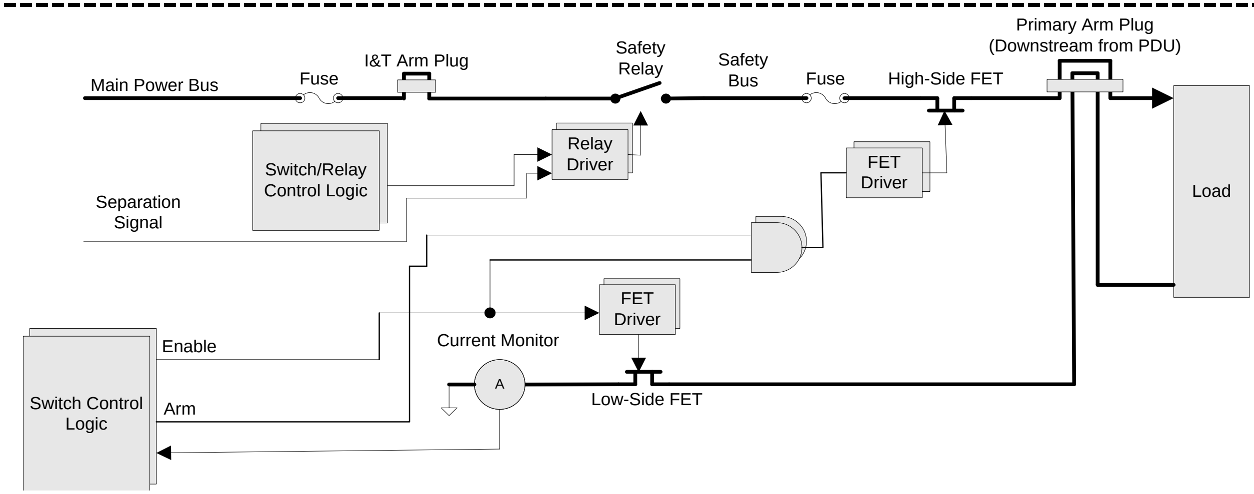
Pulsed Service



Typical Safety-Inhibited Service



Fuse and Circuit Breaker Settings

- **Range of current reading, trip current, and fuse value are set by selection of component values on the FET Switching Slice**
- **Component selection is based on Service Size**
- **Several standard options:**

New Service Sizes for SPP

Nominal Service Size (A)	Breaker Trip (A)	Max. Reading (A)	EM Fuse Rating (A)	FM Fuse Rating (A)
For Non Redundant Loads(Instruments): Use:				
1.00N	2.20	2.40	1.50	3.00
0.50N	1.10	1.20	0.75	2.00
0.25N	0.55	0.60	0.75	2.00
For Redundant Loads: Use:				
4.00	8.8	9.6	5.0	7.5
3.00	6.6	7.2	4.00	6.00
2.50	5.50	6.00	4.00	5.00
2.00	4.40	4.80	3.00	4.00
1.00	2.2	2.4	1.50	2.00
0.50	1.10	1.20	0.75	1.50
0.25	.55	.60	0.75	1.00

Uses RBSP 35% Fuse Derating (More Conservative)

Uses SPP 57% Fuse Derating

- N = Non-redundant load

- **See Backup Slides for Load Mapping to STD PDU Services**

Power Distribution Unit (PDU)

PDU Services–Spare capability

- **Switched Services**
  - 150 Switched Services Total
  - 133 used, Spares = 17/150 = 11%
    - Pulse Power services: 4 (2 Main Bus, 2 Mechanism/Misc Safety Bus)
    - Standard Switched Power Services: 11 (pulse capable)
    - Flexible Power Services: 2 (Mechanism/Misc Safety Bus)
      - Note: 6 services share common low side switch and operation may be constrained.
- **Unswitched Services**
  - 12 Unswitched Services Total
  - 12 used, Spares = 0/12 = 0%

Power Distribution Unit (PDU)

PDU Power Estimate

- **PDU Power Estimate (10.45W NTE (1 Side), 20.9W NTE (2 Sides))**

SPP PDU Powered Configuration	CBE	Rationale on Proposed CBE
A-Side = ON B-Side = OFF	9.5W	RBSP Flight PDU Quiescent Current = 0.223A @ 30V (6.7W) Flight RBSP PDU Slice Quiescent Currents • Command/Telemetry Slice = 0.150A @ 30V (4.5W) • Relay/Capacitor Slice = 0.021A @ 30V (0.63W) • FET Switching Slice = 0.021A @ 30V (0.63W) SPP PDU Powered ON Configuration with A-Side =ON, B-Side =OFF • 1 x Cmd/Tlm Slice + 2 x Relay/Cap Slices + 6 FET Slices • 1 x 4.5W + 2 x 0.63W + 6 x 0.63W = 9.54W Notes: 1. RBSP PDU is a six-slice, single-string configuration 2. Quiescent Current = No-Load Current
A-Side = OFF B-Side = ON	9.5W	SPP PDU Powered ON Configuration with A-Side = OFF, B-Side = ON • 1 x Cmd/Tlm Slice + 2 x Relay/Cap Slices + 6 FET Slices • 1 x 4.5W + 2 x 0.63W + 6 x 0.63W = 9.54W
A-Side = ON B-Side = ON	19.1W	SPP PDU Powered ON Configuration with A-Side = ON B-Side = ON • 2 x Cmd/Tlm Slice + 2 x Relay/Cap Slices + 6 FET Slices • 2 x 4.5W + 4 x 0.63W + 12 x 0.63W = 19.08W

PDU Packaging

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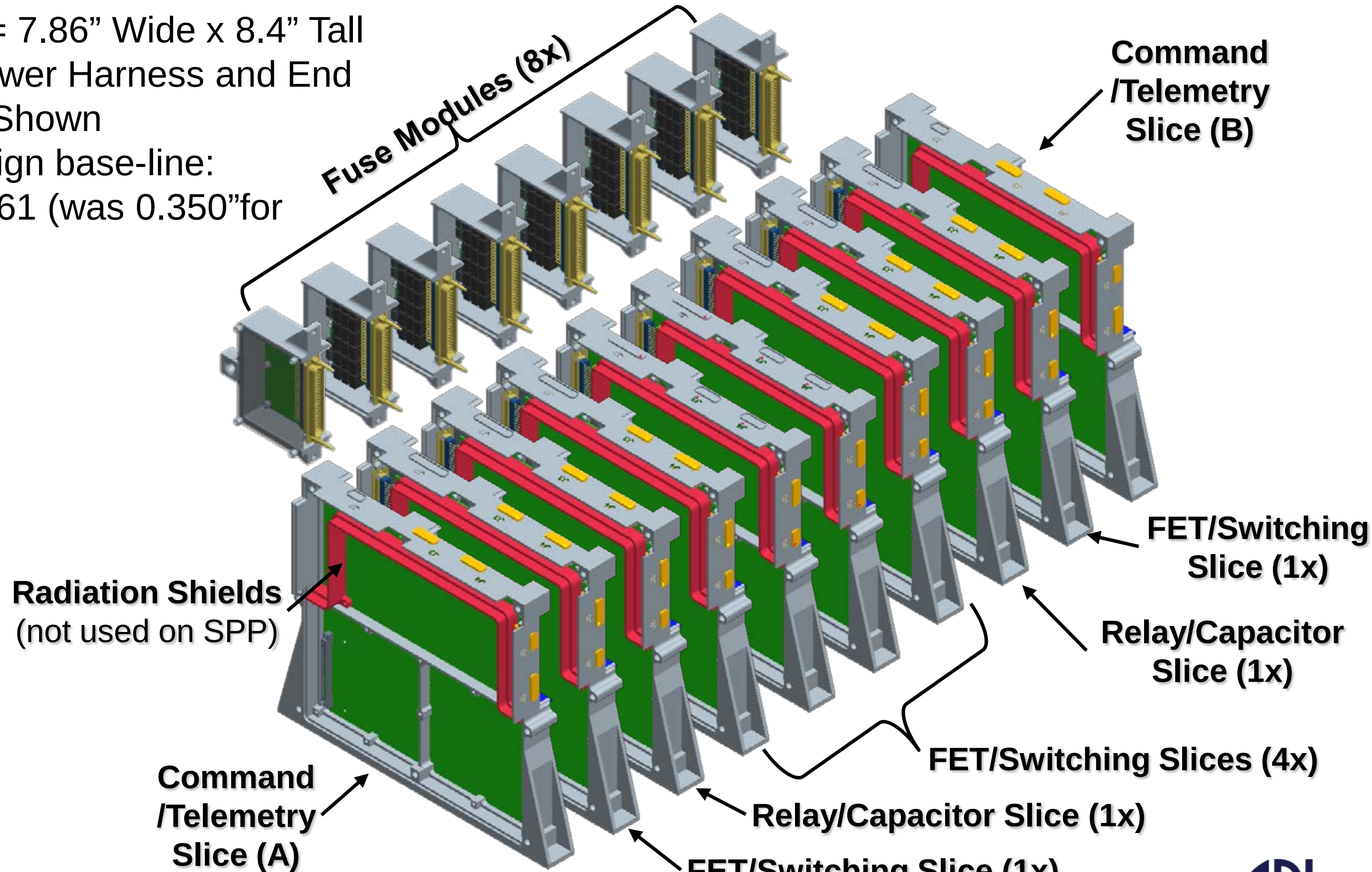
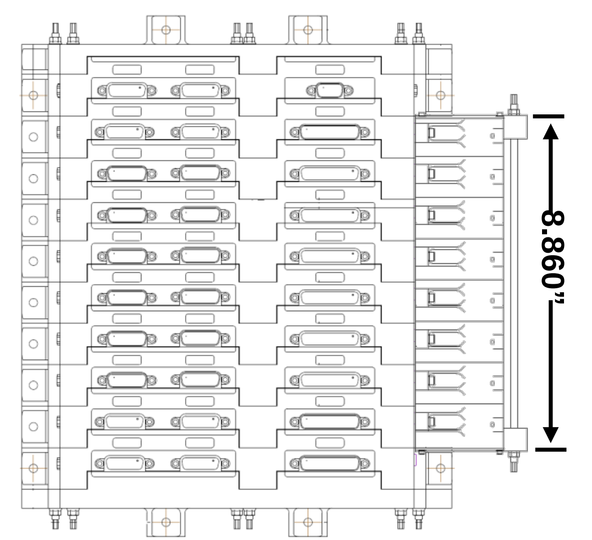
Notes:

1. Board Size = 7.86" Wide x 8.4" Tall
2. Interslice Power Harness and End Covers Not Shown
3. Chassis design base-line: 0.060" Al-6061 (was 0.350"for RBSP)

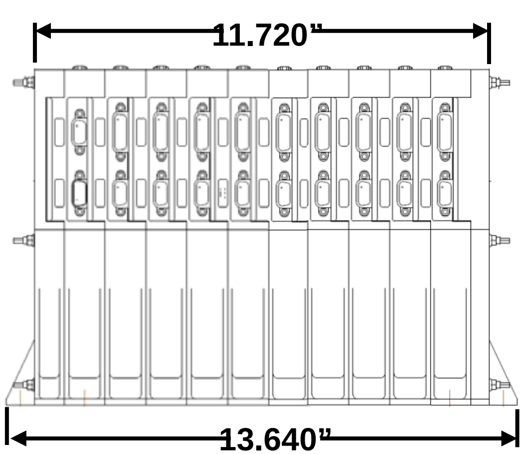


PDU Mass and Volume Estimates

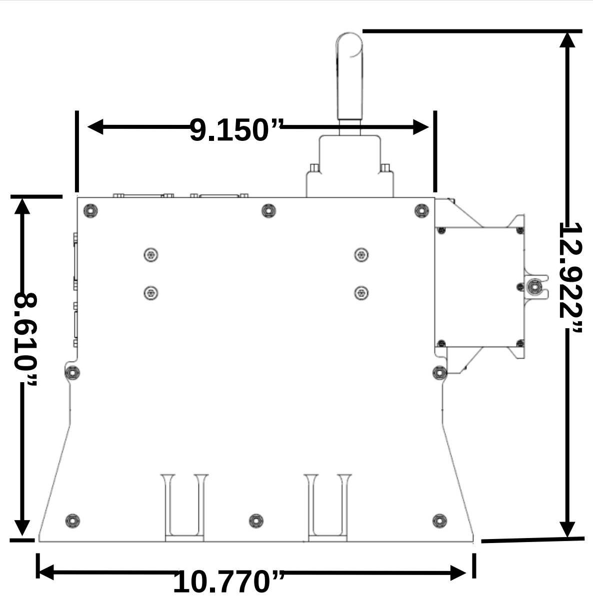
- Mass and dimensions estimated from modified RBSP build
- Does not include addition of B-side EEE parts
- Box Mass = 31.12 lbm (14.13 kg), CBE; 14.84 Kg (NTE)
- Box volume = 10.77" W x 13.64" D x 8.61" H, w/o inter-slice harness



Top View



Side View



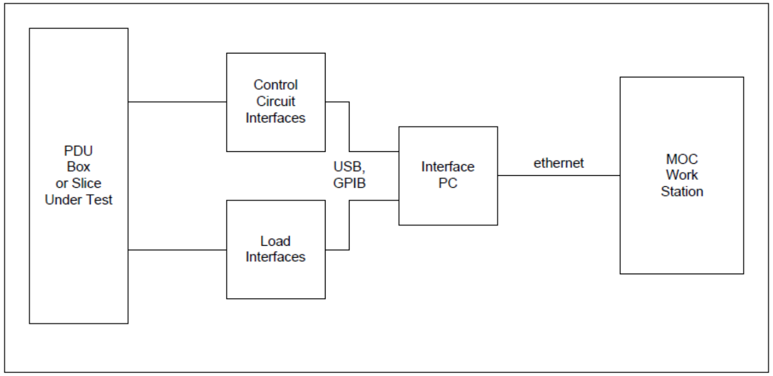
Front View

Mass Breakdown	lbm	kg
C/T Slice ea., (2x)	1.99	0.90
Frame	0.56	0.26
PWA + hardware	1.43	0.65
R/C Slice ea., (2x)	1.86	0.85
Frame	0.56	0.25
PWA + hardware	1.30	0.59
FET/Switching & Controller (6x)	2.91	1.32
Frame	0.51	0.23
PWAs + hardware	2.40	1.09
Fuse, outer ea., (2x)	0.28	0.13
Frame	0.10	0.05
PWA + hardware	0.17	0.08
Fuse, inner (6x)	0.26	0.12
Frame	0.08	0.04
PWA + hardware	0.17	0.08
Misc.		
Side Cover ea., (2x)	1.02	0.46
Box Bookbolt ea., (8x))	0.04	0.02
Fuse Bookbolt ea., (1x)	0.03	0.01
Fuse Cover (2x)	0.04	0.02
Harness, per slice (10x)	0.15	0.07
Total	**31.12**	**14.13**

Power Distribution Unit (PDU)

PDU EGSE Overview

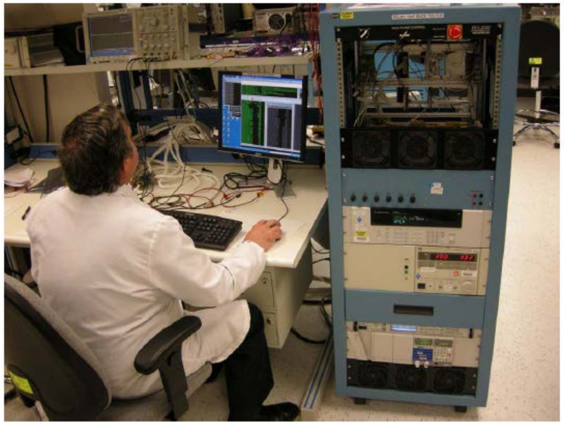
- **Testsets designed for Box and Slice level testing**
  - PDU Box-Level Testset (1)
  - PDU Slice-Level Testset (3)
    - Command/Telemetry Slice Testset
    - FET Switching Slice Testset
    - Relay/Capacitor Slice Testset
  - Re-use of the RBSP PDU Testsets
    - Requires modifications for testing redundant PDU configurations



PDU Testset Architecture Diagram

PDU Command/Telemetry Slice Testset

PDU FET Slice Testset



PDU Resistor/Capacitor Slice Testset

Power Distribution Unit (PDU)

PDU EMI/BB Test Results

- **Completed Preliminary SPP EMI Testing using RBSP HW**
  - RBSP PDU EM
    - Completed Conducted Emissions (CE) testing –passed CE01, CE03
  - RBSP CT Slice BB with enclosure
    - Completed Radiated Emissions RE testing – passed RE01, RE02
  - Will use this data to ask for Waiver to use IR2805S DC/DC converter
    - DC/DC converter required to operate at n*50KHz, >150Khz, and 500ppm
    - PDU DC/DC Converter is not synchronized and operates at 500KHz +/- 75KHz (500 ppm = +/-125 Hz)
  - See Backup Charts in EME PDR Slides for test data results

Power Distribution Unit (PDU)

PDU Testing: Flight Model (FM) Verification & Testing

- **Flight Slice Testing**
  - Comprehensive Functional and Performance Testing
  - ESS (environmental stress screening) thermal testing performed (unpowered)
- **Flight Box Testing**
  - SPP Environmental Design & Test Requirements Document, EDTR, (7434-9039) details test requirements, test sequences, test limits, etc.
    - EMI Testing: Box level CE (CE01, CE03, CE07), CS (CS01, CS02, CS06), RE (RE01, RE02), RS03, Mag Sniff and ESD
    - Powered sine and random vibration
    - Thermal vacuum temperature ranges:

      Operational: -25°C ≤ T ≤ 60 °, (RBSP: -25°C ≤ T ≤ 55°)

      Survival: -30°C ≤ T ≤ 65°, (RBSP: -30°C ≤ T ≤ 60°)

      6 operational and 1 Survival cycles

*Note: Flight Fuse Modules are environmentally tested using standalone test fixture.

Subsystem Deliverables Summary

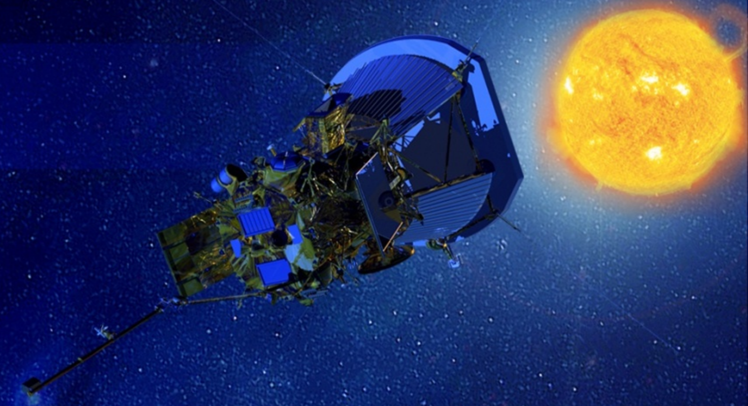
- PDU(2xCT, 2xRC, 6xFET, Interslice Harness)
    - 1 Flight Model (FM)
    - 0 Eng. Model (EM) -- Program Risk (SPP-74)
- Breadboards (BB)
    - 1 RC Slice (From RBSP RC Downgraded EM)
    - 2 CT Slices
    - 1 FET Slice
- Fuse Modules
    - 16 Flight Model (FM) (includes 8 Spares)
    - 20 Eng. Model (EM) (includes 12 Spares)

- EGSE Hardware (Modified RBSP Testers)
    - 1 PDU Box Tester
    - 3 PDU Slice Testers (RC, CT, FET)

Phase C Work Plans

- **Finalize/Update Phase B Documents (PDU Performance Specification)**
- **PDU Parts Application Stress (Derating) Analysis Reports**
- **Thermal/Structural Analysis Reports**
- **Worst-Case Analysis Reports (PDU Loss factor, I2C Bus Signal Integrity)**
- **FPGA EDR**
- **GSE Design Documentation (Hardware and Software)**
- **GSE Certification Test Procedures**
- **Component Test Procedures and Test Scripts**
- **Hold Subsystem CDR**

- **The PDU Subsystem is ready for Phase C**



Backup Slides

SD/RBSP Lesson Learned Database Review

- **APL Avionics Architecture Working Group (2003), Avionics roadmap:**
  - **"*Keep the PDU simple so that it can be delivered early…need to separate the power distribution functions from other spacecraft functions such as G&C.*"**
- **RBSP Monitor Data Sheets for late changes by the Vendor (RBSP MSK Linear Regulator) – Required large capacitance for stability**
- **Replace 5150s right-angle D-Sub connectors with off-the-shelf pre-potted versions; evaluate ITT Canon assemblies suitability for flight. (99)**
- **RBSP GSE S/W Design and Development - Database generation for the various CMDs and TLM points used to test the PDU Slices**
  - **To ease migration (re-use) of the PDU's GSE databases at RBSP I&T and Mission Ops, Subsystem GSE databases should use the same CMD and TLM naming conventions as I&T and Mission Ops.**
- **Fix known RBSP Flight PDU Bridge FPGA Issues/SW Workarounds, implement selective items on Pending list of improvements**
  - **E.g.: Command FIFO Stall if last command is a Bridge command.**

PDU Team

- **PDU Lead**
  - Sam Sawada
- **PDU Electrical Designers**
  - Chris Rose, Command/Telemetry FPGA Design
- **PDU Electrical Designers**
  - Darryl Zawada
- **PDU Mechanical/Packaging**
  - Shaughn London, Packaging Lead
    - Erik Hohlfeld
  - Richard Kuan, Mechanical Designer

PDU Team

- **PDU GSE Engineers**
  - David Storey, PDU GSE Lead
  - P. J. Clark, Test Set Software Lead
    - Lisa Segal
- **Manufacturing Engineers**
  - Karen Moore, SEE Group Product/Manufacturing Engineer
    - Katrina, Roarty
  - Steve Griffiths. REDD Manufacturing
- **Component Engineers**
  - Dave Bonner, Lead SPP Component Engineer
  - John Farnan, Lead PDU Component Engineer
  - Dave Roth, Radiation

PDU Documentation Status

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- PLM Documentation
  - Released:
    - 7434-3900 – SPP PDU Subsystem Requirements Document
  - To Be Released:
    - 7434-3901 – SPP PDU Subsystem Performance Specification & ICD
      - Expect to release by May 2014
    - TBD: SPP PDU Verification Plan

- Documentation for 5 FET Slice Design (9 Slice PDU)
  - SEM-13-7-035, Erik Hohlfeld, 3/14/13, Preliminary Thermal Analysis of SPP PDU
  - SEM-13-7-036, Shaughn London, 4/2/13, Preliminary Structural Analysis of SPP PDU

PDU Top Level Design Description and Specifications

- **The PDU provides power switching, actuation, and telemetry measurement for SPP Spacecraft**
- **The PDU consist of three types of slice designs:**
  - Command/Telemetry Slice (x2)
    - Serves as the PDU's main interface with AVIONICS/REM
    - Two of these slices are needed for full PDU block redundancy (A-Side and B-Side)
  - Relay/Capacitor Slice (x2)
    - Serves as the input for the main power bus into the PDU
    - Provides fused, unswitched power services to the spacecraft loads
    - Provides Safety Bus Relays
    - Includes redundant control and sense circuits
  - FET Switching Slice (x6)
    - Provides fused, switched and pulsed power services to the spacecraft loads
    - Includes redundant control and sense circuits

Power Distribution Unit (PDU)

PDU Services–Spare capability

- **Common Relay (Storage Bits)**
  - 6 Common Relays Total
  - 3 used, Spares = 3/6 = 50%
    - Safe Mode – Solar Array
    - Safe Mode – Standby
    - Safe Mode – Earth Acquisition

Power Distribution Unit (PDU)

FET Switching Slice -Changes

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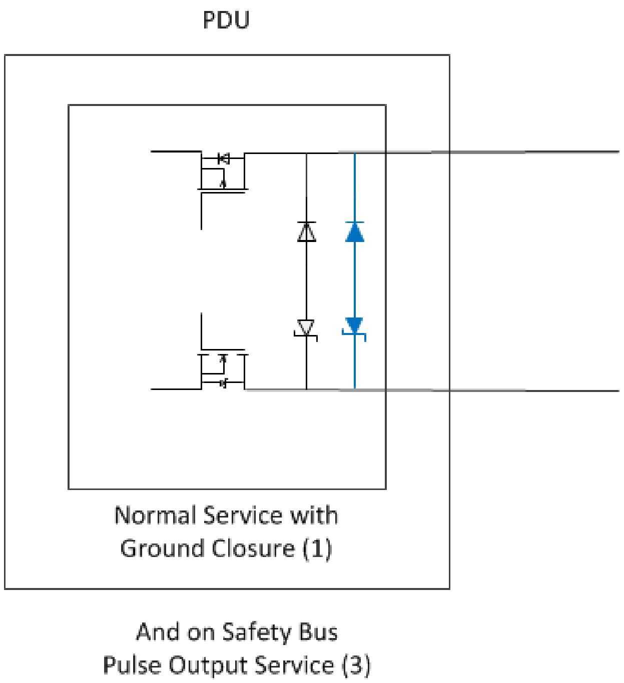
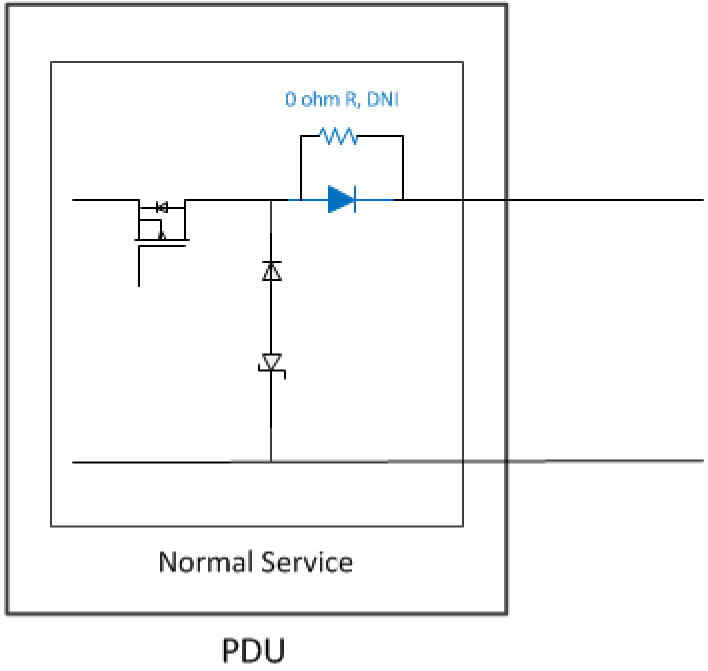
- **FET Switching Slice –Change #1: Add Redundant Back EMF Circuit for LV Loads to prevent SPF where the Back EMF circuit opens and causes the FET to short on. (Replaces some Propulsion Diode Box (PDB) functions, AVIONICS replaces remaining functions)**
  - **SW9 (1x, Propulsion Latch Valve A&B close)**
  - **Pulse 0A (2x,Accumulator LV Open A(B))**
  - **Pulse 1A (2x, Radiator 2 &3 Input & Output LV Open A(B))**
  - **Pulse 4A (2x, Propulsion Latch Valve A(B) open)**



Power Distribution Unit (PDU)

FET Switching Slice -Changes

- **FET Switching Slice –Change #2: Add Blocking diode for Propulsion Pressure Transducer Power A and B outputs**
  - **SW5 (FET Slice 3, 5)**
    - **Blocking diode installed only, for other slices 0 ohm resistor installed.**



Circuit Breaker

- **Protects the fuse during temporary load faults**
- **Each circuit breaker can be individually enabled or disabled by PDU command**
  - **When disabled, the fuse remains in place to protect the power bus**
- **Over-current threshold is proportional to maximum current reading**
- **Over-current condition must persist for approximately 4-5 ms before circuit breaker will trip**
- **Monitor indicates fault state for each switch in PDU telemetry**
- **Circuit breaker is reset when the normal PDU command to turn off the switch is received**

Load Power Services Switch Allocation Table (FET Slices)

Available Services and *Options* Per Slice	Allocations									
	Switch Slice 1 (-19)					Switch Slice 2 (-29)				
	Load	**MaxI**	**Size**	**FM Fuse**	**EM Fuse**	**Load**	**MaxI**	**Size**	**FM Fuse**	**EM Fuse**
Switched 0 (Pulse Capable)	Wheels A	3.41 A	3.5 A	7.5 A	5.0 A	Wheels B	3.41 A	3.5 A	7.5 A	5.0 A
Switched 1 (Pulse Capable)	RF Switch #1 Positon A	0.07 A	0.25 AP	1.0 A	3/4A	RF Switch #2 Positon A	0.07 A	0.25 AP	1.0 A	3/4A
Switched 2 (Pulse Capable)	RF Switch #1 Positon B	0.07 A	0.25 AP	1.0 A	3/4A	RF Switch #2 Positon B	0.07 A	0.25 AP	1.0 A	3/4A
Switched 3 (Pulse Capable)	SPARE		1.0 AN	3.0 A	1.5 A	SPARE		1.0 AN	3.0 A	1.5 A
Switched 4	EPI-Hi Operational Heater	0.03 A	0.25 AN	2.0 A	3/4 A	EPI-Hi Survival & Warm-up Heater	0.4 A	0.5 AN	2.0 A	3/4 A
Switched 5	Star Tracker B	0.34 A	0.5 A	1.5 A	3/4 A	Star Tracker A	0.34 A	0.5 A	1.5 A	3/4 A
Switched 6	Battery Heater A	0.33 A	0.5 A	1.5 A	3/4 A	Actuator Heater B	0.63 A	1.0 A	2.0 A	1.5 A
Switched 7	Propulsion Tank Heaters A	1.62 A	2.0 A	4.0 A	3.0 A	Propulsion Line and Valve Heaters A	2.2 A	2.5 A	5.0 A	4.0 A
Switched 8	FIELDS 1 Operational and Survival Heaters	0.33 A	0.5 AN	2.0 A	3/4 A	FIELDS 2 Operational and Survival Heaters	0.29 A	0.5 AN	2.0 A	3/4 A
Switched 9 (Pulse Capable)	SWEAP Operational Power	0.55 A	1.0 AN	3.0 A	1.5 A	FIELDS 1 Operational Power	0.82 A	1.0 AN	3.0 A	1.5 A
Switched 9 Ground Closure Use	Yes					Yes				
Switched 9 Ground Closure Cor	*PRIO Controlled Enable*					*PRIO Controlled Enable*				
Switched 10 (Pulse Capable)	CSPR Manifold 1&4 Warm-up Heaters A	1.94 A	2.0 A	4.0 A	3.0 A	CSPR Manifold 2&3 Warm-up Heaters A & Top Deck Line Htrs	2.35 A	2.5 A	5.0 A	4.0 A
Switched 10 Ground Closure Us	Yes					Yes				
Switched 10 Ground Closure Co	PRIO Controlled Enable					PRIO Controlled Enable				
Flexible Services Power Bus	***RF-A***					***RF-B***				
Flexible 0 (Pulse Capable)	Ka-Band TWTA A Power	3.64 A	4.0 A	7.5 A	5.0 A	Ka-Band TWTA B Power	3.64 A	4.0 A	7.5 A	5.0 A
Flexible 0 wired to ground closu	Yes					Yes				
Flexible 1 (Pulse Capable)	X-Band TWTA A Power	1.5 A	2.0 A	4.0 A	3.0 A	X-Band TWTA B Power	1.5 A	2.0 A	4.0 A	3.0 A
Flexible 1 wired to ground closu	Yes					Yes				
Flexible Services Ground Closu	PRIO Controlled Enable					PRIO Controlled Enable				
Pulsed Services Group A Powe	***Mechanism/MiscA***					***Mechanism/MiscB***				
Pulse 0A	WISPR Door Deployment Power A	3.76 A	4.0 AP	7.5 A	5.0 A	WISPR Door Deployment Power B	3.76 A	4.0 AP	7.5 A	5.0 A
Pulse 1A	Radiator 2&3 Input & Output LVs Open A	3.5 A	4.0 AP	7.5 A	5.0 A	Radiator 2&3 Input & Output LVs Open B	3.5 A	4.0 AP	7.5 A	5.0 A
Pulse 2A	Mag Boom Launch Lock 2A	1.25 A	2.0 AP	4.0 A	3.0 A	Mag Boom Launch Lock 2B	1.25 A	2.0 AP	4.0 A	3.0 A
Pulse 3A	FIELDS Antenna Deploy Whip Cages 1-2 A	2.5 A	3.0 AP	6.0 A	4.0 A	FIELDS Antenna Deploy Whip Cages 1-2 B	2.5 A	3.0 AP	6.0 A	4.0 A
Pulse 4A	FIELDS Antenna Deploy Whip Cages 3-4 A	2.5 A	3.0 AP	6.0 A	4.0 A	FIELDS Antenna Deployment Whip Cages 3-4	2.5 A	3.0 AP	6.0 A	4.0 A
Pulse 5A	SPARE		3.0 AP	6.0 A	4.0 A	SPARE		3.0 AP	6.0 A	4.0 A
Pulse Group A Ground Closure	*0,1*					*0,1*				
Pulse Group A Ground Closure	*2,3,4,5*					*2,3,4,5*				
Pulsed Services Group B Powe	***MB***					***MB***				
Pulse 0B	SSIRU #1 A (SSIRU_ON_A)	0.02 A	0.25 AP	1.0 A	3/4 A	SSIRU #1 B (SSIRU_ON_B)	0.02 A	0.25 AP	1.0 A	3/4 A
Pulse 1B	SSIRU #2 A (SSIRU_OFF_A)	0.02 A	0.25 AP	1.0 A	3/4 A	SSIRU #2 B (SSIRU_OFF_B)	0.02 A	0.25 AP	1.0 A	3/4 A
Pulse 2B	SSIRU #3 A (SSIRU_PPSMB_SEL_A)	0.02 A	0.25 AP	1.0 A	3/4 A	SSIRU #3 B (SSIRU_PPSMB_SEL_B)	0.02 A	0.25 AP	1.0 A	3/4 A
Pulse 3B	SSIRU #4 A (SSIRU_AB_OFF_A)	0.02 A	0.25 AP	1.0 A	3/4 A	SSIRU #4 B (SSIRU_AA_OFF_B)	0.02 A	0.25 AP	1.0 A	3/4 A
Pulse 4B	SSIRU #5 A (SSIRU_AC_OFF_A)	0.02 A	0.25 AP	1.0 A	3/4 A	SSIRU #5 B (SSIRU_AD_OFF_B)	0.02 A	0.25 AP	1.0 A	3/4 A
Pulse 5B	SSIRU #6 A (SSIRU_RST_A)	0.21 A	0.5 AP	1.5 A	3/4 A	SSIRU #6 B (SSIRU_RST_B)	0.21 A	0.5 AP	1.5 A	3/4 A
Pulse Group B Ground Closure	*0,1,2*					*0,1,2*				
Pulse Group B Ground Closure	*3,4,5 (tie 2 alt to 2)*					*3,4,5 (tie 2 alt to 2)*				

Commissioning order for actuators

Note: Green fill indicates 2 power/return pins available for this service

Load Power Services Switch Allocation Table (FET Slices)

Available Services and *Options* Per Slice	Allocations				
	Switch Slice 3 (-39)				
	Load	MaxI	Size	FM Fuse	EM Fuse
Switched 0 (Pulse Capable)	S/C Internal Panel Suvival Heaters A	2.42 A	3.0 A	6.0 A	4.0 A
Switched 1 (Pulse Capable)	RF Switch #3 Positon A	0.07 A	0.25 AP	1.0 A	3/4A
Switched 2 (Pulse Capable)	RF Switch #3 Positon B	0.07 A	0.25 AP	1.0 A	3/4A
Switched 3 (Pulse Capable)	SPARE		1.0 AN	3.0 A	1.5 A
Switched 4	EPI-Lo Operational Power	0.23 A	0.5 AN	2.0 A	3/4 A
Switched 5	Pressure Transducer A Power	0.03 A	0.25 A	1.0 A	3/4A
Switched 6	Battery Heater B	0.33 A	0.5 A	1.5 A	3/4 A
Switched 7	Propulsion Tank Heaters B	1.62 A	2.0 A	4.0 A	3.0 A
Switched 8	SPC & WISPR Survival Heater	0.53 A	1.0 AN	3.0 A	1.5 A
Switched 9 (Pulse Capable)	FIELDS 2 Operational Power	0.55 A	1.0 AN	3.0 A	1.5 A
Switched 9 Ground Closure Use	Yes				
Switched 9 Ground Closure Cor	*PRIO Controlled Enable*				
Switched 10 (Pulse Capable)	SPARE		1.0 A	2.0 A	1.5 A
Switched 10 Ground Closure Us	Yes				
Switched 10 Ground Closure Co	PRIO Controlled Enable				
Flexible Services Power Bus	***Mechanism/MiscA***				
Flexible 0 (Pulse Capable)	+Y/-Y Solar Array Boom Launch Lock Frangibolt A	2.5 A	3.0 AP	6.0 A	4.0 A
Flexible 0 wired to ground closu	Yes				
Flexible 1 (Pulse Capable)	SPARE		3.0 AP	6.0 A	4.0 A
Flexible 1 wired to ground closu	Yes				
Flexible Services Ground Closu	PRIO Controlled Enable				
Pulsed Services Group A Powe	***Mechanism/MiscA***				
Pulse 0A	ECU A Power	0.11 A	0.25 A	1.0 A	3/4 A
Pulse 1A	Pump Electronics A Enable A	.01 A	0.25 A	1.0 A	3/4 A
Pulse 2A	Pump Electronics B Enables A	.01 A	0.25 A	1.0 A	3/4 A
Pulse 3A	FIELDS Antenna Deploy Hinge 1 A	1.25 A	2.0 AP	4.0 A	3.0 A
Pulse 4A	FIELDS Antenna Deploy Hinge 2 A	1.25 A	2.0 AP	4.0 A	3.0 A
Pulse 5A	FIELDS Antenna Deploy Hinges 3&4 A	2.5 A	3.0 AP	6.0 A	4.0 A
Pulse Group A Ground Closure	*0,1,2*				
Pulse Group A Ground Closure	*3,4,5*				
Pulsed Services Group B Powe	***MB***				
Pulse 0B	Wheels C	3.41 A	3.5 A	7.5 A	5.0 A
Pulse 1B	SPARE		0.5 A	1.5 A	3/4 A
Pulse 2B	SSIRU #7 A (SSIRU_GB_ONPPSMB_A)	0.06 A	0.25 AP	1.0 A	3/4 A
Pulse 3B	SSIRU #8 A (SSIRU_GC_ONPPSMB_A)	0.06 A	0.25 AP	1.0 A	3/4 A
Pulse 4B	Wheel A Internal Relay Control (On)	0.08 A	0.25 AP	1.0 A	3/4 A
Pulse 5B	Wheel A Internal Relay Control (Off)	0.08 A	0.25 AP	1.0 A	3/4 A
Pulse Group B Ground Closure	*0,1*				
Pulse Group B Ground Closure	*2,3,4,5(tie 5 to slice 1 GC 5)*				

Load Power Services Switch Allocation Table (FET Slices)

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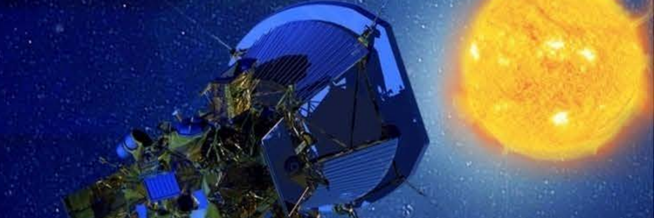
Available Services and *Options* Per Slice	Allocations				
	Switch Slice 4 (-49)				
	Load	**MaxI**	**Size**	**FM Fuse**	**EM Fuse**
Switched 0 (Pulse Capable)	S/C Internal Panel Suvival Heaters B	2.5 A	3.0 A	6.0 A	4.0 A
Switched 1 (Pulse Capable)	RF Switch #4 Positon A	0.07 A	0.25 AP	1.0 A	3/4A
Switched 2 (Pulse Capable)	RF Switch #4 Positon B	0.07 A	0.25 AP	1.0 A	3/4A
Switched 3 (Pulse Capable)	SPARE		1.0 AN	3.0 A	1.5 A
Switched 4	EPI-Lo Survival and Warm-up, and LP Op Heater	0.29 A	0.5 AN	2.0 A	3/4 A
Switched 5	Pressure Transducer B Power	0.03 A	0.25 A	1.0 A	3/4A
Switched 6	Actuator Heater A	0.63 A	1.0 A	2.0 A	1.5 A
Switched 7	Propulsion Line and Valve Heaters B	2.2 A	2.5 A	5.0 A	4.0 A
Switched 8	WISPR Operational Heaters	0.17 A	0.25 AN	2.0 A	3/4 A
Switched 9 (Pulse Capable)	Propulsion LV A&B Close	1.13 A	2.0 APN	6.0 A	3.0 A
Switched 9 Ground Closure Used?	Yes				
Switched 9 Ground Closure Control	*PRIO Controlled Enable*				
Switched 10 (Pulse Capable)	Cooling System Flex Line Heaters A	0.66 A	1.0 A	2.0 A	1.5 A
Switched 10 Ground Closure Used?	Yes				
Switched 10 Ground Closure Control	PRIO Controlled Enable				
Flexible Services Power Bus	***Mechanism/MiscB***				
Flexible 0 (Pulse Capable)	+Y/-Y Solar Array Boom Launch Lock Frangibolt B	2.5 A	3.0 AP	6.0 A	4.0 A
Flexible 0 wired to ground closure?	Yes				
Flexible 1 (Pulse Capable)	SPARE		3.0 AP	6.0 A	4.0 A
Flexible 1 wired to ground closure?	Yes				
Flexible Services Ground Closure Control	PRIO Controlled Enable				
Pulsed Services Group A Power Bus	***Mechanism/MiscB***				
Pulse 0A	ECU B Power	0.11 A	0.25 A	1.0 A	3/4 A
Pulse 1A	Pump Electronics A Enable B	.01 A	0.25 A	1.0 A	3/4 A
Pulse 2A	Pump Electronics B Enables B	.01 A	0.25 A	1.0 A	3/4 A
Pulse 3A	FIELDS Antenna Deploy Hinge 3 B	1.25 A	2.0 AP	4.0 A	3.0 A
Pulse 4A	FIELDS Antenna Deploy Hinge 4 B	1.25 A	2.0 AP	4.0 A	3.0 A
Pulse 5A	FIELDS Antenna Deploy Hinges 1&2 B	2.5 A	3.0 AP	6.0 A	4.0 A
Pulse Group A Ground Closure 0 Control	*0,1,2*				
Pulse Group A Ground Closure 1 Control	*3,4,5*				
Pulsed Services Group B Power Bus	***MB***				
Pulse 0B	Wheels D	3.41 A	3.5 A	7.5 A	5.0 A
Pulse 1B	SPARE		0.5 A	1.5 A	3/4 A
Pulse 2B	SSIRU #7 B (SSIRU_GA_ONPPSMB_B)	0.08 A	0.25 AP	1.0 A	3/4 A
Pulse 3B	SSIRU #8 B (SSIRU_GD_ONPPSMB_B)	0.08 A	0.25 AP	1.0 A	3/4 A
Pulse 4B	Wheel B Internal Relay Control (On)	0.06 A	0.25 AP	1.0 A	3/4 A
Pulse 5B	Wheel B Internal Relay Control (Off)	0.06 A	0.25 AP	1.0 A	3/4 A
Pulse Group B Ground Closure 0 Control	*0,1*				
Pulse Group B Ground Closure 1 Control	*2,3,4,5(tie 5 to slice 2 GC 5)*				

Load Power Services Switch Allocation Table (FET Slices)



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Available Services and *Options* Per Slice	Allocations									
	Switch Slice 5 (-59)					Switch Slice 6 (-69)				
	Load	MaxI	Size	FM Fuse	EM Fuse	Load	MaxI	Size	FM Fuse	EM Fuse
Switched 0 (Pulse Capable)	Pump Electronics B	2.73 A	3.0 A	6.0 A	4.0 A	Pump Electronics A	2.73 A	3.0 A	6.0 A	4.0 A
Switched 1 (Pulse Capable)	SPARE		2.0 A	4.0 A	3.0 A	SPARE		2.0 A	4.0 A	3.0 A
Switched 2 (Pulse Capable)	SPARE		2.0 A	4.0 A	3.0 A	SPARE		2.0 A	4.0 A	3.0 A
Switched 3 (Pulse Capable)	SPARE		2.0 A	4.0 A	3.0 A	SPARE		2.0 A	4.0 A	3.0 A
Switched 4	SLS Electronics A	0.14 A	0.25 A	1.0 A	3/4 A	SLS Electronics B	0.14 A	0.25 A	1.0 A	3/4 A
Switched 5	Cooling System Differential Pressure Sensor Power A	0.03 A	0.25 A	1.0 A	3/4A	Cooling System Differential Pressure Sensor Power B	0.03 A	0.25 A	1.0 A	3/4A
Switched 6	SSIRU B	1.36 A	2.0 A	4.0 A	3.0 A	SSIRU A	1.36 A	2.0 A	4.0 A	3.0 A
Switched 7	SPAN A&B Survival Heaters	0.46 A	1.0 AN	3.0 A	1.5 A	EPI-Hi Main Power (LVPS and Op Htr)	0.27 A	0.5 AN	2.0 A	3/4A
Switched 8	WISPR & FIELDS-2 Mech Pre-deployment Warm-up Heaters	0.08 A	0.25 AN	2.0 A	3/4A	FIELDS-1 Mechanisms Pre-deployment Warm-up Heaters	0.07 A	0.25 AN	2.0 A	3/4A
Switched 9 (Pulse Capable)	PSE - CMD/TLM IF B	0.59 A	1.0 A	2.0 A	1.5 A	PSE - CMD/TLM IF A	0.59 A	1.0 A	2.0 A	1.5 A
Switched 9 Ground Closure Used?	Yes					Yes				
Switched 9 Ground Closure Control	*PRIO Controlled Enable*					*PRIO Controlled Enable*				
Switched 10 (Pulse Capable)	WISPR Main Power (DPU, Cameras)	0.68 A	1.0 AN	3.0 A	1.5 A	Cooling System Flex Line Heaters B	0.66 A	1.0 A	2.0 A	1.5 A
Switched 10 Ground Closure Used?	Yes					Yes				
Switched 10 Ground Closure Control	PRIO Controlled Enable					PRIO Controlled Enable				
Flexible Services Power Bus	***THR A***					***THR B***				
Flexible 0 (Pulse Capable)	TAC A Thruster Bus Group 1	2.21 A	2.5 A	5.0 A	4.0 A	TAC B Thruster Bus Group 1	2.21 A	2.5 A	5.0 A	4.0 A
Flexible 0 wired to ground closure?	Yes					Yes				
Flexible 1 (Pulse Capable)	TAC A Thruster Bus Group 2	2.21 A	2.5 A	5.0 A	4.0 A	TAC B Thruster Bus Group 2	2.21 A	2.5 A	5.0 A	4.0 A
Flexible 1 wired to ground closure?	Yes					Yes				
Flexible Services Ground Closure Control	PRIO Controlled Enable					PRIO Controlled Enable				
Pulsed Services Group A Power Bus	***Mechanism/MiscA***					***Mechanism/MiscB***				
Pulse 0A	Accumulator LV Open A	1.75 A	2.0 AP	4.0 A	3.0 A	Accumulator LV Open B	1.75 A	2.0 AP	4.0 A	3.0 A
Pulse 1A	Mag Boom Launch Locks 1A	1.25 A	2.0 AP	4.0 A	3.0 A	Mag Boom Launch Locks 1B	1.25 A	2.0 AP	4.0 A	3.0 A
Pulse 2A	+Y Solar Array Platen Launch Lock Frangibolts A	2.5 A	3.0 AP	6.0 A	4.0 A	+Y Solar Array Platen Launch Lock Frangibolts B	2.5 A	3.0 AP	6.0 A	4.0 A
Pulse 3A	-Y Solar Array Platen Launch Lock Frangibolts A	2.5 A	3.0 AP	6.0 A	4.0 A	-Y Solar Array Platen Launch Lock Frangibolts B	2.5 A	3.0 AP	6.0 A	4.0 A
Pulse 4A	Propulsion LVA Open	0.56 A	1.0 AP	2.0 A	1.5 A	Propulsion LVB Open	0.56 A	1.0 AP	2.0 A	1.5 A
Pulse 5A	HGA Launch Lock A Frangibolt	1.25 A	2.0 AP	4.0 A	3.0 A	HGA Launch Lock B Frangibolt	1.25 A	2.0 AP	4.0 A	3.0 A
Pulse Group A Ground Closure 0 Control	*0,1*					*0,1*				
Pulse Group A Ground Closure 1 Control	*2,3,4,5*					*2,3,4,5*				
Pulsed Services Group B Power Bus	***MB***					***MB***				
Pulse 0B	Wheel C Internal Relay Control (On)	0.06 A	0.25 AP	1.0 A	3/4 A	Wheel D Internal Relay Control (On)	0.06 A	0.25 AP	1.0 A	3/4 A
Pulse 1B	Wheel C Internal Relay Control (Off)	0.06 A	0.25 AP	1.0 A	3/4 A	Wheel D Internal Relay Control (Off)	0.06 A	0.25 AP	1.0 A	3/4 A
Pulse 2B	A Group Thruster CB Heaters B	0.34 A	0.5 A	1.5 A	3/4 A	A Group Thruster CB Heaters A	0.34 A	0.5 AP	1.5 A	3/4 A
Pulse 3B	B Group Thruster CB Heaters B	0.34 A	0.5 A	1.5 A	3/4 A	B Group Thruster CB Heaters A	0.34 A	0.5 AP	1.5 A	3/4 A
Pulse 4B	C Group Thruster Catbed Heaters B	0.34 A	0.5 A	1.5 A	3/4 A	C Group Thruster Catbed Heaters A	0.34 A	0.5 AP	1.5 A	3/4 A
Pulse 5B	CSPR Manifold 1&4 Warm-up Heaters B	1.94 A	2.0 A	4.0 A	3.0 A	CSPR Manifold 2&3 Warm-up Heaters B & Top Deck Line Htrs	2.35A	2.5 A	5.0 A	4.0 A
Pulse Group B Ground Closure 0 Control	*0,1*					*0,1*				
Pulse Group B Ground Closure 1 Control	*2,3,4,5*					*2,3,4,5*				

Load Power Services Switch Allocation Table (RC Slices)

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Available Services Per Slice	Allocations									
	Relay/Capacitor Slice 1 (-19)					Relay/Capacitor Slice 2 (-29)				
	Load	MaxI	Size	FM Fuse	EM Fuse	Load	MaxI	Size	FM Fuse	EM Fuse
Unswitched 0	Transponder A (switched in ARC) (0.45A)	0.45 A	1.0 A	2.0 A	1.5 A	Transponder B (switched in ARC)	0.45 A	1.0 A	2.0 A	1.5 A
Unswitched 1	PDU Side A (switched in ARC) (0.43A)	0.43 A	1.0 A	2.0 A	1.5 A	PDU Side B (switched in ARC)	0.43 A	1.0 A	2.0 A	1.5 A
Unswitched 2	REM(SCIF-TAC) B (switched in ARC) (.37A)	0.37 A	1.0 A	2.0 A	1.5 A	SCIF-TAC A (switched in ARC)	0.37 A	1.0 A	2.0 A	1.5 A
Unswitched 3	REM (SBC) A (switched in ARC) (.25A)	0.25 A	0.5 A	1.5 A	3/4 A	REM (SBC) B (switched in ARC)	0.25 A	0.5 A	1.5 A	3/4 A
Unswitched 4	RPM (SBC) C (switched in ARC) (.25A)	0.25 A	0.5 A	1.5 A	3/4 A	Avionics Redundancy Controller C	0.07 A	0.25 A	1.0 A	3/4 A
Unswitched 5	RPM (Avionics Redundancy Controller) A (.07)	0.07 A	0.25 A	1.0 A	3/4 A	Avionics Redundancy Controller B	0.07 A	0.25 A	1.0 A	3/4 A
Internal Unswitched 1	N/A not populated (Reserved)					N/A not populated (Reserved)				
Main Bus Output	FET Switch Slice 1,3,5 Main Power	N/A	N/A	N/A	N/A	FET Switch Slices 2,4,6 Main Power	N/A	N/A	N/A	N/A
Mechanism/MIsc Bus (PP)	Mechanism/Misc Bus A	4.75 AP	5.0 A	10.0 A	7.5 A	Mechanism/Misc Bus B	4.75 A	5.0 A	10.0 A	7.5 A
Propulsion Bus	Propulsion Bus A	4.42 A	5.0 A	10.0 A	7.5 A	Propulsion Bus B	4.42 A	5.0 A	10.0 A	7.5 A
RF Bus	RF Bus A	5.14 A	6.0 A	15.0 A	7.5 A	RF Bus B	5.14 A	6.0 A	15.0 A	7.5 A
Common Relay 1	Safe Mode - Solar Array	N/A	N/A	N/A	N/A	Spare	N/A	N/A	N/A	N/A
Common Relay 2	Safe Mode - Standby	N/A	N/A	N/A	N/A	Spare	N/A	N/A	N/A	N/A
Common Relay 3	Safe Mode - Earth Acquisition	N/A	N/A	N/A	N/A	Spare	N/A	N/A	N/A	N/A

Note: Green fill indicates 2 power/return pins available for this service

Load Power Services Switch Allocation Table (by Subsystem)

Subsystem	Power Service	Service Type	"Service Rating" used to show compliance with 7434-9040, section 4.10; N/A for pulsed services	Maximum Pulse Current; N/A for switched and unswitched services	Nominal Pulse Duration; N/A for switched and unswitched services	Configured Pulse Duration; N/A for switched and unswitched services	Circuit Breaker Setting; Trips within 4-5 ms; N/A if circuit breaker not used	Flight Fuse	I&T Fuse
C&DH	PDU A	Unswitched	1.0 A	N/A	N/A	N/A	N/A	2.0 A	1.5 A
	PDU B	Unswitched	1.0 A	N/A	N/A	N/A	N/A	2.0 A	1.5 A
	REM(SCIF-TAC) A	Unswitched	1.0 A	N/A	N/A	N/A	N/A	2.0 A	1.5 A
	REM(SCIF-TAC) B	Unswitched	1.0 A	N/A	N/A	N/A	N/A	2.0 A	1.5 A
	RPM(SBC) A	Unswitched	0.5 A	N/A	N/A	N/A	N/A	1.5 A	3/4 A
	RPM(SBC) B	Unswitched	0.5 A	N/A	N/A	N/A	N/A	1.5 A	3/4 A
	RPM(SBC) C	Unswitched	0.5 A	N/A	N/A	N/A	N/A	1.5 A	3/4 A
	RPM(ARC) A	Unswitched	0.25 A	N/A	N/A	N/A	N/A	1.0 A	3/4 A
	RPM(ARC) B	Unswitched	0.25 A	N/A	N/A	N/A	N/A	1.0 A	3/4 A
	RPM(ARC) C	Unswitched	0.25 A	N/A	N/A	N/A	N/A	1.0 A	3/4 A
	Transponder A	Unswitched	1.0 A	N/A	N/A	N/A	N/A	2.0 A	1.5 A
	Transponder B	Unswitched	1.0 A	N/A	N/A	N/A	N/A	2.0 A	1.5 A
	TAC A Thruster Bus Group 1	Switched	2.5 A	N/A	N/A	N/A	11.0 A [1]	5.0 A	4.0 A
	TAC A Thruster Bus Group 2	Switched	2.5 A	N/A	N/A	N/A	11.0 A [1]	5.0 A	4.0 A
	TAC B Thruster Bus Group 1	Switched	2.5 A	N/A	N/A	N/A	11.0 A [2]	5.0 A	4.0 A
	TAC B Thruster Bus Group 2	Switched	2.5 A	N/A	N/A	N/A	11.0 A [2]	5.0 A	4.0 A
Cooling Subsystem	Pump Electronics A	Switched	3.0 A	N/A	N/A	N/A	6.6 A	6.0 A	4.0 A
	Pump Electronics B	Switched	3.0 A	N/A	N/A	N/A	6.6 A	6.0 A	4.0 A
	Pump Electronics A Enable A	Switched	0.25 A	N/A	N/A	N/A	2.2 A [3]	1.0 A	3/4 A
	Pump Electronics B Enable A	Switched	0.25 A	N/A	N/A	N/A	2.2 A [3]	1.0 A	3/4 A
	Pump Electronics A Enable B	Switched	0.25 A	N/A	N/A	N/A	2.2 A [4]	1.0 A	3/4 A
	Pump Electronics B Enable B	Switched	0.25 A	N/A	N/A	N/A	2.2 A [4]	1.0 A	3/4 A
	Cooling System Differential Pressure Sensor Power A	Switched	0.25 A	N/A	N/A	N/A	0.55 A	1.0 A	3/4 A
	Cooling System Differential Pressure Sensor Power B	Switched	0.25 A	N/A	N/A	N/A	0.55 A	1.0 A	3/4 A
	Radiator 2&3 Input & Output LVs Open A	Pulsed	N/ A	4.0 A	100 ms	104 ms	8.8 A [5]	7.5 A	5.0 A
	Radiator 2&3 Input & Output LVs Open B	Pulsed	N/ A	4.0 A	100 ms	104 ms	8.8 A [6]	7.5 A	5.0 A
	Accumulator LV Open A	Pulsed	N/ A	2.0 A	100 ms	104 ms	4.4 A [7]	4.0 A	3.0 A
	Accumulator LV Open B	Pulsed	N/ A	2.0 A	100 ms	104 ms	4.4 A [8]	4.0 A	3.0 A

Load Power Services Switch Allocation Table (by Subsystem)

Solar Probe Plus
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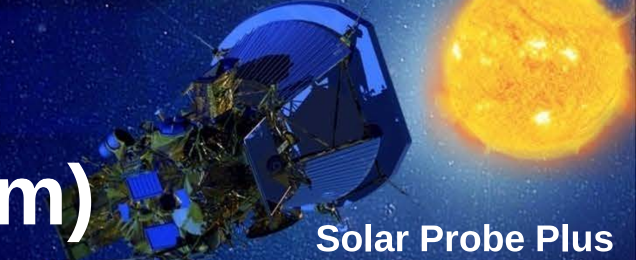
Subsystem	Power Service	Service Type	"Service Rating" used to show compliance with 7434-9040, section 4.10; N/A for pulsed services	Maximum Pulse Current; N/A for switched and unswitched services	Nominal Pulse Duration; N/A for switched and unswitched services	Configured Pulse Duration; N/A for switched and unswitched services	Circuit Breaker Setting; Trips within 4-5 ms; N/A if circuit breaker not used	Flight Fuse	I&T Fuse
G&C	SSIRU CMD #1A (SSIRU_ON_A)	Pulsed	N/ A	0.25 A	100 ms	104 ms	0.55 A [9]	1.0 A	3/4 A
	SSIRU CMD #2A (SSIRU_OFF_A)	Pulsed	N/ A	0.25 A	100 ms	104 ms	0.55 A [9]	1.0 A	3/4 A
	SSIRU CMD #3A (SSIRU_PPSMB_SEL_A)	Pulsed	N/ A	0.25 A	100 ms	104 ms	0.55 A [9]	1.0 A	3/4 A
	SSIRU CMD #4A (SSIRU_AB_OFF)	Pulsed	N/ A	0.25 A	100 ms	104 ms	0.55 A [9]	1.0 A	3/4 A
	SSIRU CMD #5A (SSIRU_AC_OFF)	Pulsed	N/ A	0.25 A	100 ms	104 ms	0.55 A [9]	1.0 A	3/4 A
	SSIRU CMD #6A (SSIRU_RST_A)	Pulsed	N/ A	0.5 A	100 ms	104 ms	1.1 A [10]	1.5 A	3/4 A
	SSIRU CMD #7A (SSIRU_GB_ONPPSMB_A)	Pulsed	N/ A	0.25 A	100 ms	104 ms	0.55 A [11]	1.0 A	3/4 A
	SSIRU CMD #8A (SSIRU_GC_ONPPSMB_A)	Pulsed	N/ A	0.25 A	100 ms	104 ms	0.55 A [11]	1.0 A	3/4 A
	SSIRU CMD #1B (SSIRU_ON_B)	Pulsed	N/ A	0.25 A	100 ms	104 ms	0.55 A [13]	1.0 A	3/4 A
	SSIRU CMD #2B (SSIRU_OFF_B)	Pulsed	N/ A	0.25 A	100 ms	104 ms	0.55 A [13]	1.0 A	3/4 A
	SSIRU CMD #3B (SSIRU_PPSMB_SEL_B)	Pulsed	N/ A	0.25 A	100 ms	104 ms	0.55 A [13]	1.0 A	3/4 A
	SSIRU CMD #4B (SSIRU_AA_OFF_B)	Pulsed	N/ A	0.25 A	100 ms	104 ms	0.55 A [13]	1.0 A	3/4 A
	SSIRU CMD #5B(SSIRU_AD_OFF_B)	Pulsed	N/ A	0.25 A	100 ms	104 ms	0.55 A [13]	1.0 A	3/4 A
	SSIRU CMD #6B (SSIRU_RST_B)	Pulsed	N/ A	0.5 A	100 ms	104 ms	1.1 A [14]	1.5 A	3/4 A
	SSIRU CMD #7B (SSIRU_GA_ONPPSMB_B)	Pulsed	N/ A	0.25 A	100 ms	104 ms	0.55 A [15]	1.0 A	3/4 A
	SSIRU CMD #8B (SSIRU_GD_ONPPSMB_B)	Pulsed	N/ A	0.25 A	100 ms	104 ms	0.55 A [15]	1.0 A	3/4 A
	SIRU A	Switched	2.0 A	N/A	N/A	N/A	4.4 A	4.0 A	3.0 A
	SIRU B	Switched	2.0 A	N/A	N/A	N/A	4.4 A	4.0 A	3.0 A
	SLS Electronics A	Switched	0.25 A	N/A	N/A	N/A	0.55 A	1.0 A	3/4 A
	SLS Electronics B	Switched	0.25 A	N/A	N/A	N/A	0.55 A	1.0 A	3/4 A
	Star Tracker A	Switched	0.5 A	N/A	N/A	N/A	1.1 A	1.5 A	3/4 A
	Star Tracker B	Switched	0.5 A	N/A	N/A	N/A	1.1 A	1.5 A	3/4 A
	Wheels A	Switched	3.5 A	N/A	N/A	N/A	7.7 A	7.5 A	5.0 A
	Wheels B	Switched	3.5 A	N/A	N/A	N/A	7.7 A	7.5 A	5.0 A
	Wheels C	Switched	3.5 A	N/A	N/A	N/A	8.8 A [12]	7.5 A	5.0 A
	Wheels D	Switched	3.5 A	N/A	N/A	N/A	8.8 A [16]	7.5 A	5.0 A
	Wheel A Relay Control On	Pulsed	N/ A	0.25 A	45 ms	45 ms	0.55 A [11]	1.0 A	3/4 A
	Wheel A Relay Control Off	Pulsed	N/ A	0.25 A	45 ms	45 ms	0.55 A [11]	1.0 A	3/4 A
	Wheel B Relay Control On	Pulsed	N/ A	0.25 A	45 ms	45 ms	0.55 A [15]	1.0 A	3/4 A
	Wheel B Relay Control Off	Pulsed	N/ A	0.25 A	45 ms	45 ms	0.55 A [15]	1.0 A	3/4 A
	Wheel C Relay Control On	Pulsed	N/ A	0.25 A	45 ms	45 ms	0.55 A [17]	1.0 A	3/4 A
	Wheel C Relay Control Off	Pulsed	N/ A	0.25 A	45 ms	45 ms	0.55 A [17]	1.0 A	3/4 A
	Wheel D Relay Control On	Pulsed	N/ A	0.25 A	45 ms	45 ms	0.55 A [18]	1.0 A	3/4 A
	Wheel D Relay Control Off	Pulsed	N/ A	0.25 A	45 ms	45 ms	0.55 A [18]	1.0 A	3/4 A

Load Power Services Switch Allocation Table (by Subsystem)



Solar Probe Plus
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Subsystem	Power Service	Service Type	"Service Rating" used to show compliance with 7434-9040, section 4.10; N/A for pulsed services	Maximum Pulse Current; N/A for switched and unswitched services	Nominal Pulse Duration; N/A for switched and unswitched services	Configured Pulse Duration; N/A for switched and unswitched services	Circuit Breaker Setting; Trips within 4-5 ms; N/A if circuit breaker not used	Flight Fuse	I&T Fuse
Mechanical	+Y/-Y Solar Array Boom Launch Lock Frangibolt A	Pulsed	N/ A	3.0 A	1.0 s	1.0 s	6.6 A [19]	6.0 A	4.0 A
	+Y/-Y Solar Array Boom Launch Lock Frangibolt B	Pulsed	N/ A	3.0 A	1.0 s	1.0 s	6.6A [20]	6.0 A	4.0 A
	+Y Solar Array Platen Launch Lock Frangibolts A	Pulsed	N/ A	3.0 A	1.0 s	1.0 s	6.6 A [21]	6.0 A	4.0 A
	+Y Solar Array Platen Launch Lock Frangibolts B	Pulsed	N/ A	3.0 A	1.0 s	1.0 s	6.6 A [22]	6.0 A	4.0 A
	-Y Solar Array Platen Launch Lock Frangibolts A	Pulsed	N/ A	3.0 A	1.0 s	1.0 s	6.6 A [21]	6.0 A	4.0 A
	-Y Solar Array Platen Launch Lock Frangibolts B	Pulsed	N/ A	3.0 A	1.0 s	1.0 s	6.6 A [22]	6.0 A	4.0 A
	HGA Launch Lock A Frangibolt	Pulsed	N/ A	2.0 A	1.0 s	1.0 s	6.6 A [21]	4.0 A	3.0 A
	HGA Launch Lock B Frangibolt	Pulsed	N/ A	2.0 A	1.0 s	1.0 s	6.6 A [22]	4.0 A	3.0 A
	Mag Boom Launch Locks 1A	Pulsed	N/ A	2.0 A	1.0 s	1.0 s	4.4 A [7]	4.0 A	3.0 A
	Mag Boom Launch Locks 1B	Pulsed	N/ A	2.0 A	1.0 s	1.0 s	4.4 A [8]	4.0 A	3.0 A
	Mag Boom Launch Locks 2A	Pulsed	N/ A	2.0 A	1.0 s	1.0 s	6.6 A [23]	4.0 A	3.0 A
	Mag Boom Launch Locks 2B	Pulsed	N/ A	2.0 A	1.0 s	1.0 s	6.6 A [24]	4.0 A	3.0 A
	ECU A Power	Switched	0.25 A	N/A	N/A	N/A	2.2 A [3]	1.0 A	3/4 A
	ECU B Power	Switched	0.25 A	N/A	N/A	N/A	2.2 A [4]	1.0 A	3/4 A
Elec Power Subsystem	PSE - CMD/TLM IF A	Switched	1.0 A	N/A	N/A	N/A	2.2 A	2.0 A	1.5 A
	PSE - CMD/TLM IF B	Switched	1.0 A	N/A	N/A	N/A	2.2 A	2.0 A	1.5 A

APL

Load Power Services Switch Allocation Table (by Subsystem)

Solar Probe Plus
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Subsystem	Power Service	Service Type	"Service Rating" used to show compliance with 7434-9040, section 4.10; N/A for pulsed services	Maximum Pulse Current; N/A for switched and unswitched services	Nominal Pulse Duration; N/A for switched and unswitched services	Configured Pulse Duration; N/A for switched and unswitched services	Circuit Breaker Setting; Trips within 4-5 ms; N/A if circuit breaker not used	Flight Fuse	I&T Fuse
Propulsion	Propulsion LVA Open	Pulsed	N/ A	1.0 A	100 ms	104 ms	6.6 A [21]	2.0 A	1.5 A
	Propulsion LVB Open	Pulsed	N/ A	1.0 A	100 ms	104 ms	6.6 A [22]	2.0 A	1.5 A
	Propulsion LV A&B Close	Pulsed	N/ A	2.0 AN	100 ms	104 ms	4.4 A	6.0 A	3.0 A
	Propulsion Tank Heaters A	Switched	2.0 A	N/A	N/A	N/A	4.4 A	4.0 A	3.0 A
	Propulsion Tank Heaters B	Switched	2.0 A	N/A	N/A	N/A	4.4 A	4.0 A	3.0 A
	Propulsion Line and Valve Heaters A	Switched	2.5 A	N/A	N/A	N/A	5.5A	5.0 A	4.0 A
	Propulsion Line and Valve Heaters B	Switched	2.5 A	N/A	N/A	N/A	5.5A	5.0 A	4.0 A
	A Group Thruster CB Heaters A	Switched	0.5 A	N/A	N/A	N/A	7.7 A [25]	1.5 A	3/4 A
	B Group Thruster CB Heaters A	Switched	0.5 A	N/A	N/A	N/A	7.7 A [25]	1.5 A	3/4 A
	C Group Thruster CB Heaters A	Switched	0.5 A	N/A	N/A	N/A	7.7 A [25]	1.5 A	3/4 A
	A Group Thruster CB Heaters B	Switched	0.5 A	N/A	N/A	N/A	7.7 A [26]	1.5 A	3/4 A
	B Group Thruster CB Heaters B	Switched	0.5 A	N/A	N/A	N/A	7.7 A [26]	1.5 A	3/4 A
	C Group Thruster CB Heaters B	Switched	0.5 A	N/A	N/A	N/A	7.7 A [26]	1.5 A	3/4 A
	Pressure Transducer A Power	Switched	0.25 A	N/A	N/A	N/A	0.55 A	1.0 A	3/4 A
	Pressure Transducer B Power	Switched	0.25 A	N/A	N/A	N/A	0.55 A	1.0 A	3/4 A
RF	Ka-Band TWTA A	Switched	4.0 A	N/A	N/A	N/A	8.8 A [27]	7.5 A	5.0 A
	Ka-Band TWTA B	Switched	4.0 A	N/A	N/A	N/A	8.8 A [28]	7.5 A	5.0 A
	RF Switch 1 Position A	Pulsed	N/ A	0.25 A	100 ms	104 ms	0.55 A	1.0 A	3/4 A
	RF Switch 1 Position B	Pulsed	N/ A	0.25 A	100 ms	104 ms	0.55 A	1.0 A	3/4 A
	RF Switch 2 Position A	Pulsed	N/ A	0.25 A	100 ms	104 ms	0.55 A	1.0 A	3/4 A
	RF Switch 2 Position B	Pulsed	N/ A	0.25 A	100 ms	104 ms	0.55 A	1.0 A	3/4 A
	RF Switch 3 Position A	Pulsed	N/ A	0.25 A	100 ms	104 ms	0.55 A	1.0 A	3/4 A
	RF Switch 3 Position B	Pulsed	N/ A	0.25 A	100 ms	104 ms	0.55 A	1.0 A	3/4 A
	RF Switch 4 Position A	Pulsed	N/ A	0.25 A	100 ms	104 ms	0.55 A	1.0 A	3/4 A
	RF Switch 4 Position B	Pulsed	N/ A	0.25 A	100 ms	104 ms	0.55 A	1.0 A	3/4 A
	X-Band TWTA A	Switched	2.0 A	N/A	N/A	N/A	8.8 A [27]	4.0 A	3.0 A
	X-Band TWTA B	Switched	2.0 A	N/A	N/A	N/A	8.8 A [28]	4.0 A	3.0 A

Load Power Services Switch Allocation Table (by Subsystem)

Subsystem	Power Service	Service Type	"Service Rating" used to show compliance with 7434-9040, section 4.10; N/A for pulsed services	Maximum Pulse Current; N/A for switched and unswitched services	Nominal Pulse Duration; N/A for switched and unswitched services	Configured Pulse Duration; N/A for switched and unswitched services	Circuit Breaker Setting; Trips within 4-5 ms; N/A if circuit breaker not used	Flight Fuse	I&T Fuse
Thermal	CSPR Manifold 1&4 Warm-up Heaters A	Switched	2.0 A	N/A	N/A	N/A	4.4 A	4.0 A	3.0 A
	CSPR Manifold 1&4 Warm-up Heaters B	Switched	2.0 A	N/A	N/A	N/A	7.7 A [26]	4.0 A	3.0 A
	CSPR Manifold 2&3 Warm-up Heaters A & Top Deck Line Htrs	Switched	2.5 A	N/A	N/A	N/A	5.5A	5.0 A	4.0 A
	CSPR Manifold 2&3 Warm-up Heaters B & Top Deck Line Htrs	Switched	2.5 A	N/A	N/A	N/A	7.7 A [25]	5.0 A	4.0 A
	S/C Internal Panel Survival Heaters A	Switched	3.0 A	N/A	N/A	N/A	6.6 A	6.0 A	4.0 A
	S/C Internal Panel Survival Heaters B	Switched	3.0 A	N/A	N/A	N/A	6.6 A	6.0 A	4.0 A
	Cooling System Flex Line Heaters A	Switched	1.0 A	N/A	N/A	N/A	2.2 A	2.0 A	1.5 A
	Cooling System Flex Line Heaters B	Switched	1.0 A	N/A	N/A	N/A	2.2 A	2.0 A	1.5 A
	Actuator Heater A	Switched	1.0 A	N/A	N/A	N/A	2.2 A	2.0 A	1.5 A
	Actuator Heater B	Switched	1.0 A	N/A	N/A	N/A	2.2 A	2.0 A	1.5 A
	Battery Heater A	Switched	0.5 A	N/A	N/A	N/A	1.1 A	1.5 A	3/4 A
	Battery Heater B	Switched	0.5 A	N/A	N/A	N/A	1.1 A	1.5 A	3/4 A

Load Power Services Switch Allocation Table (by Subsystem)

Solar Probe Plus
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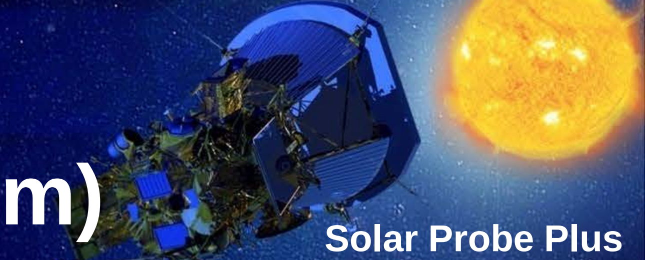
Suite	Power Service	Service Type	"Service Rating" used to show compliance with 7434-9040, section 4.10; N/A for pulsed services	Maximum Pulse Current; N/A for switched and unswitched services	Maximum Pulse Duration; N/A for switched and unswitched services	Configured Pulse Duration; N/A for switched and unswitched services	Circuit Breaker Setting; Trips within 4-5 ms; N/A if circuit breaker not used	Flight Fuse	I&T Fuse
Instruments									
EPI-Hi	EPI-Hi Main Power (LVPS and OP Htr)	Switched	0.5 AN	N/A	N/A	N/A	1.1 A	2.0 A	3/4 A
	EPI-Hi Operational Heater	Switched	0.25 AN	N/A	N/A	N/A	0.55 A	2.0 A	3/4 A
	EPI-Hi Survival and Warm-up Heater	Switched	0.5 AN	N/A	N/A	N/A	1.1 A	2.0 A	3/4 A
EPI-LO	EPI-Lo Operational Power	Switched	0.5 AN	N/A	N/A	N/A	1.1 A	2.0 A	3/4 A
	EPI-Lo Survival, Warm-up and LP Op Heater	Switched	0.5 AN	N/A	N/A	N/A	1.1 A	2.0 A	3/4 A
FIIELDS1	FIELDS1 Operational Power	Switched	1.0 AN	N/A	N/A	N/A	2.2 A	3.0 A	1.5 A
	FIELDS1 Operationaland Survival Heater	Switched	0.5 AN	N/A	N/A	N/A	1.1 A	2.0 A	3/4 A
	FIELDS-1 Mech Pre-deployment Warm-up Heaters	Switched	0.25 AN	N/A	N/A	N/A	0.55 A	2.0 A	3/4 A
FIIELDS2	FIELDS2 Operational Power	Switched	1.0 AN	N/A	N/A	N/A	2.2 A	3.0 A	1.5 A
	FIELDS2 Operationaland Survival Heater	Switched	0.5 AN	N/A	N/A	N/A	1.1 A	2.0 A	3/4 A
	WISPR & FIELDS-2 Mech Pre-deployment Warm-up Heaters	Switched	0.25 AN	N/A	N/A	N/A	0.55 A	2.0 A	3/4 A
FIIELDS	FIELDS Antenna Deploy Whip Cage 1-2A	Pulsed	N/A	3.0 A	1.0 s	1.0 s	6.6 A [23]	6.0 A	4.0 A
	FIELDS Antenna Deploy Whip Cage 3-4A	Pulsed	N/A	3.0 A	1.0 s	1.0 s	6.6 A [23]	6.0 A	4.0 A
	FIELDS Antenna Deploy Whip Cage 1-2B	Pulsed	N/A	3.0 A	1.0 s	1.0 s	6.6 A [24]	6.0 A	4.0 A
	FIELDS Antenna Deploy Whip Cage 3-4B	Pulsed	N/A	3.0 A	1.0 s	1.0 s	6.6 A [24]	6.0 A	4.0 A
	FIELDS Antenna Deploy Hinge 1A	Pulsed	N/A	2.0 A	1.0 s	1.0 s	6.6 A [29]	4.0 A	3.0 A
	FIELDS Antenna Deploy Hinge 2A	Pulsed	N/A	2.0 A	1.0 s	1.0 s	6.6 A [29]	4.0 A	3.0 A
	FIELDS Antenna Deploy Hinge 3&4A	Pulsed	N/A	3.0 A	1.0 s	1.0 s	6.6 A [29]	6.0 A	4.0 A
	FIELDS Antenna Deploy Hinge 1B	Pulsed	N/A	2.0 A	1.0 s	1.0 s	6.6 A [30]	4.0 A	3.0 A
	FIELDS Antenna Deploy Hinge 2B	Pulsed	N/A	2.0 A	1.0 s	1.0 s	6.6 A [30]	4.0 A	3.0 A
	FIELDS Antenna Deploy Hinge 3&4B	Pulsed	N/A	3.0 A	1.0 s	1.0 s	6.6 A [30]	6.0 A	4.0 A
SWEAP	SWEAP Operational Power	Switched	1.0 AN	N/A	N/A	N/A	2.2 A	3.0 A	1.5 A
	SPAN A&B Survival Survival Heater	Switched	1.0 AN	N/A	N/A	N/A	2.2 A	3.0 A	1.5 A
	SPC & WISPR Survival Heater	Switched	1.0 AN	N/A	N/A	N/A	2.2 A	3.0 A	1.5 A
WISPR	WISPR Main Power	Switched	1.0 AN	N/A	N/A	N/A	2.2 A	3.0 A	1.5 A
	WISPR Door Deploy Power A	Pulsed	N/A	4.0 A	40 ms	40 ms	8.8 A [5]	7.5 A	5.0 A
	WISPR Door Deploy Power B	Pulsed	N/A	4.0 A	40 ms	40 ms	8.8 A [6]	7.5 A	5.0 A
	WISPR Operational Heaters	Switched	0.25 AN	N/A	N/A	N/A	0.55 A	2.0 A	3/4 A

Load Power Services Switch Allocation Table (by Subsystem)



Spares

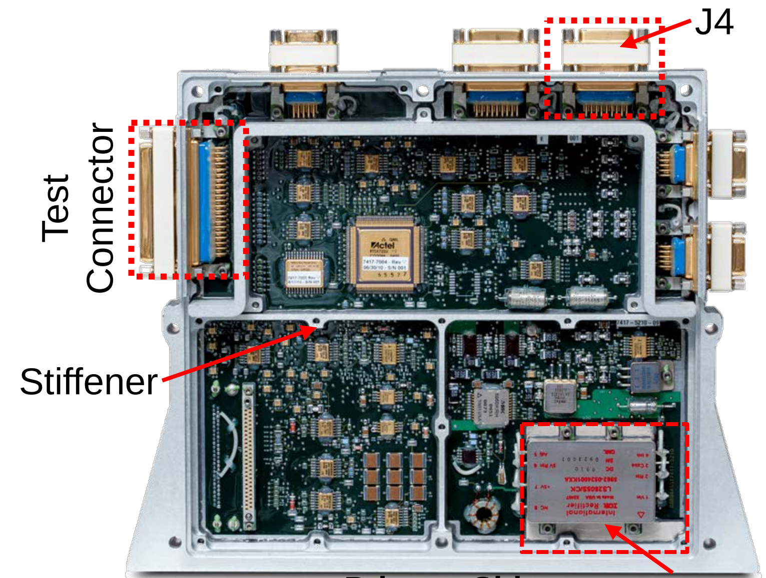
	Power Service	Service Type	"Service Rating" used to show compliance with 7434-9040, section 4.10; N/A for pulsed services	Maximum Pulse Current; N/A for switched and unswitched services	Maximum Pulse Duration; N/A for switched and unswitched services	Configured Pulse Duration; N/A for switched and unswitched services	Circuit Breaker Setting; Trips within 4-5 ms; N/A if circuit breaker not used	Flight Fuse	I&T Fuse
Spares	Switched 1.0 AN Spare (Main Bus)	Switched	1.0 AN	N/A	N/A	N/A	2.2 A	3.0 A	1.5 A
	Switched 1.0 AN Spare (Main Bus)	Switched	1.0 AN	N/A	N/A	N/A	2.2 A	3.0 A	1.5 A
	Switched 1.0 AN Spare (Main Bus)	Switched	1.0 AN	N/A	N/A	N/A	2.2 A	3.0 A	1.5 A
	Switched 1.0 AN Spare (Main Bus)	Switched	1.0 AN	N/A	N/A	N/A	2.2 A	3.0 A	1.5 A
	Switched 1.0 A Spare (Main Bus)	Switched	1.0 A	N/A	N/A	N/A	2.2 A	2.0 A	1.5 A
	3.0 A Pulsed Spare (Mechanism/Misc A)	Pulsed	N/A	3.0 A	N/A	104 ms	6.6A [19]	6.0 A	4.0 A
	3.0 A Pulsed Spare (Mechanism/Misc A)	Pulsed	N/A	3.0 A	N/A	104 ms	6.6 A [23]	6.0 A	4.0 A
	3.0 A Pulsed Spare (Mechanism/Misc B)	Pulsed	N/A	3.0 A	N/A	104 ms	6.6A [20]	6.0 A	4.0 A
	3.0 A Pulsed Spare (Mechanism/Misc B)	Pulsed	N/A	3.0 A	N/A	104 ms	6.6 A [24]	6.0 A	4.0 A
	Switched 0.5 A Spare (Main Bus)	Switched	0.5 A	N/A	N/A	N/A	8.8 A [12]	1.5 A	3/4 A
	Switched 0.5 A Spare (Main Bus)	Switched	0.5 A	N/A	N/A	N/A	8.8 A [16]	1.5 A	3/4 A
	Switched 2.0 A Spare (Main Bus)	Switched	2.0 A	N/A	N/A	N/A	4.4 A	4.0 A	3.0 A
	Switched 2.0 A Spare (Main Bus)	Switched	2.0 A	N/A	N/A	N/A	4.4 A	4.0 A	3.0 A
	Switched 2.0 A Spare (Main Bus)	Switched	2.0 A	N/A	N/A	N/A	4.4 A	4.0 A	3.0 A
	Switched 2.0 A Spare (Main Bus)	Switched	2.0 A	N/A	N/A	N/A	4.4 A	4.0 A	3.0 A
	Switched 2.0 A Spare (Main Bus)	Switched	2.0 A	N/A	N/A	N/A	4.4 A	4.0 A	3.0 A
	Switched 2.0 A Spare (Main Bus)	Switched	2.0 A	N/A	N/A	N/A	4.4 A	4.0 A	3.0 A

Notes:
[1, 2, 3, 4, 5, 6……30] Services with the same number share a common circuit breaker, trip will occur when total current exceeds the given threshold

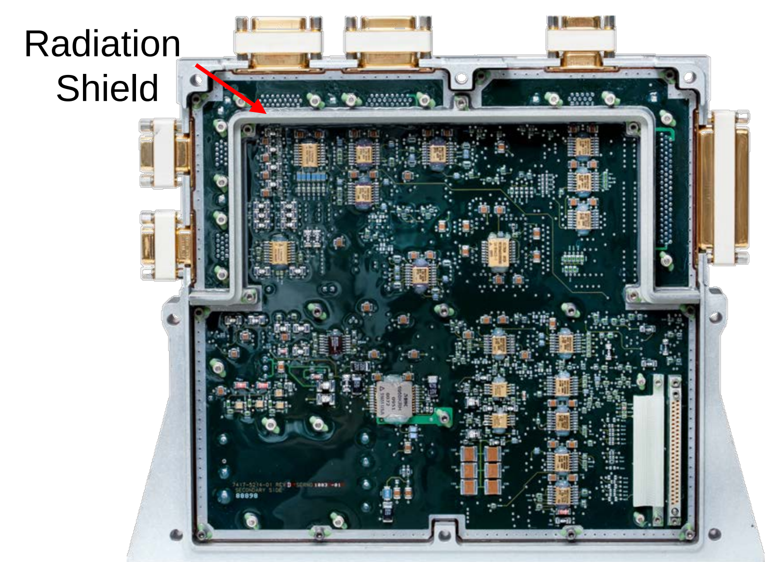
C/T (Command/Telemetry) Slice

- Does not need a fuse Module, instead test connector installed
- Utilizes center stiffener for additional board support
- Integrated heatsink in PWB design
- Changes from RBSP
  - Uniform 0.060” chassis thickness
  - Radiation shields removed from primary and secondary sides
  - Test connector will have small cover, not empty fuse housing
  - J4 connector not utilized, frame cut-out to be removed
  - Heatsink changed from Cu to Al-6061 (saves mass)
  - Swap out 5150-91XX connector assemblies with ITT Cannon 1-piece connectors

RBSP C/T Slice Flight Build

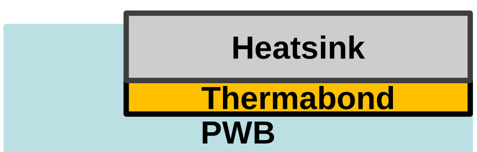


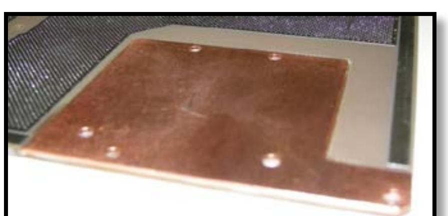
Primary Side



Secondary Side

C/T Slice Heatsink Detail

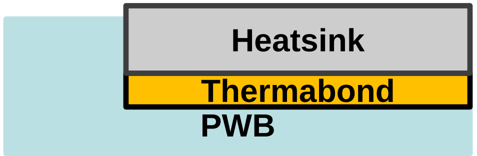


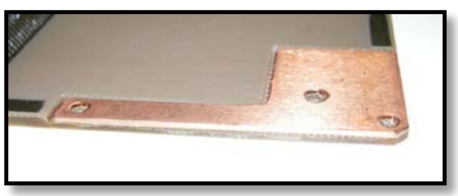


R/C (Relay/Capacitor) Slice

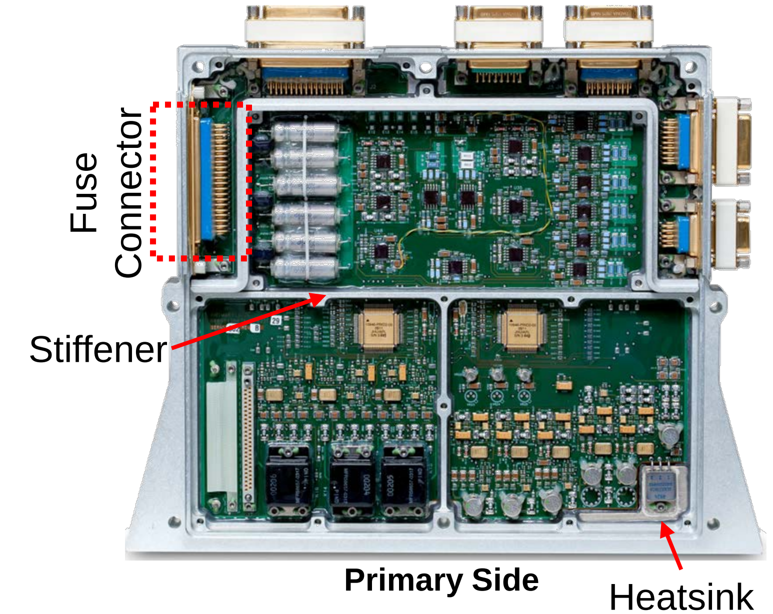
- Fuse module mounts to upper left corner
- Utilizes center stiffener for additional board support
- Integrated heatsink in PWB design
- Changes from RBSP
  - Uniform 0.060” chassis thickness
  - Radiation shields removed from primary and secondary sides
  - Heatsink changed from Cu to Al-6061 (saves mass)
  - B-side parts installed
  - Swap out 5150-91XX connector assemblies with ITT Cannon 1-piece connectors (where applicable)

R/C Slice Heatsink Detail

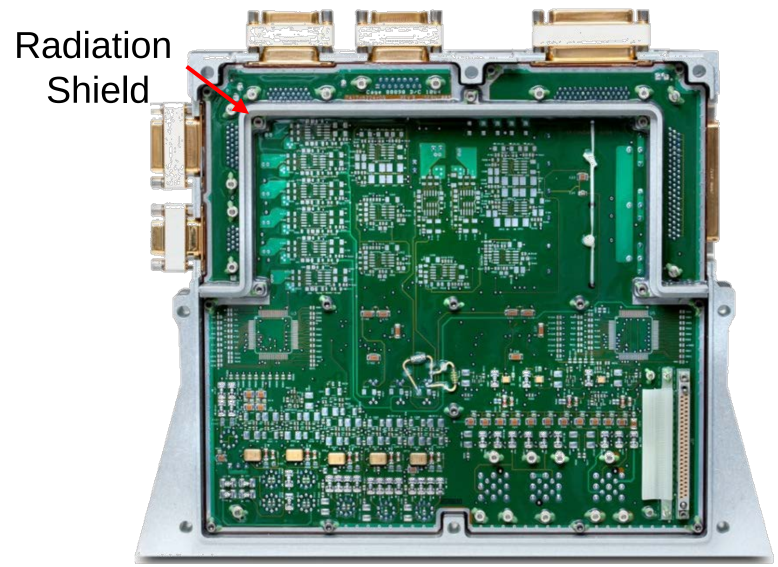




RBSP R/C Slice Flight Build



Primary Side

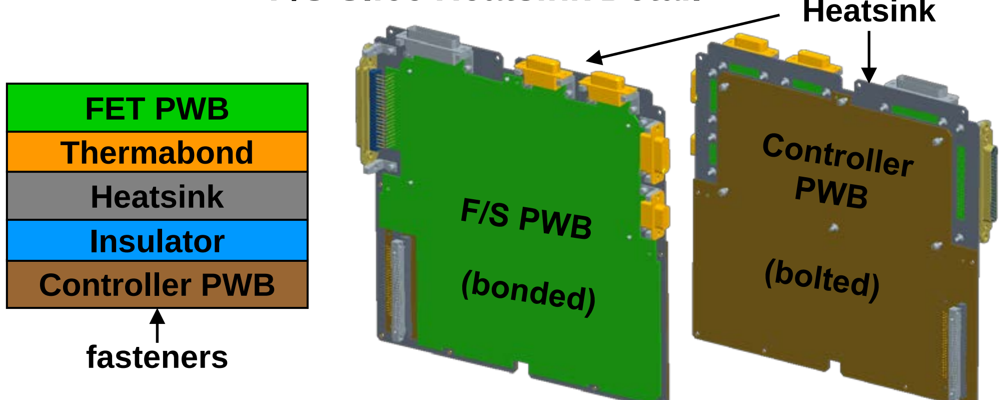


Secondary Side

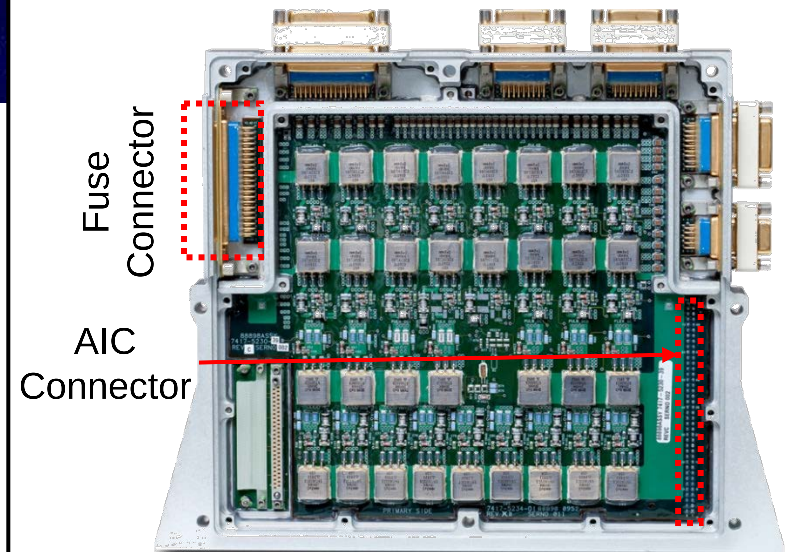
F/S (FET/Switching) Slice

- FET PWB bonded to heatsink, Controller PWB bolted to heatsink backside
- FET & Controller talk via AIC pin & socket connector
- Fuse module mounts to chassis upper left corner
- Changes from RBSP
  - Uniform 0.060” chassis thickness
  - Radiation shields removed from primary and secondary sides
  - Heatsink changed from Al-6061 to AlBeMet (saves mass, increases stiffness)
  - B-side parts installed
  - Propulsion and Cooling System diode circuitry added
  - Swap out 5150-91XX connector assemblies with ITT Cannon 1-piece connectors (where applicable)

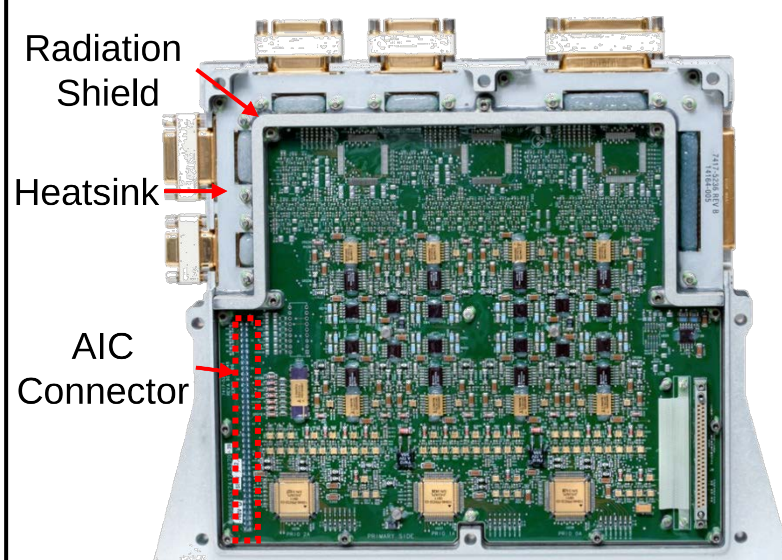
F/S Slice Heatsink Detail



RBSP F/S Slice Flight Build



Primary Side (FET)

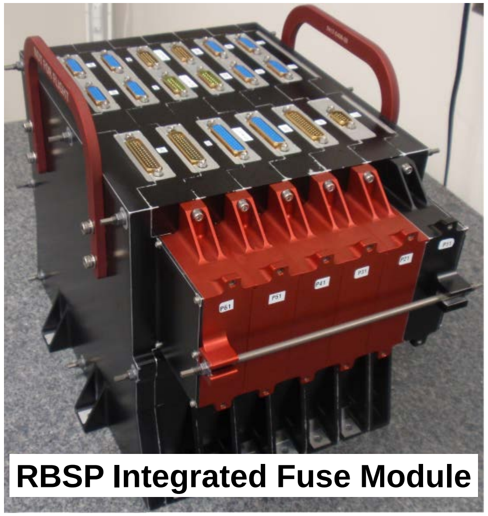


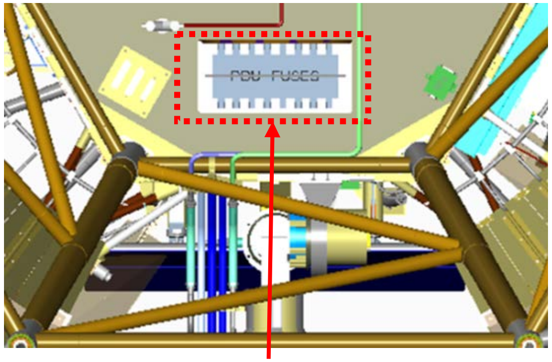
Secondary Side (Controller)

Fuse Modules

- Fuse modules mount to R/C and F/S slice frames in upper left corner
- Fuse module assembly installed after all slices and covers are mated.
- Guide pins on Fuse modules
  - Aids installation of flight fuses on integrated box
  - Necessitates specific Positronics connector on mating connector (R/C & F/S slices)
- PDU uses separate set of fuses for ground testing
- Changes from RBSP
  - Uniform 0.060" chassis thickness
  - Total of eight (8) fuses on box

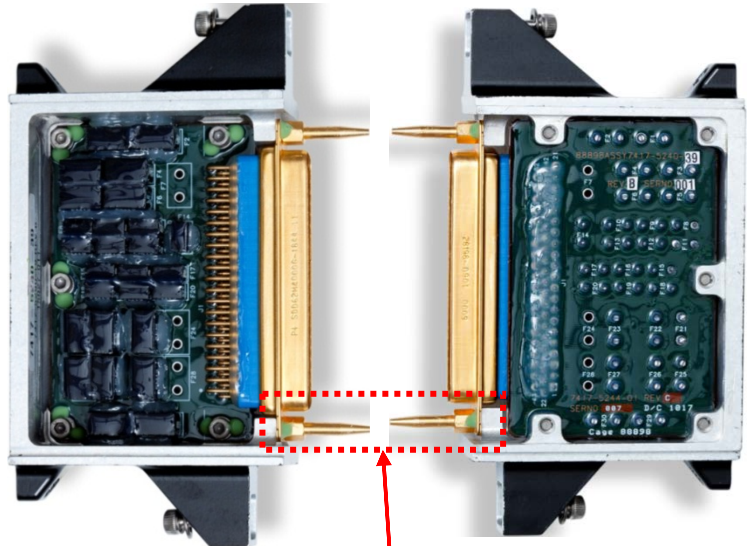
Fuse Module Assembly Detail


RBSP Integrated Fuse Module



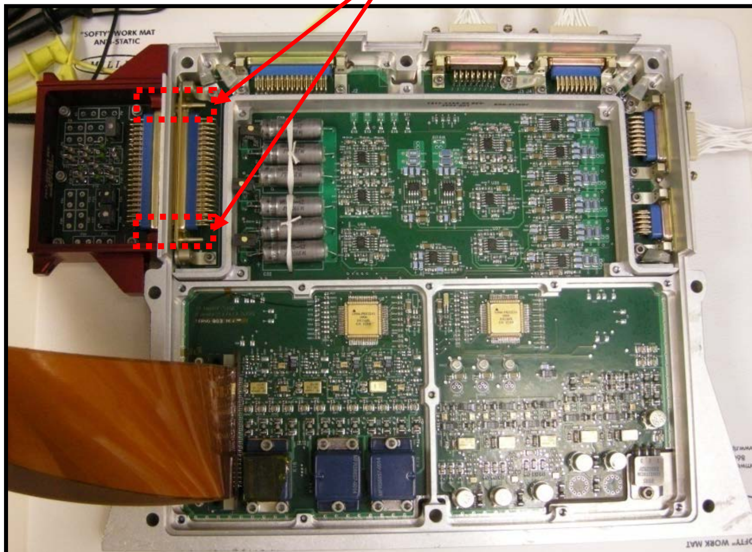
Fuse Module Assembly may need to be integrated at Cape. Done thru peephole.

RBSP Fuse Module Flight Build


Primary Side

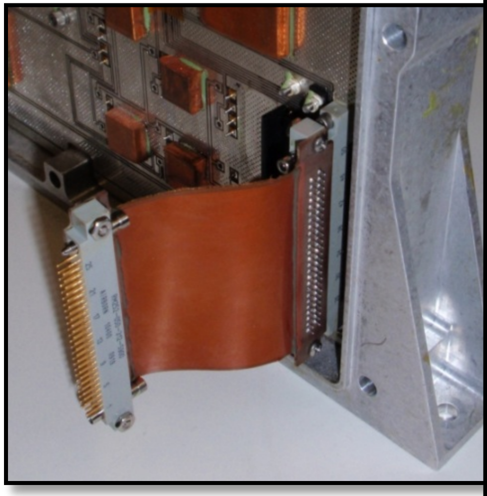
Guide Pins

Secondary Side

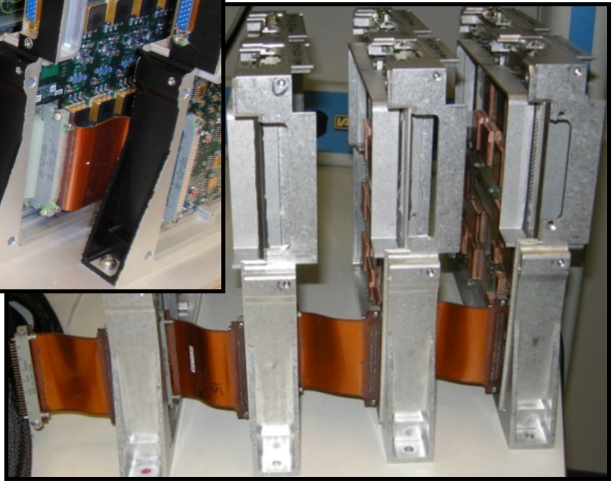


Rigid-Flex Internal Inter-slice Connection

- **Slice-to-slice interconnection with rigid-flex connectors**
- **Eliminates need for backplane type assembly**
- **Flex design is simple to fabricate for flexibility and cost saving**
- **Uses AirBorn connectors – COTS**
- **Flown on RBSP PDU**



Connector bolted and soldered to flex

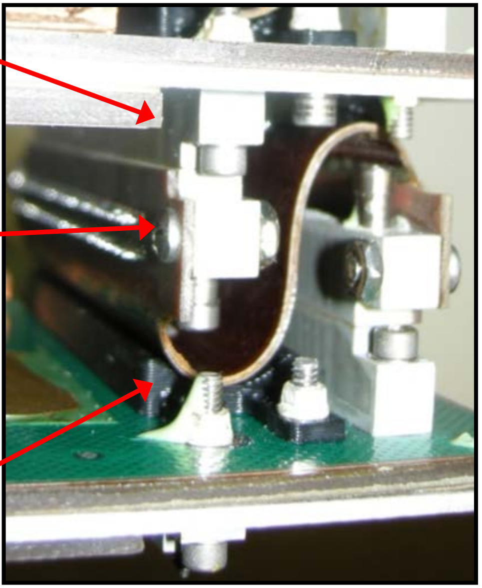


Detail of slice-to-slice connection. Installation fixture used to hold slices.

Board connector

Flex connector

Pin cover and flex holder



Flex in the closed position, frame removed

Power Distribution Unit (PDU)

PDU EGSE Status

- **EGSE Status:**
  - Hardware Design
    - Update Load Panels for New Service Size Loads (Resistive/Inductive Loads)
    - Update GSE FPGA to make compatible with New ITF format, 5Hz Command/Telemetry UART Timing
    - Add special testing capability to test Redundant Back EMF circuit and Blocking diodes
    - Convert RBSP Single Box Tester to SPP Redundant Box Tester, integrate 2 RBSP box testers into 1 SPP Box tester
  - Scripts Conversion (Epoch to L3 In Control/NG)
    - Completed Script Conversions
  - MOC Workstation
    - Received, three L3 In-Control Systems for Slice Testing, L3 System for Box Testing is due in January 2014

Power Distribution Unit (PDU)

PDU Testing: Box and Slice BB Testing/Results

- **BB (Bread Board) Slice Testing**
  - RC Slice – 1 RBSP FM RC Slice Downgraded to EM
    - Populated B-Side parts, B side Testing completed.
      - Test Results: Verified B-side functionality, 1 issue seen with current Monitor readings on B-side, higher readings traced to current sense resistor PWA layout. Change sense point from internal power common return plane to current sense resistor on primary side.
  - CT Slice – 2 CT BB will be Fabbed by 1/2014
    - Used to Test out New SPP FPGA Mods
  - FET Slice – 1 FET and 1 FET controller BB slices will be Fabbed by 2/2014
    - Populate both A/B-Side parts and Test (RBSP only tested A side)
    - Test out New Redundant Back EMF and Blocking diode functions (Propulsion Diode Box (PDB) Trade Decision)
- **BB Box Testing**
  - Only Partial BB PDU box available for Testing with above BB Slices
    - Test out PDU Box Redundancy
- **EM (Engineering Model) Testing**
  - No SPP PDU EM planned,
  - Documented as Project Risk (SPP-74)-No PDU EM Backup in case of FM PDU Rework during SC I&T.

Power Distribution Unit (PDU)

RBSP PDU vs. SPP PDU

- **Summary of Functional Differences between SPP PDU and RBSP PDU**

PDU Function	RBSP PDU	SPP PDU	SPP PDU Notes
Low-Voltage Sense Circuitry (including pre-settable LVS levels)	Yes	No	For SPP, LVS is part of EPS
Low Battery State of Charge	Yes	No	For SPP, LBSoC is part of EPS
Off-Pulsing Circuitry			
• PDU Off-Pulsing	Yes	No	For SPP, PDU is redundant. PDU A/B switched by ARC.
• XCVR Off-Pulsing	Yes	No	For SPP, Transponders A/B switched by ARC.
• IEM Off-Pulsing	Yes	No	For SPP, Avionics is redundant. REM and RPM/SBC switched by ARC.
Fusing of All Loads	No	Yes	For SPP, a redundant load services configuration allows for the fusing of all loads
No of Switched/Pulse Services	75	150	RBSP uses 3 FET Slices vs. SPP uses 6 FET Slices
Redundant Control of Power Services	No	Yes	SPP PDU configuration allows for A- and B-side control of PDU power services.
Command/Telemetry Rate	1 Hz	5Hz	For TLM Request, RBSP used Discrete 1PPS signal, SPP uses Telemetry Request Command

Solar Probe Plus

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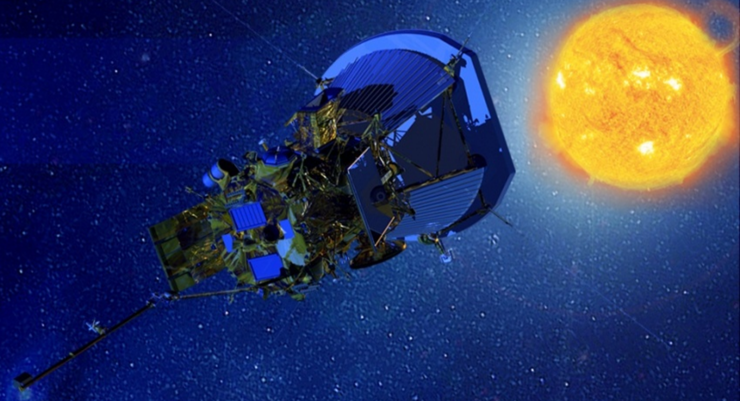

Telecomm Subsystem

Dave Copeland
Lead Telecomm Engineer

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13 – 16 January 2014

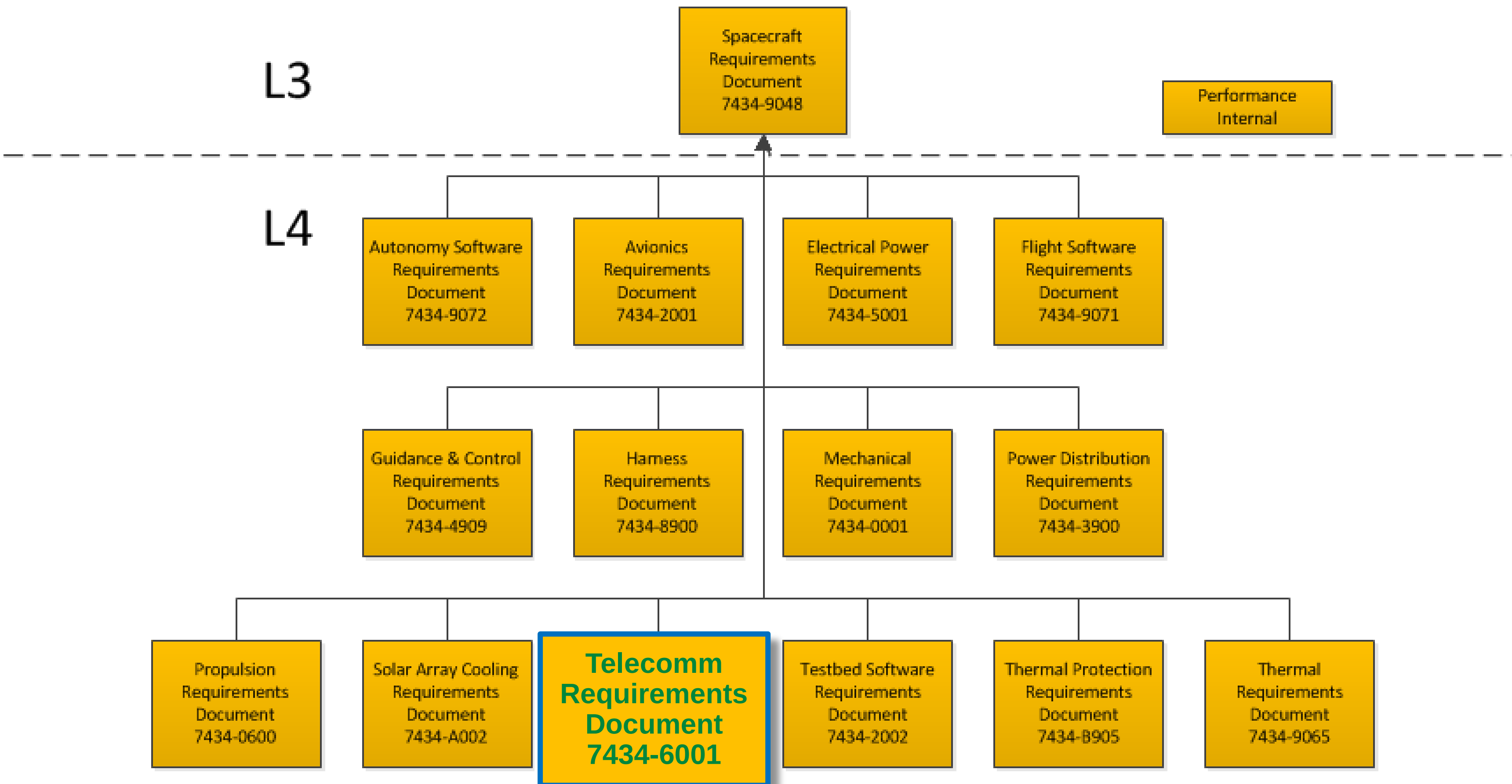
The Johns Hopkins University
APPLIED PHYSICS LABORATORY

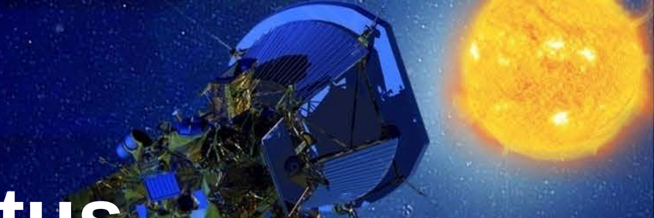
Agenda

- Driving Subsystem Requirements and Verification
- Subsystem Design Description
- Link Analysis Results
- Phase B Trades
- Phase B Development
- Summary of Phase C Plans
- Conclusions

Subsystem Requirements Status: Relationship to Mission

Consistent with 7434-9098, Requirements Document Tree

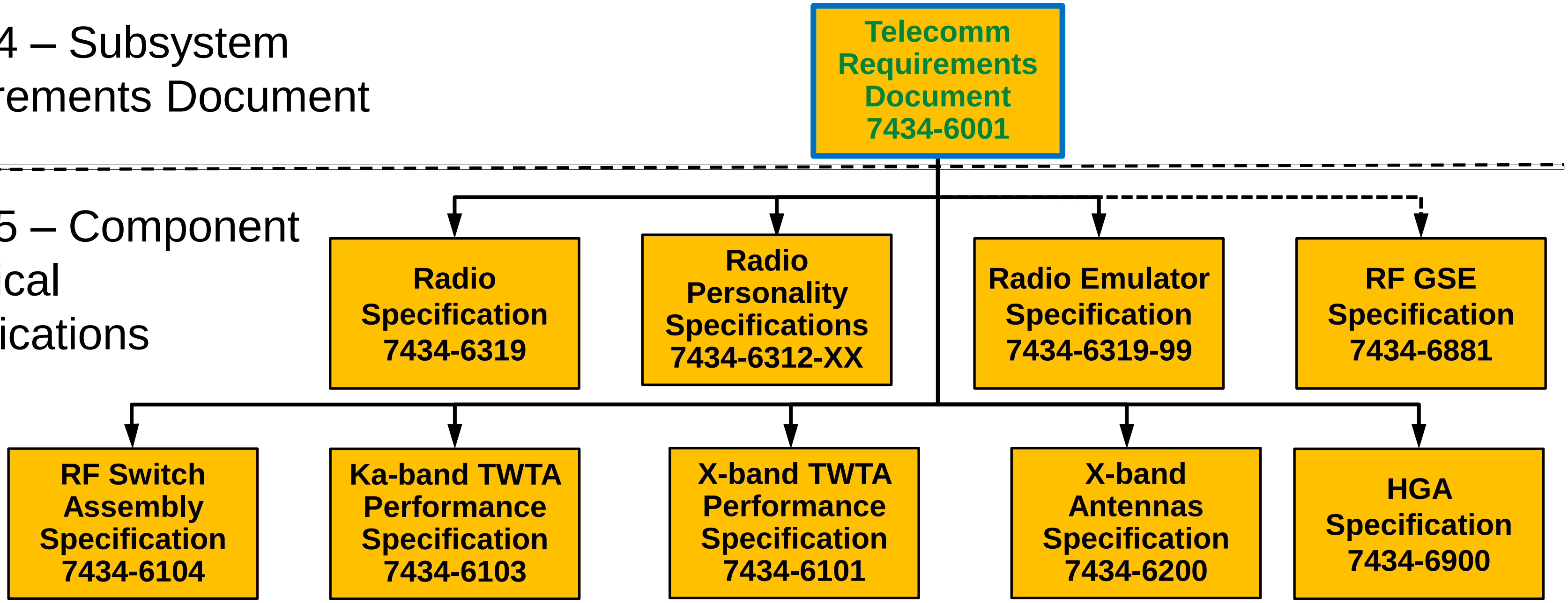




Subsystem Requirements Status

Level 4 – Subsystem Requirements Document

Level 5 – Component Technical Specifications



- Subsystem Requirements Review held 7/18/2013
- Subsystem Technical Requirements Document Released
- Component Technical Specifications in Draft

Telecomm Subsystem Driving Requirements

- **The telecomm subsystem shall:**
  - **Perform X-band uplink and downlink, Ka-band downlink**
  - **Support X-band downlink of ≥ 10 bps for housekeeping, 3 times/week***
  - **Downlink (at Ka-band) an average of 127 Gbits of data per orbit, within 2 orbits of collection***
  - **Provide downlink indication that the spacecraft is alive 3 times/ week during solar encounter***
  - **Provide 2-way Doppler 3 times/week***
  - **Support ranging***
  - **Transmit Δ-DOR tones***
  - **Provide monitoring during critical events**
  - **Support emergency communications of 7.8125 bps uplink and 10 bps downlink***
  - **Provide communications during instrument and spacecraft commissioning events**
  - **Stay within the nominal packaging umbra**
  - **Have a mass not to exceed 28.22 kg**
  - **Consume power not to exceed:**
    - **X-band downlink/ X-band uplink: 51.9W max**
    - **X-band uplink only: 12.65W max**
    - **Ka-band downlink/ X-band uplink: 101.8W max**

**** Coverage subject to link constraints***

Telecomm Subsystem Driving Requirements - Constraints

- Solar scintillation limits communication based on SEP
  - X-band – SEP > 3°
  - Ka-band (downlink) – SEP > 1°
- Thermal Protection System (TPS) blocks communications when the Earth is within 14.2 degrees of +z
- Operation within solar encounter limited to Sun Range > 20 Rs

- Ka-band and X-band not used simultaneously (power limitation)

- Ka-band operation limited by Sun Range and SPE, due to power and HGA range of motion:
  - 0.28 AU < Sun Range < 0.70 AU, 45 deg < SPE < 135 deg
  - 0.70 AU < Sun Range < 0.76 AU, SPE < 135 deg

- X-band Ranging coverage limited by X-band downlink EIRP
  - Phase B trade study on ranging baselined tone-based ranging
  - Coverage analyzed by navigation team: meet orbit determination requirements with reduced ranging coverage

Link Availability Over Mission

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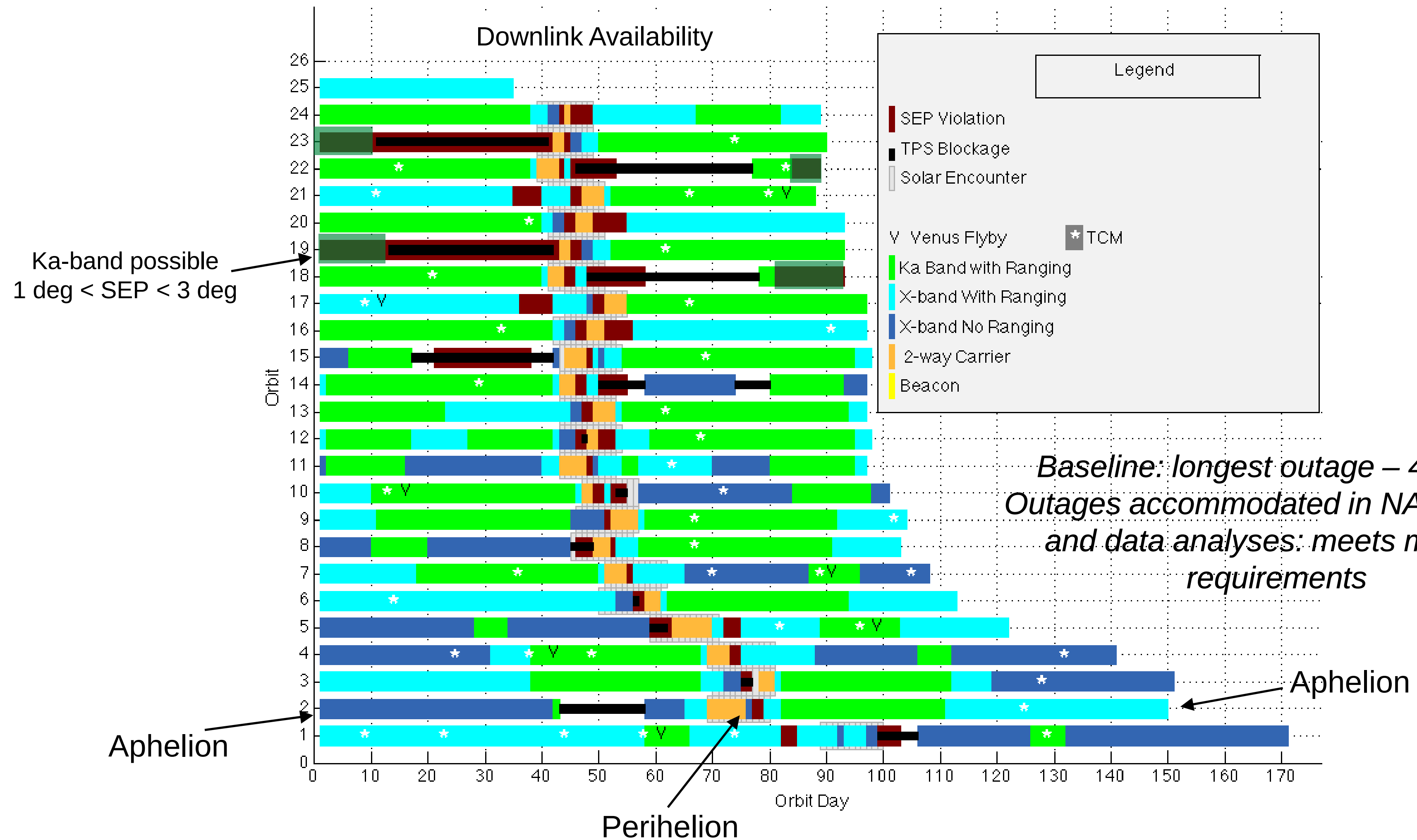

Baseline: longest outage – 40 days
Outages accommodated in NAV studies and data analyses: meets mission requirements

APL

Driving Requirements – Verification

- **Driving Requirements will be verified through Analysis and Test**
  - **Subsystem-level RF Compatibility testing with the DSN CTT**
  - **Link Analysis Tool**
  - **Link Availability**
  - **Ka-band Capacity**
  - **Notional pass scheduling and latency calculation**
- **Verification through Test at the component level (Level 5)**
  - **Comprehensive Performance Test (CPT)**
  - **Component-level compatibility testing (DTF-21)**
  - **Antenna range testing, mockup testing (extended through analysis)**
  - **Verification as per EDTRD, EMECP**

Verification matrix available in document 7434-6001

Telecomm Subsystem Block Diagram

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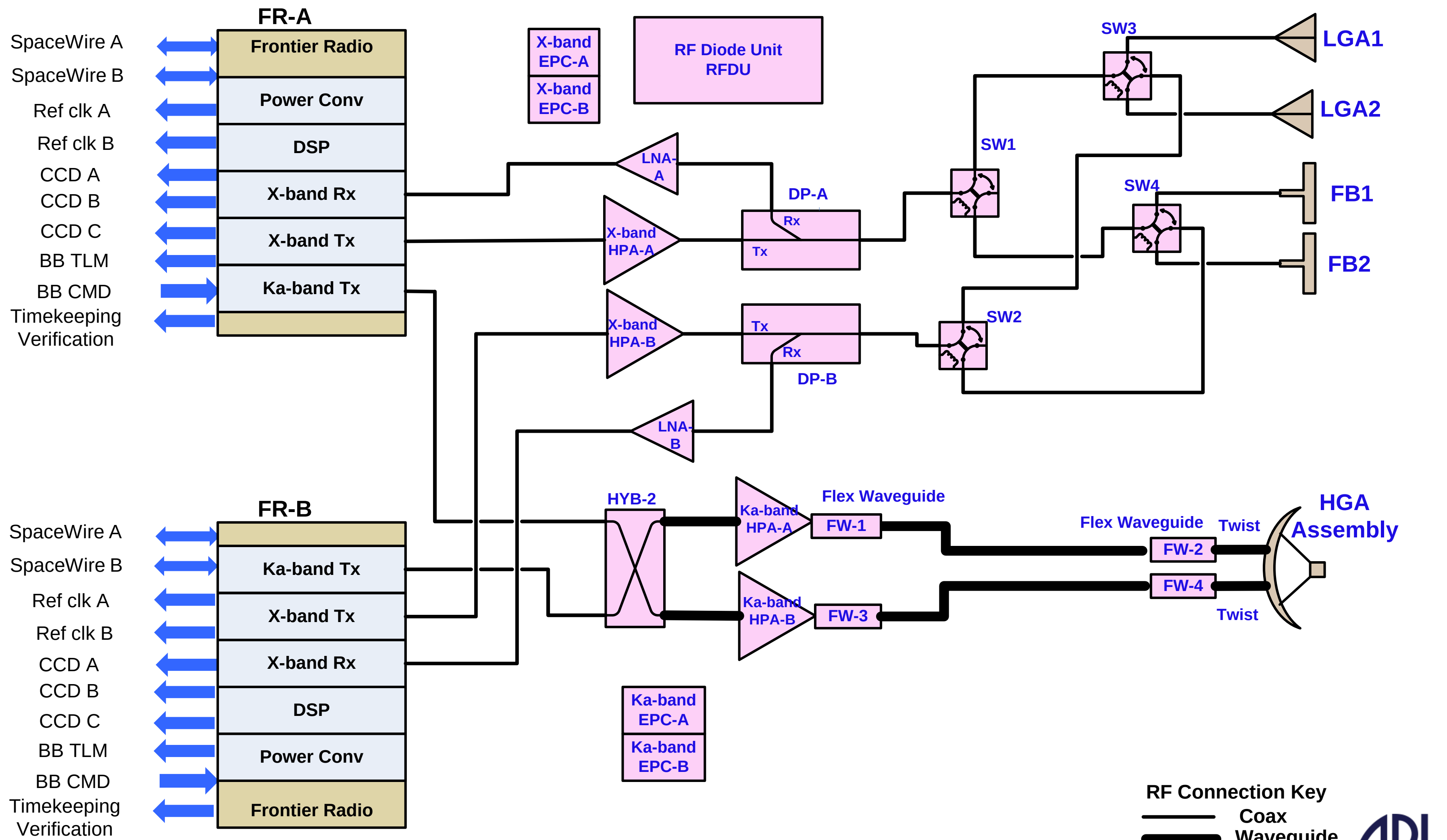
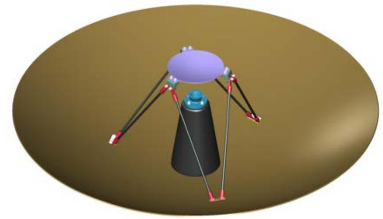
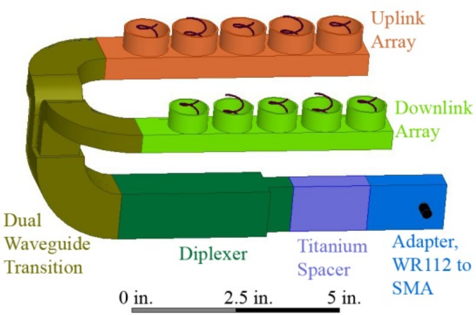
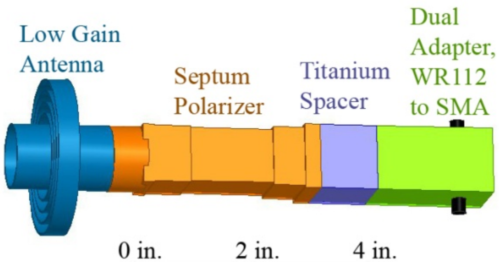


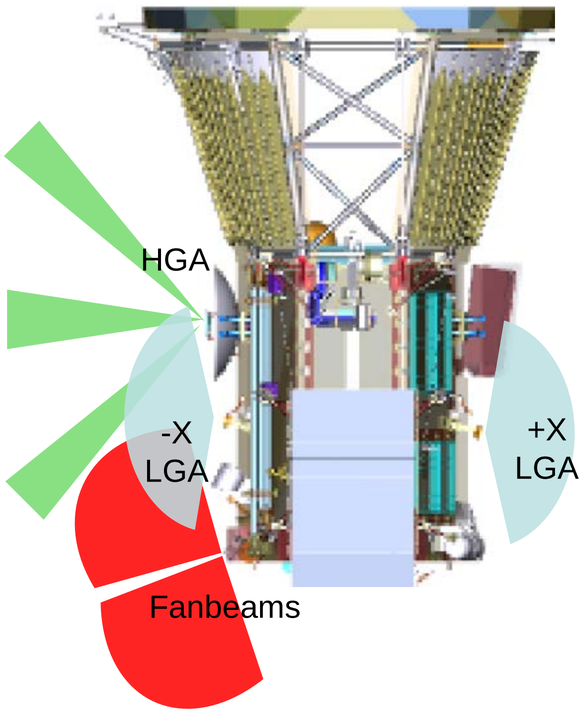
Antenna Complement

- **HGA**
  - **0.6m composite reflector**
  - **1-axis gimbal covers –X +/- 45°**
  - **Antenna size and coverage limited by the need to stay within the umbra**
- **Fanbeams**
  - **Based on MESSENGER design: waveguide-fed helix array**
  - **Cover the –x/z half-plane**
  - **Tilted down, away from TPS by 15° deg – extend coverage behind spacecraft**
- **LGAs**
  - **Circular waveguide design used on MESSENGER, New Horizons, STEREO**
  - **2 LGAs provide near-omni coverage**









Major Components

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Component	Phase B Development
Transponder - APL Frontier Radio	Breadboard Radio developed: • Capture component changes • Test new functionality
X-band TWTA (11W)	Technical specifications developed Competitive Bid conducted
Ka-band TWTA (34W)	
Diplexers, Switches, LNAs	Technical specifications developed, Vendor quotes solicited
High-Gain Antenna	Design developed, Competitive bid conducted for composite vendors, Study work on effects of paint at Ka-band, and build-to-print vs Build-to-spec trade (both studies ongoing)
Fanbeams	Design developed Vendors identified for key parts Flight Antennas will be fabricated and tested in-house
LGAs	LGA Mockup constructed and tested Flight Antennas will be fabricated and tested in-house

Mass Estimate

Description	Qty / Length	CBE Each (kg)	CBE Total (kg)
High Gain Antenna Assembly	1	6.19	6.19
Fanbeam Antenna Assembly	2	0.65	1.30
LGA	2	0.37	0.74
11W X-band TWTA	2	2.66	5.32
34W Ka-band TWTA	2	2.56	5.12
Switch Plate/Diode Unit/Switches	1	0.94	0.94
Low Noise Amplifiers (external)	2	0.01	0.02
X-band Diplexer	2	0.15	0.30
Ka-band 90 deg Hybrid	1	0.15	0.15
Waveguide/Coax	N/A	2.05	2.05
Radio	2	2.01	4.02
TOTAL:			**26.15 kg**

Mass NTE = 28.22 kg
Margin = 2.07 kg (7.3%)

APL

Power Consumption

Mode	Major Components		CBE Power	NTE	Margin
X-band receive only	Radio A in X-band receive: Radio B in X-band receive:	5.5 W 5.5 W	11 W	12.65 W	1.65 W (13%)
X-band receive, X-band transmit	Radio A X-band receive: Radio B X-band receive/transmit: X-band TWTA:	5.5 W 9.5 W 33 W	48W	51.9 W	3.9 W (7.5%)
X-band receive, Ka-band transmit	Radio A X-band receive: Radio B X-band receive/ Ka-band transmit: Ka-band TWTA:	5.5 W 9.5 W 80 W	95.5 W	101.8 W	6.3 W (6.2%)

Link Design: Changes Since MDR

- Implemented results of Phase B studies
  - 9.86 Rs mission design
  - Stepped data rates for Ka-band link
  - Tone ranging (vs PN regenerative ranging)
  - TWTA output power adjustment
- Extra 5 degrees spacecraft rotation applied to period preceding Venus #4 flyby
  - Eliminates a TPS obstruction before V4
  - Spacecraft stays within the umbra
- Changes to link assumptions (in accordance with DSN discussions)
  - DSS-54 baseline for X-band (instead of DSS-24).
  - Tighter loop bandwidths (reduced Turbo losses.
  - Shifted Aberration Loss to favor the Downlink.
- Included effect of Hot body (Sun and Venus) noise on uplink and downlink
- Included Solar Scintillation in 2-Way carrier SNR.

X-band Link Analysis Results Summary

Service	Requirement	Performance
Command Uplink (X-band)	• **≥ 7.8125 bps @ 6 dB margin** • 3 times/wk in cruise phase • Subject to link constraints	• 13.3 dB worst-case margin at 7.8125 bps • Rates available from 7.8125 bps to 2000 bps • Typical operation: 125 bps, 500 bps
Telemetry Downlink (X-band)	• **≥ 10 bps @ 3 dB margin** • 3 times / wk in cruise phase • Subject to link constraints	• 3.4 dB worse case margin at 10 bps (Orbit 14, range=1.6 AU, grazing the TPS) • Rates available from 10 bps to 1 kbps (up to 100 kbps during LEOP)
Solar Encounter Coverage (Beacon)	• ≥ 3 times/wk in solar encounter • Subject to link constraints	• Meets 3 times/wk req't at > 3 dB margin • Worse case is 2 days in Orbit 10 (1 dB margin)

Emergency Operation	• 7.8125 bps uplink
	• 10 bps downlink
	• 70 m equivalent EIRP and G/T
		• Fanbeam is baseline for Emergency acquisition
		• If an LGA is needed at max range (1.9 AU):
		  • Tlm available to ± 30º off boresight
		  • Cmd available to ± 60º off boresight

Critical Events	• Provide monitoring during event
	• Worst-case range: TCM before V1
		• Supports TCM coverage on LGAs to Day 60
		  • CW Carrier to ± 79º off boresight
		  • 10 bps Tlm to ± 62º off boresight

Link analysis results available in backup slides

Ka-band Link Analysis

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- **Developed probabilistic Ka-band link analysis tool**
- **Based on MRO Ka-band experiment techniques**

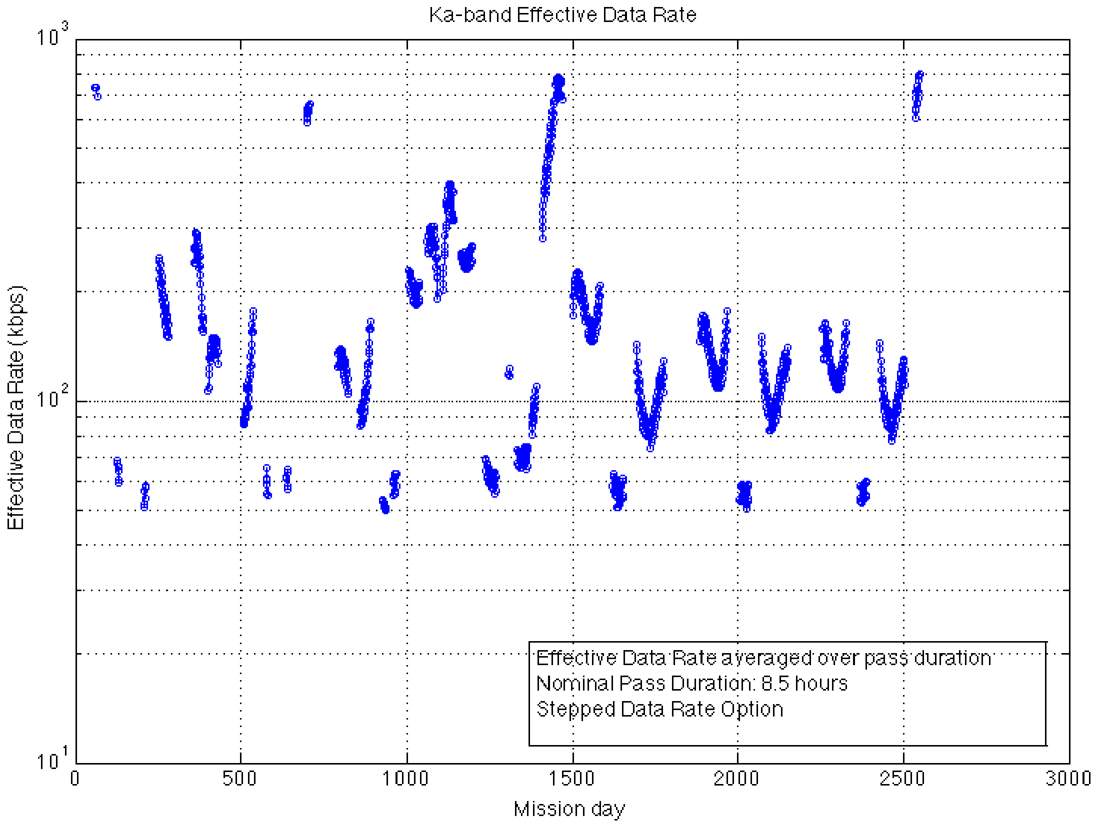
- **Optimizes *Effective Data Rate***

$$R_{eff} = \frac{1}{T} \int_T R \cdot A \, dt$$

  - ***R – data rate setpoint***
  - ***A – link availability at rate R***

- ***Trade study analyzed different methods of choosing data rate setpoint R***

- ***Outcome: use simple rate-stepping scheme similar to MESSENGER and New Horizons***



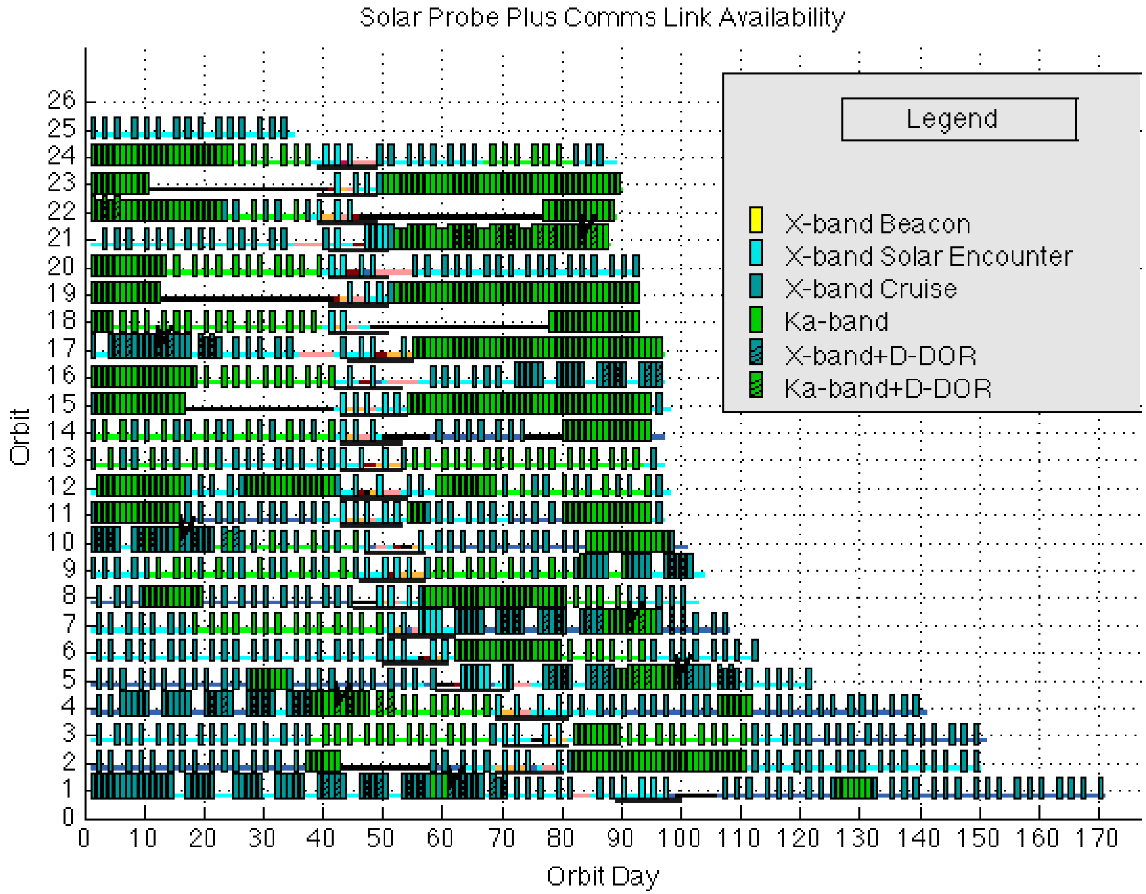
Ka-band Link Analysis: Notional Pass Schedule

- **Developed notional pass schedule including navigation and flyby requirements**
- **Populated science downlinks as needed**

- ***Demonstrates sufficient capacity to meet 127 Gb downlink requirement***

- ***All orbits meet latency requirement (downlink within 2 orbits of collection)***

- ***Worst-case latency occurs on Orbit 10: meets requirement by 20 days***



Communications at low SEP angle

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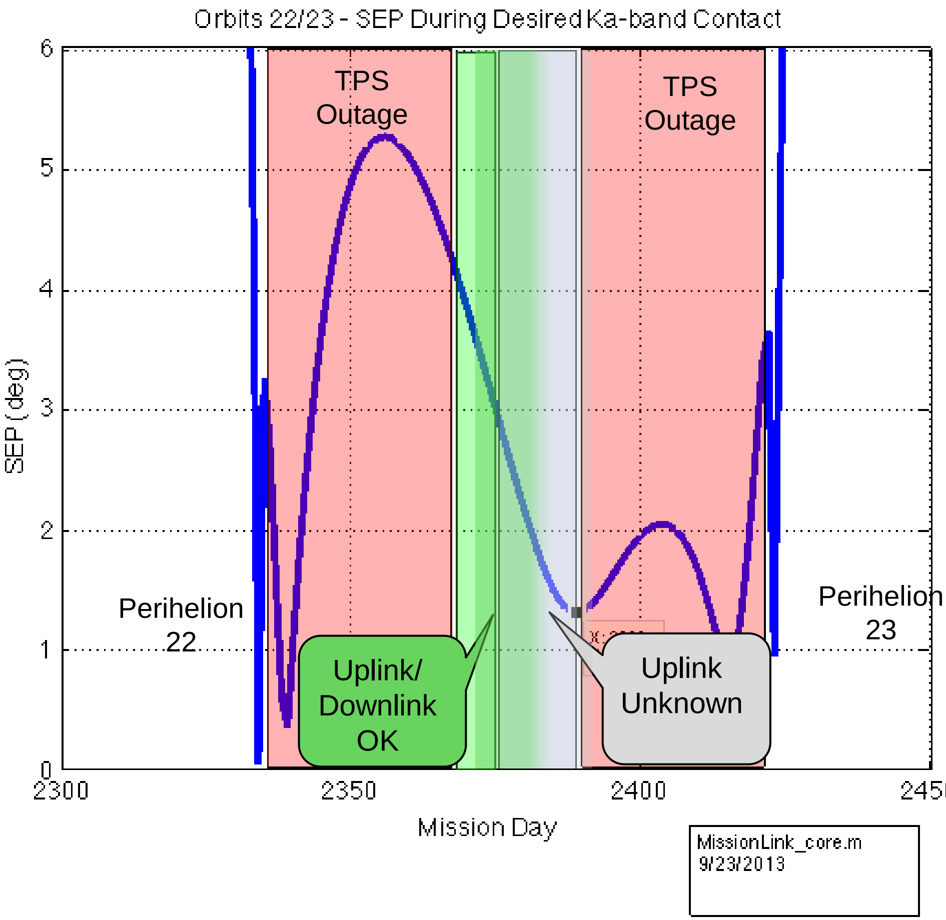
- **Aphelion between orbits 22 and 23:**
  - **Already outages due to TPS orientation for Sun Range ≤ 0.7 AU (accounted for in analyses)**
  - **Low SEP angle when S/C attitude is unconstrained by TPS orientation (Sun Range > 0.7 AU).**
  - **Performance of X-band link unknown for active sun when 1° < SEP < 3°**
- **Similar problem in orbits 18-19**



- **MESSENGER has demonstrated two-way X-band communications in this regime**
  - **SPP working with MESSENGER personnel to quantify performance**
  - **Tracked as Risk SPP-81**

Major Phase B Studies

Trade	Description	Outcome
Ka-band Link Approach	Evaluate options for setting the Ka-band data rate. Trade complexity and DSN costs.	Simple data rate switching algorithm, optimizing effective data rate over an interval of a pass.
Ranging Method	Regenerative ranging vs sequential tone ranging. Trade development cost and risk vs radiometric coverage	Sequential tone ranging. Reduced coverage did not significantly impact orbit determination.
TWTA Power	TWTA vendors unable to meet RF output power and DC power simultaneously	DC Power spec unchanged. RF output power lowered by ~0.3 dB
TWTA Power Feed/ Interface Control	Evaluate options for TWTA interface control. Trade complexity vs mass. Mass dominated by PDU services required	Lowest mass approach: Control TWTAs solely through switching the 28V bus power
X-band PA Technology	TWTA vs GaN SSPA. Trade technology development risk and cost vs mass	TWTA. Mass savings did not offset increased development effort to advance GaN amp to TRL-6.
Radio Power & TWTA input interface	Evaluate options for powering the Frontier radios, the impact to fault tolerance, and the interface from the radios to the TWTAs. Consider mass, presence of plausible failure mechanisms disabling a downlink	• Power radios through ARC switched services. • Remove X-band hybrid (eases input power budget for TWTAs) • Keep Ka-band hybrid (provides fault isolation between radios and ground station)

Engineering Development: Frontier Radio

- **Frontier Radio functional highlights**
  - **Dual-band operation**
  - **Low mass: 2011 g**
  - **Low power: 5.5 W Rx only, 10W X-band Rx, Ka-band Tx**
  - **Rate 1/6 Turbo encoding**
- **Phase B Breadboard work:**
  - **Resolved EEE parts obsolescence and achieved 41% reduction in PEMs/COTs device types over prior design.**
  - **Addressed increased radiation tolerance requirement while lowering mass. Required replacement of several EEE parts.**
  - **Completed multiple TID, heavy ion, and proton tests of new devices. Several low risk SEU/SET tests are pending and to be completed in Phase B. Recent emphasis on understanding proton environment and SEU rate for radio.**
  - **Revised packaging to reduce mass (Mg alloy), improve EMI and thermal performance, and improve structural dynamics for CCGA FPGA.**
  - **Transitioned to required external LNA design for uplink receiver.**
  - **Transitioned Ka-band vector modulator die to new semiconductor process and evaluated.**
  - **Incorporating common SpaceWire core**
- **Process Development: Finished Qualification of 1272 pin CCGA package for 4M gate FPGA**

Ka-Band Exciter MCM

Ka-Band Exciter

X-Band Receiver w/Ovenized Oscillator

Engineering Development LGA Mockup Testing

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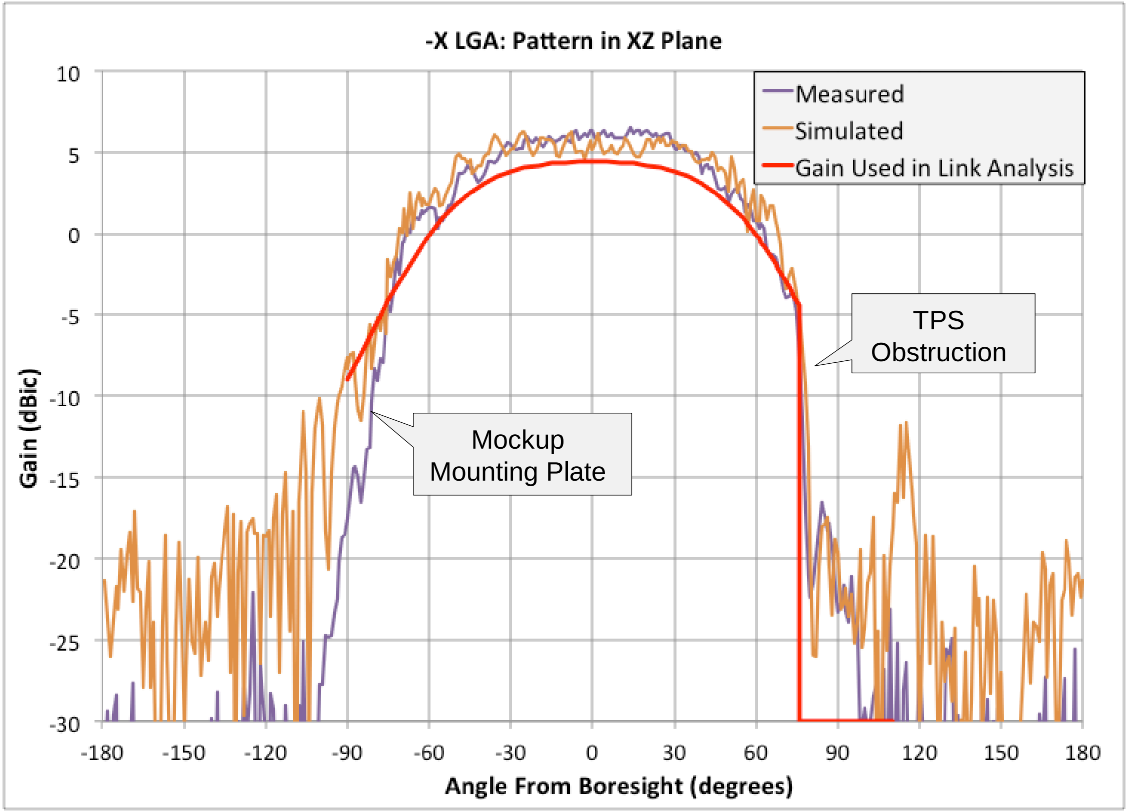
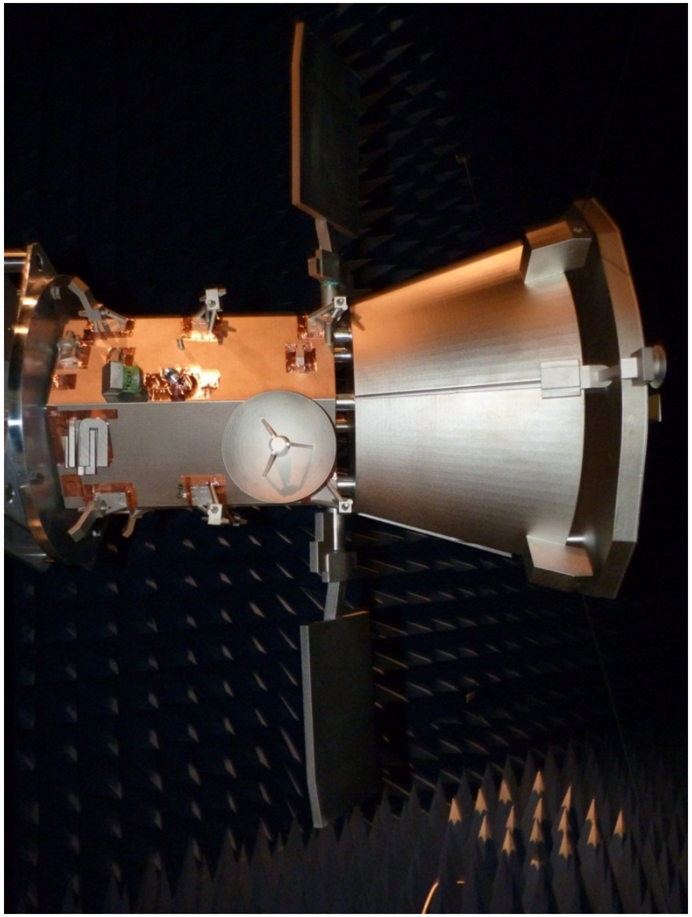
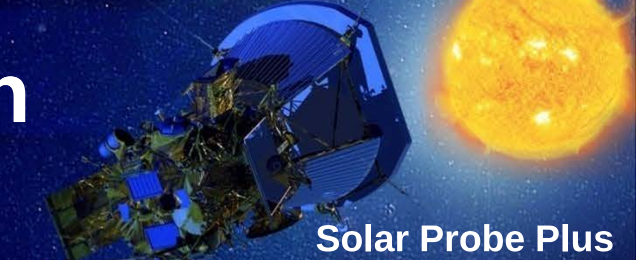
- Spacecraft and LGA mockup constructed at 4.5:1 scale
- Provides measurement of expected LGA coverage
- Provides check of simulation accuracy, for validating fanbeam coverage





Subsystem Preliminary Design Review



- **Telecomm Subsystem Preliminary Design Review held 25 October 2013**
- **Review Panel:**
  - **Jonathan Bruzzi** — **APL (Chair)**
  - **Shervin Shambayati** — **Space Systems Loral**
  - **Robert Bokulic** — **APL**
  - **Dipak Srinivasan** — **APL**
  - **Arthur Amador** — **JPL (SRB Representative)**

- **Actions (Documented in SER-13-056):**
  - **17 Action Items**
  - **16 Recommendations and Concerns**

- **Major takeaways:**
  - **Research and incorporate the latest available information on the impact of solar scintillation**

Phase C Summary

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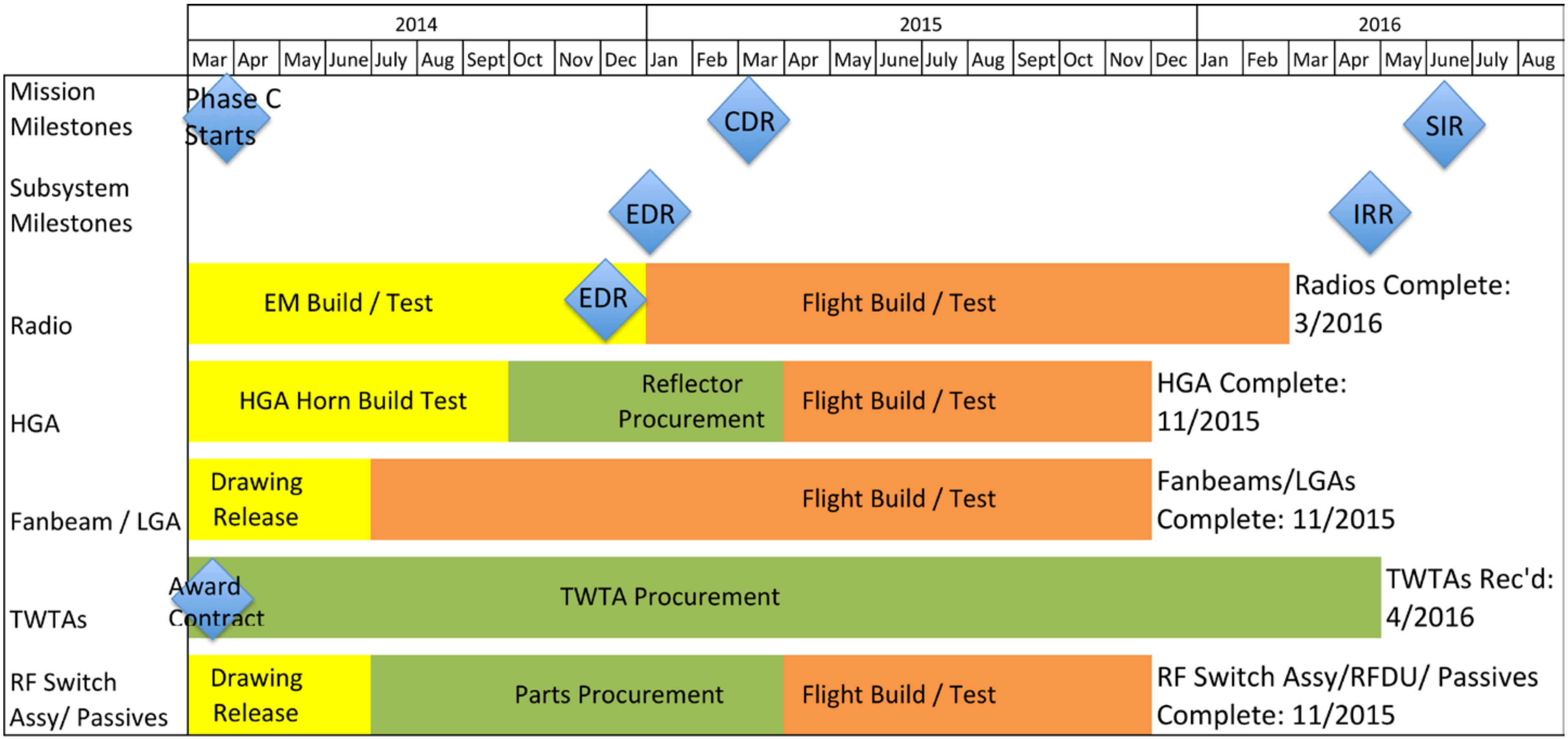

APL

Telecomm Subsystem PDR Conclusions

- Subsystem requirements are documented
- Subsystem analyses show the design meets the driving requirements
- Critical circuitry has been breadboarded
- Component details have been designed to PDR level
  - Issues identified and being worked
- Vendors identified and engaged for major purchases
- Project Plans in place for Phase C

- Telecomm subsystem is ready for Phase C

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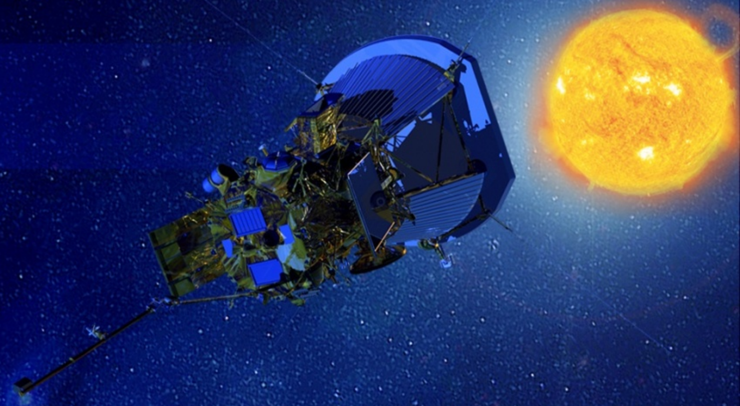

Backup

The Johns Hopkins University
APPLIED PHYSICS LABORATORY

Nominal Uplink CMD Rates
No Ranging

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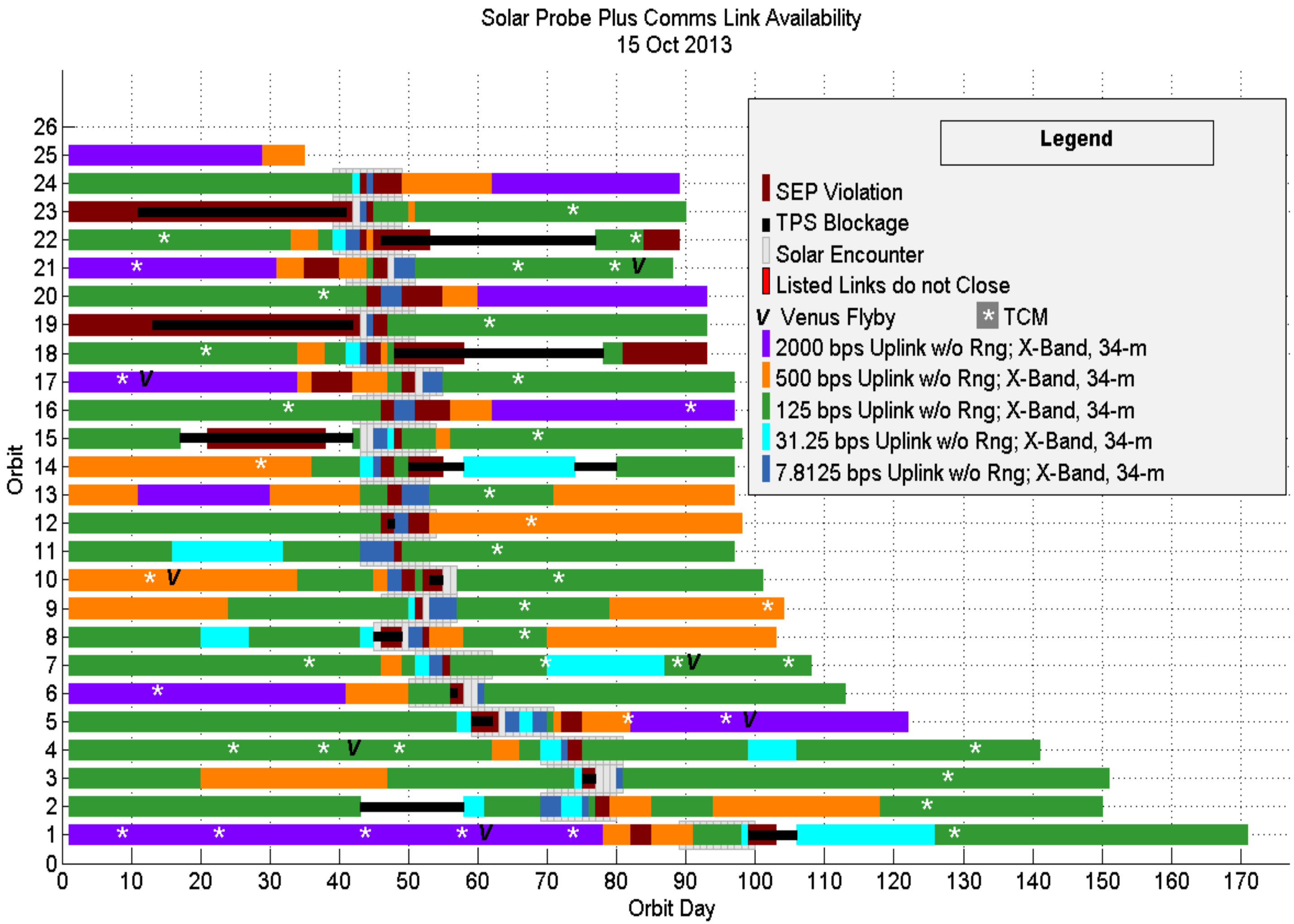

Nominal Uplink CMD Rates With Ranging

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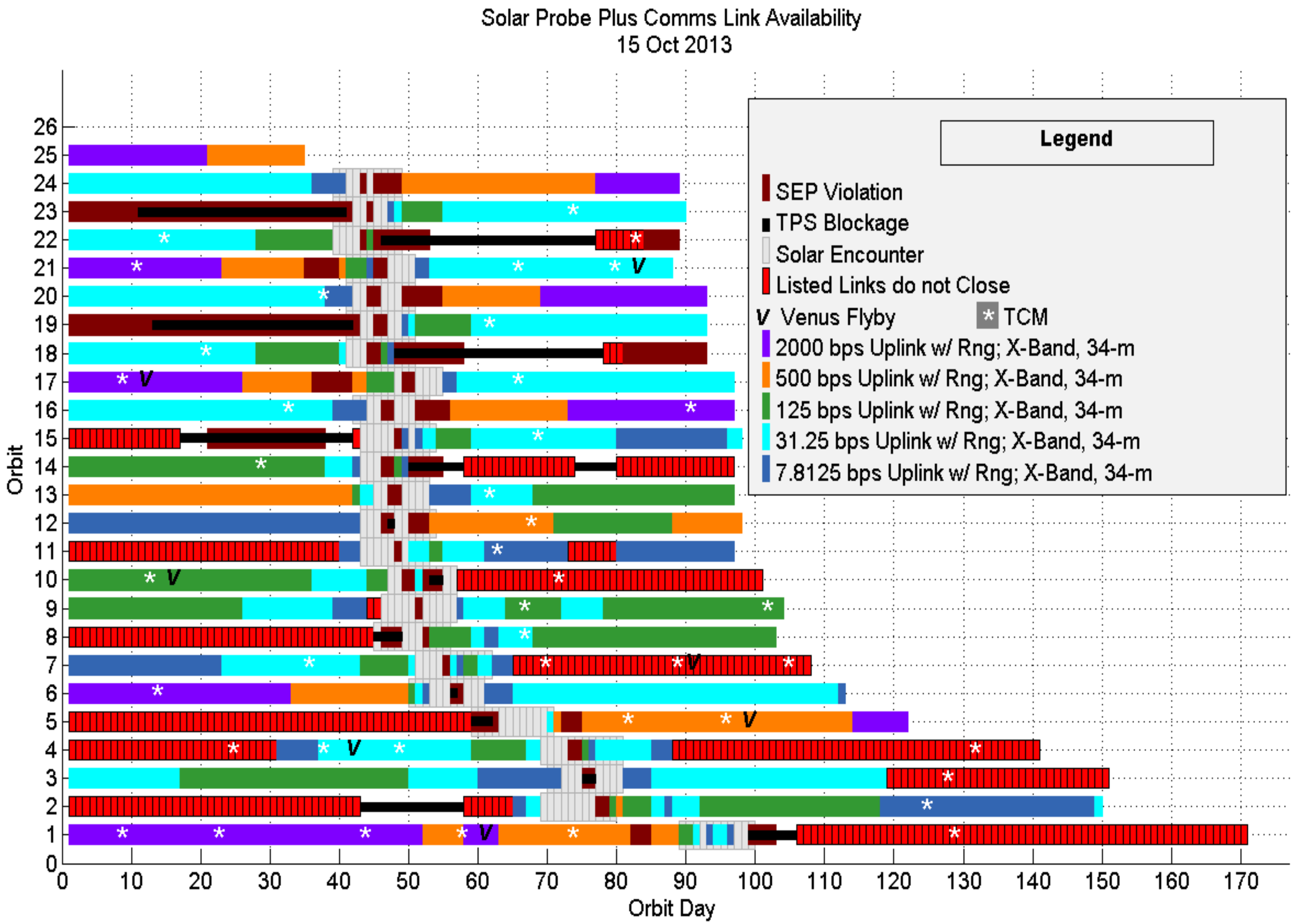

Nominal Downlink TLM Rates
X-band No Ranging

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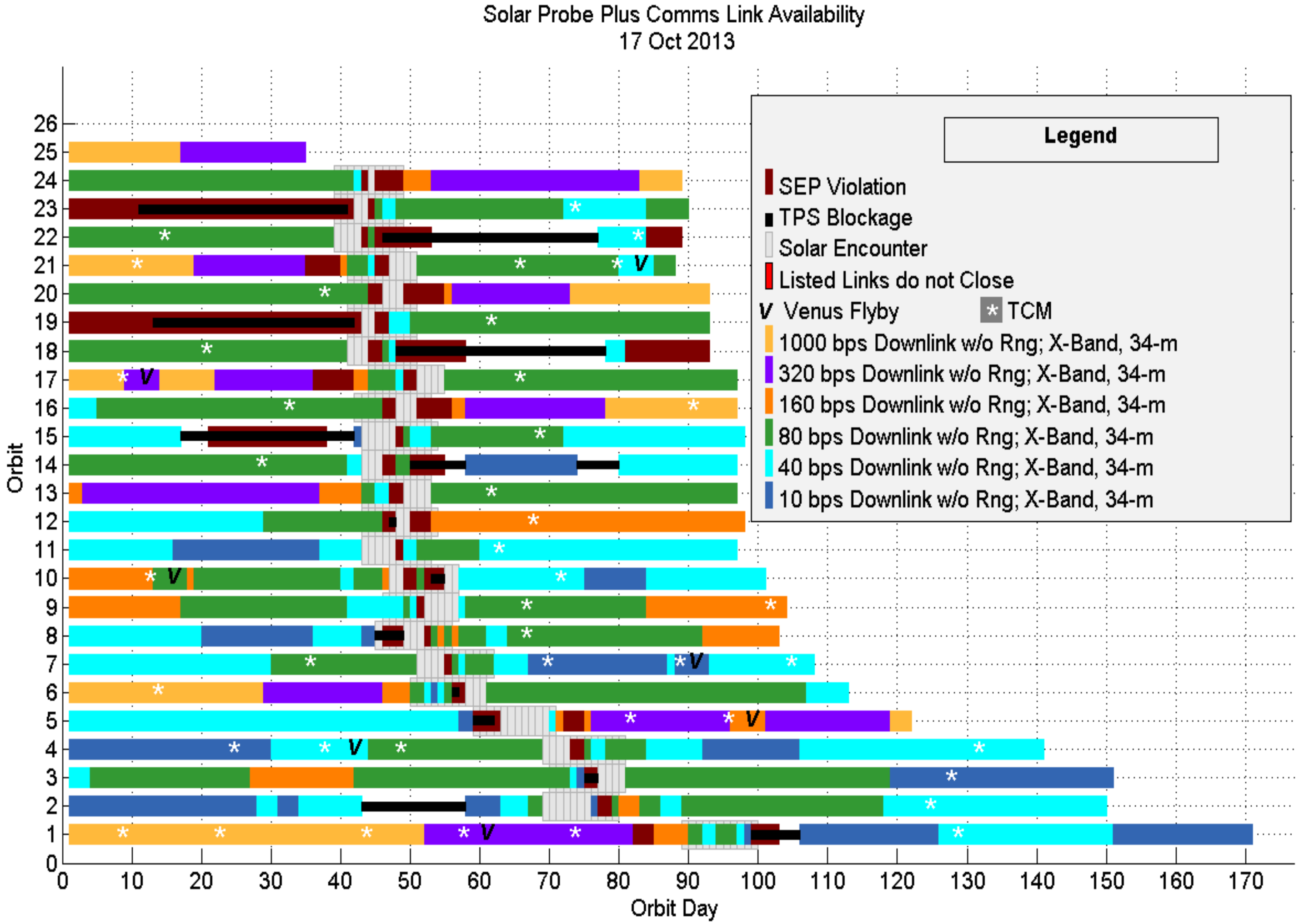
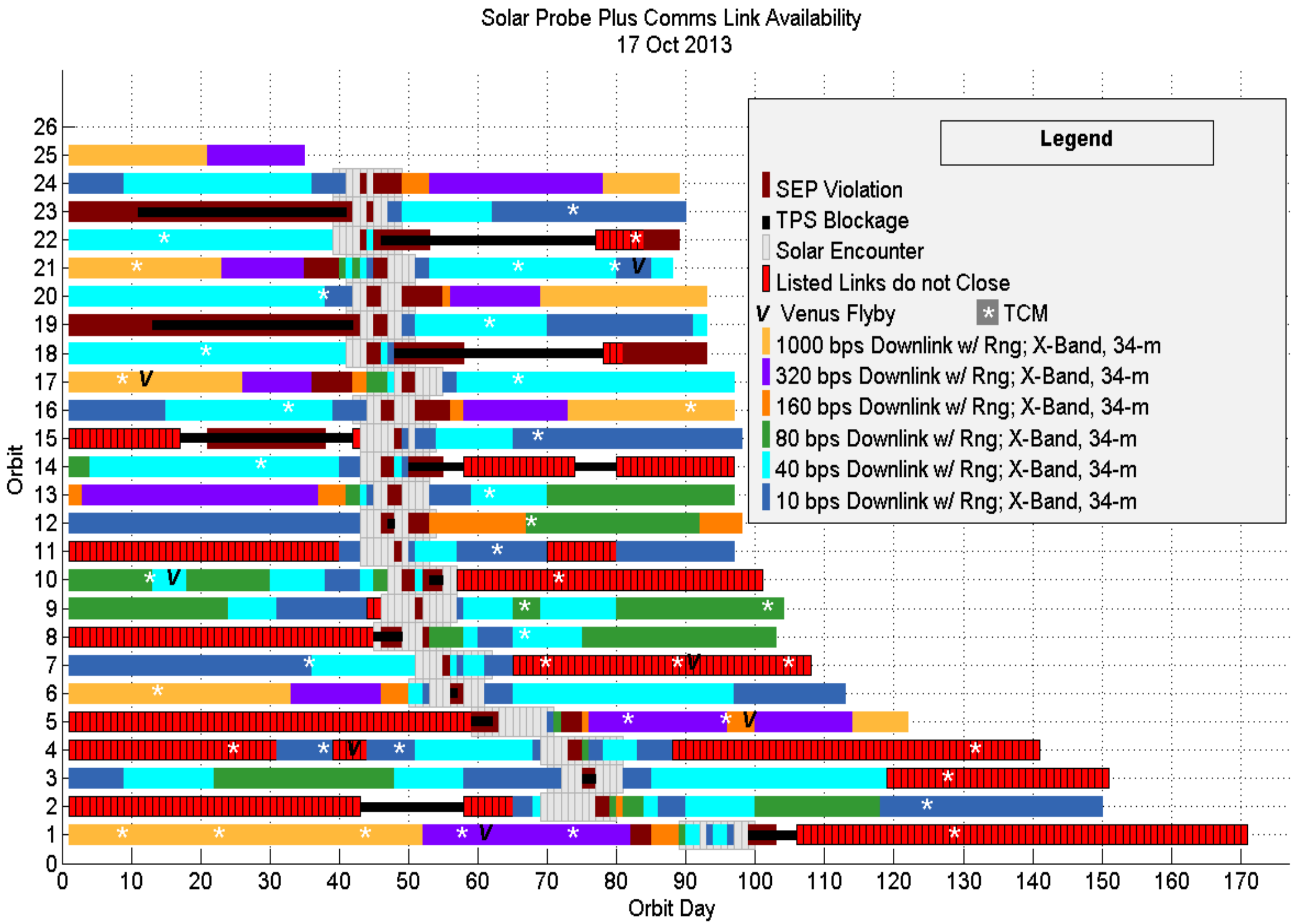


Nominal Downlink TLM Rates X-band With Ranging



Solar Encounter Coverage

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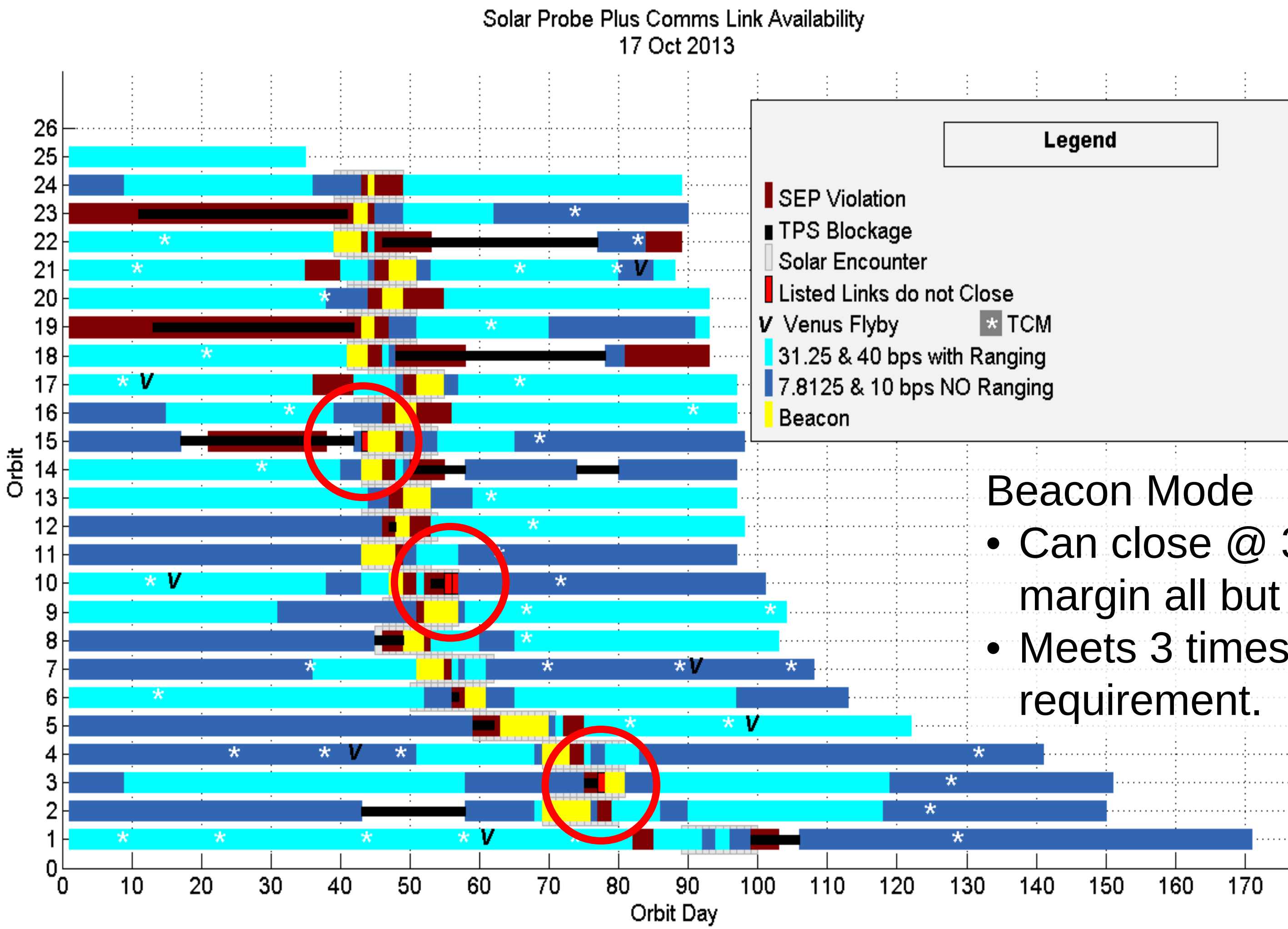

Beacon Mode

- Can close @ 3 dB margin all but 4 days.
- Meets 3 times / week requirement.

APL

2-Way Doppler Error Budget

Noise Contributor	Doppler Measurement Error	Conditions
Solar Scintillation	**0.0938 mm/sec (see Note)**	810/202B SEP = 23°
Thermal Noise	**0.034 mm/sec**	DL & UL turnaround
Spacecraft Radio	**0.01 mm/sec**	**Pt ≥ - 124 dBm**
Spacecraft Mechanical	**0.01 mm/sec (TBR)**	Drives Jitter Requirement
Ground Station	**0.002 mm/sec**	**Clocks, Electronics, Mech.**
Atmospheric	**0.015 mm/sec**	Ionosphere & Troposphere
RSS of All Error Contributors	**0.10 mm/sec**	**@ 60-seconds SEP >** 23°

Note: 2-Way Doppler is limited by Solar Scintillation for SEP < 23°.
Parameters courtesy of the Europa Doppler analysis (Dipak Srinivasan).

Phase B Trades: Ranging Study

- Phase A design proposed using Regenerative Ranging to fulfill requirements of 3 times per week (1118 contacts).
- Action Item EPR #6 and Risk # SPP-65 pursued relaxing requirements to performance offered by Tone Ranging.
- JPL NAV concluded a reduced set of Tone Ranging contacts is sufficient to support execution of trajectory correction maneuvers. New baseline = 642 contacts.

  Lau and Williams, JPL Memo 2013-392A-001, 26 August 2013
- Use of balanced uplink, downlink and ranging margins with Tone Ranging in Phase B provides **1083** contacts.
- Regenerative Ranging is not required.

Ka-band Science Downlink: Meeting Latency Requirement

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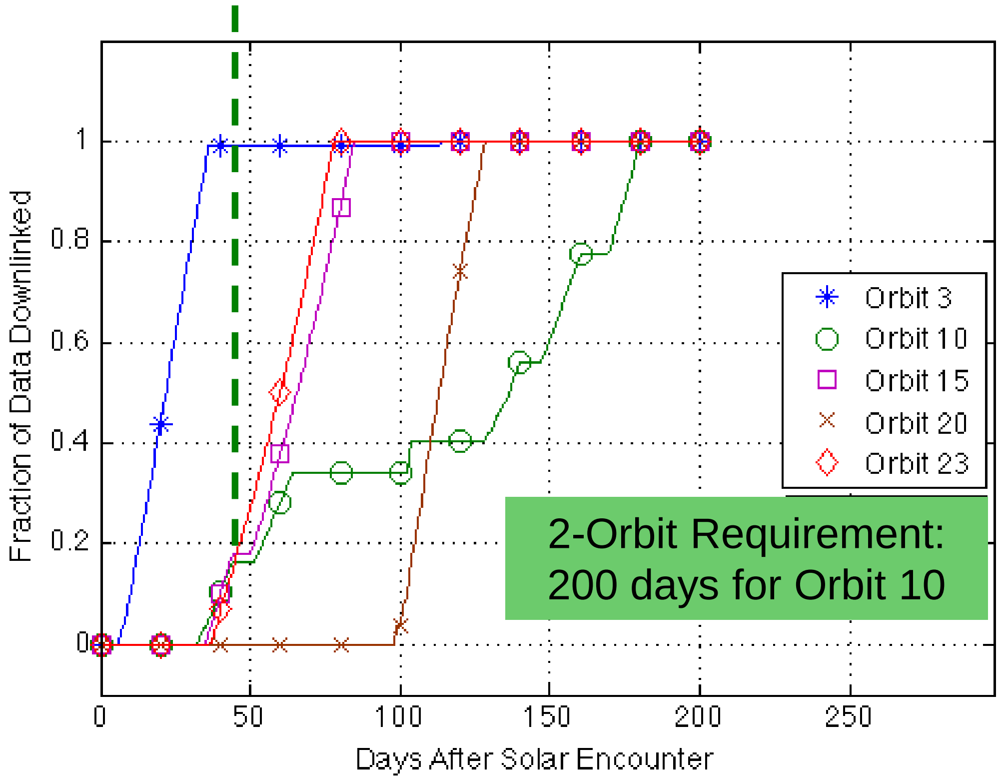
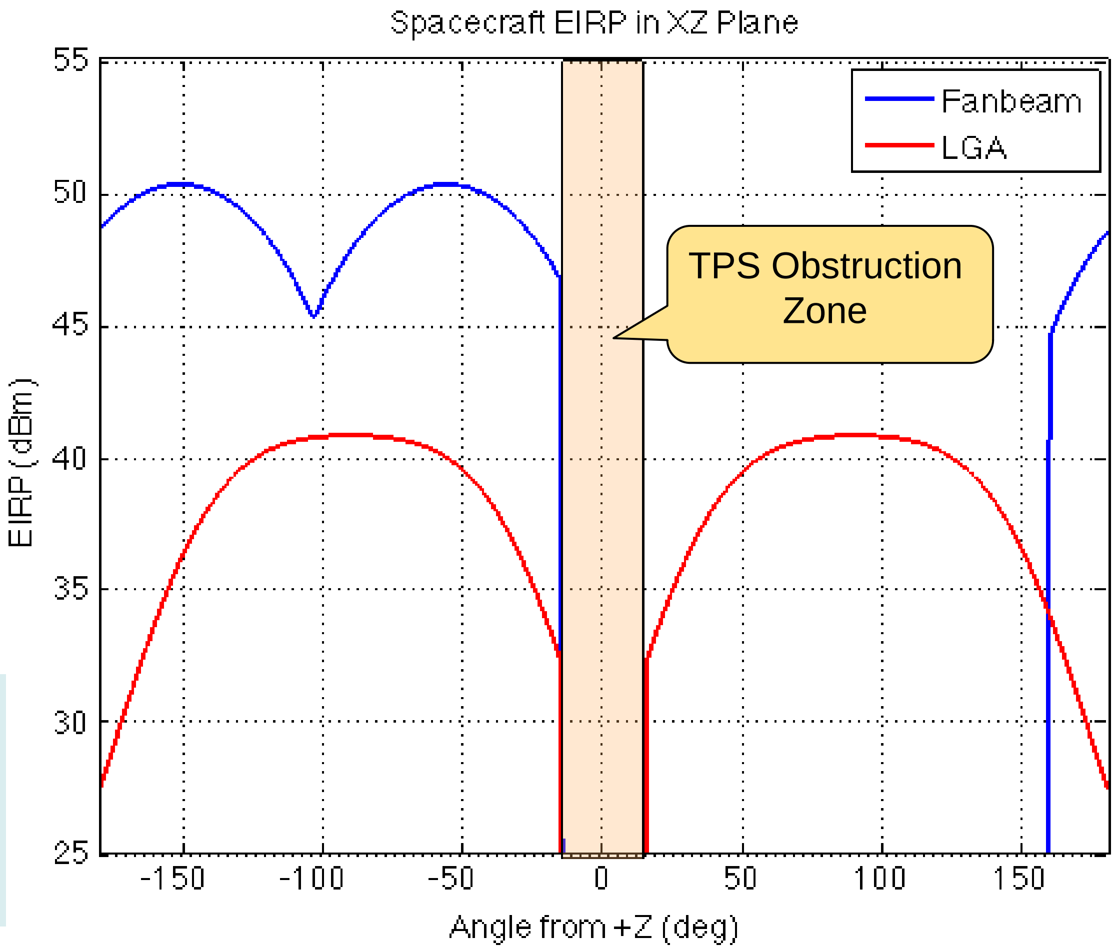
- All orbits meet latency requirement (representative orbits shown)
- Worst-case latency occurs on Orbit 10: meets requirement by 20 days



APL

X-band EIRP Requirement in XZ Plane

- **Forms basis for all performance estimates back to the mission**
- **Forms basis of Level 5 (component) requirements**
- **Verification will be by analysis based on component-level CPT**

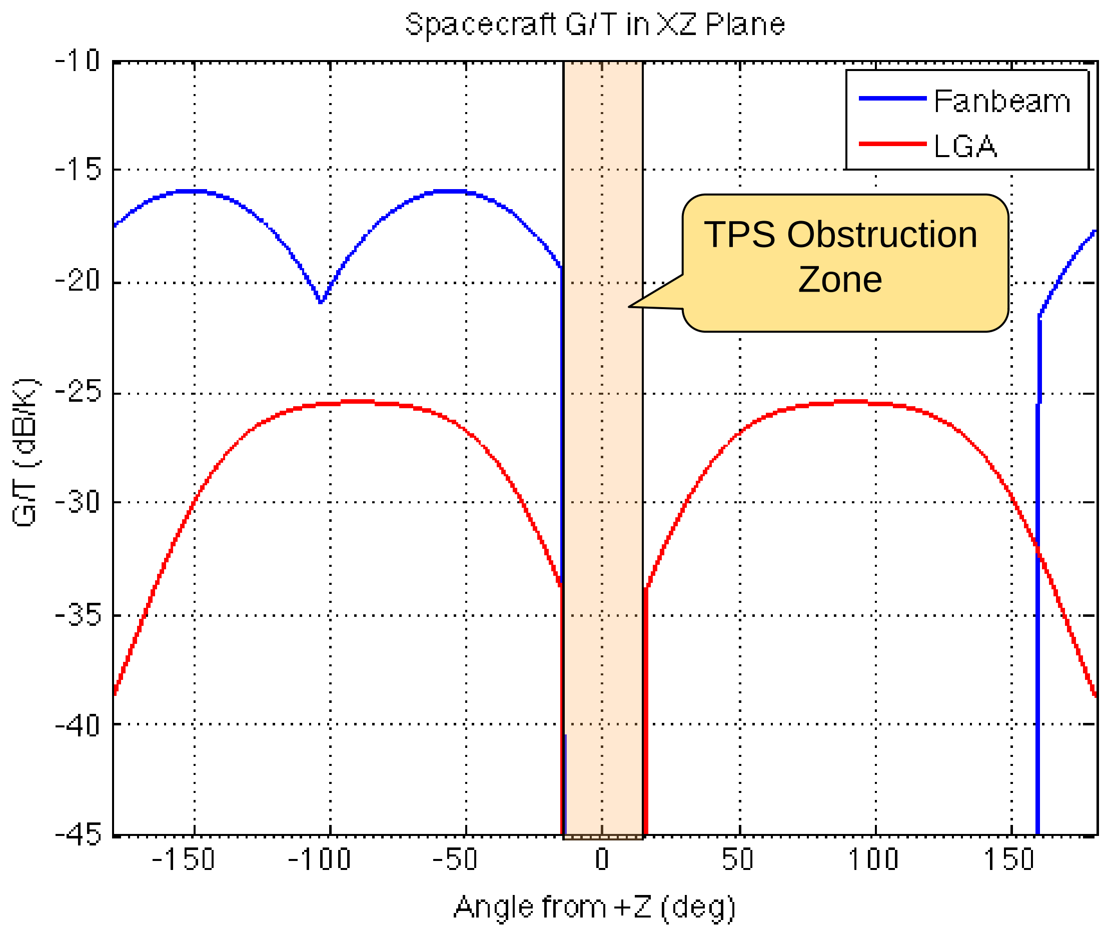


Assumptions:

- TWTA output power = 11 W
- Passive loss to fanbeams = 3.1 dB
- Passive loss to LGAs = 4 dB
- S/C Body Effect on Ant. Gain = 1 dB

X-band G/T Requirement in XZ Plane

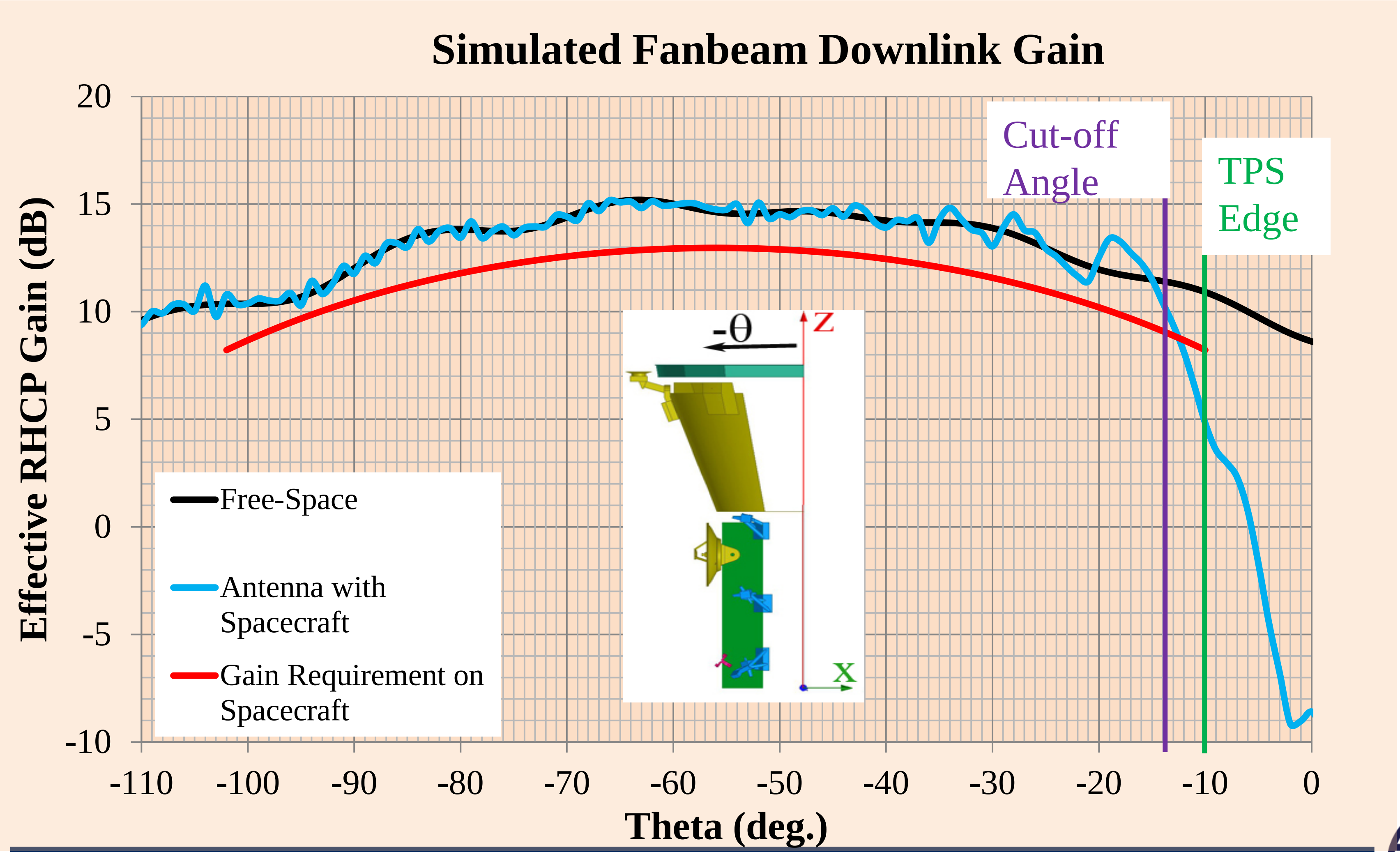
- **Forms basis for all performance estimates back to the mission**
- **Forms basis of Level 5 (component) requirements**
- **Verification will be by analysis based on component-level CPT**



Assumptions:

- Antenna noise temperature = 100 K
- Total Radio+LNA NF = 1.5 dB
- Passive loss to LGAs = 4.5 dB
- Passive loss to fanbeams = 3.7 dB
- S/C Body Effect on Ant. Gain = 1 dB

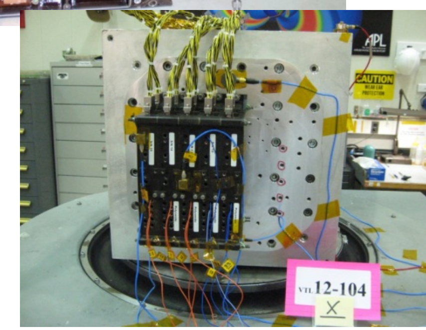
Fanbeam Antenna, Downlink Pattern with Spacecraft



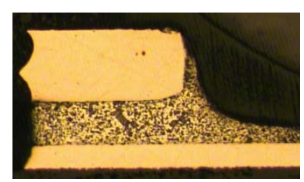
Process Development:
CCGA and QFN Qualification

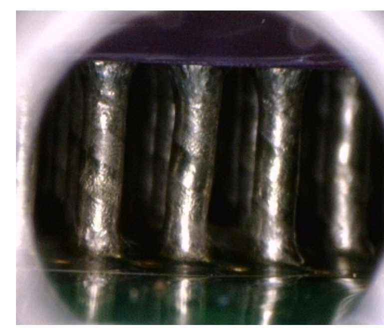
Radio FPGA exceeding capacity of previously-used 2M gate RTAX FPGA.

Switch to 4M gate FPGA necessitated qualification of 1272-pin CCGA package



- **Completed CCGA Process Development, Qualification, and Implementation in a Flight-like Frontier Radio Configuration**
  - Daisy-chained CCGA1272: Actel RTAX4000
  - Daisy-chained 10mm QFN: AD DAC, w/72 I/O
- **Conducted and Passed Qualification Tests, Including Vibration and Thermal Cycling up to 3xSPP Mission Life**
  - Thermal cycling continued for another program; 1st CCGA failure accrued at ~12x SPP mission life
- **Met Pre-defined Pass / Fail Criteria**
- **Obtained GSFC Concurrence on Qualification Results, and Incorporation in SPP Flight Radio Design**





Courtesy Sharon Ling

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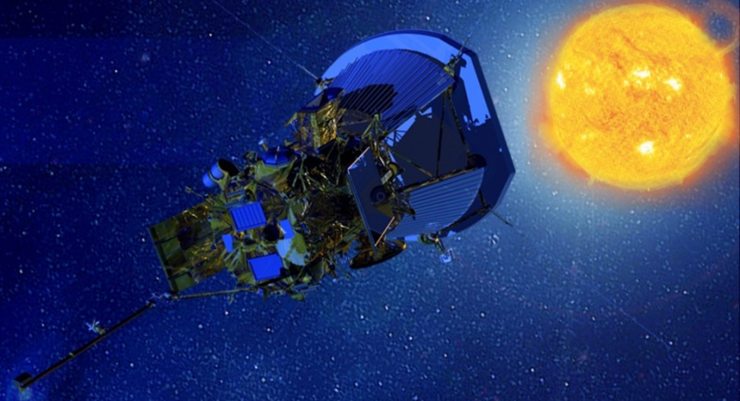


Flight Software

Chris Krupiarz
Flight Software Lead

Christopher.Krupiarz@jhuapl.edu

13 – 16 January 2014

The Johns Hopkins University
APPLIED PHYSICS LABORATORY

Flight Software Agenda

- **FSW Requirements**
- **FSW Design**
- **Resource Margins**
- **FSW Development Plan**
- **FSW Verification Plan**

FSW
Requirements Review

- **Requirements review held March 19 – 20, 2013**

- **Review Panel:**
  - **Mike Furrow, APL, Chair**
  - **Mark Reid, APL, Key Reviewer**
  - **Dan Wilson, APL, Independent Reviewer**
  - **Eric Melin, APL, Project Reviewer**
  - **Nick Pinkine, APL, End-user Reviewer**
  - **Kim Ord, APL, End-user Reviewer**
  - **Alan Cudmore, NASA GSFC, External Reviewer**

- **NASA IV&V also reviewed material**

- **Requirements document has been reviewed, released, and all review action items have been closed (Rev Dash [-])**

FSW Requirements (1 of 2)

- **Driving Requirements**
  - **Manage software operations on three processors**
  - **Operate a 3-axis stabilized spacecraft**
  - **Communicate external to boards via SpaceWire**
  - **Uplink command data files using CFDP**
    - **Provide additional uplink in BD mode**
  - **Uplink data range of 7.125bps to 2Kbps**
  - **Downlink framing at rates from 10bps up to 1Mbps**
  - **Downlink recorded data files using CFDP**
  - **Management of files on the SSR (256Gbit)**

FSW Requirements (2 of 2)

- **Driving Requirements (cont.)**
  - **Distribution of time and status**
  - **Manage spacecraft time tagged commands**
  - **Collect instrument data**
  - **Manage spacecraft subsystem commands and collect spacecraft housekeeping data**
  - **Record and downlink spacecraft housekeeping and instrument data**
  - **Support fault protection & limited autonomous instrument safing**
  - **Retention of critical spacecraft information through processor resets**

FSW Design
FSW Functionality

- **FSW Preliminary Design Review held October 9 – 10, 2013**

- **Review Panel:**
  - **Mike Furrow, APL, Chair**
  - **Mark Reid, APL, Key Reviewer**
  - **Dan Wilson, APL, Independent Reviewer**
  - **Eric Melin, APL, Project Reviewer**
  - **Nick Pinkine, APL, End-user Reviewer**
  - **Kim Ord, APL, End-user Reviewer**
  - **Chris Jones, JPL, SPP SRB**
  - **Jan Chodas, JPL, SPP SRB**

- **Post Government Shutdown Table-Top Review**
  - **Alan Cudmore, NASA GSFC**
  - **NASA IV&V**

FSW Design
FSW Functionality

- **Boot**
  - **Simple boot loader; no commanding/telemetry**
- **Command and Data Handling (C&DH)**
  - **Command management**
    - **Uplink: receive transfer frames from transponder**
    - **Commands: real-time, macros, time tags, autonomy**
    - **Packets extracted and distributed locally or to a S/C subsystem**
  - **Telemetry**
    - **Receive telemetry from subsystems/individual applications**
  - **SSR management**
    - **Record/playback spacecraft and instrument data to/from a file system**
  - **Autonomy**
    - **Autonomous fault detection and safing/switchover on Prime**
    - **Maintenance autonomy on spares pending Phase C trade**
  - **Software management**
    - **Memory object loading, CPU utilization, etc.**
- **Guidance and Control (G&C)**
  - **G&C sensor interface management, Three-axis control, momentum maintenance**
  - **Cruise phase & thruster control, 50 Hz attitude control, 1 Hz attitude estimation**

FSW Design
Managing Code Images

- **Code Image Management**
  - **Code images are uploaded as files**
  - **First uploaded to Prime**
  - **Copied to Spares to save bandwidth**

- **Upload Individual Applications**
  - **FSW contains a simple NVM memory system in RAM**
  - **Allows access to individual applications with predefined spaces**
  - **cFE selects files for execution via configuration file**

- **Upload of Libraries**
  - **Requires uploading of library image as well as applications that use the library**

FSW Design
Software on Three Processors

Solar Probe Plus
A NASA Mission to Touch the Sun

- Prime, Hot Spare, Backup Spare are all running the same software
  - Applications are controlled by Scheduler messages
    - Messages drive degree of application functionality
  - Some applications have knowledge of SBC state
  - Reduce power consumption and processor loading

- Prime sends Hot Spare (and Backup Spare during encounter) a status message at 1 Hz
  - Data includes:
    - Current & Target spacecraft configurations
    - Raw star tracker data
    - Current time data
    - Current accumulated SA flap & feather and HGA step counts
    - Current spacecraft FM mode(s)
    - Processor rotation count & MET of last rotation count reset
    - Safe Mode – Solar Array entry time

  - G&C code on spare will verify raw star tracker data

- Hot Spare promoted to Prime on Prime demotion
  - G&C primed via previously received message
  - Scheduler sends full compliment of messages to applications

FSW Design
Software Environment

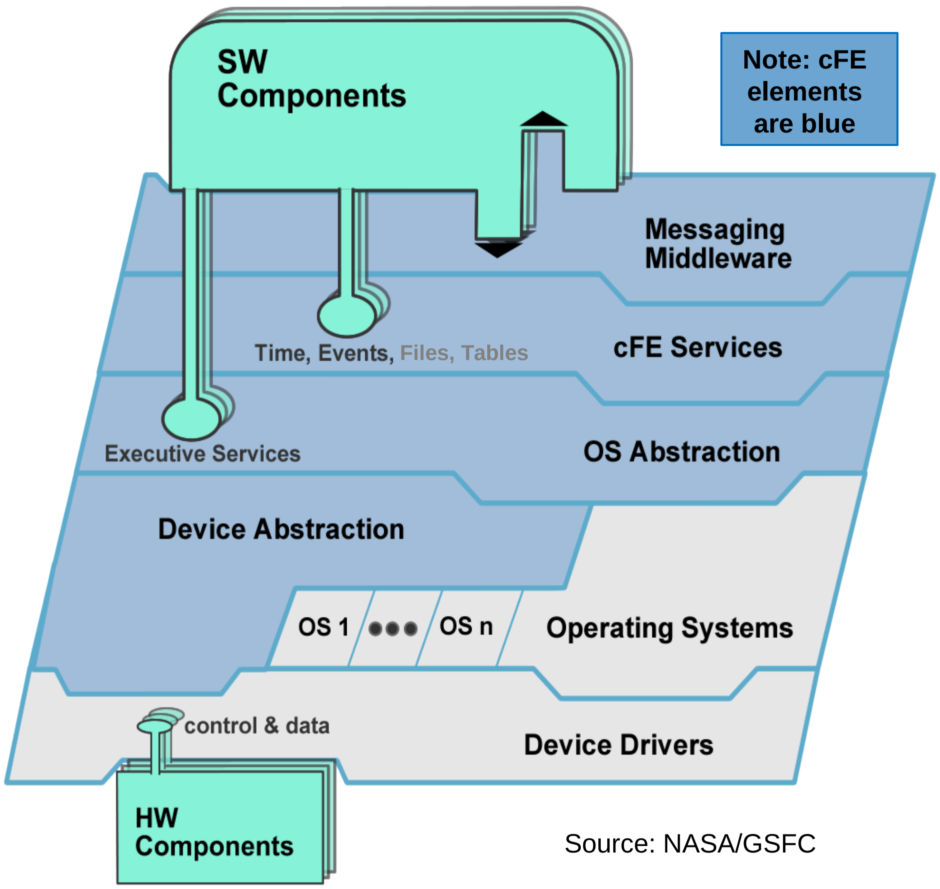
- APL Developed Single Board Computer (x3):
  - Big Endian UT699 LEON3FT (Sparc V8 architecture) 60MHz from Aeroflex Colorado Springs
  - 32 MB SRAM with EDAC
  - 8 MB of MRAM (Non-Volatile Memory) 6.4 MB usable
    - 3.2 MB per logical bank
  - FPGA facilitates NVM image verification during boot
  - Boot loader executes out of NVM
  - 256Gbits (32GBytes) NAND Flash Bulk Memory (SSR) on processor board
    - Memory mapped I/O
  - SBC interfaces
    - UARTs to Avionics Redundancy Controller (ARC)
    - SpaceWire to spacecraft and instrument subsystems as well as other single board computers

FSW Design
FSW Baseline

- **Operating System**
  - **Real-Time Executive for Multiprocessor Systems (RTEMS) 4.10 with support from OAR Corporation**
  - **Build tools and RTEMS distribution from Aeroflex Gaisler**
- **NASA GSFC Core Flight Executive (cFE) 6.3.1 middleware**
- **Operating System Abstraction Layer (OSAL) 3.4.1**
  - **Planned to move to OSAL 4.0**
- **Mission FSW Applications and Libraries**
  - **Significant reuse from Van Allen Probes**
  - **New development**
    - **SpaceWire**
    - **CFDP Uplink**
    - **Flash file system**
- **C&DH, G&C and Autonomy operate on same processor**
- **Each SBC executes same FSW in different modes**

FSW Design
Core Flight Executive (cFE)

- Developed and maintained by NASA Goddard Space Flight Center
- Provides common flight executive functions
- Well documented application programmer interface (API)
- Project-independent configuration management
- Applications do not perform any platform specific dependent calls



Source: NASA/GSFC

FSW Design
FSW Context Diagram (Prime)

Solar Probe Plus
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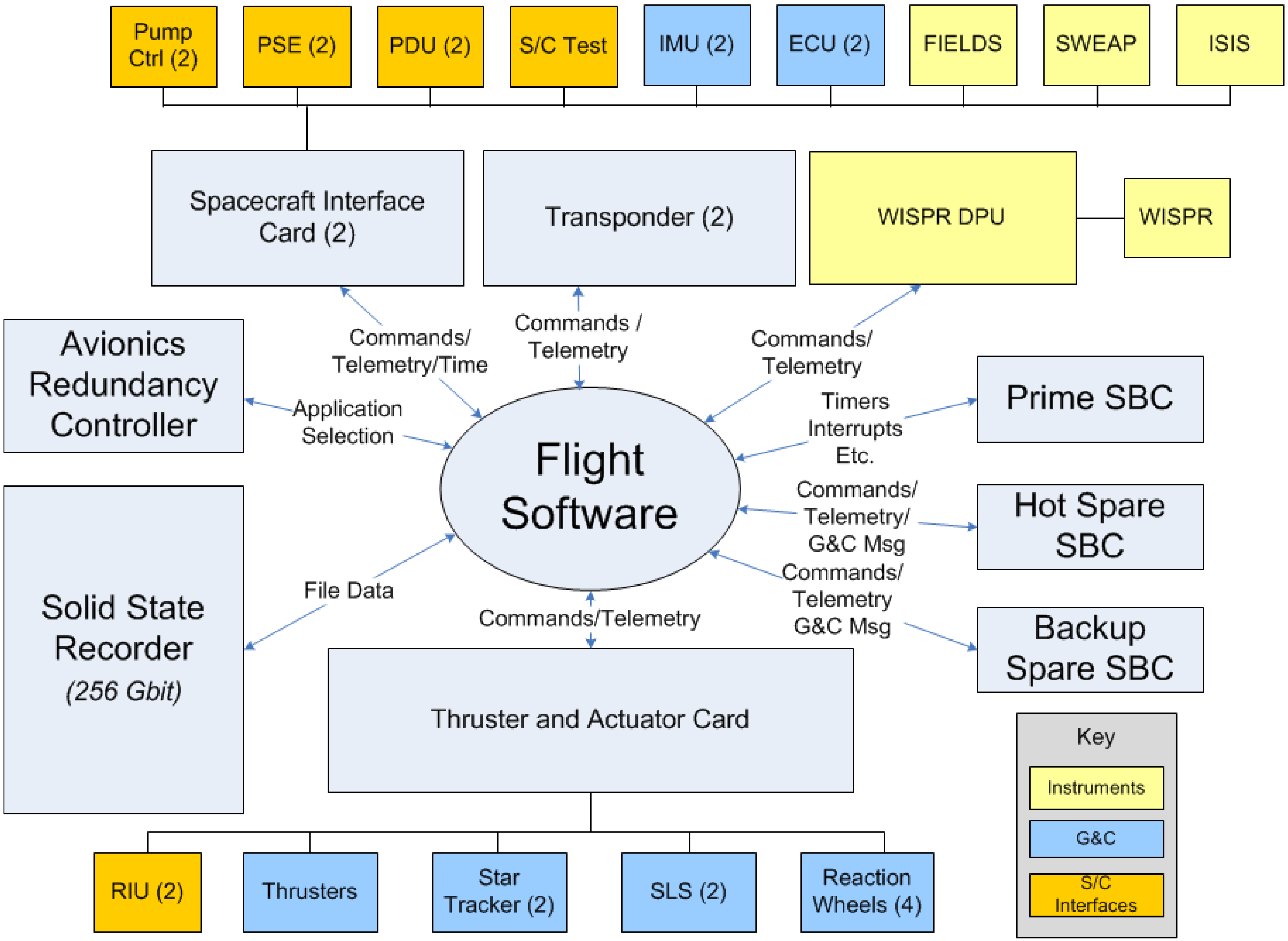
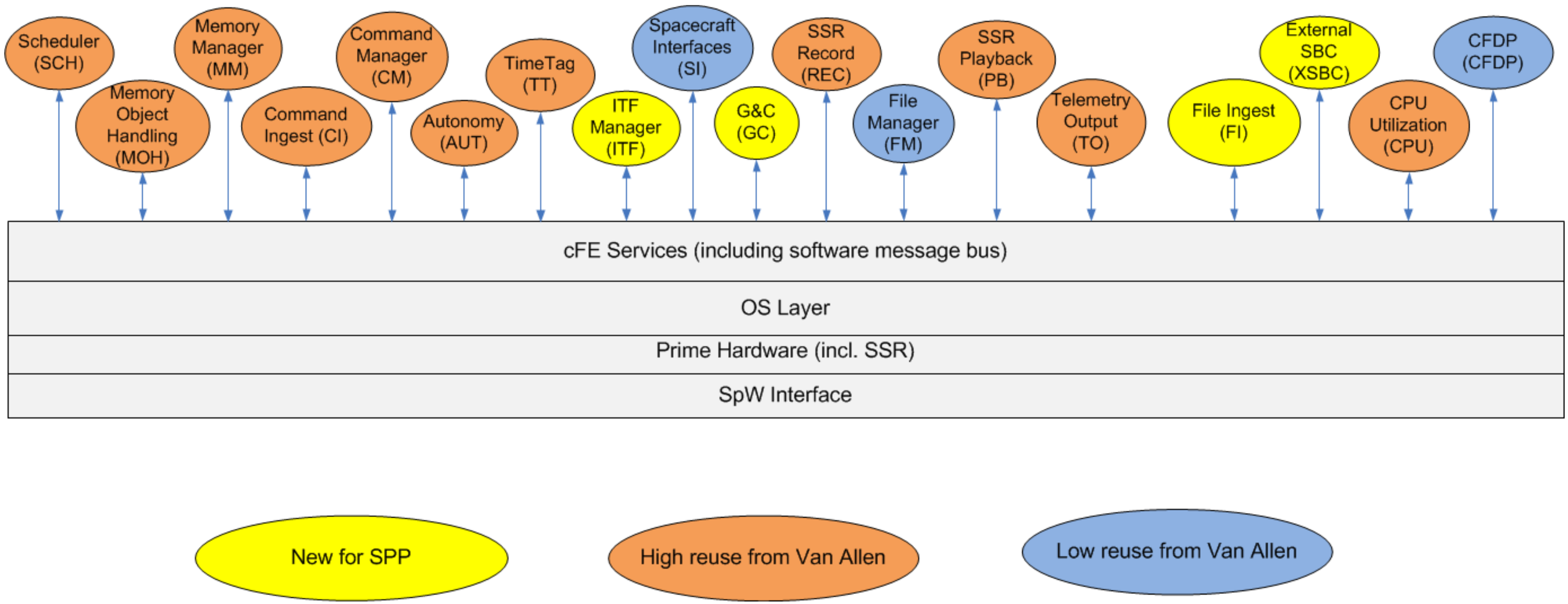


APL

FSW Design
FSW Task Diagram



FSW Design
Operation Level for Apps on Spares

Solar Probe Plus
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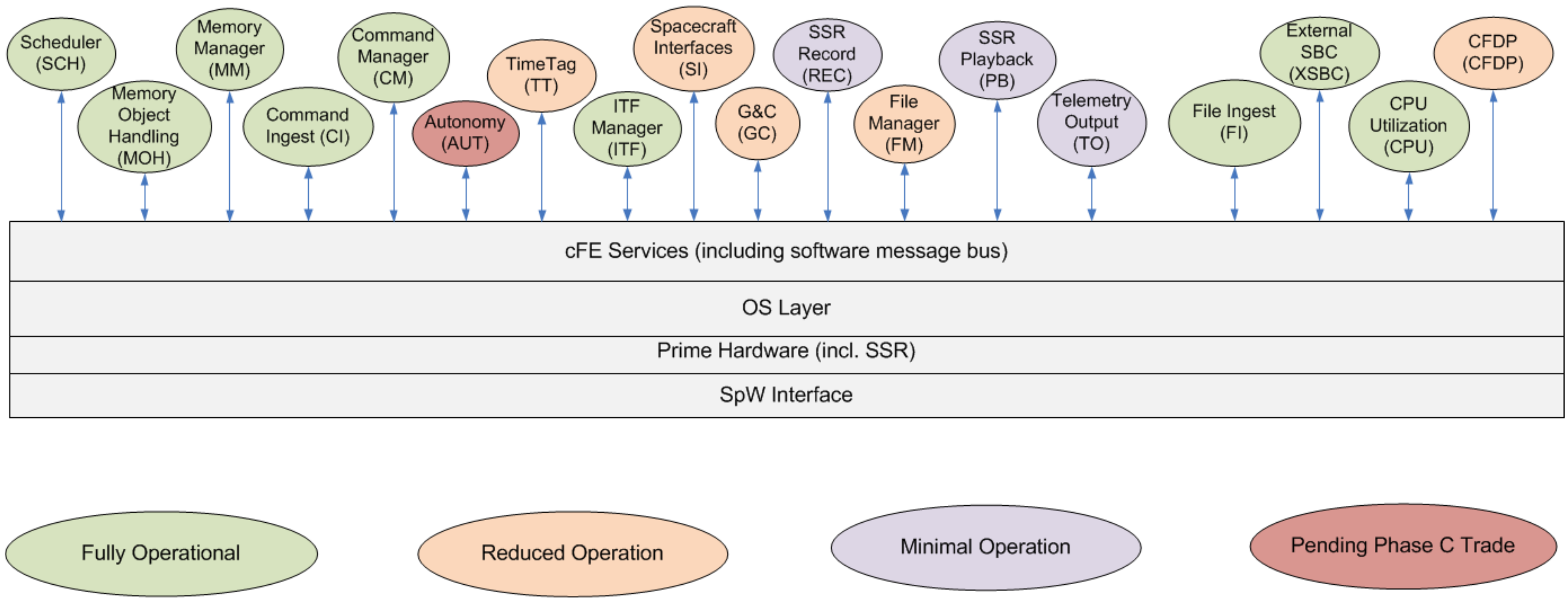
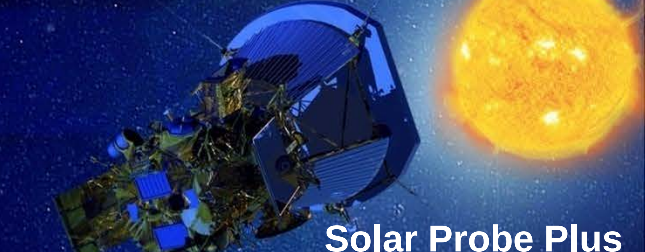


FSW Design
FSW Boot Process



- **Initial boot combination of:**
  - **FPGA (Checksum of image, image selection)**
  - **Commercial-off-the-shelf (Uncompress image, load to RAM)**
  - **APL code (RAM checking)**

- **RTEMS Kernel (Executing from SRAM)**
  - **Initializes RTEMS**
  - **Mounts the EEFS**
  - **Loads and executes the cFE core**

- **cFE Core**
  - **Initializes cFE**
  - **Loads the cFE startup script**
  - **Decompresses, loads and initializes specified mission libraries**
  - **Decompresses, loads and spawns specified mission applications**

Resource Margins
QMS Flight Software Margin

- **APL QMS Document: SD-QP-600-2, <u>Systems Engineering Standards</u>**
  - **Software related margins for critical processor margin, processor memory (RAM) margin and non-volatile memory (NVM) margin is defined as *"the percentage of the resource left unused under worst case conditions"*.**

Margin = (Available – Estimate) / Available

Critical Resource	Green	Yellow	Red
CPU Time	>= 50%	40% - 50%	< 40%
EEPROM	>= 50%	40% - 50%	< 40%
RAM	>= 50%	40% - 50%	< 40%

Resource Margins
Flight Software Margin

- **Unused Processor 41% (40 - 50% Margin – Yellow)**
  - **Based on UT699 operating @ 60 MHz**
  - **Includes conservative numbers for G&C loading**
    - **Currently being reworked, expect improvements**
  - **High confidence in C&DH numbers given level of reuse**
  - **Program examining use of faster UT699e**

- **Unused NVRAM 48% (40 - 50% Margin – Yellow)**
  - **FSW apps and FSW memory objects**
  - **Includes several mature FSW applications**

- **Unused RAM 50% (> 45% Margin – Green)**

- **Margins derived from:**
  - **Van Allen Probes code running on the UT699/LEON3FT**
  - **Robotic Lunar Lander G&C running on the UT699/LEON3FT**
  - **Synthetic benchmark comparisons between RAD750/UT699**

FSW Development Plan Schedule

- **Documented in:**
  - **SPP Software Development Plan, 7434-9042**

- **Phase C/D – Detailed Design / Implementation**
  - **Technical Peer Reviews prior to Mission CDR:**
    - **FSW Detailed Design – July 2014**
  - **Incremental Flight Software Builds (planned delivery date)**
    - **Build 0 – Hardware Checkout (November 2014)**
    - **Build 1 – Component Interface (June 2015)**
    - **Build 2 – RPM Qual Testing (January 2016)**
    - **Build 3 – I&T (July 2016)**
    - **Build 4 – Operational Freeze (June 2017)**

FSW Independent Acceptance Test Overview

- **Independent verification will be done on all requirements for the following CSCIs:**
  - **Boot**
  - **C&DH and G&C**
  - **Perform independent acceptance test on each incremental software release which includes regression test**
- **Use independent test engineers who have no involvement in development of the software component under test**
- **Adhere to verification process outlined in APL's Space Department Software Development Process (QMS SD-QP-650) for a Class B mission**
  - **Formal peer reviews for test plan and test specifications**
  - **Software Quality Assurance (NASA IV&V and APL) involvement**

SPP FSW Summary

- **Requirements**
  - **Completed Requirements Review (March 19 – 20, 2013)**
  - **Closed Action Items**
  - **Released Requirements**
- **Design**
  - **Completed Preliminary Design Review (October 9 – 10, 2013)**
  - **Closed Action Items**
- **Team**
  - **Fully Staffed**
    - **Chris Krupiarz** — **Flight Software Lead**
    - **Chris Monaco** — **C&DH Lead**
    - **Gail Oxton** — **G&C Lead**
    - **Jacob Firer** — **Boot & C&DH**
    - **Nate Parsons** — **G&C**
    - **Alan Mick** — **Spacecraft Interfaces**
    - **Kristin Wortman** — **Independent Acceptance Test Lead**
- **Flight software team is ready to proceed to Phase C**

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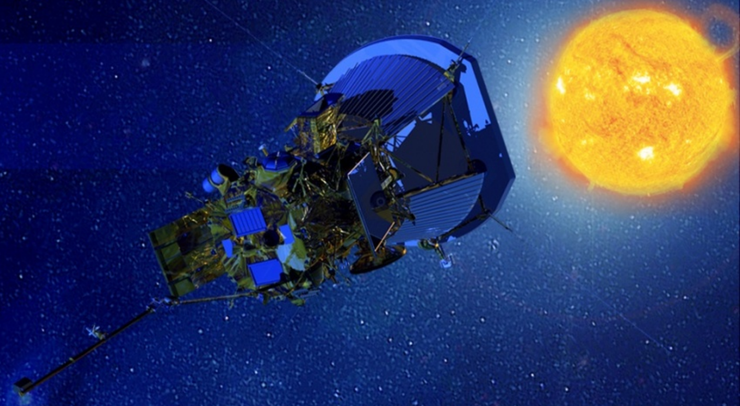

Backup

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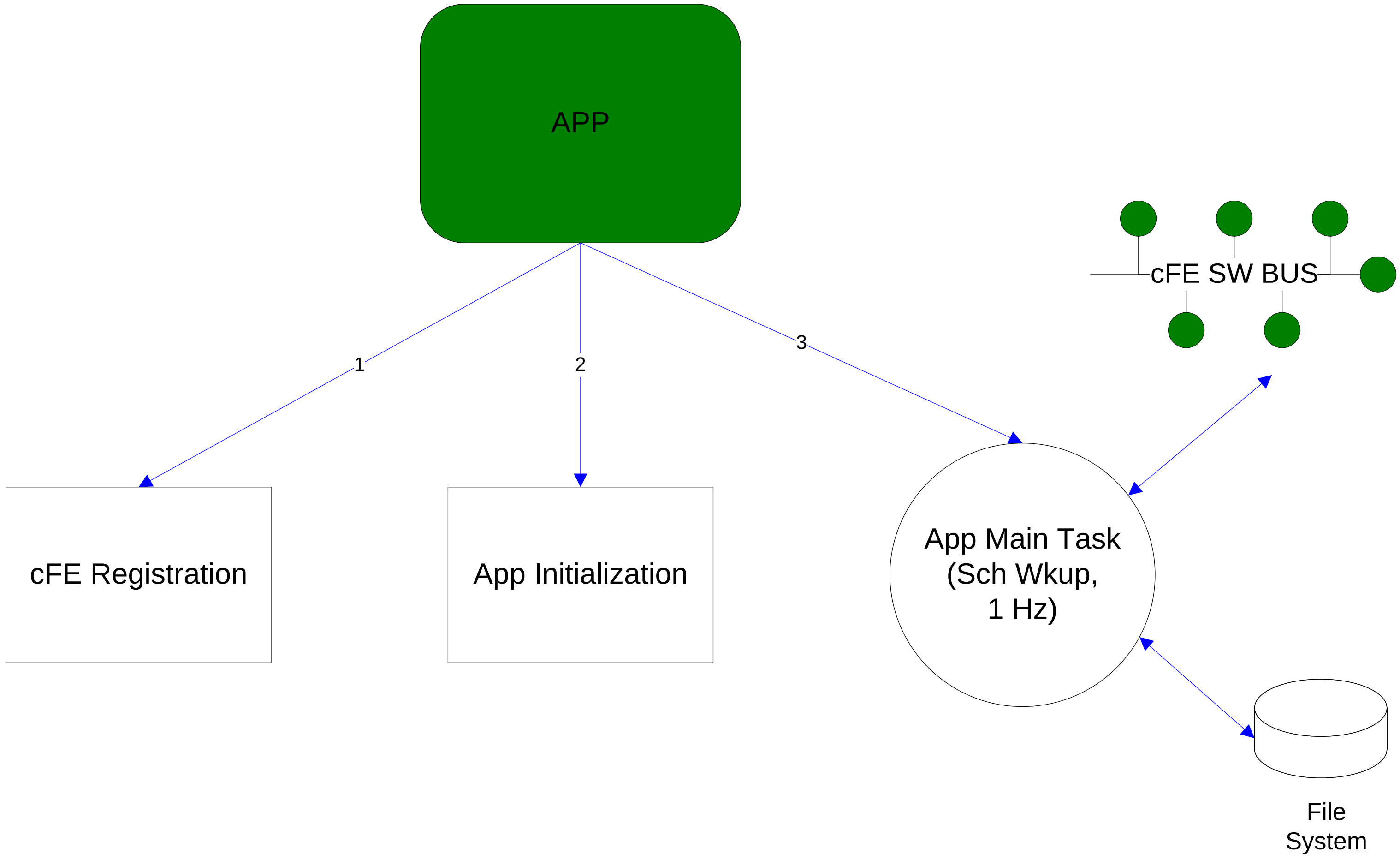
FSW Configuration Management

- Using Subversion as configuration management tool
- Products placed under CM include
  - Source code, make files, configuration files
  - Database definition files
  - Test scripts
  - Documentation
- Change control will use JIRA issue tracking tool
- Change Requests (CR) will be used to track defects
  - Includes CSCI/CSC identification, description of problem, severity of problem, person responsible for resolution, resolution
- Problem/Failure Reporting (PFR) tool will be used during I&T
  - Software related PFRs will be submitted as CRs
- Project CCB will be established prior to I&T to control changes
  - Documented in SPP Configuration Management Plan

FSW Design
FSW Boot Process (Backup)

- **FSW boot process is initiated upon SBC POR or reset**
- **Begins with FPGA verification of selected FSW image**
  - **Compute CRC over fixed region & check against stored value at the end of the region**
  - **If selected image verification is unsuccessful, FPGA will perform verification on alternate FSW image.**
    - **If alternate image verification is unsuccessful "choose" selected image.**
    - **If alternate image verification is successful "choose" alternate image.**
  - **If selected image is successful "choose" selected image**
- **FPGA maps the chosen image to address 0x00000000 and releases the LEON3 from reset**
- **FPGA maintains a boot record to store selected and chosen images at the time of boot**
- **LEON3 boots from 0x00000000 of MRAM - executing the boot loader**
  - **Boot loader is created from the executable FSW RTEMS kernel image using Aeroflex Gaisler MKPROM2 to compress and generate attached boot loader**
  - **Boot loader executes within MRAM,**
    - **initializes the LEON3,**
    - **Initializes SRAM EDAC on SRAM to clear uncorrectable errors**
      - **On POR SRAM memory test & initialization**
    - **Decompresses the kernel image from MRAM into SRAM**
    - **Jumps to the FSW kernel image (in SRAM)**

FSW Design
Sample Application Architecture



FSW Design
Sample Application Context Diagram

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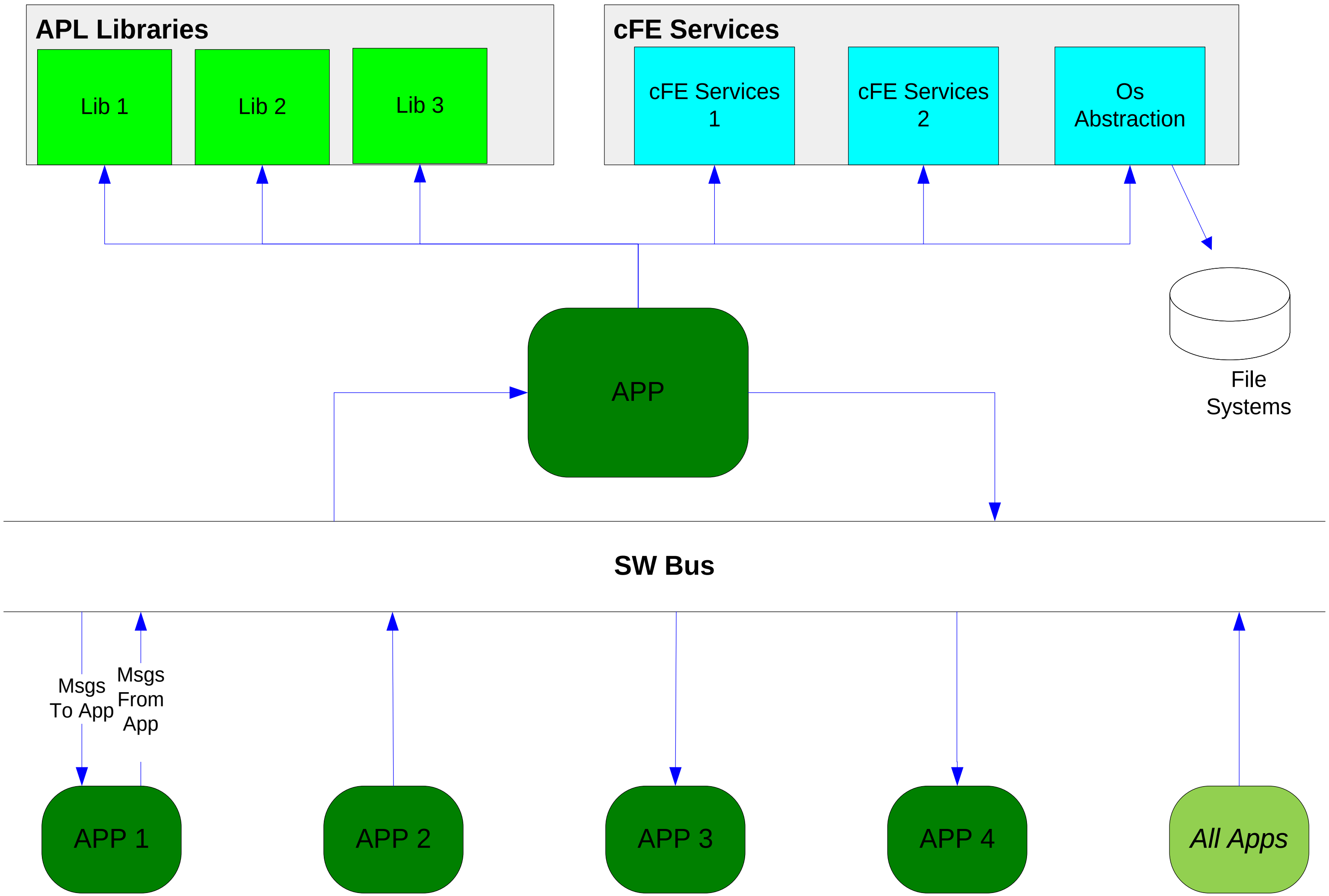
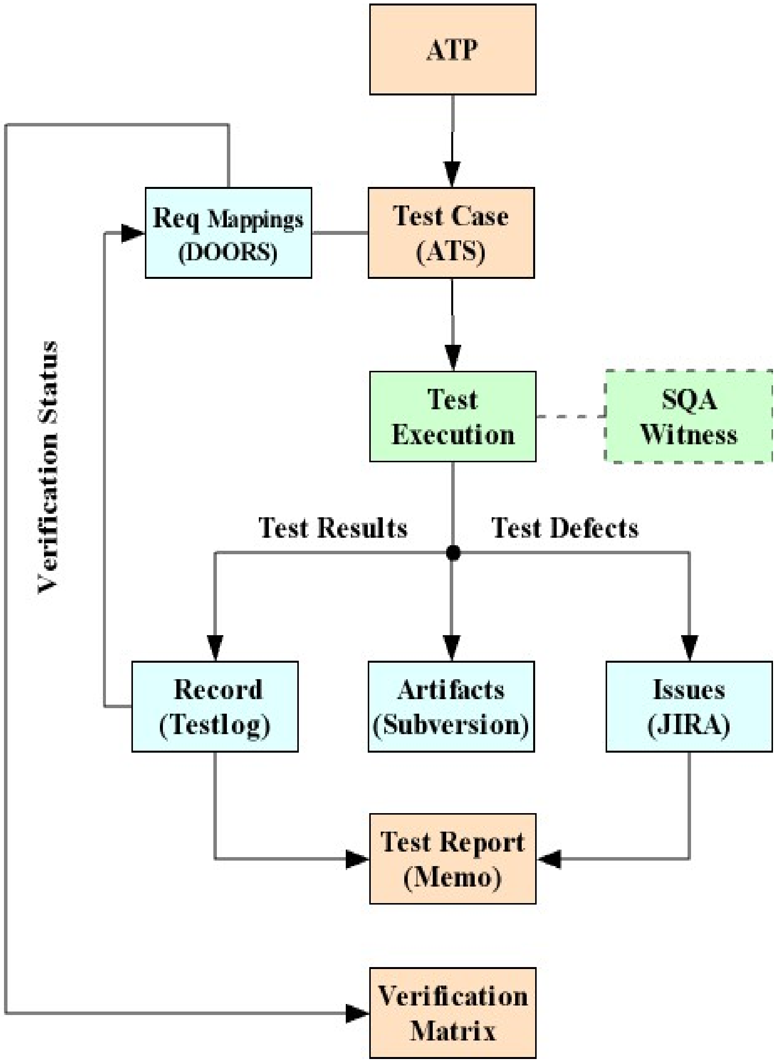


FSW Verification Plan Flow

- **Test documentation set**
  - Acceptance Test Plan (ATP)
  - Acceptance Test Specifications (ATS)
  - Test closure reports
  - Verification matrix
- **Test process**
  - Test case/requirement(s) mapping
  - Formal peer review process for ATP and ATS
- **Repeatable test design**
  - Automate test scripts (when possible)
  - Regression test suite
- **Test records**
  - Artifacts
  - Issues
  - Test execution results
- **Commercial tool set**



FSW Verification Plan Strategy

- Review the system-level tests to eliminate duplication of testing and to add value to verification program
- Leverage on system-level tests (e.g., extend existing test scripts, use for test setup)
- Reuse the Van Allen Probes test designs (CORE C&DH applications)
- Automate test execution when possible
- Reuse the Van Allen Probes test framework for script development and build a regression test suite
- Merge automated functional tests with system-level tests to create a comprehensive regression system test suite

FSW Verification Plan Schedule

- **Phase C**
  - **Acceptance Test Plan Review (July 2014) and baseline the ATP in PLM**
  - **Test case mappings to requirements (Test Specifications)**
  - **Test engineers on-board August 2014, fully staffed January 2015**
  - **Attend Critical Design Review**
  - **Test Specification peer reviews for Builds 1 & 2 test cases**
  - **Complete Builds 1 & 2 acceptance test executions, generate closure reports, update verification matrix and baseline the ATS in PLM**
- **Phase D**
  - **Test Specification peer reviews for Builds 3 & 4, Operational Stress test cases**
  - **Complete Build 3 & 4 acceptance test executions, generate closure reports, update verification matrix and baseline the ATS in PLM**
  - **Complete Operational Stress Test Execution and generate Findings Report**

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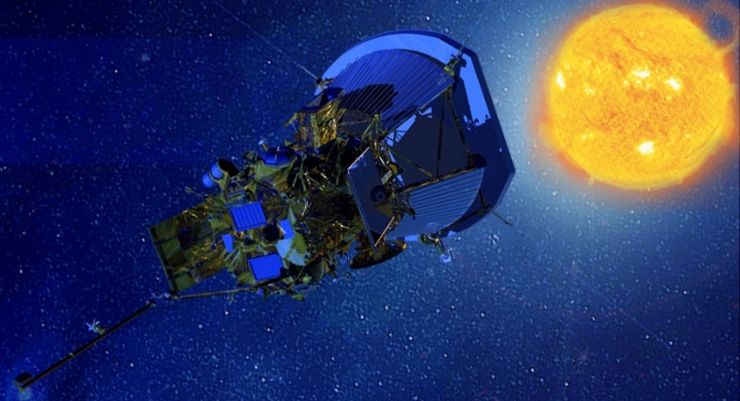

Data Systems Overview

Alan Mick

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13 – 16 January 2014

APL
The Johns Hopkins University
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Data Systems Review

- Driving Requirements
- Reference Design
- Spacecraft Data Network
- High Rate Science & Telemetry Data Return
- Low Rate Health and Safety Telemetry

Data System Overview

DRIVING REQUIREMENTS

Data Return

- **CDH: DATA RETURN: The mission shall provide an average of 85 (TBR) Gbits of science data per orbit to the ground. (MDR-52)**
- **S/C HOUSEKEEPING COLLECTION: The spacecraft shall collect, store and downlink, during designated contacts, housekeeping data from spacecraft subsystems at a combined, total rate of no more than 0.090 Gbits/day (TBR). (SCRD-255)**
- **TOTAL DOWNLINK VOLUME: The spacecraft shall be capable of downlinking an average of 127 Gbits (TBR) of data per orbit, including science, housekeeping, margin, and packetization and framing, during the first and/or second orbit period ≥ 0.25AU. (SCRD-232)**

Data Return Summary

Category	Per Day	Per Orbit Nominal	Data Rate + 28%	CFDP + 3%	CCSDS + 2.2%
Science Data	NA	85.0	108.8	112.1	114.5
S/C Telemetry	0.083	9.3	11.9	12.3	12.5
Totals	NA	94.3	120.7	124.3	127

All Values in Gbits (10^9)

Data Return – Real Time

- **The mission shall provide real-time communication during instrument commissioning.**
- **The mission shall (during cruise) provide real-time housekeeping data at least three times per week for the purposes of monitoring spacecraft and instrument health and status from the ground.**
- **The mission shall provide an indication of aliveness at least three times per week during encounter periods.**
- **The mission shall provide instrument fault protection to include ground system monitoring of selected instrument health data.**

Prioritize Onboard G&C Data

- **The mission shall include a 3-axis stabilized spacecraft.**
- **The mission shall ensure that the observatory (with the exception of the TPS, solar arrays, SLS, FIELDS PWI antennas, and SWEAP SPC) remains in the umbra within 0.7 AU.**

To meet these requirements high rate guidance and control processing must be prioritized.

This requires prioritization of G&C sensor data on the spacecraft data network.

5 Hz Onboard Telemetry

- **Fault Management response time budget trade study determined that response time is sensitive to telemetry collection frequency.**
- **Varying persistence requirements and subsystem telemetry collection rates showed a significant gain in minimizing latency with 5 Hz telemetry collection, and little gain at rates above 5 Hz.**
- **This analysis determined that a 5 Hz telemetry collection rate is required to meet spacecraft safing needs.**

This requirement is met by inclusion of the required information volume in the spacecraft data network rate estimates, and inclusion of the necessary transactions in the spacecraft data network schedule.

Spacecraft & Instrument Onboard Data Sharing

- **The mission shall provide an indicator to instruments prior to firing a thruster.**
- **The mission shall provide the capability to share a limited amount of instrument messaging information sufficient for the purposes of coordinating concentrated or focused measurement (burst mode) periods.**
- **The mission shall ensure that the absolute time knowledge accuracy for measurements made by the instruments is to within +/- 1 second (3-sigma) after post-processing on the ground when the spacecraft is within 0.25 AU of the Sun.**

These requirements are met by conformance to the General Instrument ICD message formats and by inclusion of the required information in the spacecraft data network rate estimates.

Data System Overview

DESIGN DESCRIPTION – ONBOARD SPACECRAFT DATA NETWORK

Simplified Spacecraft Block Diagram

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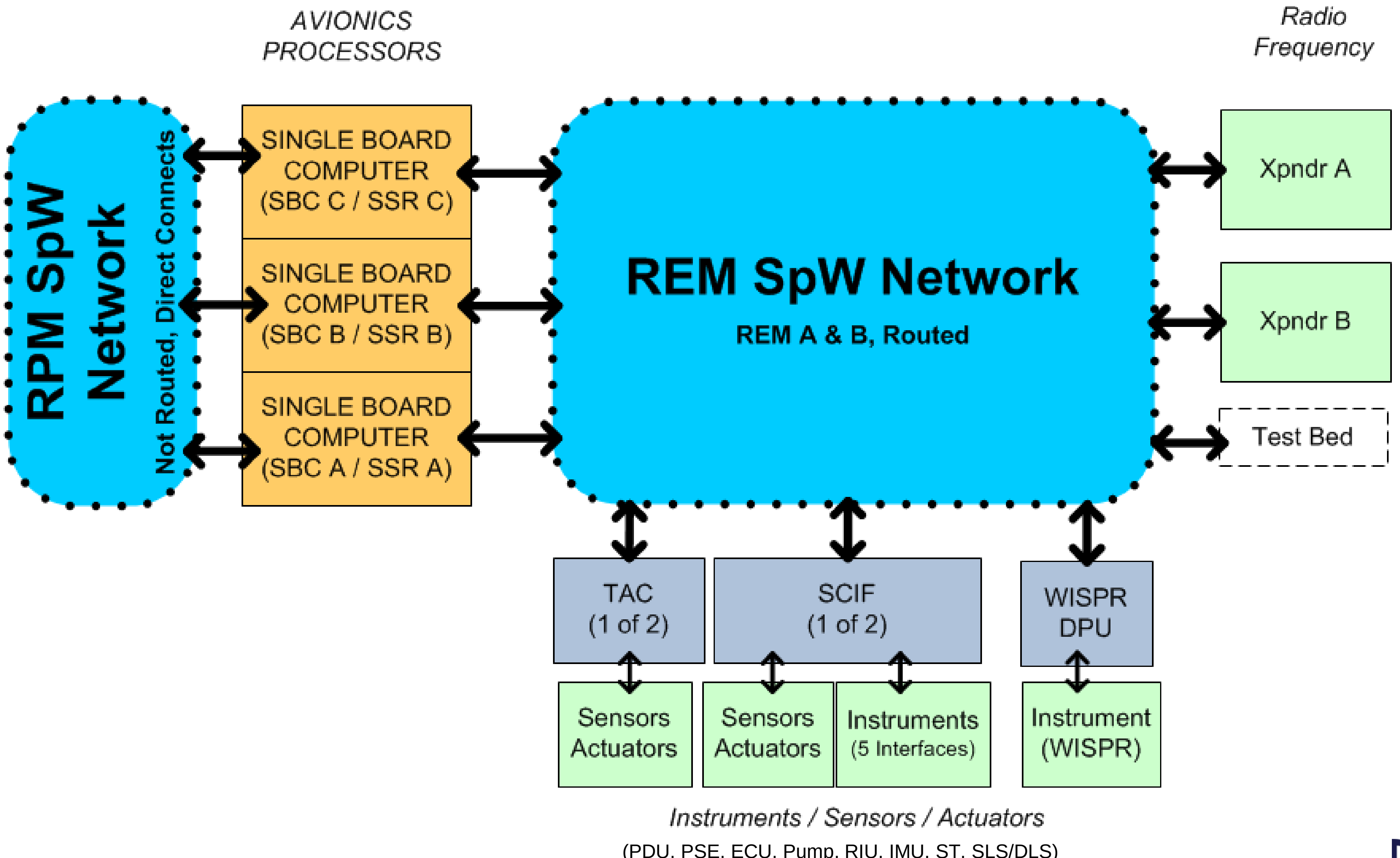


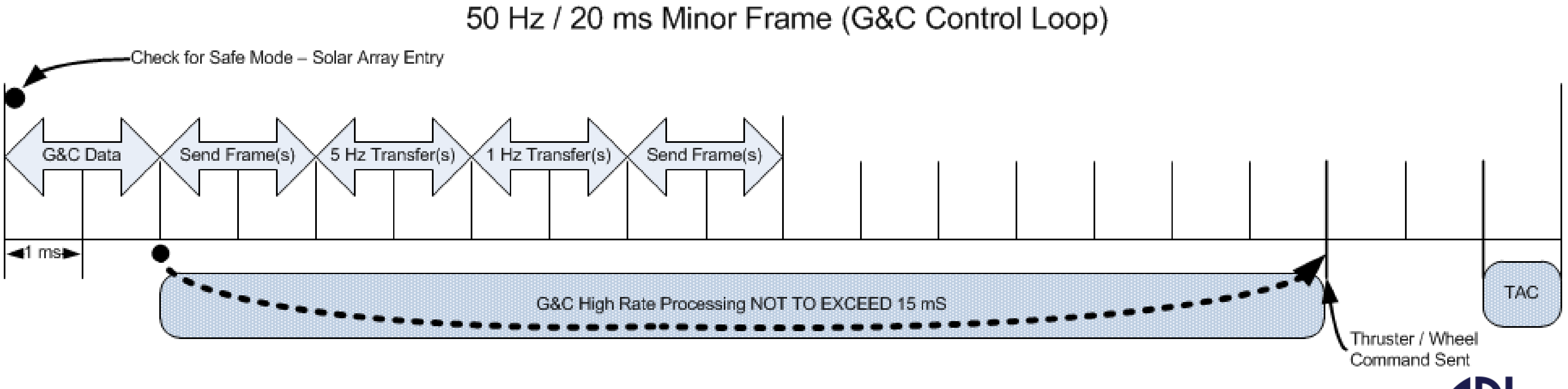
Onboard S/C Data Rate Estimates

REM Data Path	Phase	Highest Average (kbps)	Max Possible (kbps)	Value Used (kbps)
Instrument Data to SBC Prime	Encounter	758	1078	1078
G&C Data Rate to SBC Prime	All	83	~	83
Component Telemetry to SBC Prime	All	328	~	328
Command & Spacecraft Telemetry to Components	All	~	311	311
Commands from both XPNDR s to SBC Prime	Cruise	4	~	4
Downlink Telemetry SBC Prime to one XPNDR	Cruise Downlink	1000		1000
Frame Request from one XPNDR to SBC Prime	Cruise Downlink	2		2
Total 2.8 Mbps, SpW Capacity 24 Mbps				

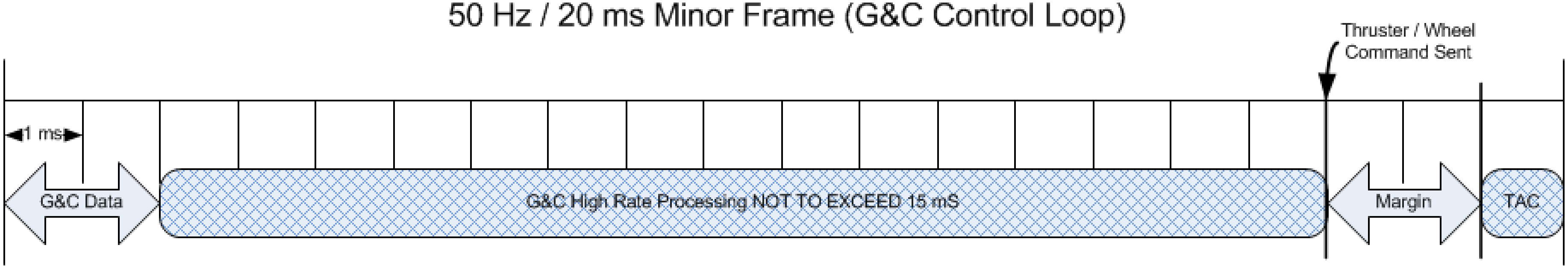
RPM Data Path	Phase	Highest Average (kbps)	Max Possible (kbps)	Value Used (kbps)
Instrument Data to SBC Spare SSR	Encounter	341	~	758
S/C Housekeeping for Downlink to Spare SSR	All	1	~	1
S/C Housekeeping for Contingency to Spare SSR	All	2.7	~	2.7
Total 0.762 Mbps, SpW Capacity 24 Mbps				

Onboard Spacecraft Network Transaction Schedule

- **SpaceWire time codes are generated and distributed by the SCIF / router card. These delineate the 50 Hz / 20 ms minor frame.**
- **SBC Prime initiates data transfers within each minor frame to ensure response time and throughput requirements are met:**
  - **50 Hz G&C High Rate Control Loop**
  - **5 Hz Critical Telemetry Collection**
  - **1 Hz Command and Telemetry**
  - **Telemetry Transfer Frames to the transmitting XPNDR.**
  - **Telecommand Transfer Frames from the XPNDR(s).**



G&C Data Collection Margin



- **G&C High Rate Processing is *not to exceed* 15 ms out of the 50 Hz / 20 ms frame**
  - **7.5 ms nominal CBE with margin.**
  - **The CBE was doubled to provide a "not to exceed" limit for G&C processing.**
- **1 ms is allocated for TAC processing. With high rate G&C processing not to exceed 15 ms, 4 ms maximum is available for G&C data collection.**
- **G&C data collection worst-case must allow for a frame request and two commands to arrive during execution.**
- **At a SpaceWire link rate of 30 MHz the worst-case time to collect the G&C data at the beginning of the 20 ms frame is 1.96 ms.**
- **1.96 ms out of a maximum of 4 ms represents a 100% margin.**

Spacecraft Network Margin

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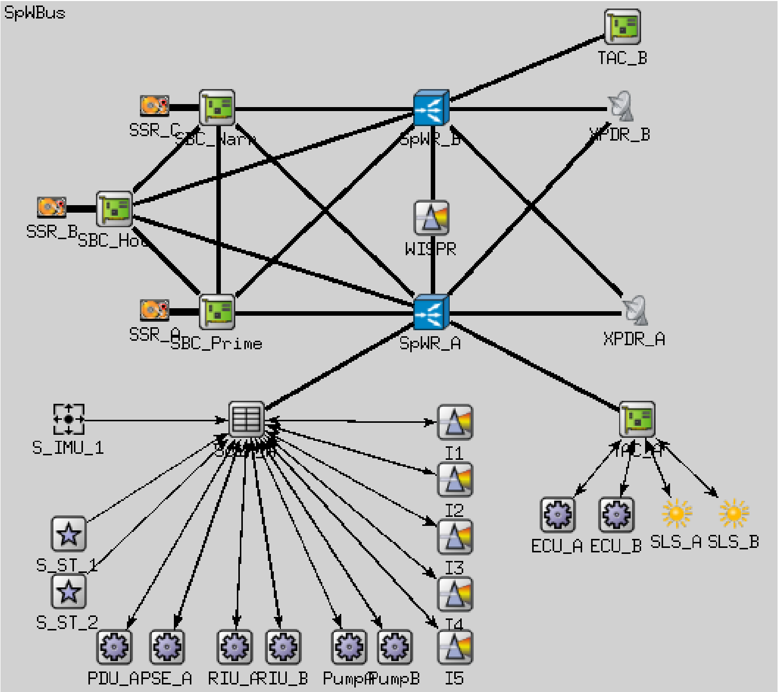


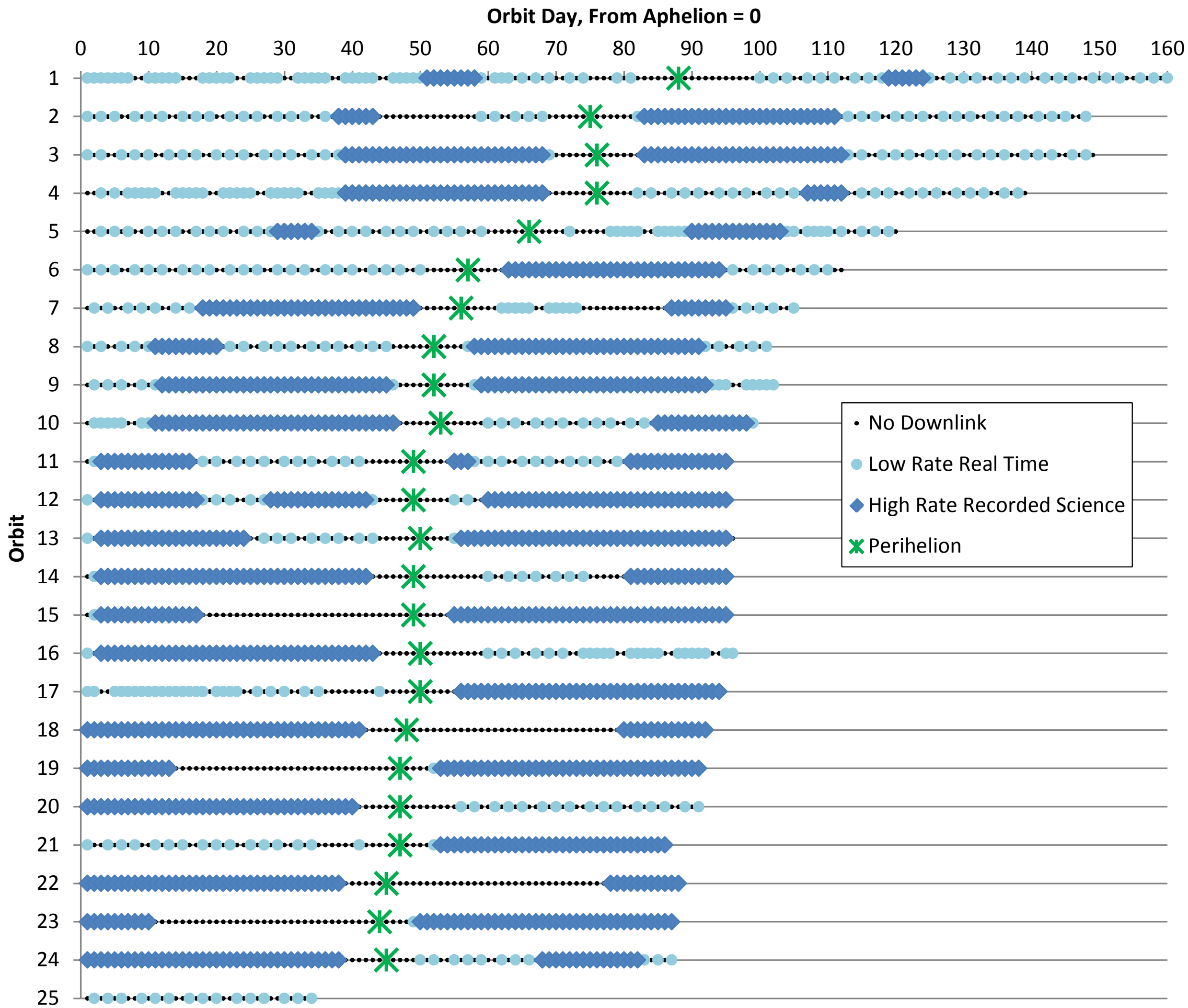
- **A discrete event model of the SpaceWire transactions has been developed**
- **Adds SpaceWire and RMAP protocol overhead (headers, ACKs) to the estimates**
- **Accounts for scheduling inefficiencies**
- **Allows transaction schedule to be developed experimentally**
- **Based on the worse case usage scenario**

- **G&C Data Collection: 2.0 out of 4 ms = 100%**
- **Data Rate Margin: 7.5 out of 17 ms = 126%**

Data Systems Overview

SCIENCE DATA RETURN

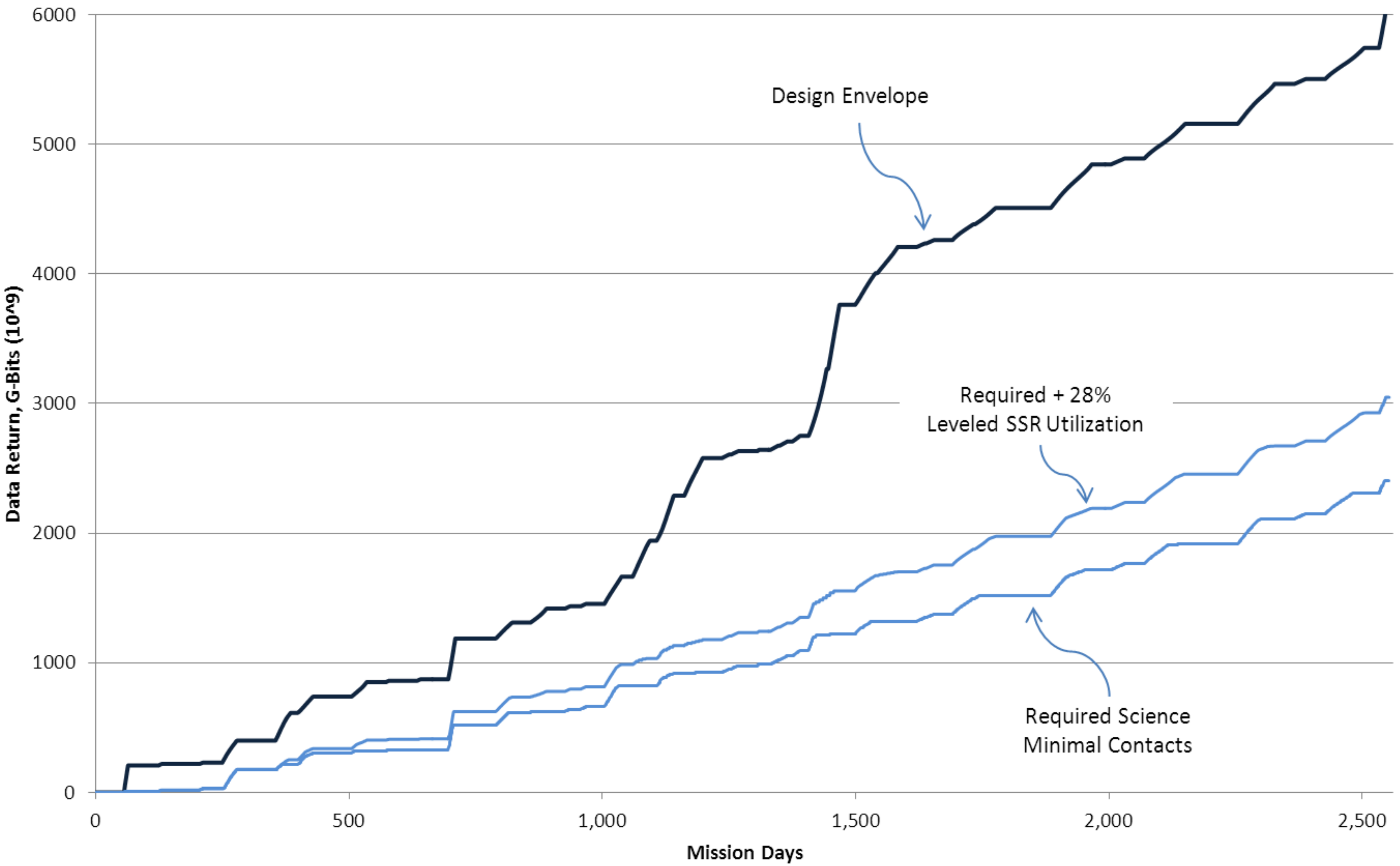
Ka Band Downlink Opportunities



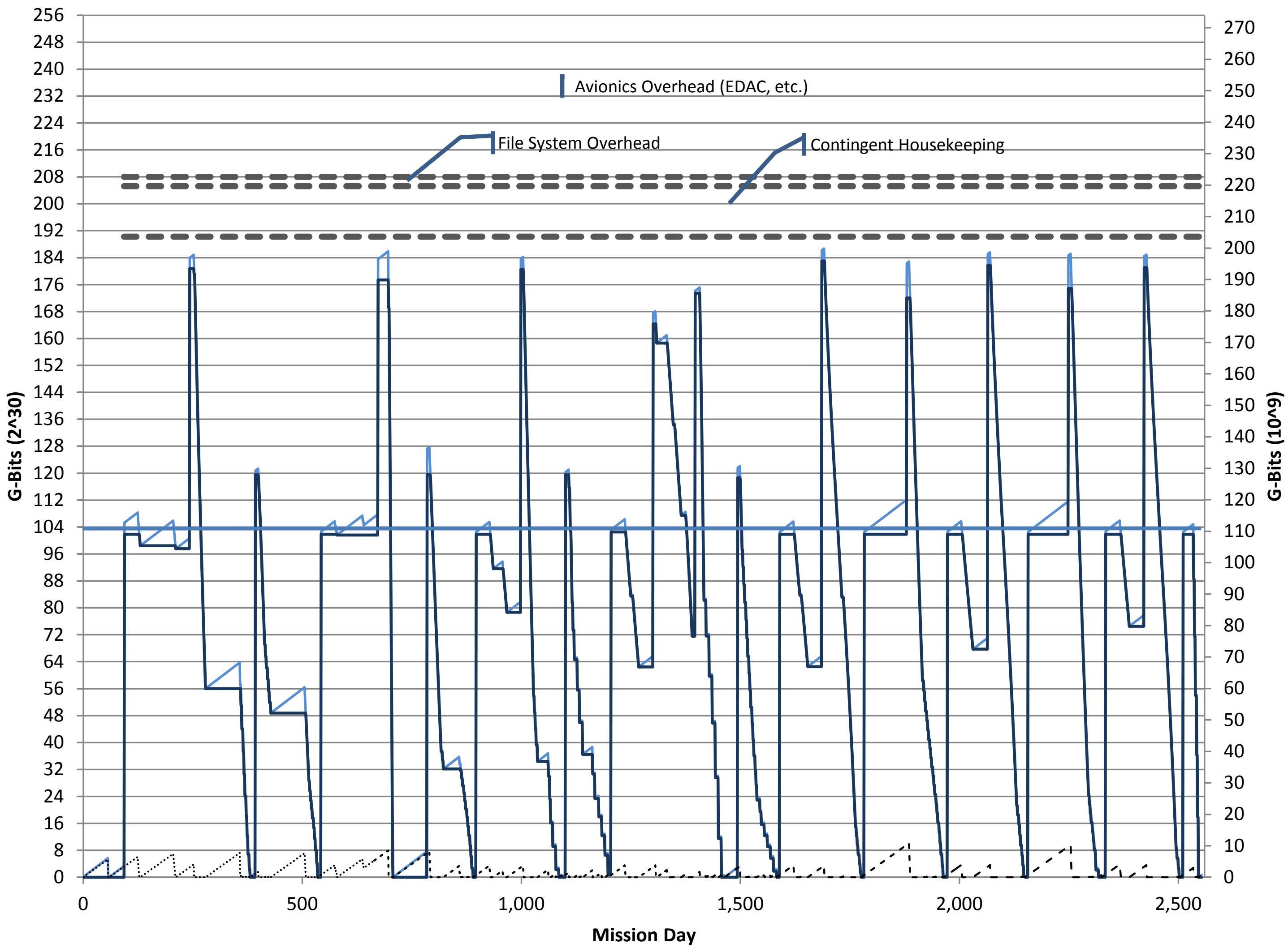
Notional Contact Schedules

Contact Schedule Description	Net Science per Orbit	Ka Contacts	Total Mission Data	Average Per Orbit
Downlink Contact Design Envelope	NA	1,087	6,067	253
1. Required + 28% Margin, Leveled SSR Utilization	110.5 (Average)	744	3,170	132
2. Required Science Return, Nominal Contacts	85	627	2,652	111

Contact Schedule Design Envelope and Notional Schedules



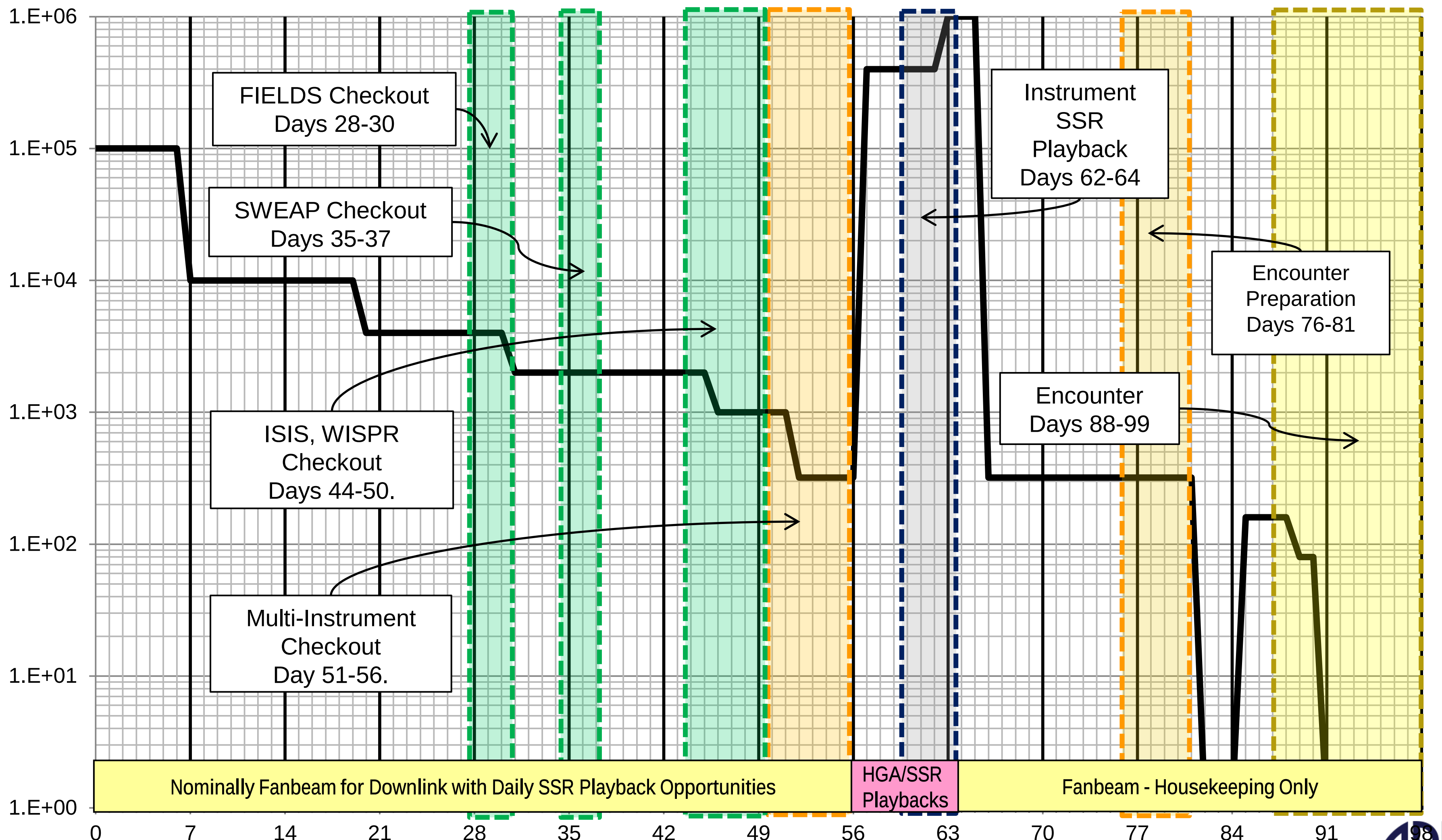
SSR Utilization / Downlink Profile



Data System Overview

LOW RATE / REAL TIME TELEMETRY

Instrument Commissioning DL Data Rates



Low Rate X-Band Telemetry

- Real Time Housekeeping Data Frequency and Rate (SCRD-233)
  - Three Times per Week
  - Rate of ≥ 10 bps
  - Exceptions apply:
    - During encounter,
    - Sun-Earth-Probe angle is less than 3 degrees
    - Blocked by the Thermal Protection System.
- Current schedule provides both 8.5 and 10 hour low rate contacts

- **Notional health and status pass:**
  - **Based on the minimal x-band data rate of 10 bps**
  - **Based on nominal spacecraft status**

Notional Low Rate / X-Band Contact

- Based on New Horizons low rate spacecraft / instrument health and status contacts
- Fault Management Summary
- Guidance & Control
- Instrument Critical Housekeeping
- Spacecraft Data Summary Table:
  - Collects maximum and minimum values, along with the time of occurrence, for varying measurement points
    - Temperatures
    - Currents
    - Voltages
    - Pressures
- Selected and Summary Subsystem Telemetry
  - C&DH + Subsystems
  - Current Temperatures
  - Current PDU State
  - Current PSE S/A PV Sensors
  - SSR Data Summary

Two Transfer Modes

- Foreground
  - Critical cyclic and evolving real time telemetry
  - Intermittent, short real time packets
  - Immediately displayed
  - Allows triggers and alarms

- Background
  - Data for trending and analysis
  - Large data structure files, delivered by CFDP during contact
  - Available for use within the contact period, but not immediately displayed
  - The background data stream also contains a small volume of CFDP control responses for the uplink commanding.

Low Rate X-Band Pass Data Plan

- **Real Time, Immediate, Foreground Telemetry**
  - **Fault Management Summary**
  - **Critical Instrument Summary**
  - **Critical Power System Summary**
  - **Critical Cooling System Summary**
  - **ECU / Pump Summary**

  - **Downlink time of 5 Minutes per iteration at the lowest (10 bps) x-band rate.**

- **Background Trending and Analysis Telemetry**
  - **Guidance and Control (1.5 KB)**
  - **Instrument Critical Housekeeping, Sample (0.5 KB)**
  - **Data Summary Table (9.0 KB)**
  - **Current C&DH + Subsystems (2.0 KB)**
  - **Current Temperatures (All) (0.5 KB)**
  - **Current PDU State (1.3 KB)**
  - **Current PSE S/A PV Sensors (3.0 KB)**
  - **SSR Summary (0.5 KB)**

  - **Total of 18.3 KB, Downlink time of 5.5 Hours at 10bps, including framing and CFDP overhead and retransmissions due to nominal 10^{-3} frame error rate.**

Low Rate X-Band Pass Margin: 30%

- Nominal pass is 8.5 Hours
- Foreground real time telemetry
  - Two iterations per hour, once every 30 minutes
  - Over the 5.5 Hour file downlink period, 11 iterations
  - 11 iterations at 5 Minutes each = 55 Minutes ~ 1 Hour
- Background 5.5 Hour downlink + 1 Hour Foreground = 6.5 Hours per pass
- 6.5 Hours + 30% = 8.5 Hours

Conclusion

- **Data Systems and Components support critical requirements**
  - **Spacecraft Data Network**
  - **High Rate Science & Telemetry Data Return**
  - **Low Rate Health and Safety Telemetry**
- **Analysis, risk reduction activities have demonstrated soundness of approach.**
- **Data Systems are ready to proceed to Phase C.**

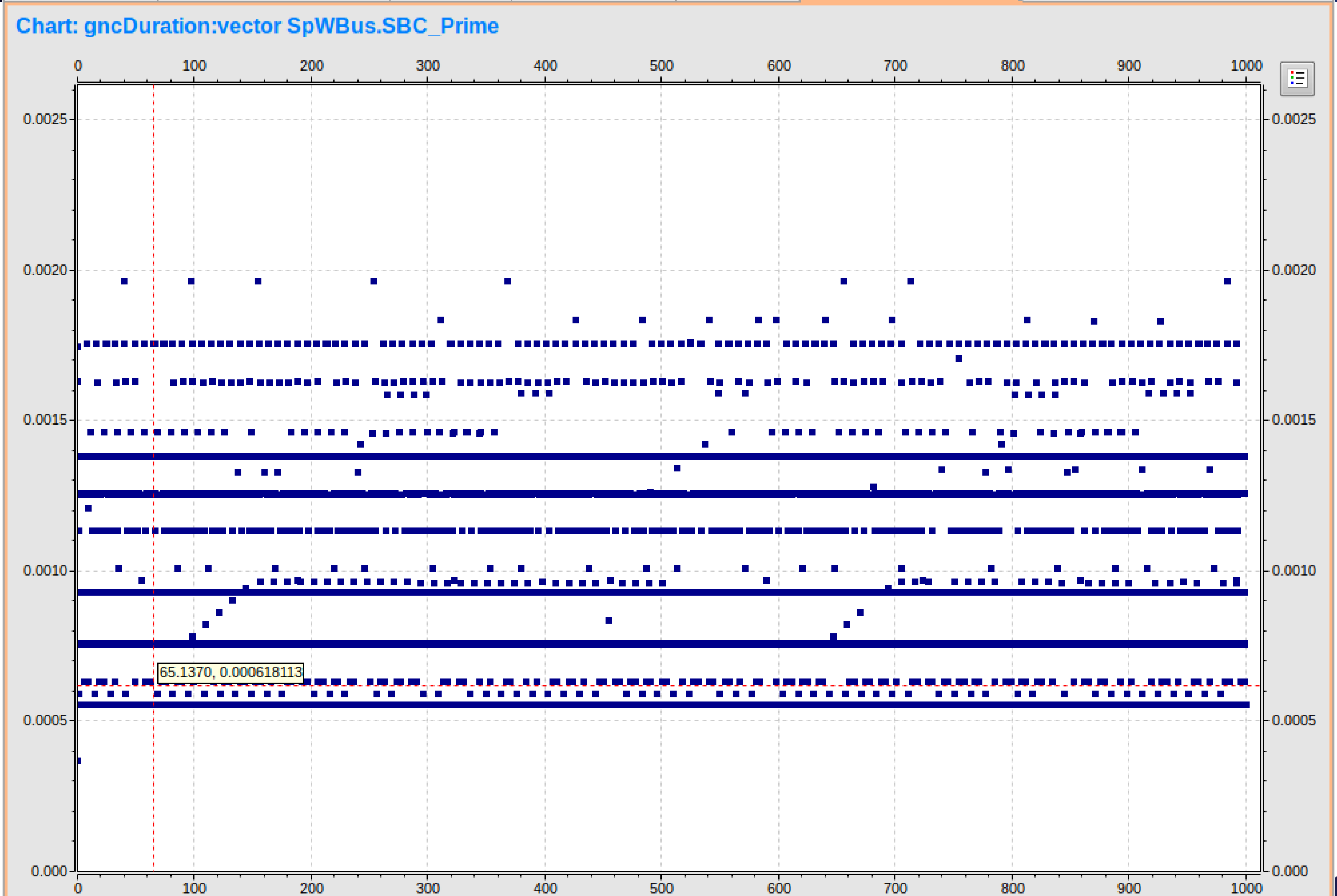
Data System Overview

BACKUP

Science Data Volumes / Rates

Instrument	Gbit / orbit	+ 30%	Avg. Rate <0.25 AU 11 days	Continuous Data Rate	Peak Encounter Rates kbps	Physical Maximum kbps
WISPR	23	30	30 kbps	260 kbps	350	350
					8	8
FIELDS 1 & 2	20	26	26 kbps		80	240
					80	80
SWEAP	20	26	26 kbps		80	240
ISIS EPI Hi & Lo	12	16	16 kbps		80	80
					80	80
Science campaign “data bank”	10	13	13 kbps		NA	
	85 Gbit	111 Gbit	111 kbps	341 kbps	758 kbps	1078

G&C Response Times



Minor Frame Durations

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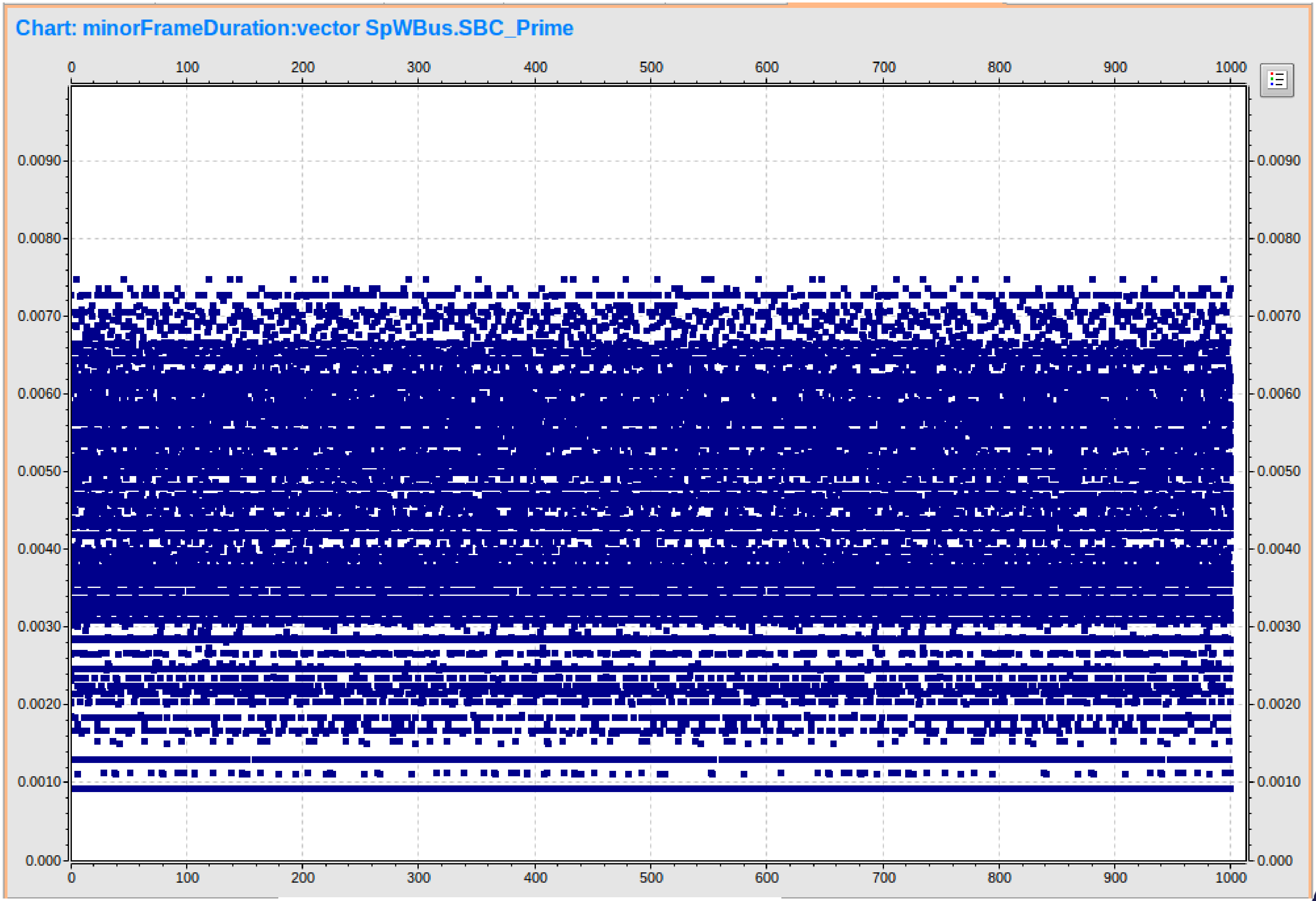

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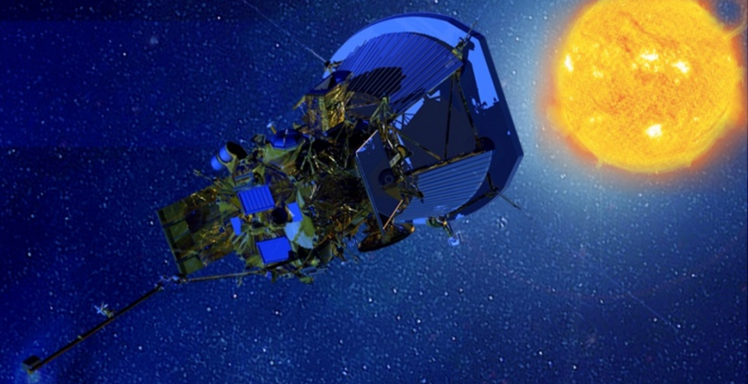

Fault Management

Sanae Kubota
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13 – 16 January 2014

The Johns Hopkins University
APPLIED PHYSICS LABORATORY

Agenda

- **Summary of previous reviews**
- **Requirements flow to & from Fault Management design**
- **Fault Management design**
  - **System Robustness**
    - Redundancy Approach
    - Continuity of Control
  - **Fault Detection & Response**
    - Fault Analyses & Response Planning
    - Critical Faults & Safing Approach
    - Fault Management Modes
    - Ground Intervention Concept
    - Instrument Fault Management
  - **Critical Sequence**
- **V&V plan**
- **Phase C**

Summary of Previous Reviews

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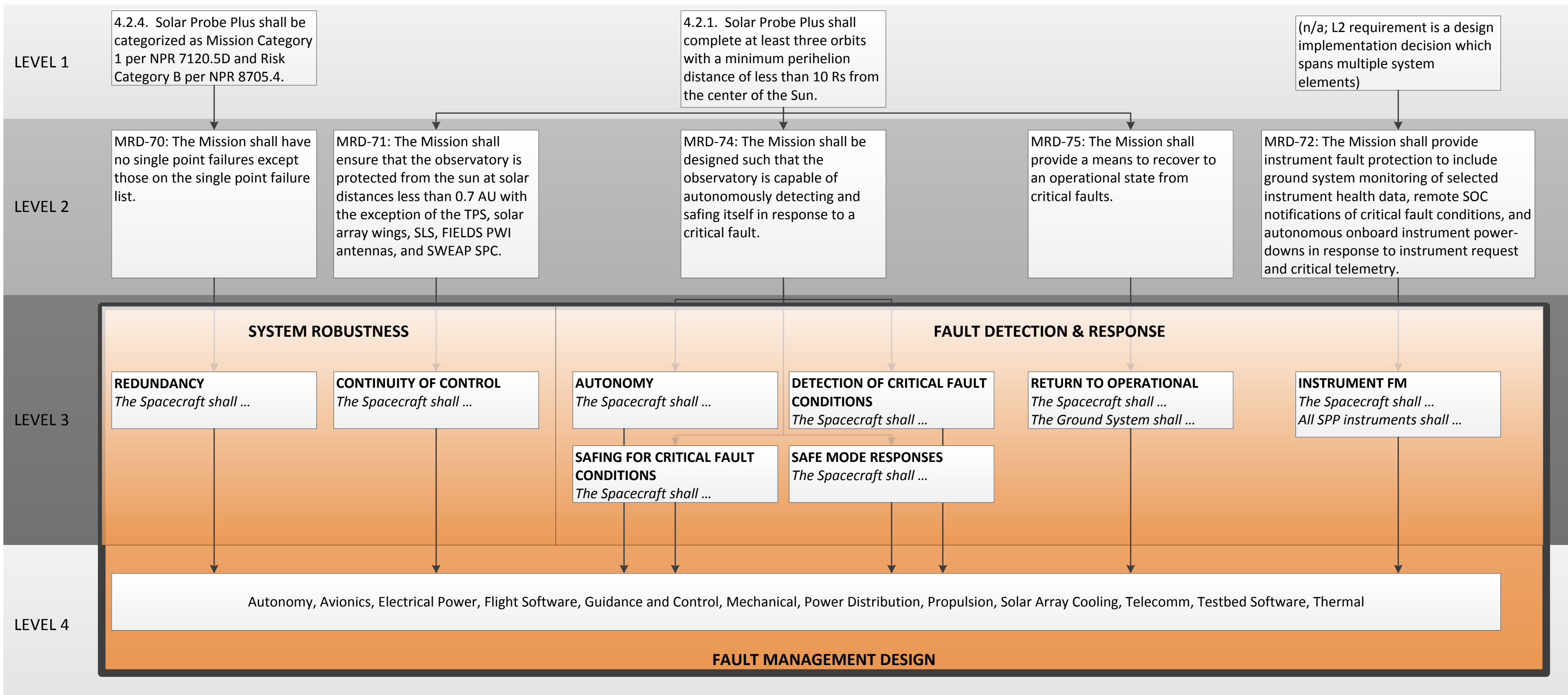
	Mission Design Review	Fault Management PDR*
Date	November 1-3, 2011	May 21-22, 2013
Review Board	SRB	SRB: Chris Jones (JPL), Steve Battel (Battel Engr.), Steve Scott (GSFC) Independent: Ann Devereaux (JPL), Adrian Hill (APL, review chair)
FM Action Items		
- Total	1	8
- Complete	1	8
- Concurred	1	8

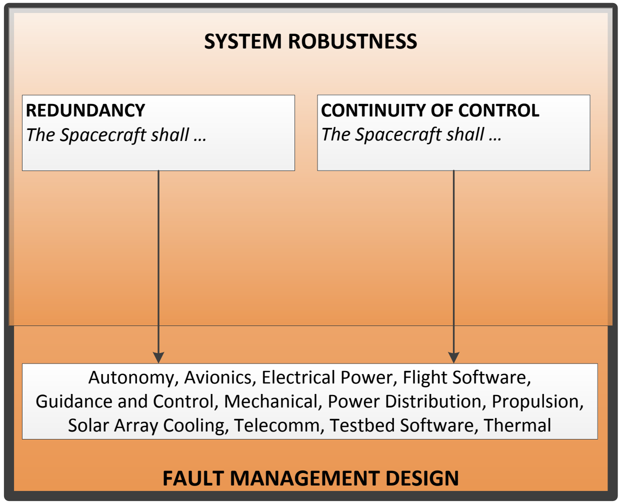
* Held in advance of Level 3 and Level 4 requirements reviews and subsystem PDRs

Requirements Flow to Fault Management Design



- Level 3 and Level 4 requirements are in DOORS and PLM.

Distributed Design for System Robustness



- **Level 3 and Level 4 Requirements* are in place to**
  - **Manage redundant system.**
  - **Be capable of attitude control and wing angle control within time constraints following Prime processor demotion and Safe Mode – Solar Array initiation.**
  - **Ensure redundant pump is operational within time constraints following pump failure.**

*Level 3 Fault Management requirements are provided in back-up. Level 4 Fault Management requirements are referenced in subsystem presentations.

Component-Avionics Interface Redundancy Approach

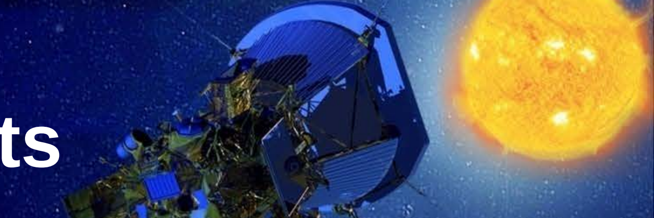
- **Block redundancy offers fewer configurations, and is typically lower mass. Simplicity of block-redundant design favors testability and meets requirements.**
- **Components are block redundant with avionics unless cross-strapping is warranted by time criticality required for continuity of control or component-specific interface issues.**

Type	Components
Block-Redundant	PDU, PSE, Breakwires, Propulsion System pressure transducers
Cross-Strapped	IMU, Star Trackers, Wheels, Thrusters, Processors, Sun Sensor Electronics, Pump Controllers, ECUs, Transponders, SACS dP sensors & accumulator pressure sensor, RIUs, Payload Suite

Cross-Strapping Rationale

Time criticality of continuous control	Simultaneous access to both sides needed	Other (rationale)
Processors	ECUs	Payload suite (internally redundant to provide 7 of 9 measurements to meet L1 science requirements)
G&C sensors & actuators	RIUs	SACS accumulator pressure sensor (non-redundant, non-critical)
Sun Sensor Electronics	Transponders	
Pump controllers		
SACS dP sensors		

L3 Redundancy Management & Continuity of Control Requirements Flow to Avionics (L4)



- **Requirements for continuity of control drive avionics architecture.**
  - With three processors, a Hot Spare processor is available to assume control if Prime resets (not a fault), even if one processor has failed.
  - Decoupled RPM and REM allows
    - REM side-switching without removing Prime processor from control.
    - Prime reset/demotion without REM side-switching.

- **Avionics Redundancy Controller (ARC) has been designed to manage the 3 processor architecture.**
  - Contains 3 identical mode controller (MC) cards whose output is triple-voted (2 for 3 redundancy)
  - Controls processor logical states and state transition paths
  - Provides Prime and Hot Spare processor acknowledge timers
    - Prime processor will be demoted to Back-Up Spare if resetting or unresponsive
    - Hot Spare is allowed to reset; will be demoted to Failed if unresponsive
  - Controls power switching for processors, REMs, PDUs, and XPDRs to meet FM requirement

Redundancy Management: Prime processor transitions

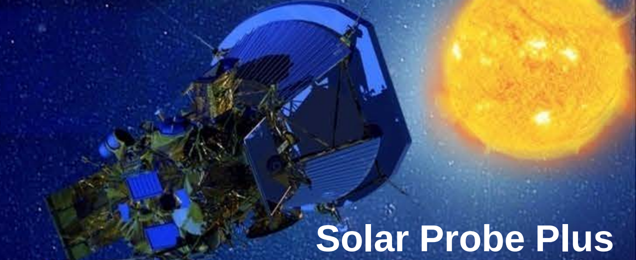
- **To facilitate new Prime initialization, the current Prime will send status messages to both spare processors at 1 Hz.**
  - A new Prime will use the data provided in the most recent valid status message as well as ground-uploaded critical state information stored in non-volatile memory on all three processors.
  - In the event of missing status message data, back-up methodology to regain necessary knowledge has been identified.

- **Status message contents:**
  - Current & Target spacecraft configurations
  - Raw star tracker data
  - Current time data
  - Current accumulated SA flap & feather and HGA step counts
  - Current spacecraft FM mode(s)
  - Processor rotation count & MET of last rotation count reset
  - Safe Mode – Solar Array entry time

Continuity of Control: New Prime G&C Initialization

- **Raw star tracker data provided to HS from Prime in 1 Hz status message**
  - HS performs initial validation checks on ST data and buffers only compliant data (older data will remain available if newer data is non-compliant)
  - Limited Prime processing of ST data lowers likelihood of corruption of data (vs Prime sending computed attitude solution)
  - New Prime uses buffered ST data only if new ST data is not immediately available
- **G&C software starts running with the new Prime 50 Hz bus schedule initialization**
  - Nominally this is immediate
  - In Safe Mode – Solar Array, this is ~3.5 seconds after safing response initiation
- **New attitude estimate is available after 2 seconds from G&C start on new Prime**
  - High rate collection of new sensor data begins immediately
  - In the 2^{nd} second, G&C calculates attitude estimate based on
    - New data if available
    - Buffered data if new data not available
  - Validity check or wait period may follow acquisition of first new attitude estimate prior to commanding of actuators

Requirements Flow to Fault Management Design



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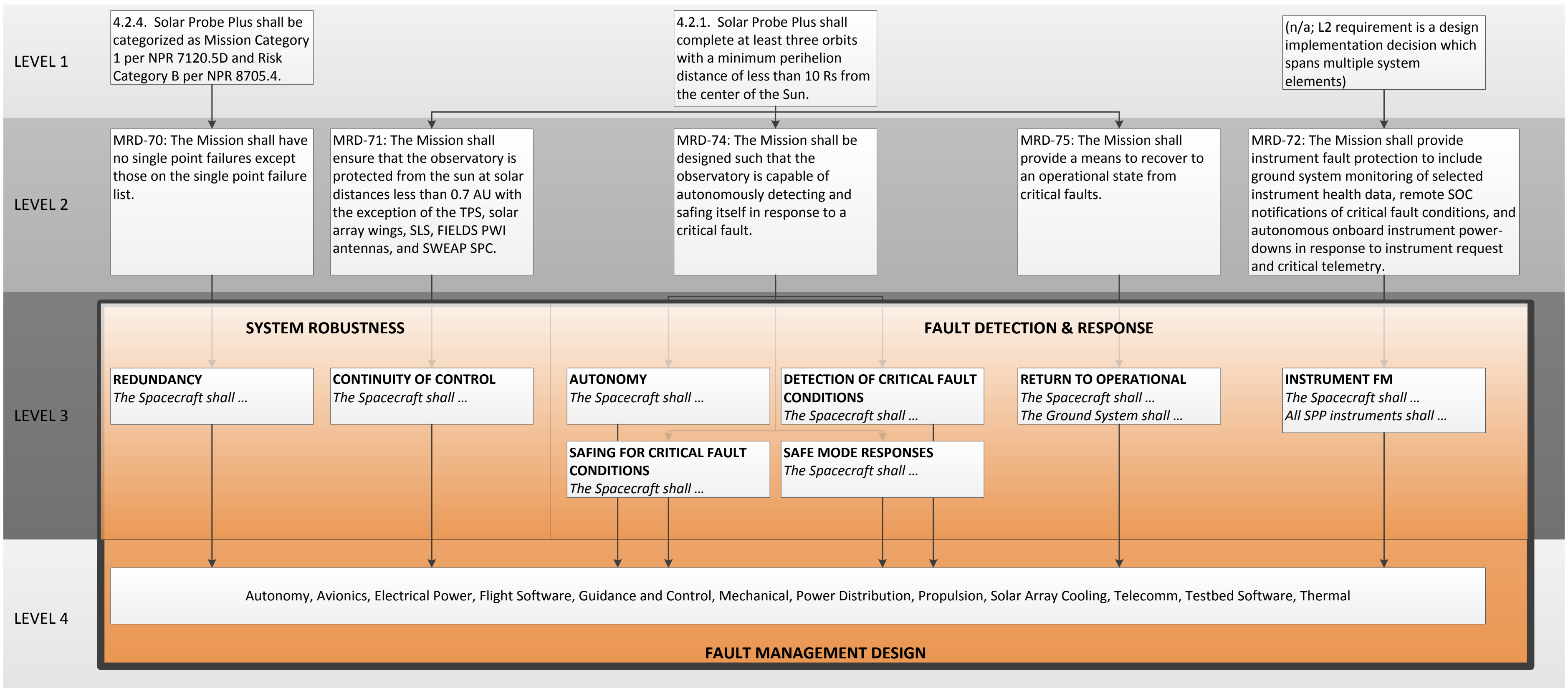
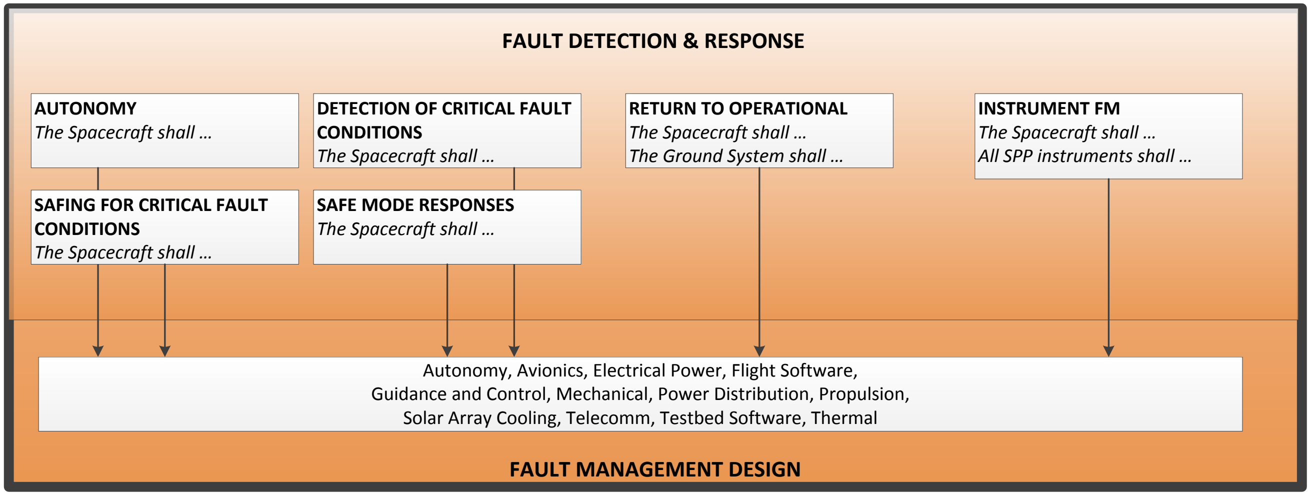


- Level 3 and Level 4 requirements are in DOORS and PLM.

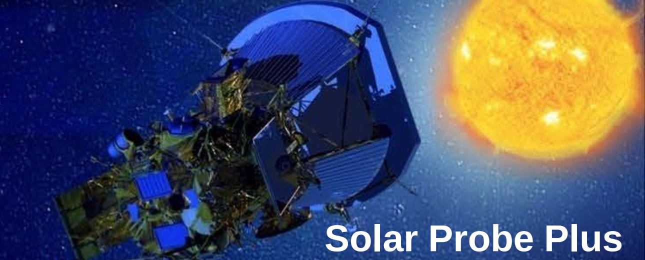
Distributed Design for Fault Detection & Response



- **Level 3 and Level 4 Requirements* are in place to**
  - **Provide an on-board autonomous system to detect and respond to faults**
  - **Provide telemetry to enable fault detection, including each critical fault condition**
  - **Identify and initiate safing response to each critical fault condition**
  - **Execute Safe Mode actions / restrictions, within time constraints when applicable**
  - **Return to Operational Mode and transition between Operational Mode levels.**
  - **Monitor and respond to indications of instrument health**

*Level 3 Fault Management requirements are provided in back-up. Level 4 Fault Management requirements are referenced in subsystem presentations.

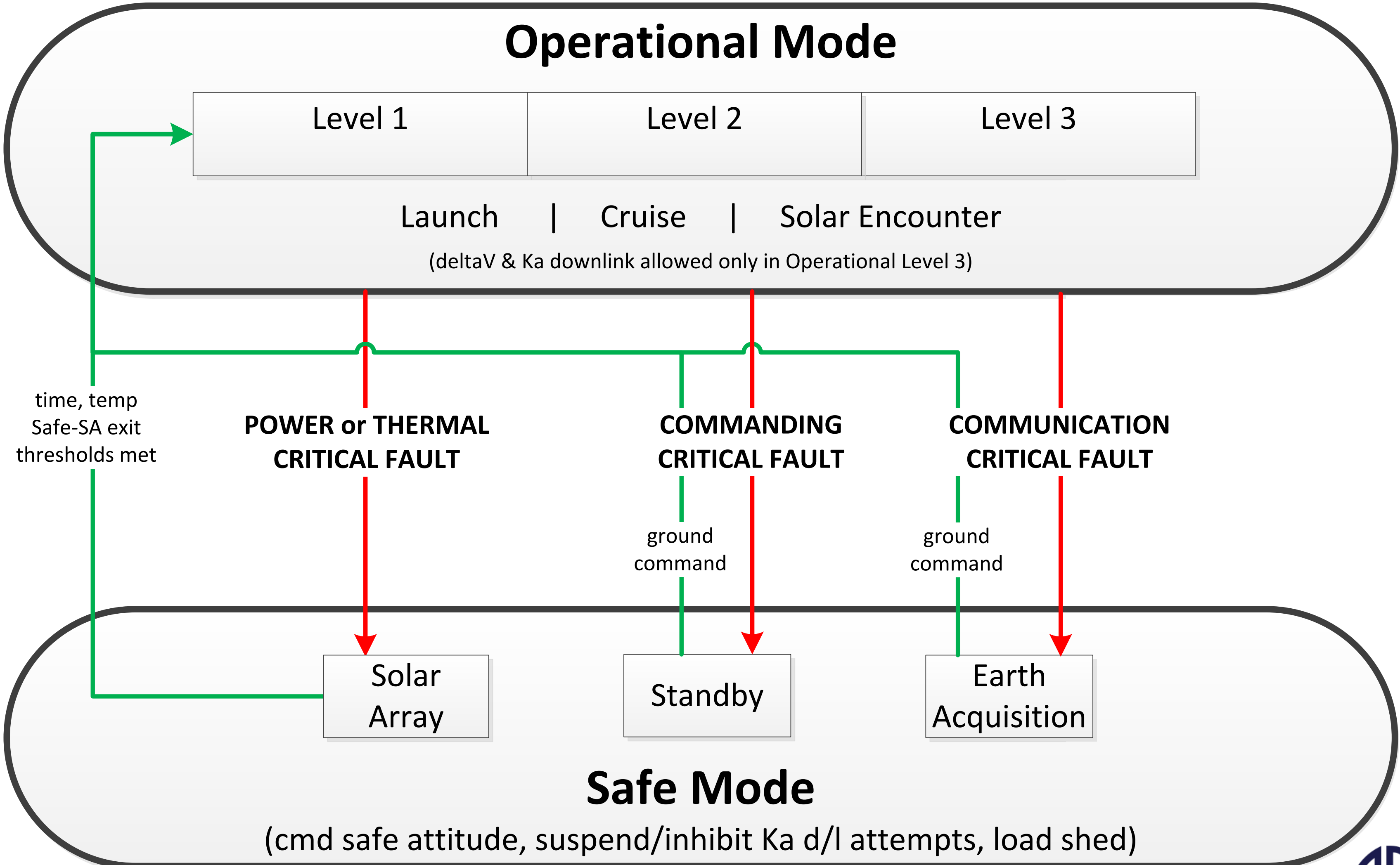
Spacecraft Fault Response Approach and FM Modes



- **SPP Fault Management (FM) utilizes a layered approach to protect the mission, with faults categorized by severity and responses executed at two redundant levels.**

- **Fault response approach is designed to**
  - Implement a simple process with minimized impact to the observatory in the detection and response to less severe and isolated **(local) faults.**
    - **Observatory remains in Operational Mode.**
  - Enable a power-, communication-, commanding-, and thermally-safe observatory in the event of **critical faults** through a system-wide response to protect against “unknown unknowns.”
    - **Observatory demoted to Safe (Non-Operational) Mode.**
    - Meets L2 requirement to autonomously detect and safe in response to a critical fault.

Fault Management Modes – quick look



Fault Analysis & Response Planning

Three step iterative process:

1. **Bottom-up fault analysis: FMEA**
   - **Identification of failure modes, analysis of effects, and preliminary response planning**

2. **Top-down fault analysis: "EFMA"**
   - **Analysis of effects, completeness of list of causes, and further development of response planning**

3. **Fault response plan developed based on symptoms**
   - **Linked with Level 4 hardware and software requirements to achieve planned response**
   - **Will be linked with FMEA line-items to ensure completeness**
   - **Majority of fault responses are component switching**

Component Switch Types

	REM Switch	Cross Switch	Global Switch
Fault Response Type	Local	Local	System-wide response to critical faults
Applicable Mode	Operational Mode or Safe Mode	Operational Mode or Safe Mode	Safe Mode
Power removed from	Original REM side and all components which are block redundant to it	Original cross-strapped component	All original components (except active pump and G&C sensors)
Power applied to	Redundant REM side and all components which are block redundant to it	Redundant cross-strapped component	All redundant components (except non-critical loads)
Power maintained to	All cross-strapped loads	All other loads	Active pump and G&C sensors

Fault Response Arbitration, p1 of 2

- **Priority-based fault response system**
  - **Ensures immediate execution of time critical responses and**
  - **Resolves potential conflict from competing responses**

- **Preliminary Interference analysis**
  - Examined local and system effects of fault response execution concurrent with
    - Other fault responses (local and system), and
    - Mission scenarios (example: one avionics processor powered off).
  - Preliminary response priority order has been assigned based on results of interference analysis, which includes relative time-criticality of fault responses.

Fault Response Arbitration, p2 of 2

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Ensure immediate execution of higher priority responses:

- Trigger of a higher priority rule will pre-empt an on-going lower priority response.
- Upon completion of the higher priority response macro, the lower priority macro will resume.

Autonomy Evaluation		Autonomy Evaluation				
Rule A (Priority 6) fires	Response A (Priority 6) command #1 of 2					Response A (Priority 6) command #2 of 2
		Rule B (Priority 1) fires	Response B (Priority 1) command #1 of 3	Response B (Priority 1) command #2 of 3	Response B (Priority 1) command #3 of 3	

Resolve potential conflict from competing responses:

- When a REM-switch is commanded, autonomy will suspend rules below the highest priority until 2 s (TBR) after the REM switch is complete.
  - Prevents back-to-back REM-switch commands from resulting in return to original hardware
  - Suspends persistence evaluation for lower priority rules, allowing the REM-switch to clear the fault condition

Critical Faults overview

Unanticipated faults which create conditions that require a timely response to preserve the mission.

- **Persistent,**
- **Not identified in advance or diagnosed in flight,**
  - **"unknown unknowns"**
  - **Responses are designed for identified potential faults to prevent the system from reaching a critical fault condition**
- **Could be attributed to one or more subsystems, and**
- **Pose an immediate risk to mission success.**
  - **Create a condition in which there is a time-critical threat to spacecraft thermal, power, communication, or commanding ability.**

Critical Faults

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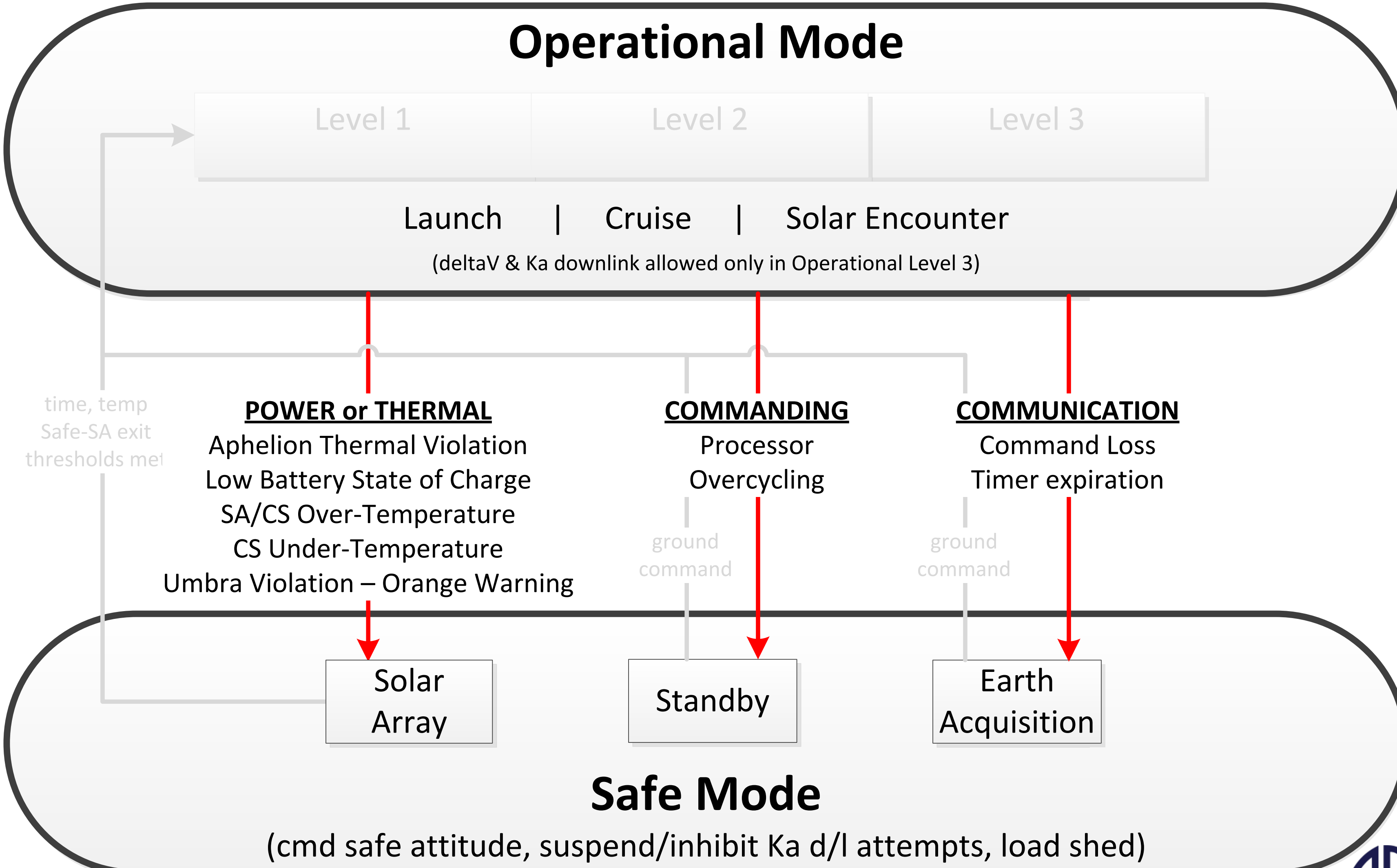
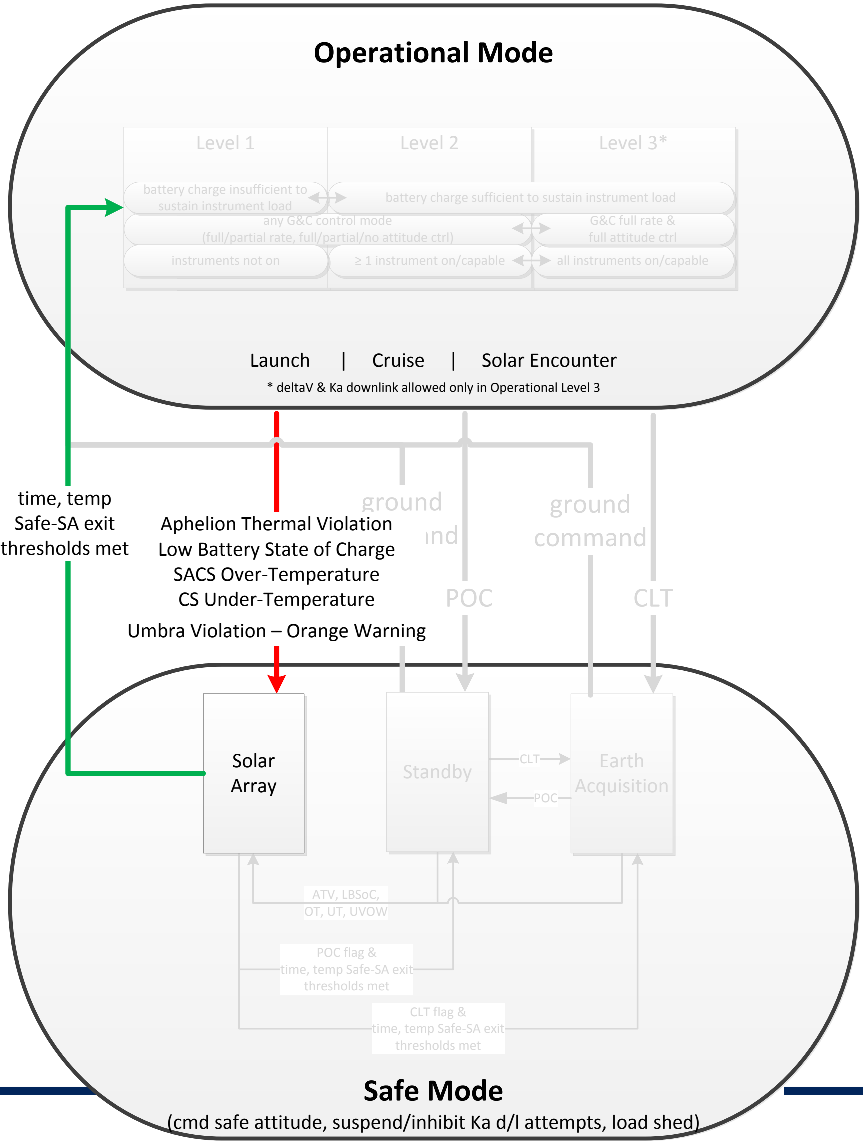


Safe Mode operations

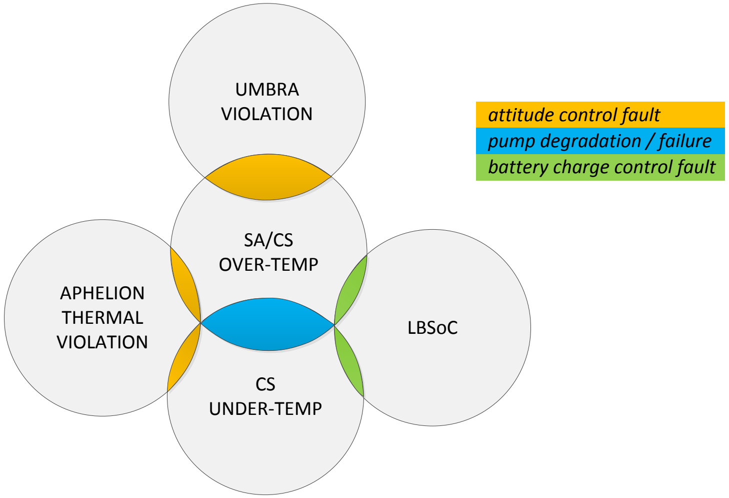
- **Safe Mode commanded by Autonomy following detection of critical fault condition.**
  - **Current Fault Management mode stored in FSW**
- **System-wide recovery procedure**
  - **Processor switch (except in Processor Overcycling response)**
  - **Global-Switch, including:**
    - **Power-Cycle**
    - **Load Shed**
- **Limited spacecraft activity; the following are not executed while the spacecraft is in Safe Mode:**
  - **Delta V maneuvers**
  - **Spacecraft slews (except to mission default or Earth comm)**
  - **Ka downlink**

Power & Thermal Critical Faults: Safe Mode – Solar Array



Power & Thermal Critical Faults: Transient Safe Mode – Solar Array

- ***<u>Discussed in detail in dedicated Solar Array Safing section.</u>***
- **SPP's G&C, power, and cooling systems are tightly coupled; multiple critical scenarios may result from a single fault source.**



- **Safing responses to all power and thermal critical fault symptoms are identical, allowing the response to simultaneously provide recovery action to multiple critical scenarios.**
- **In the event of power and thermal critical faults within 0.35 AU, a steady state safe mode is not available to SPP.**
  - **There is no fixed solar array wing angle that will maintain the cooling system within thermal limits (steady-state) and allow attitude error up to umbra violation.**
- **SPP implements a <u>transient</u> solar array safing operation within Safe Mode – Solar Array for power and thermal critical faults.**

Solar Array Safing Sequence

- **Prime processor demotion and global switch take place prior to solar array safing**
  - Allows SA safing to be commanded and implemented by new components

- **Global switch includes power-cycle of most components**
  - Exceptions include cooling system pump, solar limb sensors, star trackers, IMU, new Prime
  - Instruments will be powered off

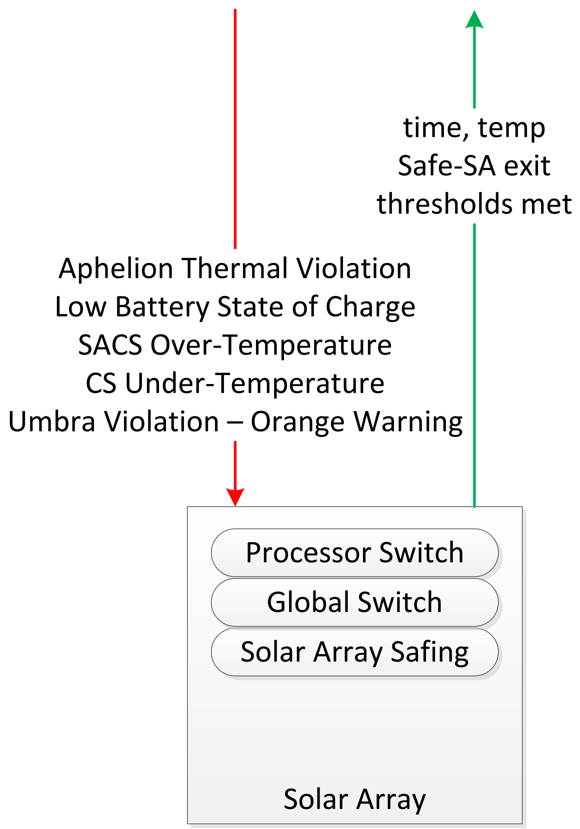
- **Command solar arrays to target safing angle**
  - Determine current wing angles based on majority vote
  - Reference MET-based stored table of safing angles
    - MET stored redundantly in hardware and software
  - Determine & command required steps to reach target angle (0.5 deg/s)

- **Exit criteria*:**

  (> 90 seconds TBR from safing start & <= 125C TBR)

  or 308 seconds TBR from SA safe angle achieved

Solar Array Safing presentation



*Implementation of timers is TBR; purpose is to show worst-case stack-up of time from fault detection to wings return to operational

Power-Cycling Exceptions

- **Pump**
  - A pump failure resulting in pump switch at full cooling system capacity may result in SA platen temperature reaching safing threshold before the new pump is fully operational.
    - Undesirable to power-cycle the new pump while it is attempting to recover the system.
    - Resulting Safe Mode-Solar Array operations will include moving the SA wings to a minimal load position, increasing the rate of temperature drop.
- **Star Trackers**
  - Removal of star tracker power induces start-up transients which
    - Delays determination of valid attitude solution due to loss of prior attitude knowledge, and
    - Removes potential ability to maintain generation of valid attitude solutions when radiation or stray light is increasing
  - Star trackers will be power-cycled upon SLS illumination.
- **IMU**
  - Removal of IMU power induces start-up transients for gyros which
    - Invalidate prior trending of biases, and
    - Degrades attitude knowledge, most significantly when propagating on gyro rates when star trackers are not available
- **Sun Sensor Electronics**
  - Removal of SLS power interferes with the ability to detect changes in Sun offset angle
  - Computation of Sun offset angle requires continuous monitoring of the two Sun intensity levels
  - Sun presence determination remains available following loss of power

Detection and Response to Power & Thermal Critical Faults: Timing Budget Summary

- **Time from safing threshold met until commanding of SA to transient safe position: 10 seconds allocated**

Step*	CBE (seconds)
Initial fault detection to safe mode command sent	1.7
Prime processor demotion	1.4
Global switch (until ready to evaluate SA position & command safing)	1.5
Solar array safing (wing position evaluation & command to target angle)	0.8
TOTAL	**5.4**
Margin remaining in allocation	*4.6*

- **Time for movement of wings to transient safe position and return to operational: budget presented in Solar Array Safing presentation**

* detailed timeline is included in back-up

Operational Mode

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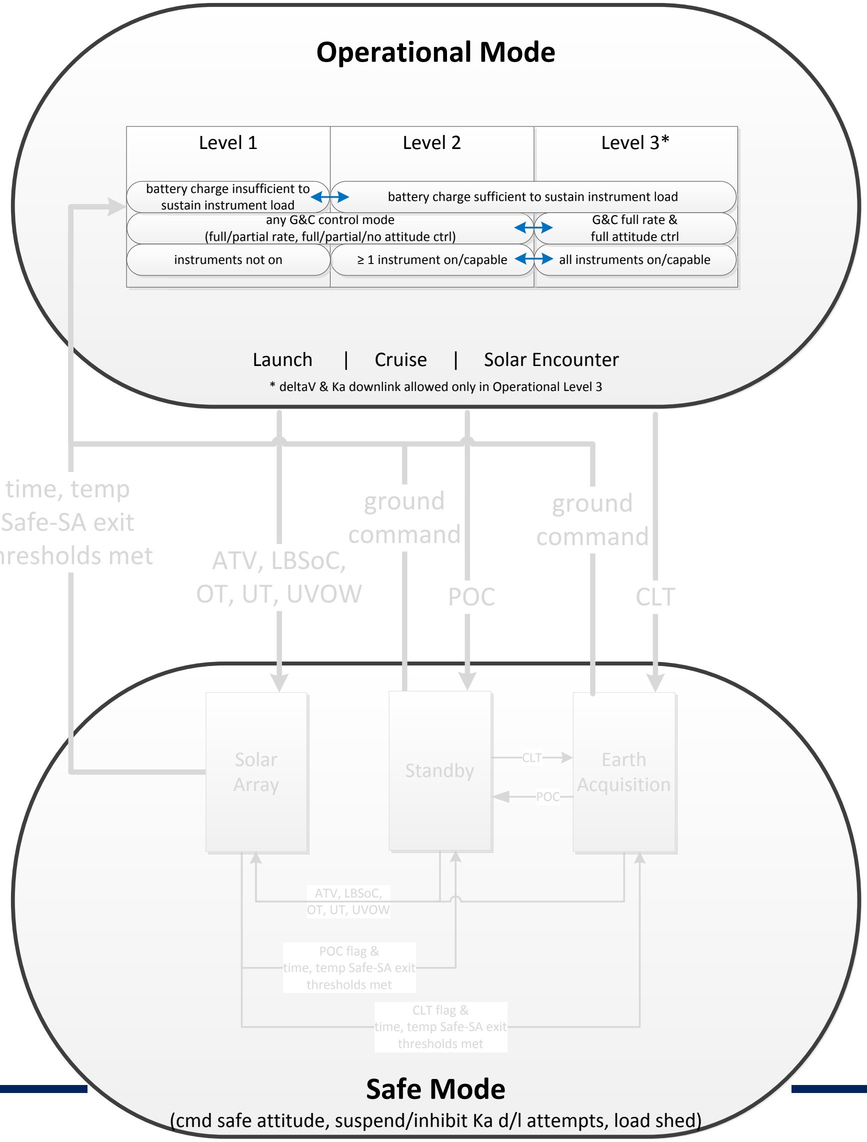


APL

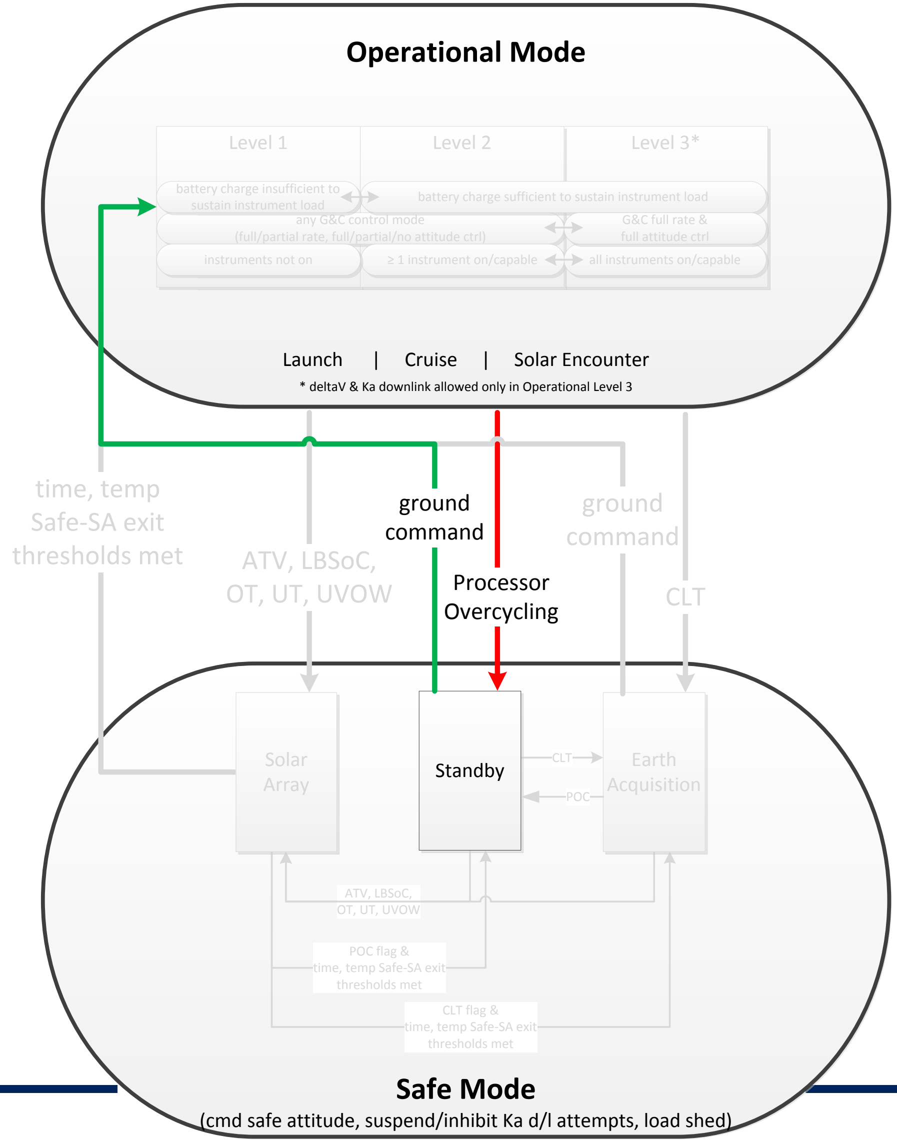
Operational Mode

- **SPP will autonomously return to Operational Mode Level 1 following the transient solar array safing response to thermal and power critical faults.**
- **Operational Mode contains three levels:**
  - **Level 1: Returns autonomous solar array wing angle control.**
  - **Level 2: Entered upon sufficient battery recharge to support return of instrument loads.**
  - **Level 3: G&C full rate and full attitude control. Battery charge level sufficient to support all instrument loads.**

Level 1	Level 2	Level 3*
battery charge insufficient to sustain instrument load	battery charge sufficient to sustain instrument load	
any G&C control mode (full/partial rate, full/partial/no attitude ctrl)		G&C full rate & full attitude ctrl
instruments not on	≥ 1 instrument on/capable	all instruments on/capable

* delta V & Ka downlink allowed only in Operational Level 3

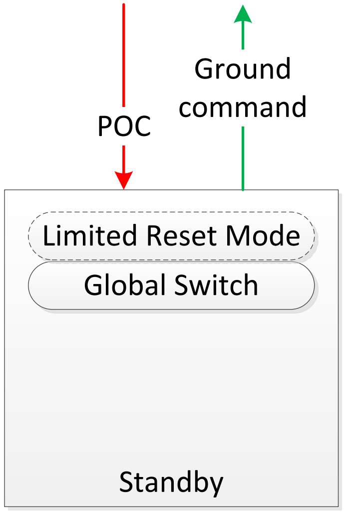
Commanding Critical Faults: Safe Mode - Standby



Commanding Critical Fault: Safe Mode - Standby

- Processor Overcycling
  - Excessive Prime processor demotions

- Safing operation
  - Enable limited reset mode
    - Failure of non-critical tasks to feed the SBC WDT will not result in a reset.
  - Discontinue Autonomy-commanded Prime self-demote
  - Global Switch



- Exit criteria
  - Ground command

Communications Critical Faults: Safe Mode – Earth Acquisition

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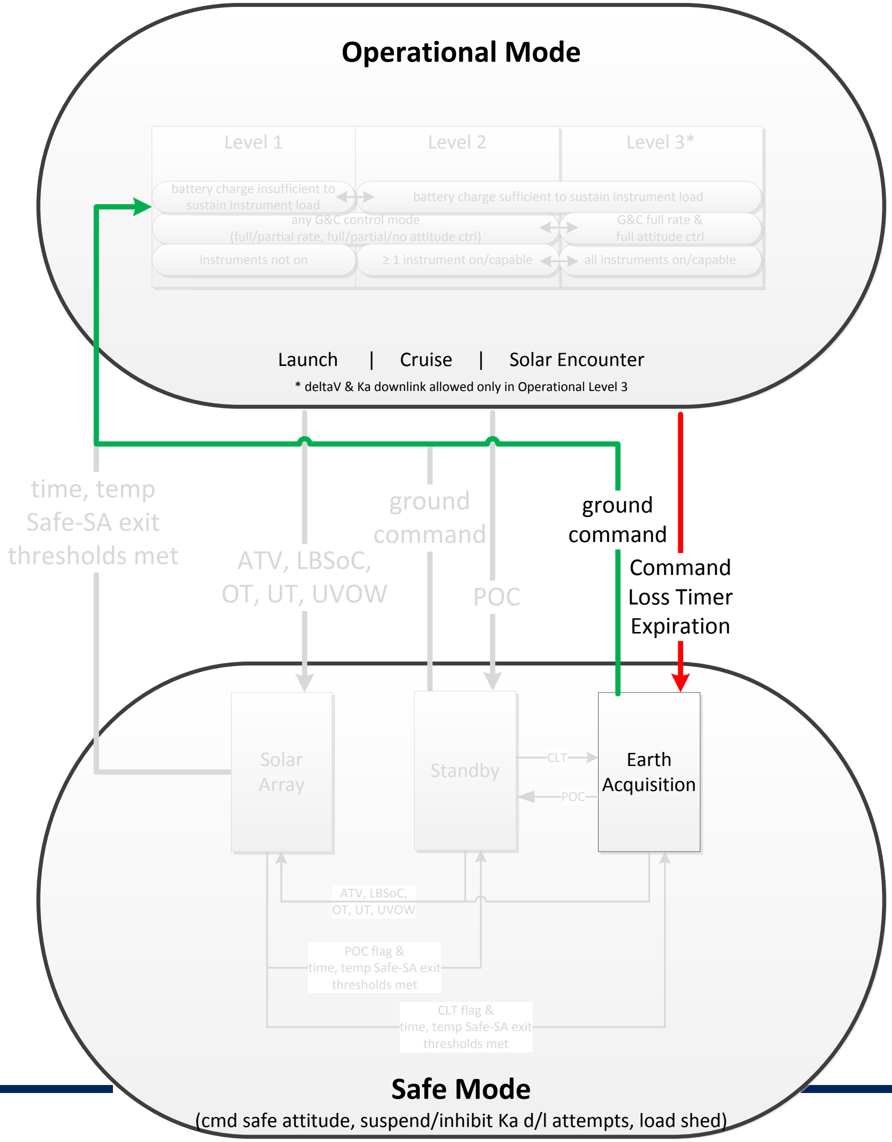
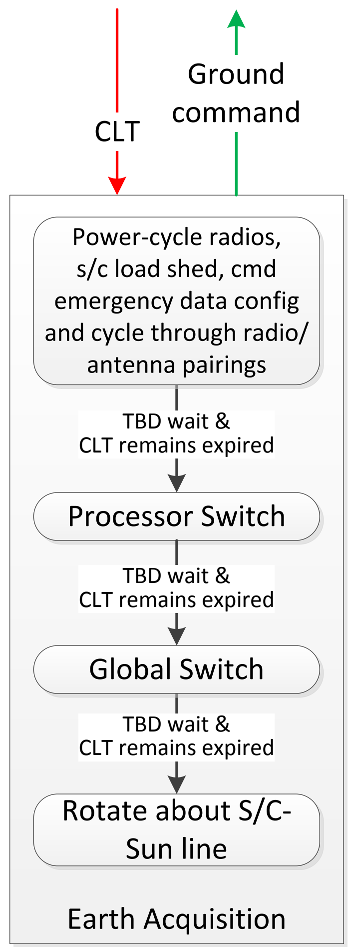
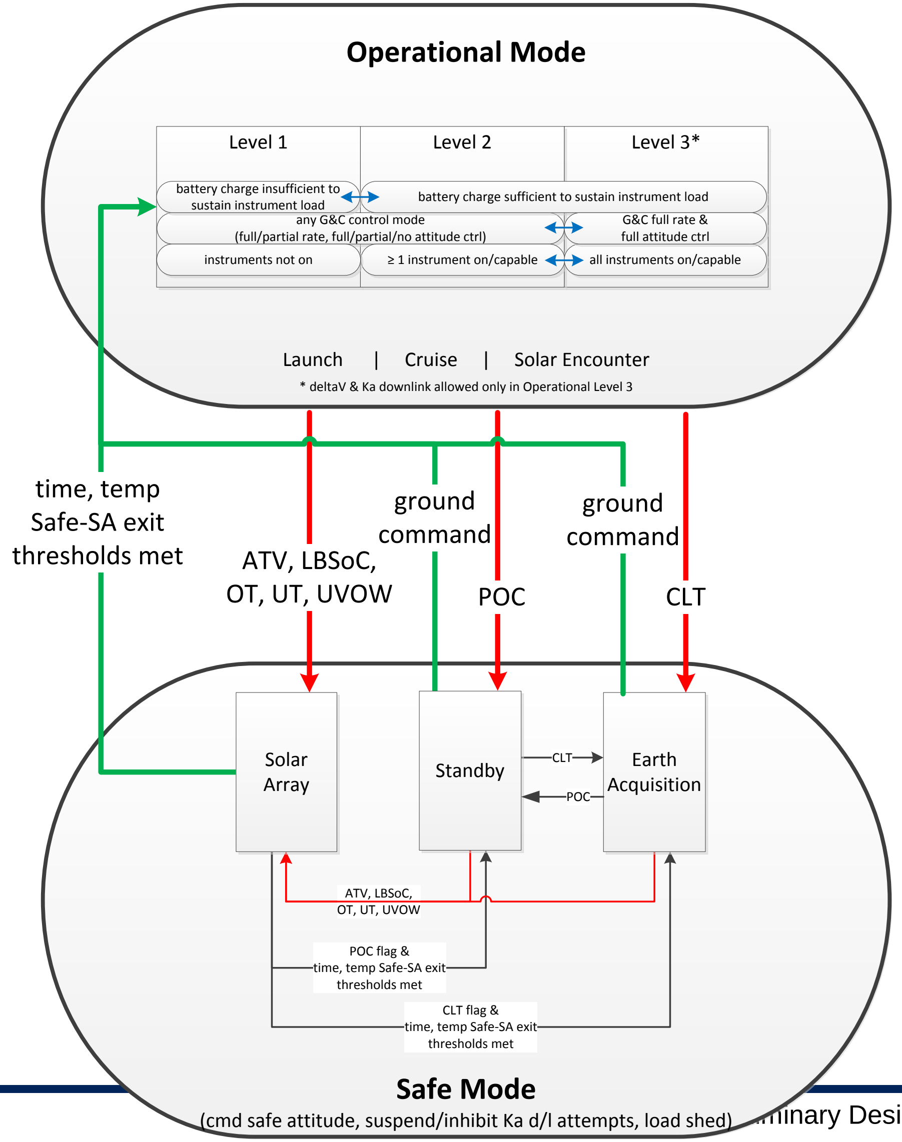


Communication Critical Fault: Safe Mode – Earth Acquisition

- **Command Loss Timer expiration**
  - Ground comm not achieved at next expected contact
- **Safing operation**
  - Power-cycle radios, s/c load shed, command emergency data configuration
  - Configure pre-defined radio/antenna pair sets
    - Comm pointing, assumes valid Earth ephemeris
    - Pairs fanbeam antennas with a transmit & receive radio
    - Pairs –X low gain antenna with a receive-only radio
  - Processor switch
  - Global switch
  - Rotate about s/c sun line (maintains thermal-safe attitude)
    - Allows for invalid Earth ephemeris
    - Configure pre-defined radio/antenna pair sets
      - Pairs fanbeam antennas with a transmit & receive radio
      - Pairs –X low gain antenna with a receive-only radio
      - Includes all LGA-only permutations
    - Repeat global switch
- **Exit criteria**
  - **Ground command**



Fault Management Modes



Acronym Definition:

ATV = Aphelion Thermal Violation
CLT = Command Loss Timer expiration
LBSoC = Low Battery State of Charge
OT = Solar Array / Cooling System Over-Temperature
POC = Processor Overcycling
UT = Cooling System Under-Temperature
UVOW = Umbra Violation – Orange Warning

G&C Modes and Fault Management Modes

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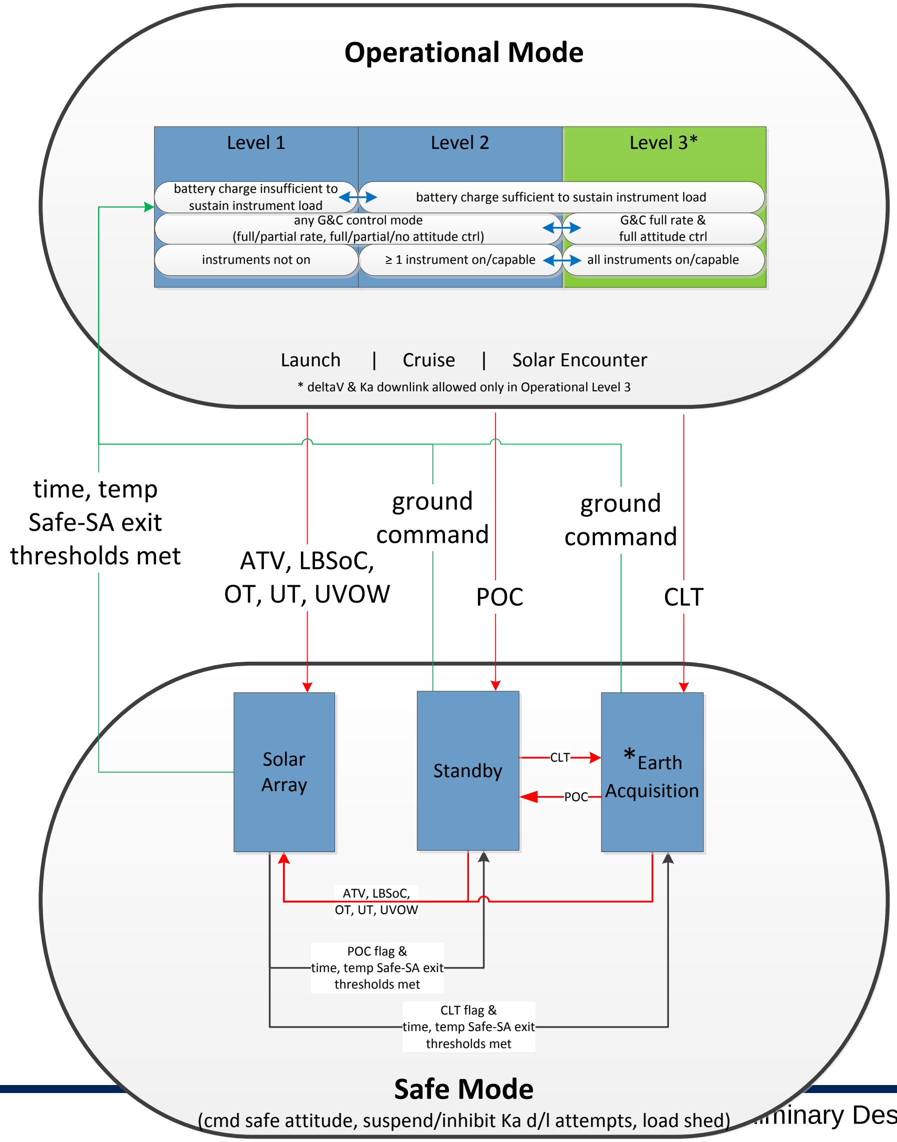


G&C Modes	sensors
Full 3-Axis Attitude & Rate	star trackers, gyros
Partial Attitude & Full Rate Full Rate Only Partial Attitude/Rate	SLS/DSS, gyros gyros SLS/DSS
Any G&C Mode	

* If Safe-EA and not full attitude control, Earth point delayed until full attitude control regained.

Ground Intervention Concept

- **Fault resolution via ground commanding is accommodated, however the system is designed for autonomous fault detection, diagnosis, and response.**

- **Reliance on ground intervention is precluded due to**
  - Short fault-resolution time requirements
  - Periods of link unavailability
  - Long spacecraft-Earth distances

- **In the event of processor overcycling or command loss timer expiration, the spacecraft will autonomously detect the fault condition and demote to Safe Mode.**
  - The spacecraft is capable of remaining in this condition until ground contact is available, and
  - Ground command is required for promotion from Safe – Standby and Safe – EA to Operational Mode.

Instrument Fault Management

- **SPP implements decoupled payload operations; this results in limited instrument fault management.**
- **Local instrument fault management includes:**

<table>
<tr><th rowspan="2">Instrument fault</th><th rowspan="2">Warning Availability</th><th colspan="2">Response</th></tr>
<tr><th>< 0.25 AU</th><th>>= 0.25 AU</th></tr>
<tr><td>Stale aliveness</td><td>Yes</td><td rowspan="2">Power-cycle</td><td rowspan="6">Power-down</td></tr>
<tr><td>Power-cycle request</td><td>Yes</td></tr>
<tr><td>Power-down request</td><td>Yes</td><td rowspan="4">Power-down</td></tr>
<tr><td>Over-temperature</td><td>Yes</td></tr>
<tr><td>Over-power</td><td>Yes</td></tr>
<tr><td>Over-current</td><td>No (circuit breaker)</td></tr>
</table>

- **In the event of spacecraft critical fault conditions, the instruments will be powered-down immediately and without warning**
  - **Instruments are designed to accommodate the immediate loss of power, without warning, without damage to the instrument**

Critical Sequence

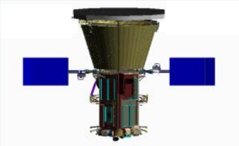
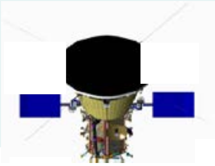
- **Critical Sequence: An event, or sequence of events, which must be executed within a specified time in order to achieve mission success.**

- **For SPP, the sequence <u>from launch through initial cooling system activation until ready for battery recharge</u> is critical.**
  - The sequence steps will be autonomously executed.
  - Ground-based commanding of the sequence is planned as a back-up to the autonomous commanding.

- **The sequence is time critical to prevent low battery state of charge and cooling system temperature violation.**

Post-Launch Sequence

Sequence duration: 1 hour, including margin

Activity	Prerequisite
Upper stage separation	
Power-on G&C sensors and actuators	Separation detection in PDU and Prime processor via redundant breakwires
Release SA wings, command SA wings to 0° flap, 85° feather, detumble, power-on manifold 1&4 heaters, & slew spacecraft to heat radiators 1&4	
Verify radiators 1 & 4 and SA wings >= 20C	7 of 8 temp sensors on each radiator indicate >= 20C and 3 of 4 temp sensors on each SA wing indicate >= 20C
Command accumulator LV open	Verification of radiator & SA wing temp >= 20C
Power on Pump Electronics (PE), set PE Enable, and command PE to enable Pump	Accumulator pressure sensor and LV tell-tale indicate water release
Slew spacecraft & command SA wings to point cell side normal to the Sun to recharge battery	

Fault Management V&V Overview

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

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

- **Verification of L2, L3, and L4 FM requirements tracked in DOORS**

FM System-Level Testing

- **FM scenario tests are:**
  - Black-box, requirements based tests
  - Objective is to verify mission and element-level FM requirements
  - Designed and performed by FM team
  - Similar to MSIMs (scenario based) except one or more faults are injected during the simulation

- **FM scenario test must prove that:**
  - Spacecraft can perform the scenario correctly (i.e., without fault injection)
  - Spacecraft can autonomously recover to nominal operations when required within time constraints

- **Majority of L2 and L3 FM requirements verification accomplished via scenario testing, however, may be tested via other system-level spacecraft tests to take advantage of test schedule and personnel**

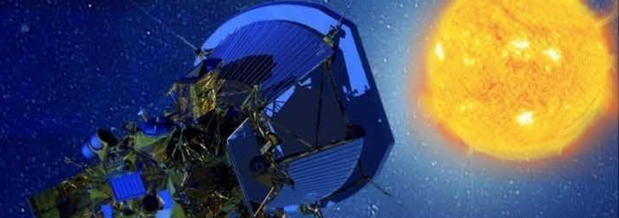
- **Draft scenario test list defined and mapped to:**
  - L2 and L3 requirements
  - Necessary fault injection & emulation capabilities

Draft Scenario Test List* (p1 of 2)

*Safe Mode – Solar Array scenario tests are referenced in the Solar Array Safing presentation

Processor Overcycling (Safe Mode - Standby)	general
	during maneuver (abort maneuver)
	during X downlink (return to mission default orientation)
	during Ka downlink (abort Ka d/l, return to mission default orientation)
	during RAD 2&3 activation (return to mission default orientation)
	during momentum dump
	9.86 Rs
	before, after, and concurrent with REM switch
	before, after, and concurrent with pump switch
Command Loss Timer expiration (Safe Mode - Earth Acquisition)	general
	during maneuver (abort maneuver)
	during X downlink (return to mission default orientation)
	during Ka downlink (abort Ka d/l, return to mission default orientation)
	during RAD 2&3 activation (return to mission default orientation)
	during momentum dump
	0.25 AU inward (resume mission default attitude)
	0.7 AU inward (resume mission default attitude)
	0.82 AU inward (resume mission default attitude)
	0.82 AU outward (resume mission default attitude)
	before, after, and concurrent with REM switch
	before, after, and concurrent with pump switch
Operational Level Transitions	
Safe Mode Standby -> Safe Mode Earth Acquisition	
Safe Mode Earth Acquisition -> Safe Mode Standby	

Draft Scenario Test List (p2 of 2)



Post-Launch Sequence	nominal
	LBSoC prior to SA release
	CLT prior to G&C full att/rate ctrl
	POC prior to G&C full att/rate ctrl
	Prime demote prior to G&C full att/rate ctrl
	REM switch prior to G&C full att/rate ctrl
	anomalous temp sensor readings (sensor failure or attitude error)
	Accum LV failure to open
	Pump failure
Pump Switch	9.86 Rs
	eclipse
	greatest aphelion with fully activated CS
	before, after, and concurrent with REM switch
	before, after, and concurrent with other cross-switch
Prime Demotion	with concurrent HS reset >= 0.5 AU
	with concurrent HS reset < 0.5 AU
	during maneuver
	during momentum dump
	9.86 Rs
	before, after, and concurrent with pump switch
	before, after, and concurrent with REM switch
REM Switch	during maneuver
	before, after, and concurrent with cross switch

Phase C Activities

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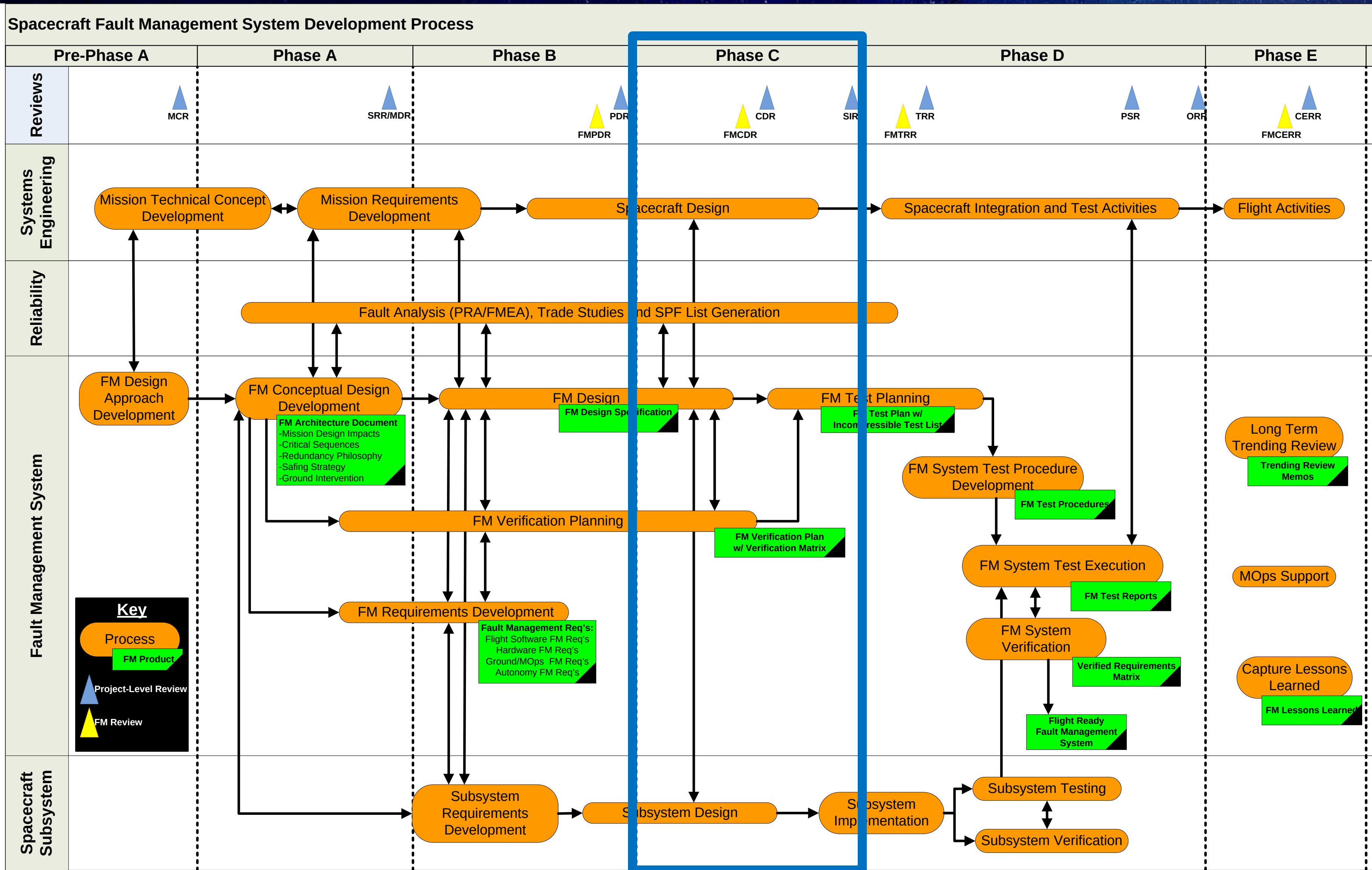

Phase C Activities

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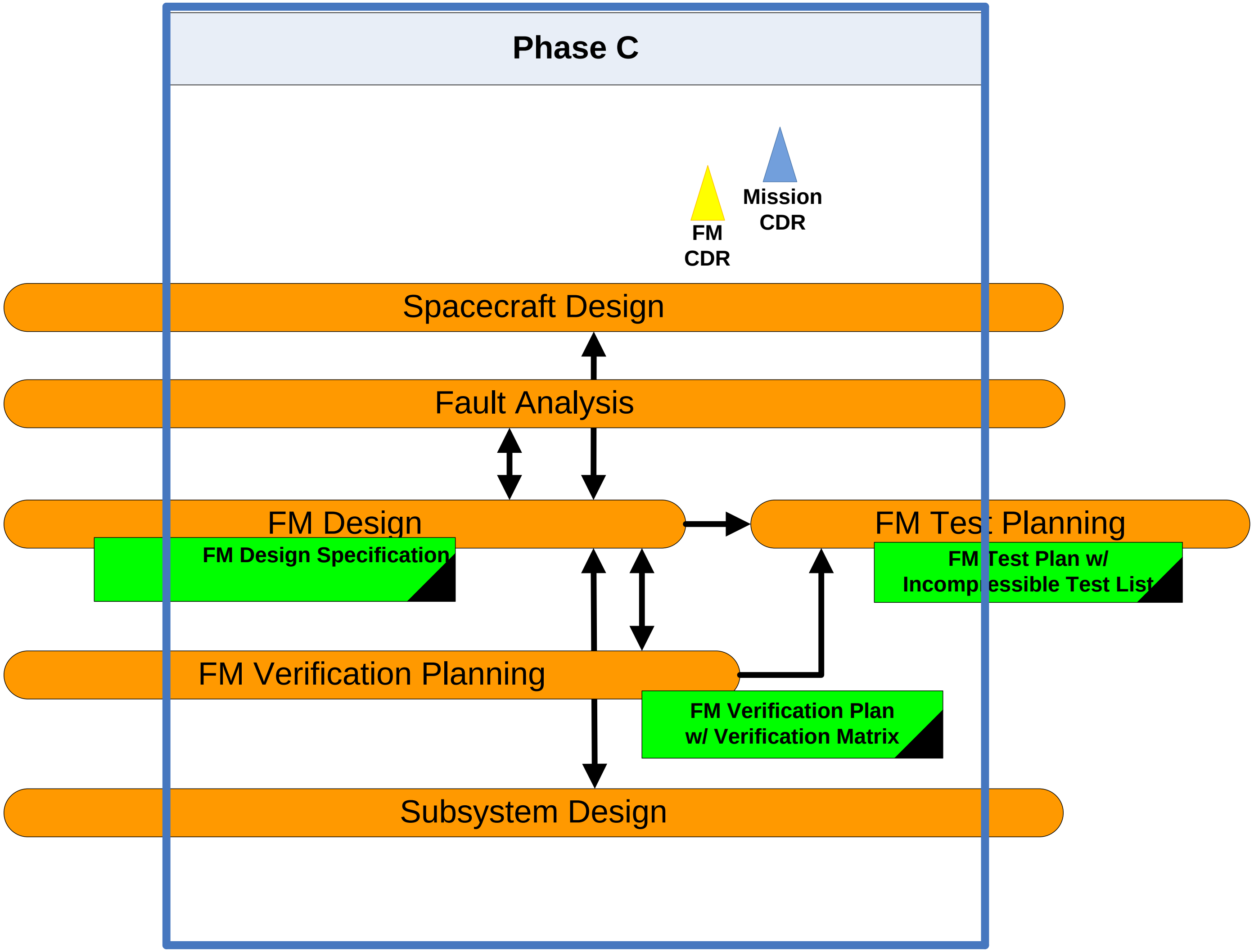

Summary

- **The Fault Management design meets mission requirements.**
- **Fault Management requirements are integrated throughout element and subsystem requirements.**

- **The Fault Management design is ready to proceed to Phase C.**

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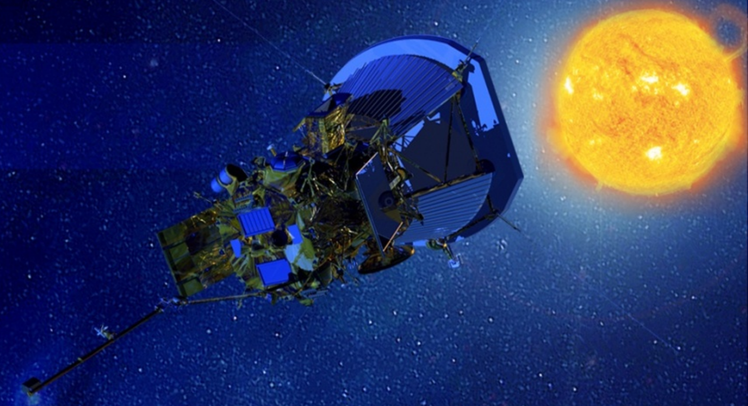

BACK UP

The Johns Hopkins University
APPLIED PHYSICS LABORATORY

Cross-Strapping Rationale, p1 of 2

- **G&C sensors & actuators:** Time criticality of continuous attitude control.

- **Processors**
  - Three processors are required to meet SPP requirement for single fault tolerance through processor reset. Three processors need to be accessible from two REM sides.
  - Decouple from REM; processor reset/demotion does not cause block side switch, and vice-versa.

- **Sun Sensor Electronics:** Availability of both DSS/SLS signals when/if their data is needed provides robustness. Unable to test SLS functionality, and determine if side-switch is necessary, prior to critical fault.

- **Pump Controllers:** Time criticality of continuous cooling system operation. Cross-strapped pumps allow pump operation to be decoupled from REM-switching.

- **ECUs:** Cross-strapping allows data from both to be accessible from the active REM. ECUs include potentiometers which measure actuator position; potentiometer data is used as 2 of 3 voting members for solar array position knowledge.

Cross-Strapping Rationale, p2 of 2

- **Cooling system dP sensors:** Time criticality of continuous cooling system operation. dP sensors are used (in addition to motor speed and current) to assess pump health.

- **Transponders**
  - Provides near-spherical uplink coverage for early ops.
  - Precision clock sources are currently integrated into the transponders; both are available to the active REM.
  - Prevents a frozen coax switch from causing spacecraft side-switch.

- **Cooling system accumulator pressure sensor:** Non-redundant (non-critical) sensor.

- **RIUs:** Cross-strapping, with selected redundancy for critical temperature sensors, provides mass savings.

- **Payload suite:** Redundancy within the payload suite to provide 7 of 9 measurements to meet Level 1 science requirements.

L3 Requirements for Redundancy

- **have no single point failures except those on the single point failure list.**
- **be designed such that at least one REM side, at least one PDU, at least one XPDR, and at least two processors are powered at all times.**
- **provide block-redundant interfaces for the PSE, PDU, propulsion pressure transducers, and separation breakwires to the redundant avionics interfaces.**
- **cross-strap the transponders, pump controllers, cooling system latch valves, cooling system dP sensors and accumulator pressure sensor, ECUs, IMU, star trackers, wheels, thrusters, propulsion system latch valves (TBD), SLS, processors, and instruments, to the redundant avionics interfaces.**

L3 Requirements for Redundancy

- be designed to manage redundancy.
- be designed such that at least one REM side, at least one PDU, at least one XPDR, and at least two processors are powered at all times.
- be designed such that the prime processor issues all onboard spacecraft commanding.
- be designed such that the prime processor performs all autonomy, with the exception of prime processor demotion via ARC acknowledge timer.
- provide the capability to perform health checks on redundant components.
- ensure that health checkout of redundant side does not interfere with operation of primary side.
- capable of gathering diagnostic data from a failed processor.

L3 Requirements for Continuity of Control

- demote the prime processor upon its reset.
- be capable of attitude control within 4 seconds TBR in the event of a prime processor demotion at ≤ 0.5 AU and 30 seconds TBR > 0.5 AU.
- be capable of wing angle control within 2 seconds (TBR) in the event of a prime processor demotion for solar distance ≤ 0.5 AU and 30 seconds TBR for solar distance > 0.5 AU.
- be capable of attitude control within 5 seconds (TBR) of safe mode solar array initiation at < 0.5 AU and 30 seconds (TBR) > 0.5 AU.
- be capable of wing angle control within 5 seconds (TBR) of safe mode solar array initiation at < 0.5 AU and 30 seconds (TBR) > 0.5 AU.
- ensure that three processors are powered on when the spacecraft is ≤ 0.5 AU from the Sun.
- ensure that the redundant pump is operational within 10 seconds TBR of pump failure.

L3 Requirements for Autonomy

- **provide an on-board autonomous system to detect and respond to faults.**
- **be designed to provide spacecraft telemetry to enable fault detection on-board.**

L3 Requirements for Detection & Response to Critical Faults (p1 of 2)

- **Umbra Violation – Orange Warning**
  - provide telemetry to indicate Umbra Violation - Orange Warning condition at 5 Hz TBR.
  - autonomously detect Umbra Violation Orange Warning and initiate Safe Mode-Solar Array
- **Aphelion Thermal Violation**
  - provide telemetry to indicate an aphelion thermal violation condition.
  - autonomously detect Aphelion Thermal Violation and initiate Safe Mode-Solar Array.
- **SACS Over-Temperature**
  - provide telemetry to support diagnosis of SA over-temperature condition at 5 Hz TBR.
  - autonomously detect Solar Array Cooling System Overtemp and initiate Safe Mode-Solar Array.

L3 Requirements for Detection & Response to Critical Faults (p2 of 2)

- **CS Under-Temperature**
  - provide telemetry to support diagnosis of CS under-temperature condition at 1 Hz TBR.
  - autonomously detect Cooling System Undertemp and initiate Safe Mode-Solar Array.
- **Low Battery State of Charge**
  - provide telemetry to support diagnosis of LBSoC condition at 5 Hz.
  - autonomously detect LBSoC condition and initiate Safe Mode-Solar Array.
- **Command Loss Timer Expiration**
  - provide telemetry to indicate CLT-expired condition.
  - autonomously detect CLT expiration and initiate Safe Mode - Earth Acquisition.
- **Processor Overcycling**
  - provide telemetry to indicate Processor Overcycling condition.
  - autonomously detect Processor Overcycling and initiate Safe Mode - Standby.

L3 Requirements for All Safe Modes

- be capable of operating in safe mode.
- be capable of changing to Mission Default Spacecraft Pointing Orientation, as defined in the EDTRD 7434-9039, upon entering Safe Mode, except during Activate 1 & 4 Special Event Spacecraft Pointing Orientation.
- be designed to shed non-critical loads in spacecraft safe mode.
- be capable of remaining in Activate 1 & 4 Spacecraft Pointing Orientation, as defined in the EDTRD 7434-9039, if spacecraft is in Activate 1 & 4 Pointing Orientation upon entering Safe Mode.
- suspend and inhibit deltaV maneuvers while in Safe Mode.
- suspend and inhibit spacecraft slews, except to mission default, while in Safe Mode.
- suspend and inhibit Ka downlink while in Safe Mode.

L3 Requirements for Safe Mode – Solar Array

- **begin execution of Safe Mode-Solar Array initiation command within 80 ms TBR in the event of LBSoC, SA/CS over-temperature, CS under-temperature, Aphelion Thermal Violation, or Umbra Violation - Orange Warning.**
- **complete a processor rotation and side switch, and follow the sequence specified in the FM Design Specification, 7434-****, prior to commanding the solar array to a safe angle.**
- **promote new Prime processor within 1.5 seconds TBR from Safe Mode-Solar Array initiation.**
- **execute Safe Mode-Solar Array side-switch operation to enable solar array commanding, as defined in FM Design Specification 7434-****, within 2 seconds TBR.**

L3 Requirements for Safe Mode – Solar Array

- maintain power to Continuously Powered Loads through Safe Mode-Solar Array Side Switch.
- command power on to the Block Redundant Loads on the new side through Safe Mode-Solar Array Side Switch.
- be capable of determining current solar array angle, determining target solar array angle, and commanding solar array movement within 1 second TBR when in Safe Mode-Solar Array.
- remove power from the solar array drive within 2.5 seconds TBR of Safe Mode-Solar Array initiation.
- be capable of receiving telemetry from both redundant coarse potentiometers.

L3 Requirements for Safe Mode - Standby

- **not allow further Prime processor demotions in the event of Processor Overcycling.**

L3 Requirement for Safe Mode – Earth Acquisition

- **execute telecomm subsystem reconfiguration when in Safe Mode-Earth Acquisition.**
- **be capable of spacecraft rotation about the spacecraft-sun line when in Safe Mode-Earth Acquisition.**

L3 Requirements for Operational Mode transitions

- **provide a means to recover to an operational state from critical faults as specified in Fault Management Design Specification 7434-*** document.**
- **be capable of returning from Safe Mode - Solar Array to Operational Level 1 in sufficient time to ensure the SA and cooling system remain within temperature constraints.**
- **reset the CLT only upon receipt of dedicated CLT-reset ground command.**
- **provide the capability for ground to re-enable processor cycling capability.**
- **provide the capability for ground commanded promotion from Safe Mode Standby or Earth Acquisition to Operational Mode Level 1.**
- **provide the capability for ground commanded promotion from Safe Mode Solar Array to Operational Mode Level 1 for solar distances > 0.5 AU (TBR).**

L3 Requirements for Operational Mode transitions

- **transition from Operational Level 1 to Operational Level 2 when battery state of charge is within TBD% of that indicated in the Spacecraft System Engineering Power Required Table.**
- **transition from Operational Level 2 to Operational Level 3 when G&C has full rate and full attitude control.**
- **transition from Operational Level 3 to Operational Level 2 if G&C does not have full rate and full attitude control.**
- **transition from Operational Level 2 to Operational Level 1 if battery state of charge is TBD% below the level specified in the Spacecraft System Engineering Power Required Table.**

L3 Requirements for Ground Intervention

- be capable of receiving and executing uplinked critical commands to control critical avionics functions via a path that is not dependent on flight software.
- be designed to provide spacecraft telemetry to enable fault diagnosis on Ground.

L3 Requirements for Instrument Fault Management

- **The spacecraft shall**
  - **be designed such that a fault or failure of one instrument does not propagate to one or more instruments or to the spacecraft.**
  - **be designed to provide autonomous onboard instrument power-downs in response to instrument request and critical telemetry.**
  - **provide capability to power cycle instruments in response to instrument requests.**
  - **provide a bit in the Spacecraft status message to request an instrument put itself in a safe state for power down.**

- **All instruments shall**
  - **provide data to support instrument fault protection (including ground system monitoring of selected instrument health data, remote SOC notifications of critical fault conditions, and autonomous onboard instrument power-downs in response to instrument request, detection of stale instrument heartbeat, or overcurrent).**
  - **be capable of entering a safe state of powering down upon receipt of a spacecraft-provided bit in the spacecraft status message to request an instrument put itself in a safe state for power down.**
  - **be capable of safely powering down within TBD s upon receipt of a status message with a bit indicating power-down command.**
  - **be capable of autonomous reconfiguration to a pre-defined operational state following spacecraft-commanded power-down and subsequent power-on.**
  - **be designed to accommodate immediate loss of power (without warning) without damage to the instrument.**

L3 Requirements for Fault Management Testing

- **be capable of over-writing subsystem telemetry with injected values during spacecraft testing.**
- **be capable over-writing subsystem telemetry with injected values during testbed/subsystem testing.**

Preliminary Fault Response Priority Levels*

- **Preliminary response priority order has been assigned based on results of interference analysis, including relative time-criticality of fault responses.**

- **Level 1: Safe Mode – Solar Array and Pump switch**
- **Level 2: Safe Mode – Standby and REM switch**
- **Level 3: Prime demotion**
- **Level 4: Earth Acquisition**
- **Level 5: remaining responses**

*** Note numerical assignments to levels here are used to indicate hierarchy but do not necessarily correspond with software commanding priority level number assignments.**

Step 1:
Fault detection until safing cmd

Event	**Prime cmds:**	**Command(s)**	**Notes**	**time (ms)**	**cumulative time (s)**
fault occurs and fault symptoms persist			Assumes 3 of 5 persistence requirement 5 Hz single buffered subsystem tlm collection	400 ms	0.40
next subsystem tlm collection	SCIF A	collection of subsystem tlm	Assumes fault persistence met concurrently with previous subsystem tlm collection	200 ms	0.60
max time from subsys tlm collection to tlm in DCB	SCIF A	send subsystem tlm to Prime DCB	1Hz Assumes fault persistence met just after last Prime DCB update	800 ms	1.40
autonomy execution			Autonomy reads DCB, analyses telemetry, & generates cmds	200 ms	1.60
autonomy commands response	SCIF A	cmd Prime to initiate safe-mode entry	25 Hz commanding; cmd sent at next minor frame	80 ms	1.68

Step 2:
Prime processor demotion

Event	Prime cmds:	Command(s)	Notes	time (ms)	cumulative time (s)
halt 50 Hz SpW bus schedule			20 ms to complete current minor frame & receive notice at start of next minor frame to halt bus sched.	20ms	1.70
Prime informs HS of safe-mode entry & time	HS & SCIF A	cmd setting 'safe-mode entered' flag in HS & indicating safe mode entry & time, & target config, & step count, sent via direct-connect cmd setting 'safe-mode entered' flag in HS & indicating safe mode entry & time, & target config, & step count, sent via SpW router	2 redundant commands via separate paths	< 1 ms	1.70
Prime self-demotes	ARC	suppresses commands to ARC, timing-out acknowledge timer	max of 515 ms to time-out one MC	515 ms	2.22
new Prime triple-votes logical state to see that it is Prime			max of 186 for all three MC ack timer time-outs and transmit new logical states to SBCs + SBC role voting time (negligible)	186 ms	2.40
contingency for resetting HS scenario			if original HS is resetting (not a fault), it may not ack ARC timer when promoted to Prime and ARC will promote original BS to Prime	701 ms	3.10

Step 3a: Side-Switch / Power-Cycle powering on the new side

Event	Prime cmds:	Command(s)	Notes	time (ms)	cumulative time (s)
new Prime recognizes 'safe-mode entered' flag & initiates safing side-switch			New Prime continues safing operation		
power-off SCIF/TAC A and power-on SCIF/TAC B and PDU B	ARC	select "SCIF/TAC B, PDU A&B" power state	~20 ms to change power state + max of 1/6 sec until next opportunity for Prime to send command (6 Hz cmding of ARC by SBCs)	187 ms	3.29
		SCIF B & PDU B power-on delay	Current estimate for POR clear is 286 ms	350 ms	3.64
		Prime cmds SCIF B SpW connect PDU B power-on default initialization	Current estimate for PROM initialization sequence is 113.5 ms	150 ms	3.79
configure SCIF B	SCIF B	configure routing table select precision oscillator initialize MET initialize time code master select which UART interfaces to enable	this set of commands sent as one RMAP command	< 1 ms	3.79

Step 3b: Side-Switch / Power-Cycle maintain power to select loads, power-on/cycle/shed remaining loads

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Event	Prime cmds:	Command(s)	Notes	time (ms)	cumulative time (s)
power-on default safing side-switch loads	SCIF B to PDU B	Pump Electronics A Pump Electronics Enable A x2cmds Pump Electronics B Pump Electronics Enable B x2cmds SLS A SLS B ST A ST B IMU A IMU B TAC B thruster bus x2cmds Prop System PT B	maintain power to active pump, SLS, ST, IMU power-on B-side-only loads FSW to start bus controller but not use bus schedule. 5 Hz commanding of PDU, 10 cmds per slot. 16 ms for execution of 10 cmds.	216 ms	4.01
power-off PDU A*	ARC	selects “SCIF/TAC B, PDU B” power state	powers down PDU A (switched in ARC) <u>Time allocation for this step not included in timeline</u>; completion of PDU A power-down not required for start of next step.	20 ms	4.01

* Removes power from all components (including solar array drive) except those listed in previous step.

Step 3c: Side-Switch / Power-Cycle: power-on new side to enable SA movement

Event	Prime cmds:	Command(s)	Notes	time (ms)	cumulative time (s)
configure PDU B & begin configuration of REM multiplexer	SCIF B to PDU B & SCIF B or TAC B	power on/off loads as appropriate given known previous power configuration and desired changes: ECU A x2cmds ECU B x2cmds Power down Pump Electronics A or B as approp. Power down Pump Electronics Enable A or B as approp. PSE CMD/TLM IF B Wheel A x3cmds Wheel B x3cmds Wheel C x3cmds Wheel D x3cmds cmd to configure relays in REM multiplexer for B-side	table of active components & desired config post-switch maintained in FSW & updated by autonomy, & sent to HS in 1Hz msg & with 'safe-mode entered' flag 5 Hz commanding of PDU, 10 cmds per slot. 180ms remaining since last PDU cmd, given 20ms in last step. 200ms x 2 for next two cmd slots + 16 ms to e xecute 10 cmds. ECU power first so that they are ready to accept cmds (next step) ASAP	596 ms	4.60

Step 4:
Preparation for solar array safing

Event	Prime cmds:	Command(s)	Notes	time (ms)	cumulative time (s)
collect ECU potentiometer tlm	SCIF B	cmd ECU-A to send potentiometer tlm cmd ECU-B to send potentiometer tlm	5 Hz commanding of ECU, cmds sent to both ECUs at same time 399ms remaining of 600ms ECU power-on delay + 100ms for 10 Hz cmd execution rate = 499 ms	499 ms	5.10
Prime votes 2 ECU potentiometer readings and commanded step count to determine current SA position.					5.10
power-off ECU A	SCIF B to PDU B	power-off ECU A	Time allocation for this step not included in timeline; completion of ECU A power-down not required for start of next step.	200 ms	5.10
Prime determines target SA safing angle with MET-based table reference.					5.10
command SA safing	SCIF B	cmd ECU-B to execute step commands to move wings to target angle with flag indicating safing operation (increased step rate).	5 Hz commanding of ECUs need to maintain 200ms gap since last ECU cmd 10 Hz cmd execution rate	300 ms	5.40

5.4 seconds from fault occurrence until execution of command to safe solar arrays

Earth Acquisition Telecomm Reconfiguration Strategy (p1 of 2)

- **Step through radio/antenna pairs at defined intervals**
  - **Ensures predictability of configuration at any given time (keyed off of last CLT-reset command from MOps)**

- **First level of response assumes valid Earth ephemeris**
  - **Pairs fanbeam antennas with a transmit & receive radio**
  - **Pairs –X low gain antenna with a receive-only radio**

Transponder A		Transponder B		S/C attitude
mode	antenna	mode	antenna	
Tx/Rx	FB 1	Rx	-X LGA	Comm
Tx/Rx	FB 2	Rx	-X LGA	Comm
Rx	-X LGA	Tx/Rx	FB 1	Comm
Rx	-X LGA	Tx/Rx	FB 2	Comm

Earth Acquisition Telecomm Reconfiguration Strategy (p2 of 2)

- **Second level of response allows for invalid Earth ephemeris**
  - **Includes s/c rotation about the s/c-Sun line (maintains thermal-safe attitude)**
  - **Pairs fanbeam antennas with a transmit & receive radio**
  - **Pairs –X low gain antenna with a receive-only radio**
  - **Includes all LGA-only permutations**

Transponder A		Transponder B		S/C attitude
mode	antenna	mode	antenna	
Tx/Rx	FB 1	Rx	-X LGA	EA Rotation
Tx/Rx	FB 2	Rx	-X LGA	EA Rotation
Rx	-X LGA	Tx/Rx	FB 1	EA Rotation
Rx	-X LGA	Tx/Rx	FB 2	EA Rotation
Tx/Rx	-X LGA	Rx	+X LGA	EA Rotation
Tx/Rx	+X LGA	Rx	-X LGA	EA Rotation
Rx	-X LGA	Tx/Rx	+X LGA	EA Rotation
Rx	+X LGA	Tx/Rx	-X LGA	EA Rotation

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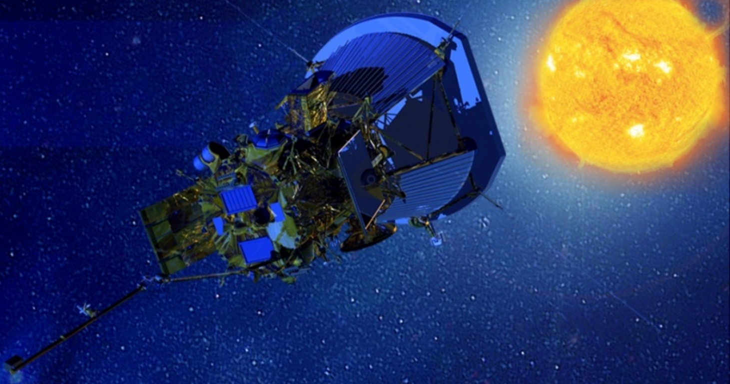

Solar Array Safing

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13 – 16 January 2014

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APPLIED PHYSICS LABORATORY

Outline

- Introduction
- Solar Array Safing Context within FM Architecture
- Driving Requirements and Assumptions
- Critical Temperature Points
- Modeling and Analysis Capabilities
- Solar Array Safing Design
  - Conditions Resulting in Safe Mode – Solar Array
  - Safe Angles
  - Exiting Safe Mode – Solar Array
- Verification
- Phase C Work

Introduction

- Nominal autonomous wing angle control is designed to:
  - Correct for over-temp (by preventing too much power)
  - Correct for LBSoC (by preventing too little power)
  - Correct for low-temp (compensates for less than expected solar array degradation)
  - Compensate for spacecraft attitude errors

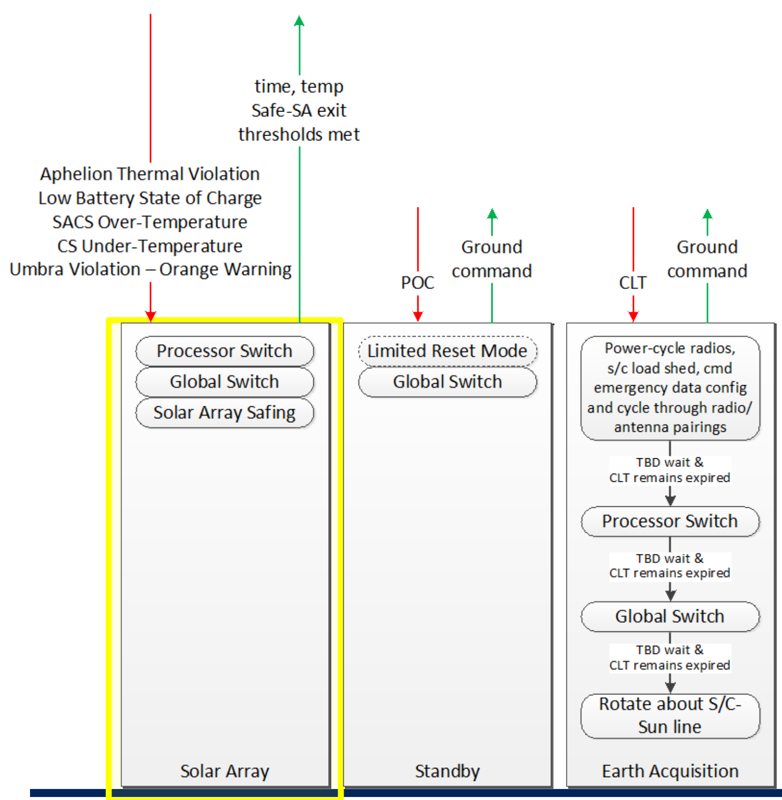
- Safe Mode – Solar Array is a system-wide recovery procedure in the event of power and thermal critical faults and includes processor switch, side-switch, and solar array safing
  - Solar Array/Cooling System Over-Temp
  - Cooling System Low-Temp
  - Low Battery State of Charge
  - Umbra Violation
  - Aphelion Thermal Violation

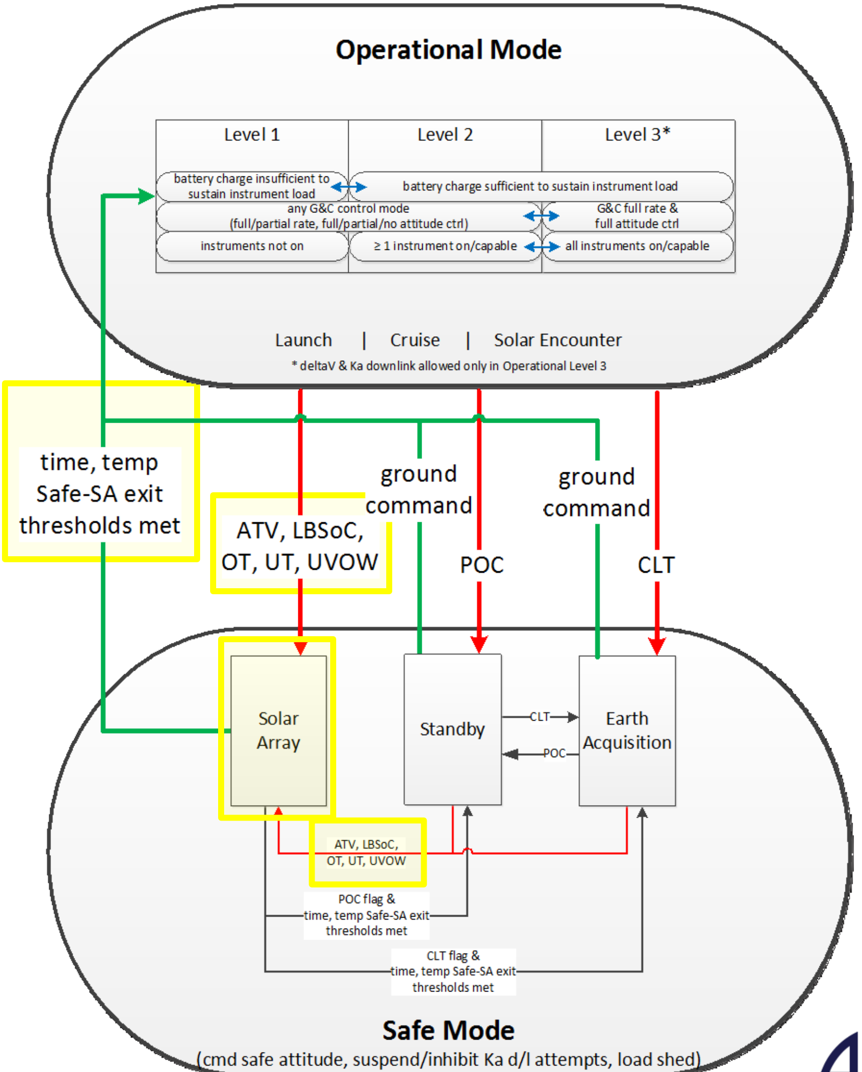
- Safe Mode – Solar Array uses the same response for all critical faults, and includes tucking the solar array into the umbra (nearly full shadow) inside of 0.35AU
  - *Inside of 0.35AU, there is NO steady-state safe mode for Solar Probe*

- Reviews:
  - Solar Array Safing design reviewed at FM PDR (May 2013)
  - Solar Array Operations and Safing requirements documented in SCRD and reviewed at SPP Level III Requirements Review (June 2013)

Context within FM Architecture

Acronym Definition:
ATV = Aphelion Thermal Violation
CLT = Command Loss Timer expiration
LBSoC = Low Battery State of Charge
OT = Solar Array / Cooling System Over-Temperature
POC = Processor Overcycling
UT = Cooling System Under-Temperature
UVOW = Umbra Violation – Orange Warning





Context within FM Architecture

- **Prime processor demotion and global switch take place prior to solar array safing**
  - Allows SA safing to be commanded and implemented by new components

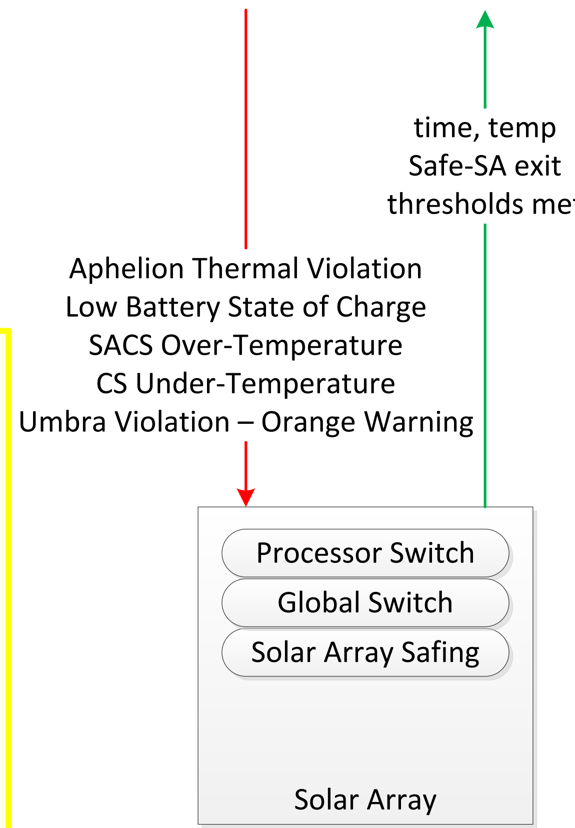
- **Global switch includes power-cycle of most components**
  - Exceptions include cooling system pump, solar limb sensors, star trackers, IMU, new Prime
  - Instruments will be powered off

- **Command solar arrays to target safing angle**
  - Determine current wing angles based on majority vote
  - Reference MET-based stored table of safing angles
    - MET stored redundantly in hardware and software
  - Determine & command required steps to reach target angle (0.5 deg/s)

- **Exit criteria*:**

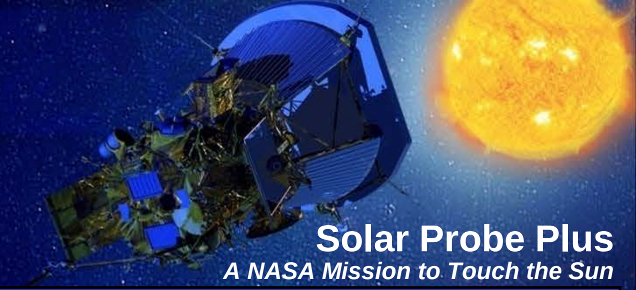
  (> 90 seconds TBR from safing start & <= 125C TBR)

  or 308 seconds TBR from SA safe angle achieved



*Implementation of timers is TBR; purpose is to show worst-case stack-up of time from fault detection to wings return to operational

Driving Requirements



Parameter	Requirement
Thermal limits	Cooling system survival: 10C – 190C Cooling system operational: 20C – 150C Solar array survival: 240C
Cooling system capacity	Max capacity at 9.86Rs: 6480W (150C, 21 Suns into substrate) Min load to prevent freezing: - 2,350W (20C yellow limit) - 2,050W (10C red limit)
Temperature Control (T-C) control point	65C +/-5C
Critical telemetry knowledge	Wing angle: 0.5 deg (coarse pot only) Solar flux: 6%
Flap angle rotation rate	Max rate: 0.5 deg/s Max outward rate allowed during nominal operations: 0.1 deg/s - Derived to constrain safing approach - Exceptions: deploying array after launch, exiting safe mode Rate accuracy: 10%
Safe mode timing	Fault detection to power cut to SAD: 5s - Bounds wing overshoot in fault scenario Fault detection to wings moving to safe angle: 10s
Solar array stow angle	88 deg - Safe angle must be shallower than stow angle
MET	Fault tolerant
Solar array safing approach	Must not constrain nominal operations - Accommodate attitude error up to umbra violation - Accommodate temperatures up to EOL nominal operating temps Must be entered/exited completely autonomously

Critical Temperature Points

Cooling System Temperature	Description	Notes
190C	Survival limit	Also assumed to be max overtemp starting condition (conservative)
160C	Overtemp threshold	Allows safing to occur before survival limit reached and without constraining nominal ops
150C	Max nominal operating temp	9.86Rs, 6,480W into cooling system, ~21 Suns into both wings
130C	Max temp with wings normal to Sun, ≥ 0.5AU	Allows wings to be normal to Sun during safing outside of 0.5AU, with margin on 150C nominal operating temp
125C	Max temp to exit safe mode	Provides margin on 150C when exiting safe mode
65C +/-5C	T-C control point	If T_{water} < 60C, mode will be T-C
43C	Undertemp threshold	Provides 5 min to 20C yellow limit, with wings fully shadowed
20C	Yellow limit for cooling system freeze protection	2,350W into cooling system, steady-state
10C	Red limit for cooling system freeze protection	2,050W into cooling system, steady-state

Modeling and Analysis Capabilities

- Integrated G&C/EPS/Cooling System model - developed in Simulink
- Detailed thermal models as a function of irradiance, flow rate, radiator geometry, solar array geometry
  - Cooling system level – steady-state and transient models of cooling system temps (bulk and local water temps)
  - Solar cell level – models of platen, water, and cell temperature through stack along length of solar array
    - Equations are integrated into above Simulink model

Model Portion	Model Capabilities	Input Parameters	Outputs
G&C model	Spacecraft dynamics (includes closed-loop actuator control)	Orbit Spacecraft geometry Mass properties Sensor parameters (noise, gain) Actuator parameters Disturbances	Spacecraft position Spacecraft attitude Spacecraft rates
EPS model	Irradiance on solar array SA and battery performance Power conversion model	Spacecraft load SA string out SA degradation Battery parameters SA parameters (cell layout, I/V characteristics)	SA operation Battery I, V, SoC
Autonomous flap angle control	Flap angle control modes - power - temperature - fixed angle	SAD rate SAD step-size Control update frequency	Flap angle
Cooling system model	Thermal performance - water flow - water, platen, and cell temps	Water cycle time CS parameters (rad. size, thermal mass) Temperature time constants	Water temperature Platen temperature Cell temperature

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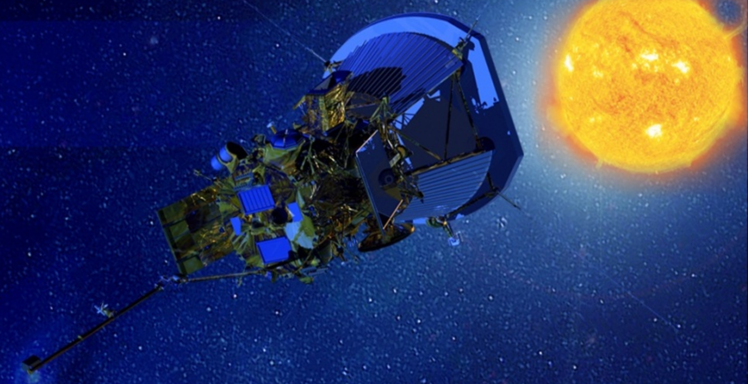

Conditions Resulting in Safe Mode – Solar Array

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Critical Fault Conditions

Critical Fault	Potential Causes	Telemetry Used	Survival Limit	Violation Limit
Solar Array/Cooling System Overtemp	SA control fault Attitude control fault Cooling system pump fault	Platen temp Isc/Voc	Platen Temp = 190C SA temp = 240C*	Solar flux > parametric table Water Temp > 160C
Cooling System Undertemp	SA control fault Cooling system pump fault	Radiator temp Platen temp	Water Temp = 10C	Water Temp < 43C
LBSoC	SA control fault Battery charge control fault	SoC estimate in PSE telemetry	SoC = 10%	SoC < 30%
Umbra Violation – Orange Warning	Attitude control fault	Sun direction from SLS	Off-point angle = 2.18 deg (at 9.86Rs)	Off-point angle > 1.5 – 1.8 deg (at 9.86Rs, exact value TBD)
Aphelion Thermal Violation	Attitude control fault	Sun direction from DSS	Off-point angle = 5 deg	Off-point angle > 4 – 4.8 deg (exact value TBD)

Overtemp and Undertemp critical faults bound the response in both time and thermal environment

*Note that solar cell survival limit is 240C

- At 190C platen with high-flux (40 Suns), test data shows that upper bound on cell temp is approximately 230C (~1C/Sun)
  - 40 Suns is worst-case transient (see later slides)
  - Cooling system (platen) temperature will be violated first

Sensors, Measurements, and Computed Telemetry

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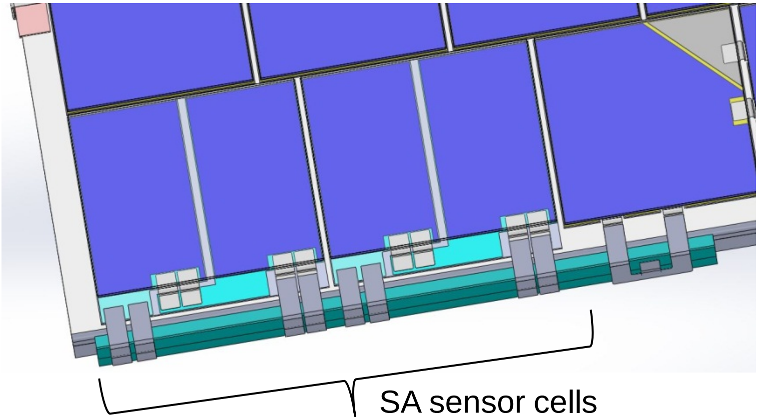
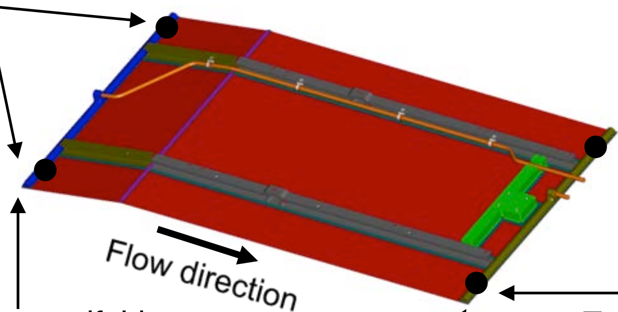
- **Solar array sensor cells (Isc/Voc)** – 2 primary/redundant sensor cell sets (2 cells/set) on outboard corner of each wing
  - Measure short circuit current (Isc), accurate to ±3%
    - Proportional to solar flux ("Suns") at leading edge, accurate to ±6%
  - Measure open circuit voltage (Voc), accurate to ±3%
    - Indicates cell temperature at leading edge, accurate to ±15C
  - Relationships dependent on solar array degradation and are calibrated in-flight
  - Cross-strapped to PSE - may be large variation in irradiance between corners of one wing
- **Platen temp sensors** – 4 primary/redundant PT-103 sensor pairs on back of each platen manifold
  - Measure inlet and outlet water temp, accurate to ±5C
  - Block redundant to PSE - little variation in temp across inlet corners and across outlet corners of wing
    - Accommodates failed sensor without side-switch
- **Radiator temp sensors** - 4 primary/redundant PT-103 sensor pairs on each radiator
  - Cross-strapped with RIU A and RIU B strings to avionics



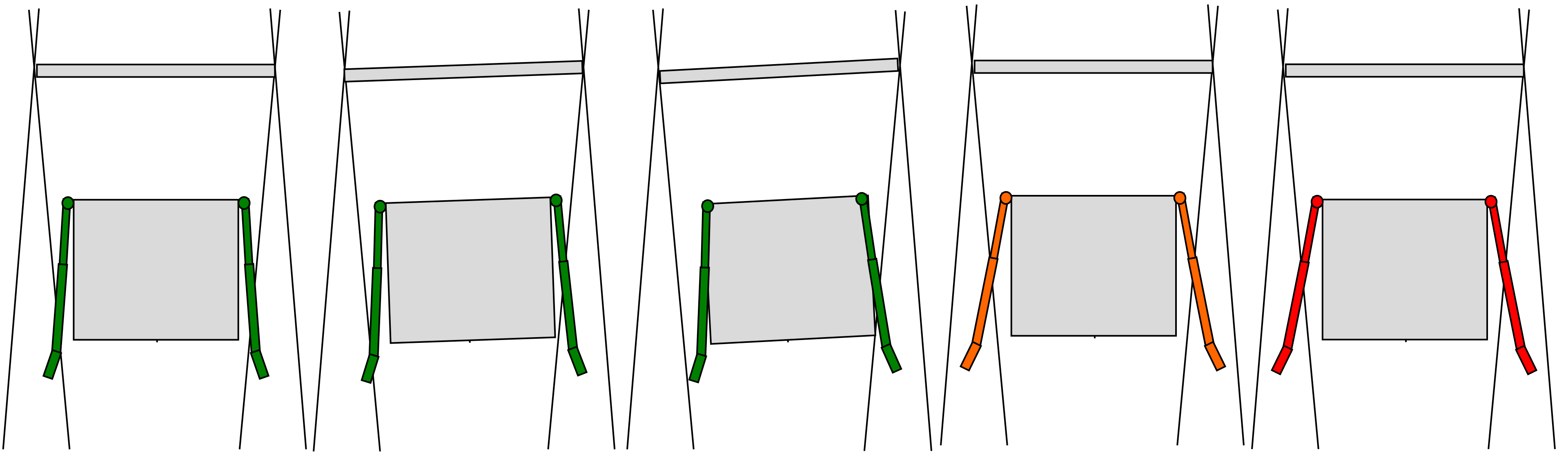


Over-Temp Approach

- **Solar flux at leading edge** – catches "fast" faults (no thermal lag), upper bound for over-temp approach
  - If solar flux reaches threshold on either wing, immediately trigger safing, regardless of temperature measurements
    - Catches scenarios where a fault causes the wings to move out at a constant rate and thermal lag does not keep up
    - By the time temp rises to violation, wings could be beyond point to reach safe angle in time
  - Amount of solar flux that can be tolerated by system varies with solar distance and attitude error
    - Set threshold to max solar flux that can be tolerated by the system at umbra violation, with all heat load coming from one wing (removes attitude error from the problem)
      - One wing illuminated, one wing shadowed -> what solar flux on illuminated wing causes 6,480W into cooling system?
      - Translates into max allowable solar flux on either wing as a function of solar distance
    - This profile will cause high transients in certain fault scenarios (e.g. wing angle control fault causes both wings to be illuminated with max solar flux)
  - Solar flux thresholds define worst-case transients seen by the system and worst-case time to safe the wings (minimum safe mode entry angle)

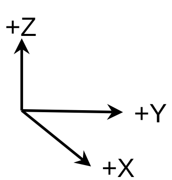
- **Outlet water temperature** – catches "slow" faults, lower bound for over-temp approach
  - If the array is operating above cooling system capacity but below the solar flux threshold, temperature measurements will trigger safing
    - Catches scenarios where a fault causes the wings to be at an angle that is too shallow to be safe steady-state, but not too shallow to trip a solar flux violation

Over-Temp Approach



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

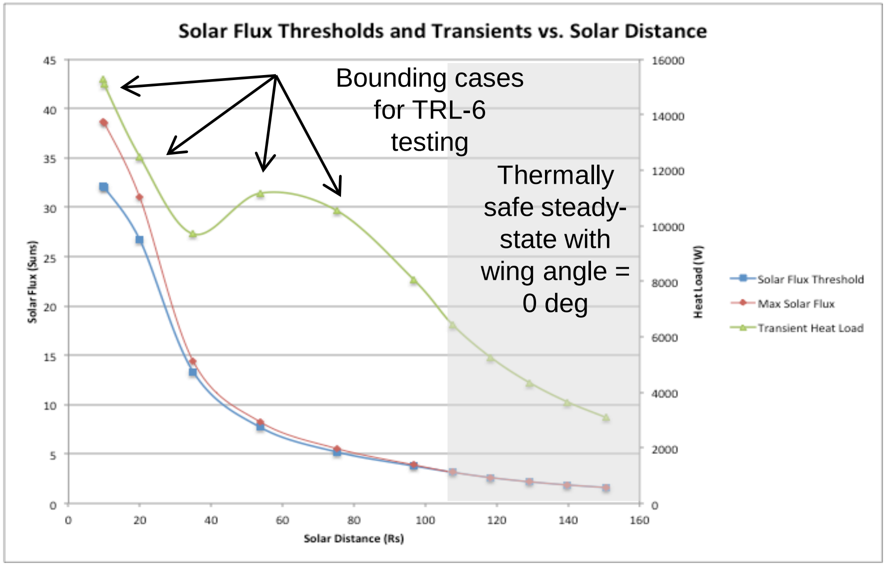
Nominal operating points (within cooling system capacity)	Above nominal operating point Below solar flux threshold Safe on temp	Above nominal operating point Worst-case transient Safe on solar flux

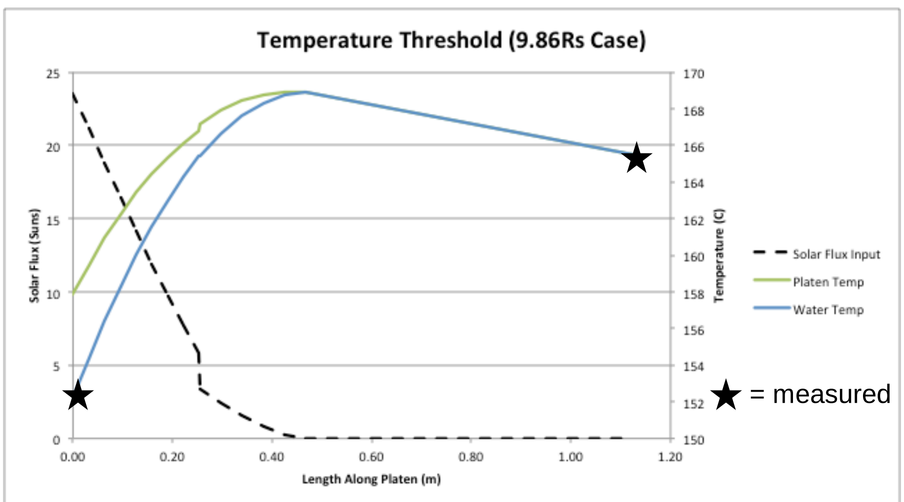


Note: Example is for 9.86Rs

APL

Over-Temp Thresholds and Resulting Transients





Solar Flux – violation thresholds dependent on solar distance and provide upper bound to safing approach (40 Suns max transient at 9.86Rs)

- Worst-case transients occur with solar flux violation on two wings prior to safing
- "Max Solar Flux" = solar flux that will actually be seen on either wing before safing occurs, due to measurement error (6%) and wing overshoot (0.1 deg/s for 5s)

Water Temperature – violation threshold is 160C (+/-5C)

- Hottest temp will be in between inlet and outlet (not measured), 4C delta between measured temp and max temp along length of platen
- 160C outlet water temp measurement -> 165C actual water temp -> 169C actual platen temp, worst-case (9.86Rs, 23.6 Suns into substrate, 7,400W into cooling system)
  - Provides margin on 190C survival limit
- Maximum EOL outlet water temp is 144C and platen temp is 148C (9.86Rs, 21 Suns into substrate, 6,480W into cooling system)
  - Nominal operations not constrained

Transient Thermal Analysis

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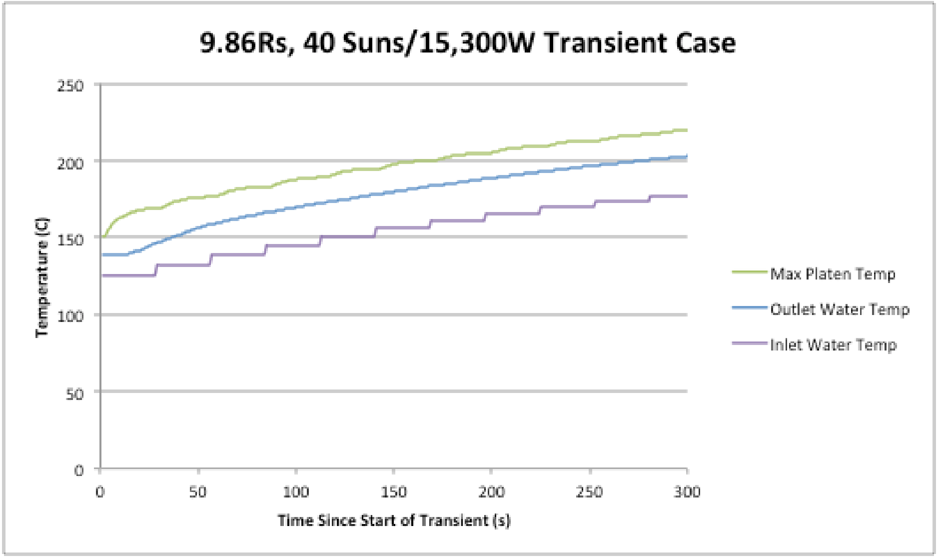
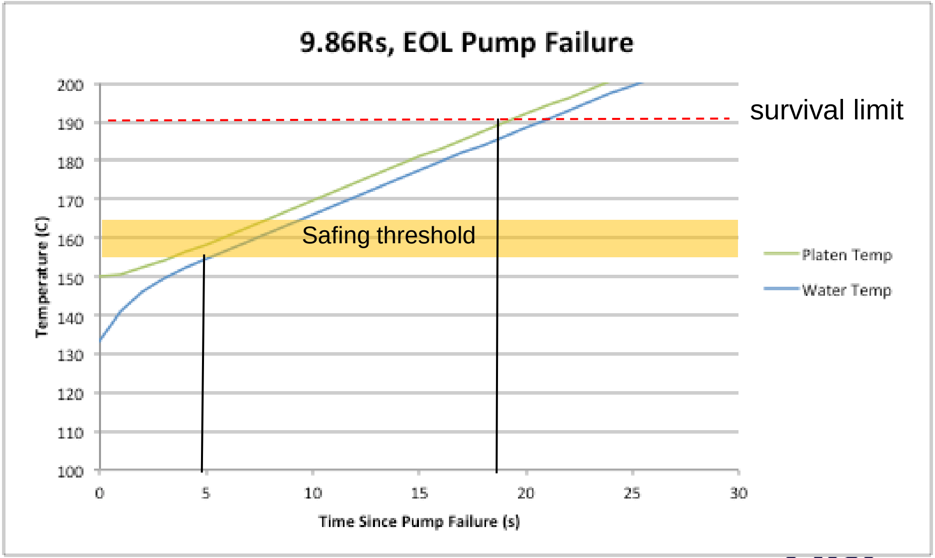
- **9.86Rs transient case from safing on solar flux (40 Suns)** – 190C survival limit will be reached within 110s
  - Wings will be at safe angle within 30s of fault detection at 9.86Rs
  - In worst-case timing at 0.25AU, wings will be at safe angle within 75s of fault detection
- **Pump failure** – At EOL (max cooling system capacity), pump failure will cause 160C over-temp threshold to be reached within 5s (measured water temp) and 190C survival limit to be reached within 19s (actual platen temp), assuming constant heat load
  - Timing budget shows that new pump will reach full speed within 10s of pump failure
- **Bounding transient cases tested during TRL-6 cooling system test (Nov 2013)**
  - 40 Suns case ran for 5 min 46s before 190C survival limit reached
  - Pump failure case ran for 41s before 190C survival limit reached





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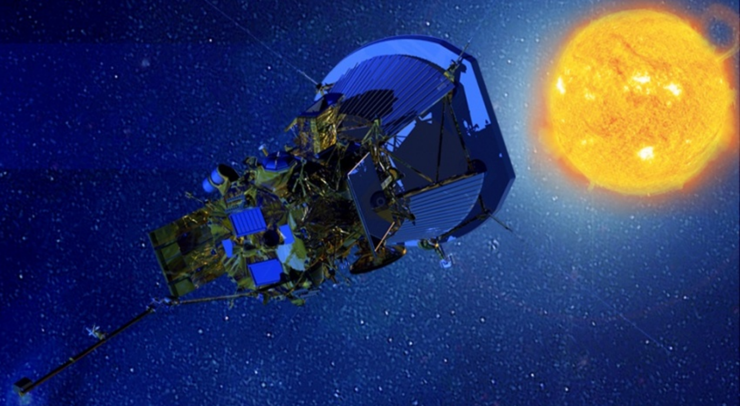

Safe Angles

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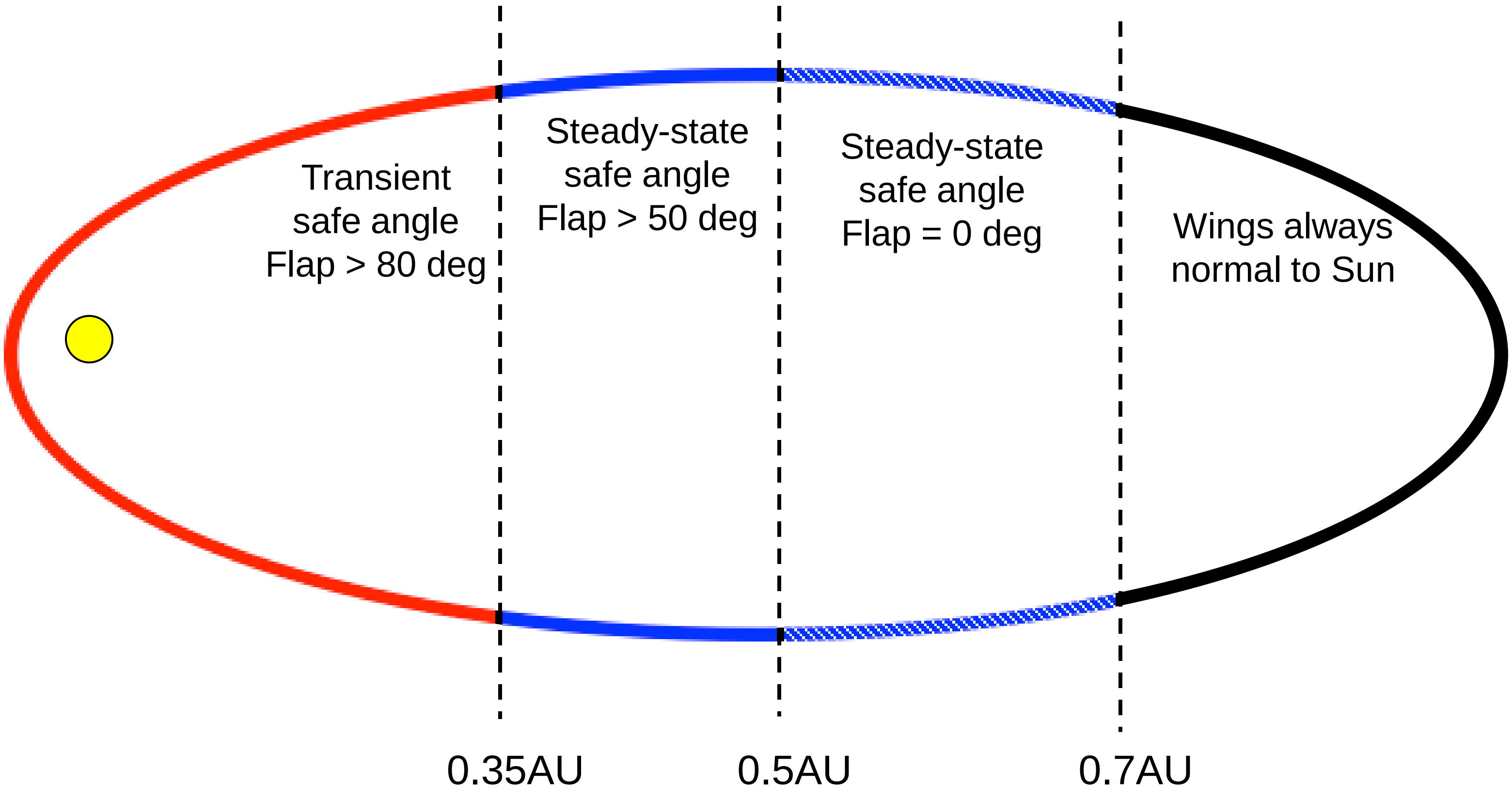
Safe Angles Overview



System Temperatures

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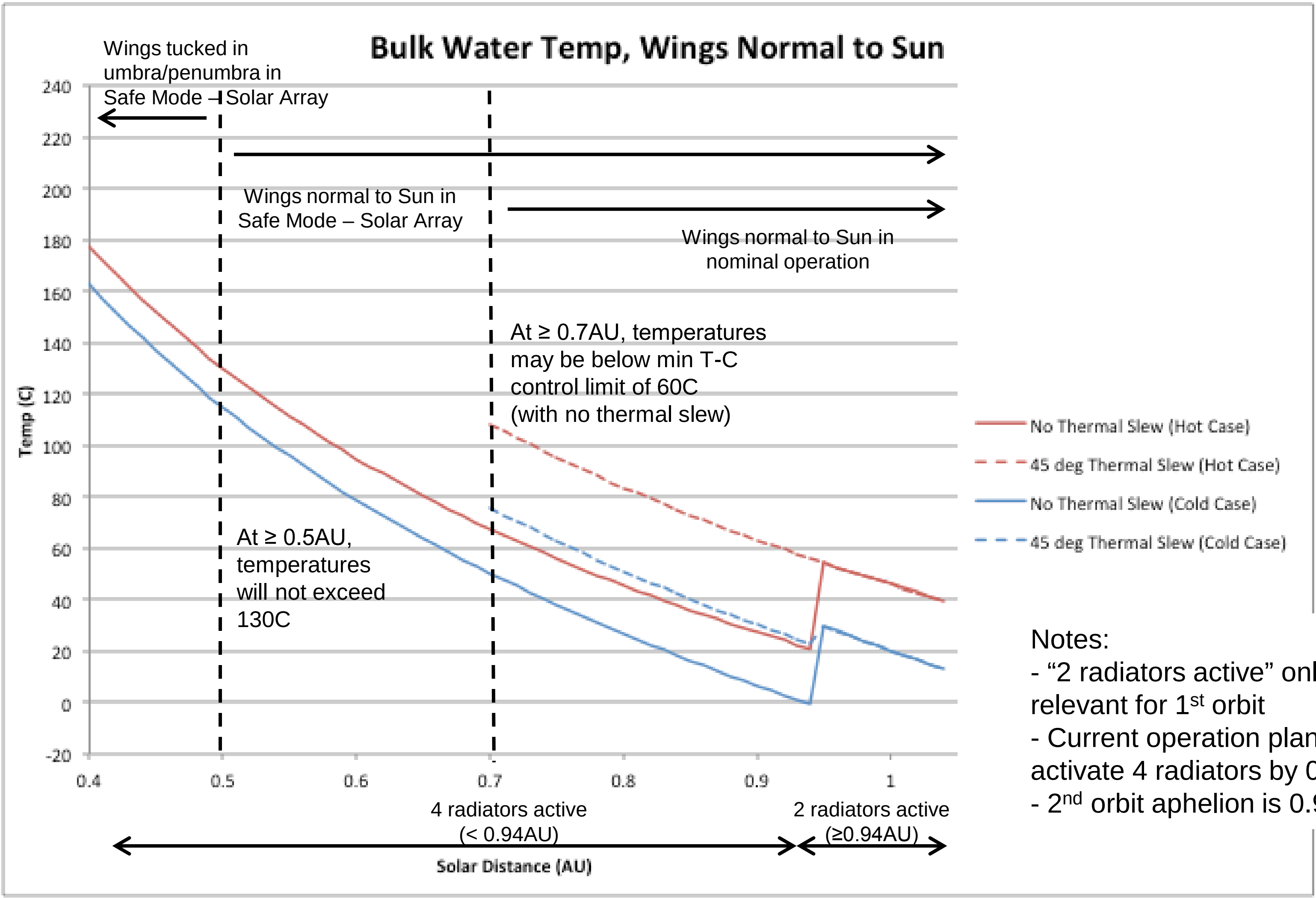
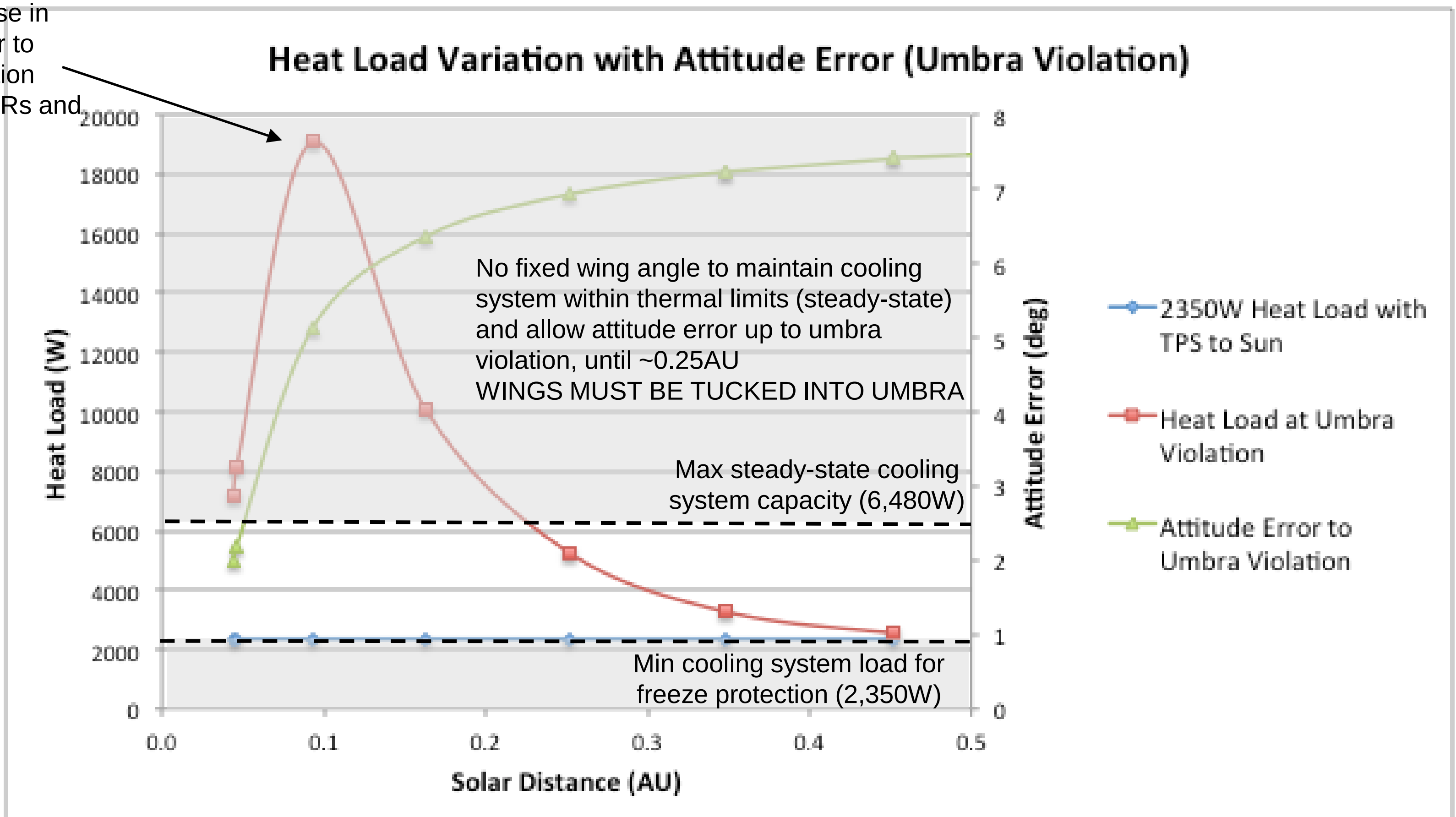


Notes:
- "2 radiators active" only relevant for 1st orbit
- Current operation plan is to activate 4 radiators by 0.90AU
- 2nd orbit aphelion is 0.94AU

Safe Angles Inside 0.5AU

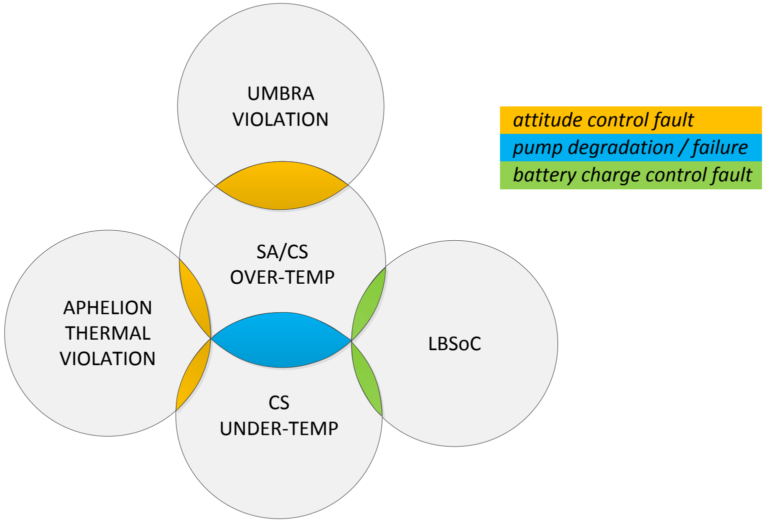
Local max due to large increase in attitude error to umbra violation between 9.9Rs and 20Rs



Safe Angle Approach

- **One safing response (including wing angle) for all power/thermal critical faults, as a function of solar distance**
  - Results in robust design and protects against situations where multiple critical faults may arise (tight coupling of G&C, power, thermal systems)

- **Freeze protection -** wings cannot be indefinitely tucked into umbra -- cooling system will freeze
  - If initial temp > 43C, wings can be tucked for 5 min before 20C yellow limit (assumes operational pump)
    - 43C will be cooling system undertemp threshold (allows same response for all faults)
      - 43C is sufficiently low to bias solar array cold during nominal operations
      - 5 min is sufficient time for safing and recovery actions to complete
  - If pump failed, 43C initial temp provides 2.4 min to 20C, therefore timing is driven by 19s overtemp pump failure case



Position Sensing and Safe Angle Margin

- **Position Sensing –** solar array safing requires absolute knowledge of wing angle
  - Potentiometers provide wing angle knowledge to ±0.5 deg (coarse only) and ±0.03 deg (coarse + fine)
    - Must rely on accuracy of coarse pots for safing (one fine pot in deadband and one failed)
  - Commanded step-count is primary means of tracking wing angle during flight
  - Pots and step-count are monitored, compared, and corrected for mismatch in nominal operations

- **Safe Angle Margin –** solar array safing angles must maintain at least 0.5 deg flap angle margin with solar array stowed position (88 deg) in order to avoid contact between wings and spacecraft
  - Required margin depends on angle knowledge (accuracy of coarse pots)
  - Fully shadowing the wings during safing and accommodating attitude error up to umbra violation is not feasible
    - Requires a flap angle > 88 deg for all solar distances
    - Wings will therefore see some heat load > 0W during safing
      - Allowable heat load during safing set to 2,050W (10C steady-state), up to umbra violation – sufficient to allow wings to cool down in overtemp case while avoiding wing contact with spacecraft

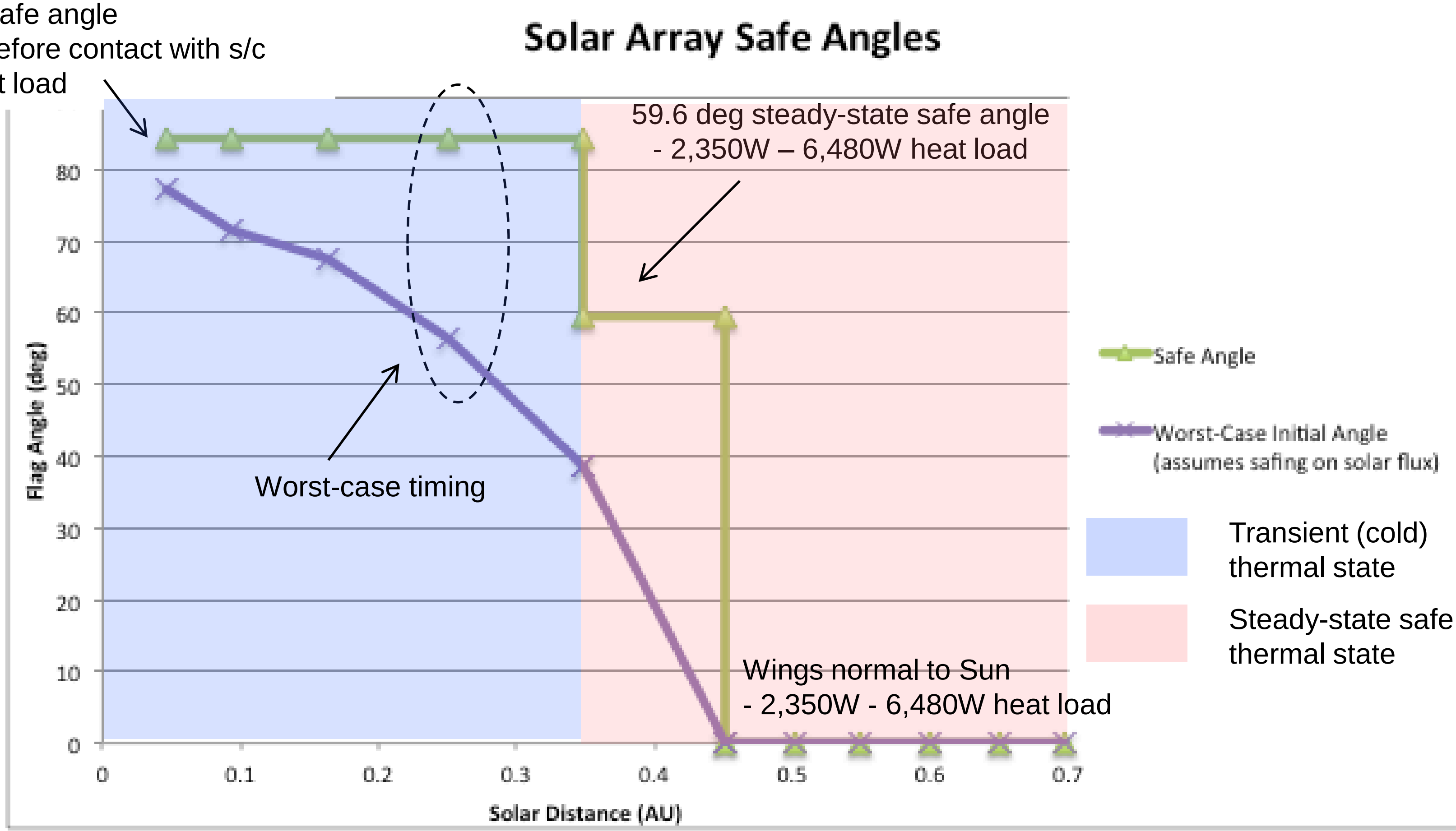
Safe Angles

Solar Distance	Flap Angle	Feather Angle	Min Initial Temp	Total Load into Cooling System	Description
9.86Rs – 0.35AU	84.3 deg	0 deg	43C	≤2,050W	Thermally safe for at least 5 min Power safe for ~20 min
0.35AU – 0.5AU	59.6 deg	0 deg	43C	2,350W – 6,480W	Thermally safe steady-state Power safe for ~20 min
0.5AU – 0.7AU	0 deg	0 deg	43C	2,350W – 6,480W	Thermally safe steady-state Power safe steady-state High irradiance increases solar array degradation
≥0.7AU	0 deg	0 – 90 deg	20C	< 3,000W	Thermally safe steady-state Power safe steady-state Wings should nominally always be normal to Sun

Note: 0.35AU used as min solar distance for steady-state safe angle, to provide margin

Safe Angles

84.3 deg transient safe angle
- 3.2 deg margin before contact with s/c
- Max 2,050W heat load



Worst-case timing is 73s (0.25AU) and assumes:
- 10s from fault occurrence to wings moving
- 0.5 deg error on wing angle knowledge (must target safe angle 0.5 deg steeper)
- 0.5 deg/s rate, 10% error on rate accuracy

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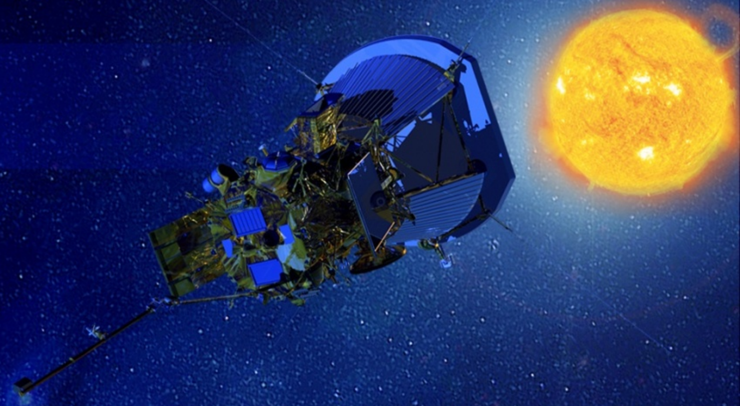

Exiting Safe Mode – Solar Array

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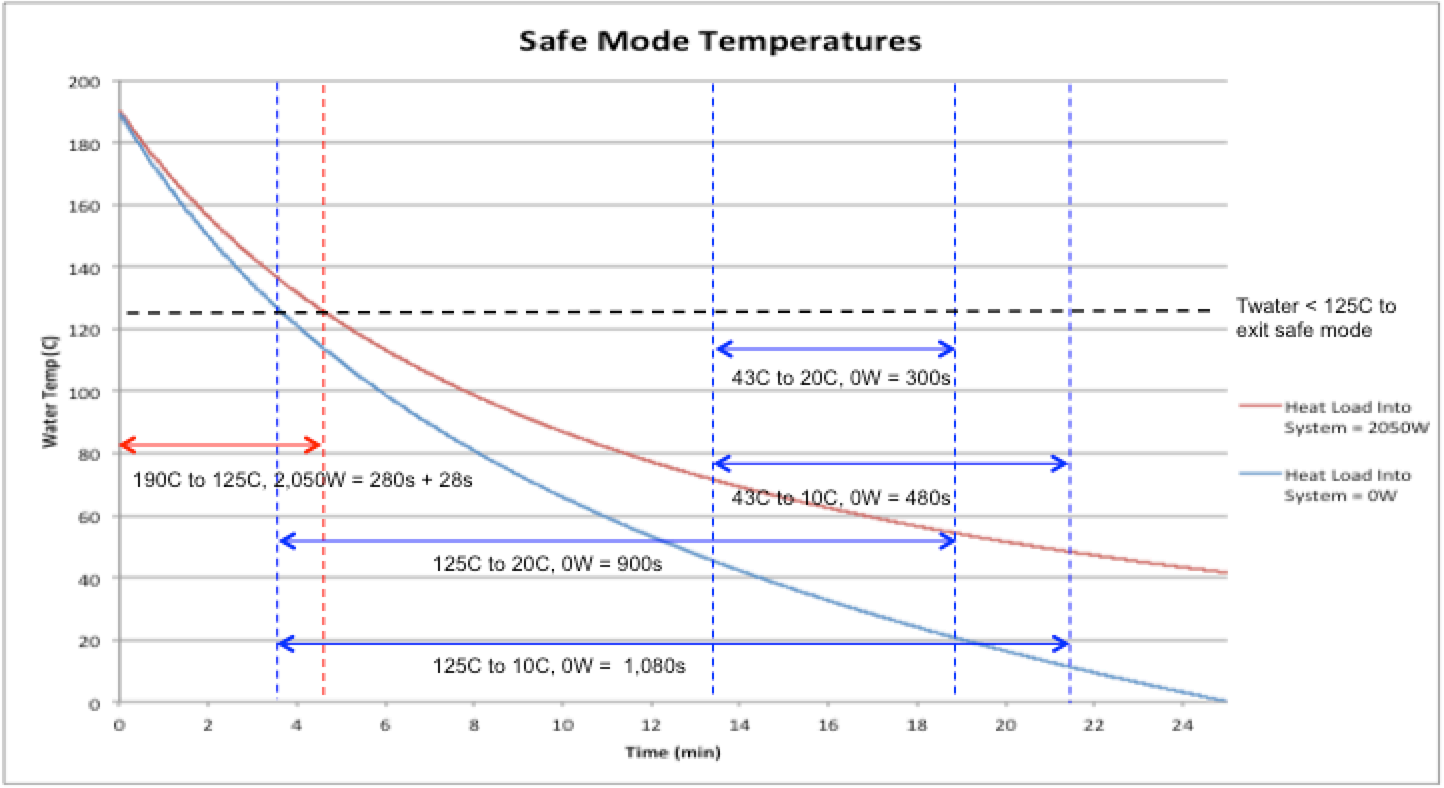
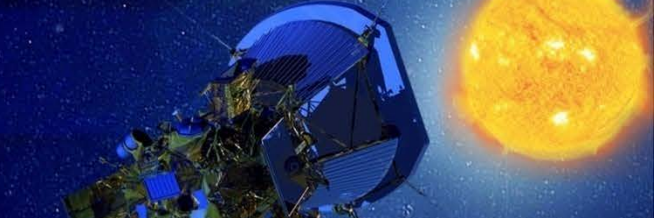
Exiting Safe Mode – Solar Array

When wings are tucked in umbra (< 0.35AU), approach for exiting Safe Mode – Solar Array must:

- Provide sufficient cooldown time in over-temp scenarios (T_{water} < 125C to exit safe mode)
- Return wings to thermally safe operation before freezing in low-temp scenarios (≥ 2,350W heat load into system)
  - Wings drive out at max rate until required electrical power is met
  - Normal P-C/T-C transitions resume – analysis shows that response times for T-C will ensure temperature remains above 20C





Exit Criteria

- At t = 90s from fault detection, check telemetry to determine if wings should exit safe mode immediately, or wait duration of allocated cooldown time
  - If $T_{water} \leq$ 125C, exit safe mode immediately (“low-temp path”)
    - 5 min to 20C yellow limit, 8 min to 10C red limit (margin defined from fault detection)
  - $T_{water} >$ 125C, wait duration of cooldown time (“over-temp path”)
    - At t = 280s + 28s from safe angle reached, cooldown time met, exit safe mode immediately (additional 28s includes water cycle time)
    - 15 min to 20C yellow limit, 18 min to 10C red limit (margin defined from fault detection)
- Implementation of timers is TBR; purpose is to show worst-case stack-up of time from fault detection to wings return to operational
  - Telemetry check at 90s allows for a set amount of time in budget for wings to move to safe angle (envelopes all solar distances < 0.35AU) and recovery actions to complete
  - Cooldown time of 280s + 28s allows for a set amount of time in budget for wings to cool down to 125C

- Timing of other critical fault scenarios (LBSoC, umbra violation) enveloped by over-temp and low-temp scenarios
  - Depending on initial temperature, these scenarios will either exit safe mode at 90s from fault detection (“low-temp path”) or at 280s + 28s from safe angle reached (“over-temp path”)
  - Telemetry check at 90s before exiting safe mode keeps wings safe in umbra violation scenario as long as possible

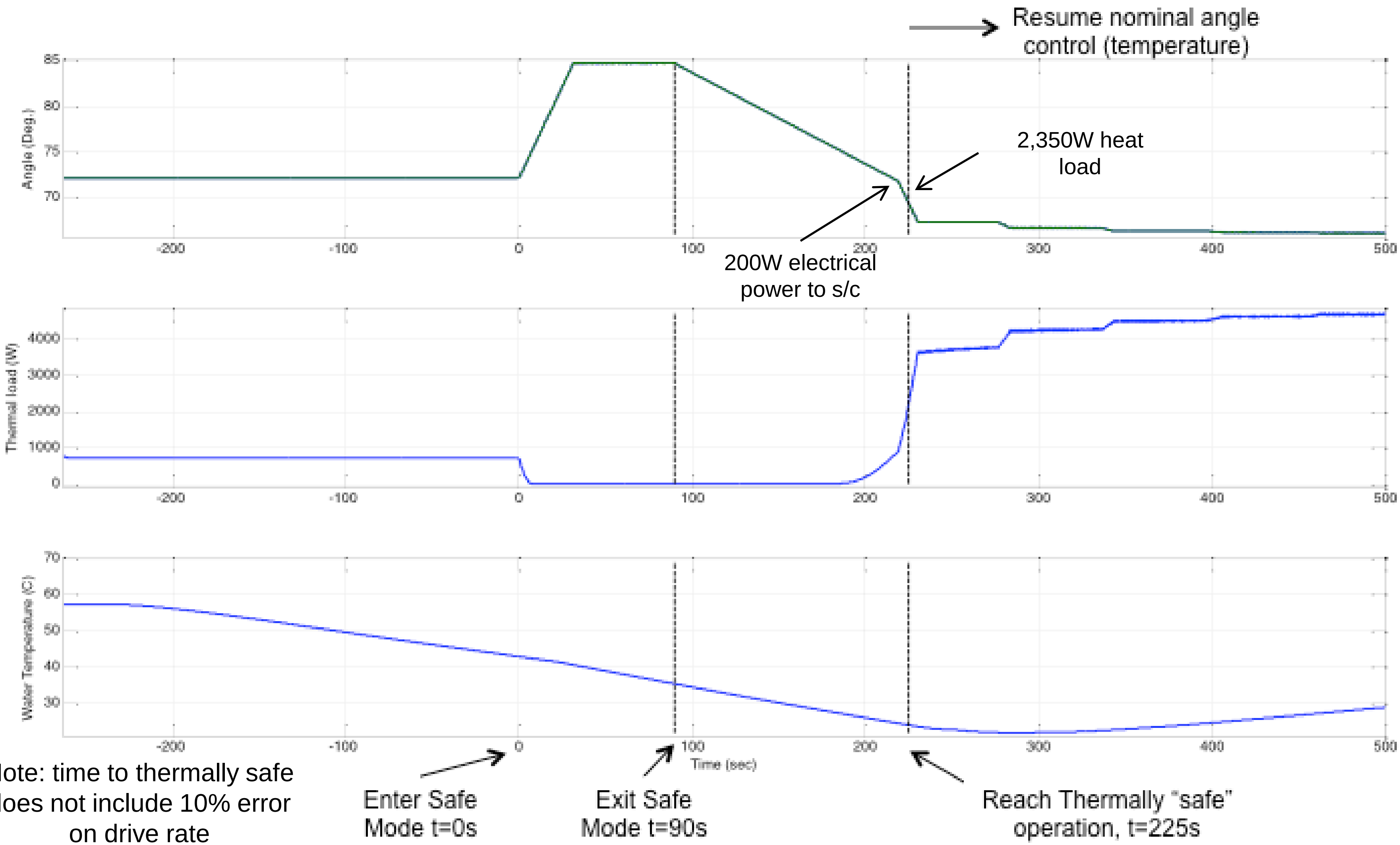
Steps to Exit Safe Mode

1. Autonomous wing angle control extends the wings at a constant rate until electrical power meets spacecraft load
   - Rate will depend on ability to PPT (faster rate likely achievable at further solar distances)

2a. If in a low-temp scenario: T-C will take over and continue extending the wings
   - T_{water} < 43C when wings reach required electrical power
   - If solar array degradation or spacecraft power load are low, wings may meet electrical power with heat load < 2,350W into the system (wings might not extend far enough in step 1 to be safe steady-state)
     - Analysis shows T-C will move fast enough to achieve 2,350W heat load before cooling system violates freeze limit, not too fast to overshoot and risk overheating

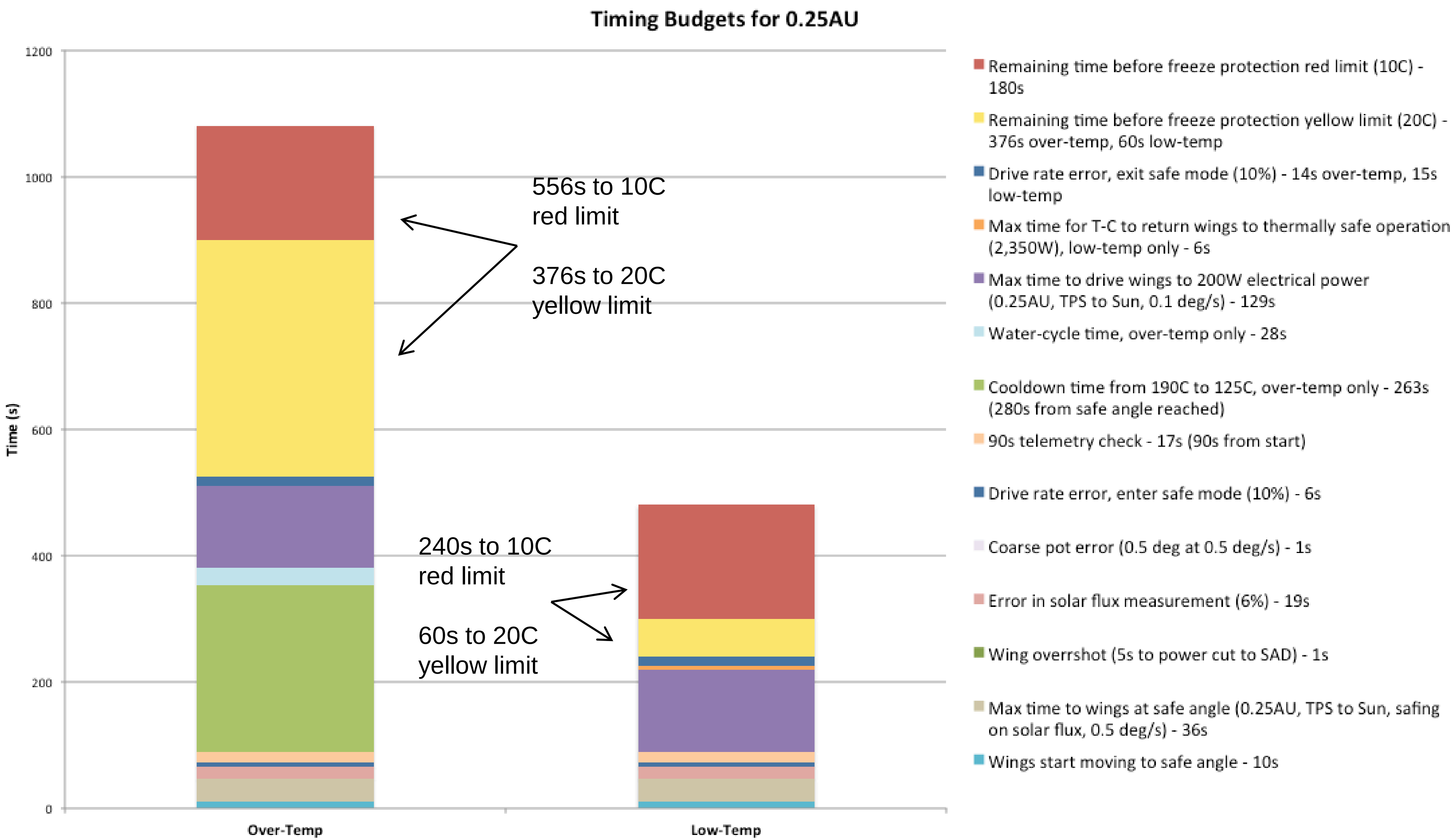
2b. If in an over-temp scenario: normal P-C/T-C transitions will take over
     - T_{water} > 60C when wings reach required electrical power

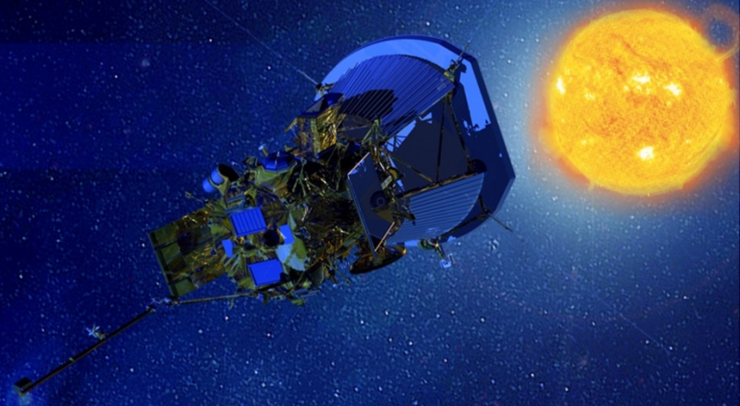
Safe Mode Exit at 0.25AU



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

Timing Budgets for 0.25AU





Verification

Verification

- **Solar Array Operations and Safing requirements are distributed among various levels**
  - System-level testing will verify level III requirements
  - Subsystem-level testing will verify level IV and lower requirements

- **Solar Array Operations and Safing verification will include system level testing of:**
  - **Nominal solar array control** - test all modes, transitions, stressing cases (e.g., momentum dumps, SLS control, TCMs)
  - **Faulted solar array control** - test that solar array control operates as expected through local faults
    - Using subsystem FMEAs to define and develop tests (e.g., pot/count mismatch, component over-temps)
  - **Safe Mode – Solar Array** - test end-to-end scenarios of nominal operation, critical fault injection (e.g. attitude control fault, angle control fault), solar array safing, and recovery to nominal operation
    - Encompass driving solar distances (e.g., perihelion, safe angle transition points), mission activities (e.g., momentum dumps, downlink slews), and transitions between safe modes
    - Break up scenarios to leverage early testing
      - Processor switch – early FM testing with RPM
      - Side switch – early FM testing with REM
      - Solar array safing – early EPS testing with EPS GSE and G&C truth model

Verification

- **Verification will be accomplished through:**
  - Analysis using integrated G&C/EPS/Cooling System model (on-going)
  - Analysis using high-fidelity stand-alone steady-state and transient thermal models (on-going)
  - Cooling system TRL-6 testing (Oct – Nov 2013)
    - Results form basis of verification for safing approach and will be incorporated into modeling and development of safing strategy (e.g., temperature time constants, validation of solar flux thresholds
  - Testing on EPS Testbed and Spacecraft

- **Initial set of required fault injection capabilities defined**
  - Includes telemetry override and truth model manipulation capabilities

- **Initial set of tests defined** – mapped to level III requirements, mapped to fault injection capabilities needed, mapped to testbed/spacecraft capabilities needed (e.g., testbed emulations, hardware in the loop)

EPS Testbed

EPS GSE Testbed is currently in use for Phase B/C to support development of solar array angle control algorithms

- Integrated G&C/EPS/Cooling System model (Simulink)
- Breadboard EPS hardware (PSE, battery, SAS)

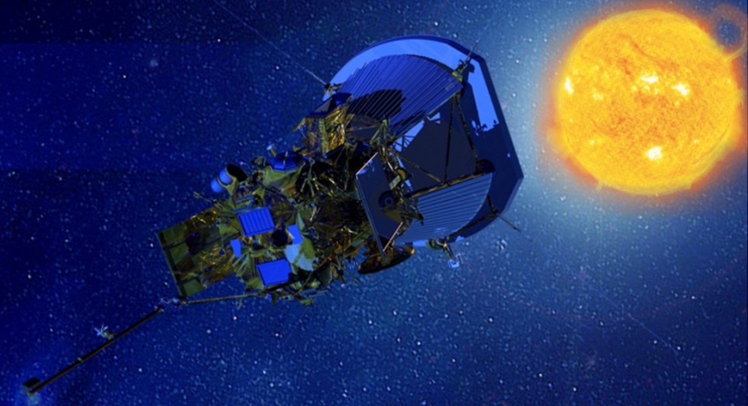
- EPS Testbed with Avionics hardware in the loop will be delivered in FY15 (1 year prior to I&T) and will include:
    - Avionics hardware – full RPM and REM (breadboard hardware)
    - EPS hardware – PSE EM, battery EM, SAS, PDU/load simulator
    - FSW – C&DH software, G&C software, Autonomy (in development)
    - Testbed Software – Irradiance link to SAS, G&C truth model, emulations of SAD/ECU/pots, Isc/Voc sensors, platen temp sensors, radiator temp sensors, SLS, battery, PDU (in development)
  - Shared resource between EPS (including SA control) and Solar Array Operations and Safing

Early testing of highly coupled EPS and G&C algorithms with Avionics hardware and FSW in the loop will significantly buy down I&T schedule risk

Phase C Plans

- Incorporate results of TRL-6 cooling system test into modeling and refinement of solar array safing approach
  - Validation of solar flux violation limits
  - Model correlation (temps through cell stack, temp time constants)
    - Coordinated effort with APL and HS model developers and users
- Show end-to-end safing simulations using EPS GSE testbed
- Refine verification plan for solar array operations and safing (develop SA Ops and Safing Test Spec)
- Solar Array Operations and Safing CDR

Solar Array Operations and Safing is ready for Phase C



Backup

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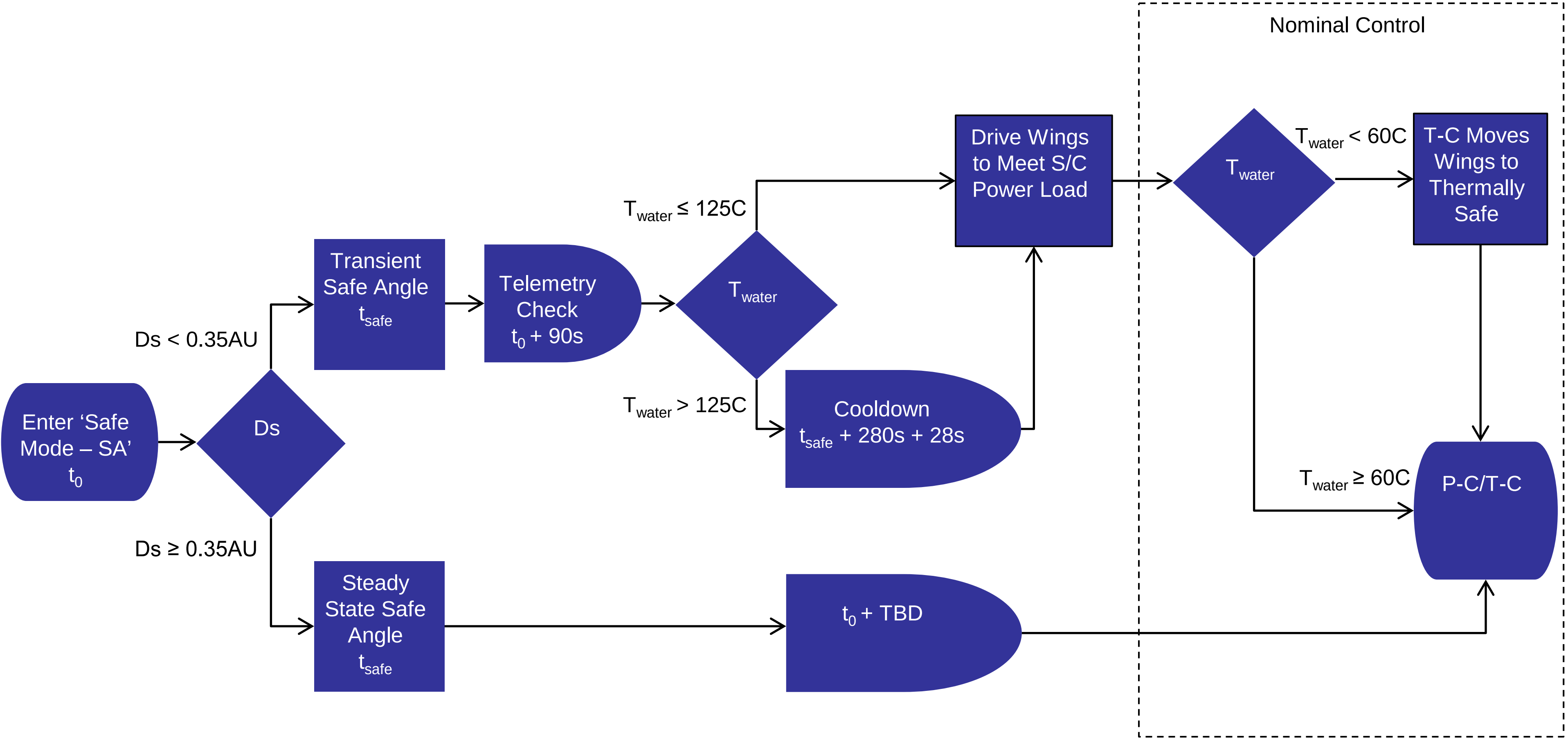
Flowchart


Nominal Control
Enter 'Safe Mode – SA' t_0
Ds
Ds < 0.35AU
Ds ≥ 0.35AU
Transient Safe Angle t_{safe}
Telemetry Check t_0 + 90s
T_{water}
T_{water} ≤ 125C
T_{water} > 125C
Drive Wings to Meet S/C Power Load
Cooldown t_{safe} + 280s + 28s
T_{water}
T_{water} < 60C
T_{water} ≥ 60C
T-C Moves Wings to Thermally Safe
P-C/T-C
Steady State Safe Angle t_{safe}
t_0 + TBD

Low-Temp Timing Budget for 0.25AU

- Time to begin moving wings to safe angle (10s)
- Time to move wings to defined safe angle at 0.5 deg/s (36s + 1s +19s)
    - Time to move wings from solar flux threshold starting point to safe angle at 0.5 deg/s, 0.25AU (36s)
        - Min angle bound not yet defined for low-temp scenarios (conservative)
    - Wing overshoot (1s)
        - Assume 5s to power cut to SAD, 0.1 deg/s outward rate for overshoot -> 0.5 deg extra travel distance, 0.5 deg/s inward rate for safing
    - 6% error on solar flux measurement (19s)
- 0.5 deg error on coarse pot (1s)
        - Must target safe angle that is 0.5 deg steeper
- 10% error on drive rate, entering safe mode (6s)
    - Apply to time to move wings to safe angle and to coarse pot error
- Telemetry check (90s, from fault detection)
    - If $T_{water} \leq 125C$, exit safe mode
- Time to move wings to 200W electrical power at 0.1 deg/s, 0.25AU (129s)
    - Rate will depend on ability to PPT
- Time to move wings to 2,350W heat load using T-C at 0.5 deg/s, 0.25AU (6s)
- 10% error on drive rate, exiting safe mode (15s)
    - Apply to time to move wings to 200W electrical power and time to move wings to 2,350W heat load

Note: not included in timing budget is time to accelerate SAD to max rate; expected to be < 1s

Over-Temp Timing Budget for 0.25AU

- Time to begin moving wings to safe angle (10s)
- Time to move wings to defined safe angle at 0.5 deg/s (36s + 1s +19s)
  - Time to move wings from solar flux threshold starting point to safe angle at 0.5 deg/s, 0.25AU (36s)
  - Wing overshoot (1s)
    - Assume 5s to power cut to SAD, 0.1 deg/s outward rate for overshoot -> 0.5 deg extra travel distance, 0.5 deg/s inward rate for safing
  - 6% error on solar flux measurement (19s)
- 0.5 deg error on coarse pot (1s)
    - Must target safe angle that is 0.5 deg steeper
- 10% error on drive rate, entering safe mode (6s)
  - Apply to time to move wings to safe angle and to coarse pot error
- Cooldown time (280s, from time at safe angle)
  - Assumes 190C to 125C, 2,050W heat load into system
  - 90s telemetry check occurs within this time
- Water-cycle time (28s)
  - Accounts for hot water that may be lagging the telemetry checks
- Time to move wings to 200W electrical power at 0.1 deg/s, 0.25AU (129s)
  - Rate will depend on ability to PPT
- 10% error on drive rate, exiting safe mode (14s)
  - Apply to time to move wings to 200W electrical power

Note: not included in timing budget is time to accelerate SAD to max rate; expected to be < 1s

Margin Summary

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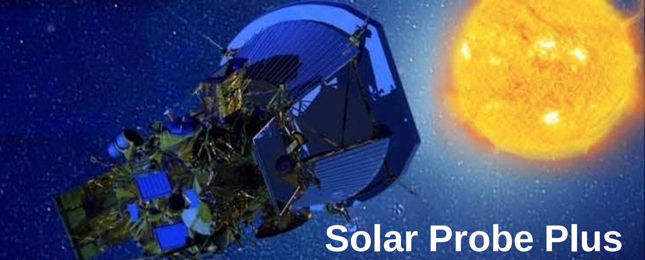
Item	CBE (s)	NTE (s)	Allocated Margin (s)	Total (s)	Unallocated Margin (s)
Wings to Safe Angle: Safe Solar Array – Overtemp	**41.5**	**110.0**	**31.5**	**73.0**	**37.0**
1. Wings start moving to safe angle	***5.4***		***4.6***	***10.0***	
• Margin held in timing budget			4.6		
2. Wings move to safe angle (solar flux threshold starting point)	***36.1***		***26.9***	***63.0***	
• Wing overshoot			1.0		
• Error in solar flux measurement			18.6		
• Coarse pot error			1.0		
• Drive rate error			6.3		

Margin Summary



Item	CBE (s)	NTE (s)	Allocated Margin (s)	Total (s)	Unallocated Margin (s)
Wing Return to Nominal: Safe Solar Array – Overtemp	**450.5**	**900.0**	**73.8**	**524.3**	**375.7**
1. Wings to Safe Angle (from previous slide)	***41.5***		***31.5***	***73.0***	
• Allocated margin (from previous slide)			31.5		
2. Cooldown time (280s from safe angle reached)	***280.0***		***28.0***	***308.0***	
• Water cycle time			28.0		
3. P-C drive wings to meet electrical power	***129.0***		***14.3***	***143.3***	
• Drive rate error			14.3		

Margin Summary

Item	CBE (s)	NTE (s)	Allocated Margin (s)	Total (s)	Unallocated Margin (s)
Wing Return to Nominal: Safe Solar Array – Undertemp	**176.5**	**300.0**	**63.5**	**240.0**	**60.0**
1. Wings to Safe Angle (from previous slide)	***41.5***		***48.5***	***90.0***	
• Allocated margin (from previous slide)			31.5		
• Telemetry check (90s from fault occurrence)			17.0		
2. P-C drive wings to meet electrical power	***129.0***		***14.3***	***143.3***	
• Drive rate error			14.3		
3. T-C drive wings to thermally safe	***6.0***		***0.7***	***6.7***	
• Drive rate error			0.7		

Preliminary Test List

Verification Activity	Condition	Event
Nominal Solar Array Control	Perihelion P-C	Nominal
		Momentum Dump
		SLS Control
	Aphelion P-C (Inbound, Outbound)	Nominal
		Downlink Slew
		TCM
	Fixed Angle	Nominal
		Downlink Slew
	T-C	Nominal
		Momentum Dump
		SLS Control
		TCM
		Downlink Slew
	P-C to T-C (Perihelion, Aphelion)	Nominal
		Momentum Dump
		SLS Control
		TCM
		Downlink Slew
	T-C to P-C (Perihelion, Aphelion)	Nominal
		Momentum Dump
		SLS Control
		TCM
		Downlink Slew

Verification Activity	Condition	Event
Faulted Solar Array Control	P-C, T-C (Perihelion, Aphelion)	ECU Switch
		PSE Reset
		Power Cycle PSE
		Pump Switch
		SLS Control, Power Cycle SLS
		Power Cycle ST
		IMU Switch
		Avionics Side Switch
Safe Mode - Solar Array	SA/Cooling System Over-Temp (Temp Violation, Solar Flux Violation)	Nominal
		Momentum Dump
		SLS Control
		TCM
		Downlink Slew
	Cooling System Low-Temp	Nominal
	LBSoC	Nominal
	Umbra Violation	Nominal
		Momentum Dump
		SLS Control
		TCM
	Aphelion Thermal Violation	Nominal
		Downlink Slew
	From Safe Mode - Stby	Nominal
	From Safe Mode - EA	Nominal

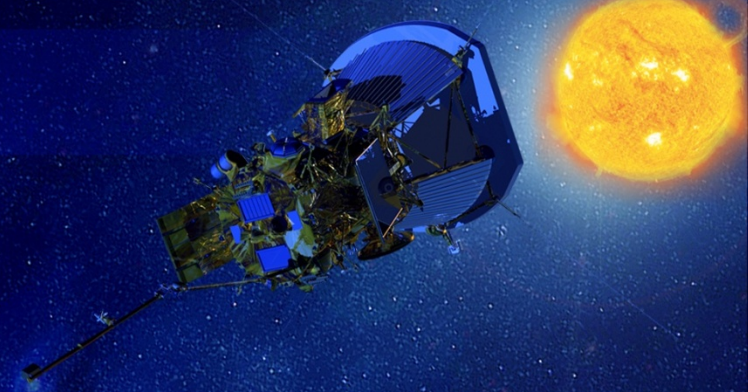
Freeze Protection

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

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

Solar Probe Plus

A NASA Mission to Touch the Sun



Reliability

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13 – 16 January 2014

The Johns Hopkins University
APPLIED PHYSICS LABORATORY

Reliability Requirements

NASA Procedural Requirements

- **NPD 8720.1 "NASA Reliability and Maintainability (R&M) Program Policy"**
  - Establish reliability performance requirements
  - Integrate all reliability activities with systems engineering, risk management, and other processes, assessments, and analyses including, but not limited to, safety, security, quality assurance, logistics, probabilistic risk assessment, life-cycle cost, configuration management, and maintenance
- **NPR 8705.4 "Risk Classification for NASA Payloads"**
  - Classification Level B
- **NPR 8705.5 "Probabilistic Risk Assessment (PRA) Procedures for NASA Programs and Projects"**
  - "Limited" scope
    - Same level of rigor as a full PRA focused on "mission-related end-states" instead of "all applicable end-states."

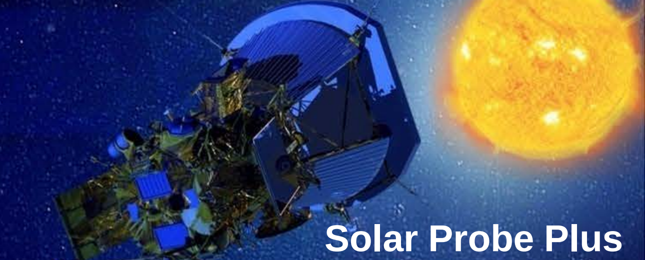
Reliability Engineering

Philosophy

- **Redundancy as directed by Class B mission**
  - Critical single point failures may be permitted but are minimized and mitigated by use of high reliability parts and additional testing
  - Essential spacecraft functions and key instruments are typically fully redundant
  - Other hardware has partial redundancy and/or provisions for graceful degradation
- **Design implementation**
  - Block redundancy as much as possible
    - Less complex system
    - Fewer configurations to test
  - Cross-strap redundancy where timing, local control, or reliability issues warrant
  - Single point failures where unavoidable
- **Qualitative and quantitative assessments to identify risks and validate mitigation strategies**

Reliability Requirements

Mission Success Criteria



- **Mission objectives are defined in Level 1 requirements document**
  - "Appendix E to the Living With a Star Program Plan"
- **Success criteria are mapped to Instruments measurements and then to PRA end-states**
  - Probabilities (with uncertainties) will be calculated
  - Failure/fault sequences will be identified and analyzed
- **Functional redundancy exists within/among instruments**
  - Alternative measurements exist to answer multiple sub-questions

Reliability Documentation

- **Reliability Program Plan**
  - 7434-9041

- **Probabilistic Risk Assessment Plan**
  - 7434-9106

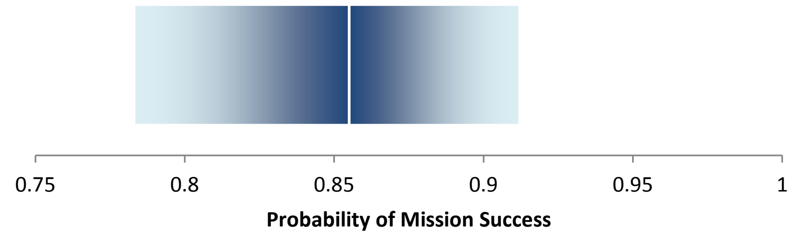
- **Failure Mode and Effects Analysis Peer Review**
  - May 7, 2013

- **Probabilistic Risk Assessment Peer Review**
  - Oct 24, 2013

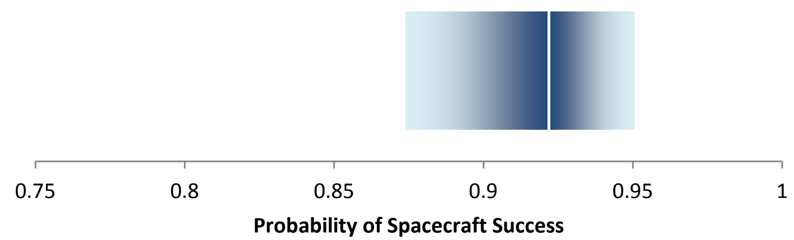
Reliability Analyses Summary

- **Failure Mode and Effects Analysis**
  - Spacecraft bus and instruments
  - Input to Fault Management process
  - Foundation for PRA
- **Science Fault Tree**
  - Developed to identify dependencies among instruments
- **Single point failure list**

- **Probabilistic Risk Assessment**
  - Probability of Mission success



  - Probability of Spacecraft success



Reliability Analysis

Scope

- **Spacecraft bus**
  - Completion consistent with design maturity
- **Instruments**
  - Inputs provided by instrument teams
- **Environmental impacts**
  - Protons
  - Dust
- **Third Stage**
  - In progress, preliminary results from motor vendor
- **GSE (not yet included)**
- **Mission Operations Center (not yet included)**

Failure Mode and Effects Analysis

Description

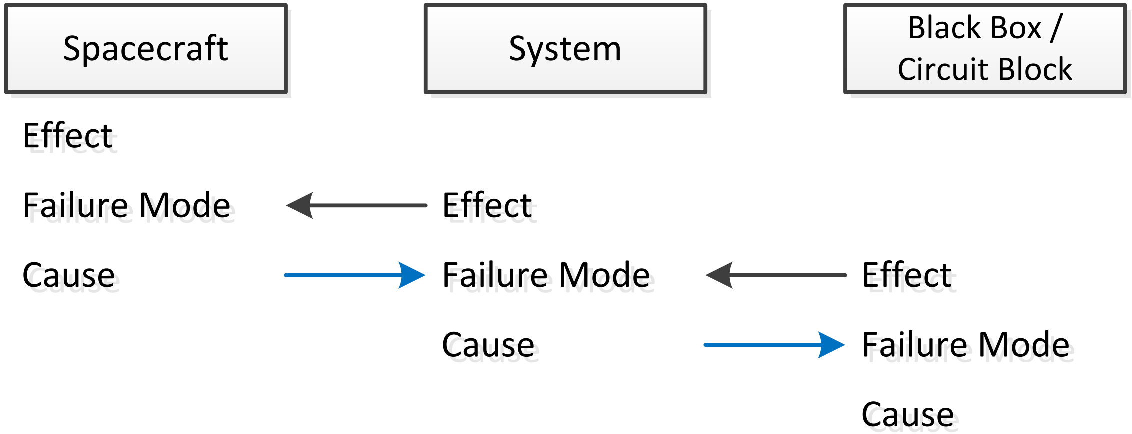
- **FMEA is a systematic approach for identifying potential failures in the design**
  - “Failure modes” means the ways in which something might fail
  - “Effects analysis” refers to studying the consequences of those failures
- **Provides a basis for identifying root failure causes and developing effective corrective actions**
- **Class B requires detail down at “black box (or circuit block diagram) level as minimum”**
- **Includes greater than 725 failure modes analyzed**

Failure Mode and Effects Analysis

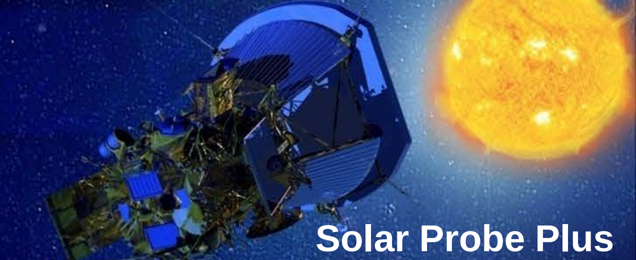
Level of Detail

- **At this point the FMEA is analyzed down to a level consistent with design maturity**
  - Lowest level of detail varies from system to system
  - Board/slice for most systems
  - Components such as RF Switches and mechanisms where necessary to adequately describe the failure mode and cause
  - Box level for COTS items such as Star Trackers and Wheels

- **FMEA analysis shows cascading interactions among level of detail**



PRA Overview



- **Probabilistic Risk Assessment (PRA) is a structured, systematic, scenario-based, approach to assess factors contributing to risk and determine their relative significance within the system**

- **PRA ask questions such as:**
  - What can go wrong? (accident scenario)
  - How likely is it to occur? (probability, frequency)
  - What will be the outcome? (consequences)

- **Scenarios describe sequence of events starting with various initiators to undesired end-states by way of pivotal events**

PRA Overview

Assumptions

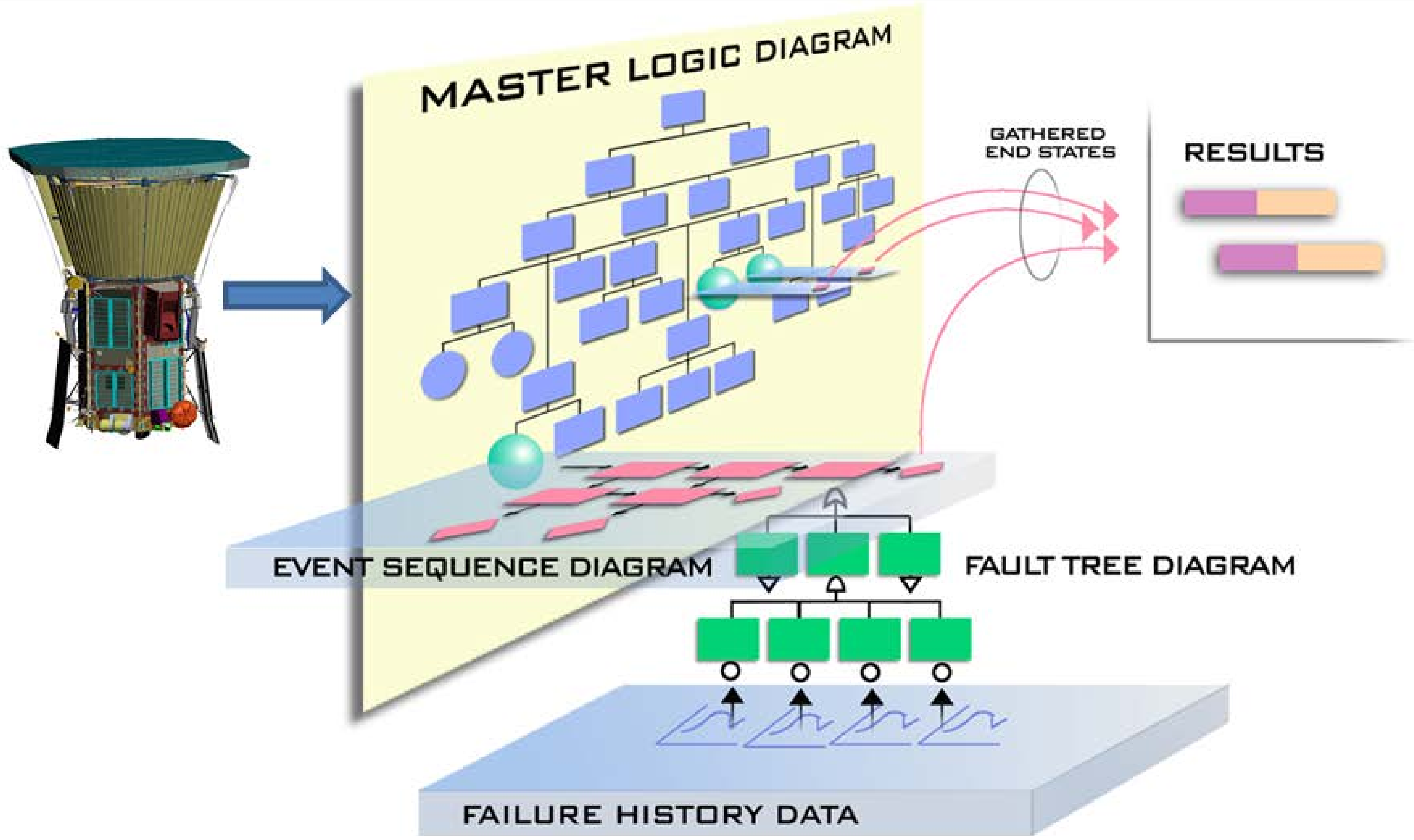
- **Constant failure rate**
  - Allows for the use of exponential failure rate models
    - Current state-of-practice
    - Literature shows this is a very conservative model of spacecraft lifetimes
- **Design, build, assembly, and integration processes are similar to past APL programs**
  - Allows for the treatment of past program experience as a homogeneous population
  - GSFC failure data is of a similar population as APL data
- **Initiating events are independent and mutually-exclusive**
- **System is completely functional at time of launch**

PRA Framework

Process

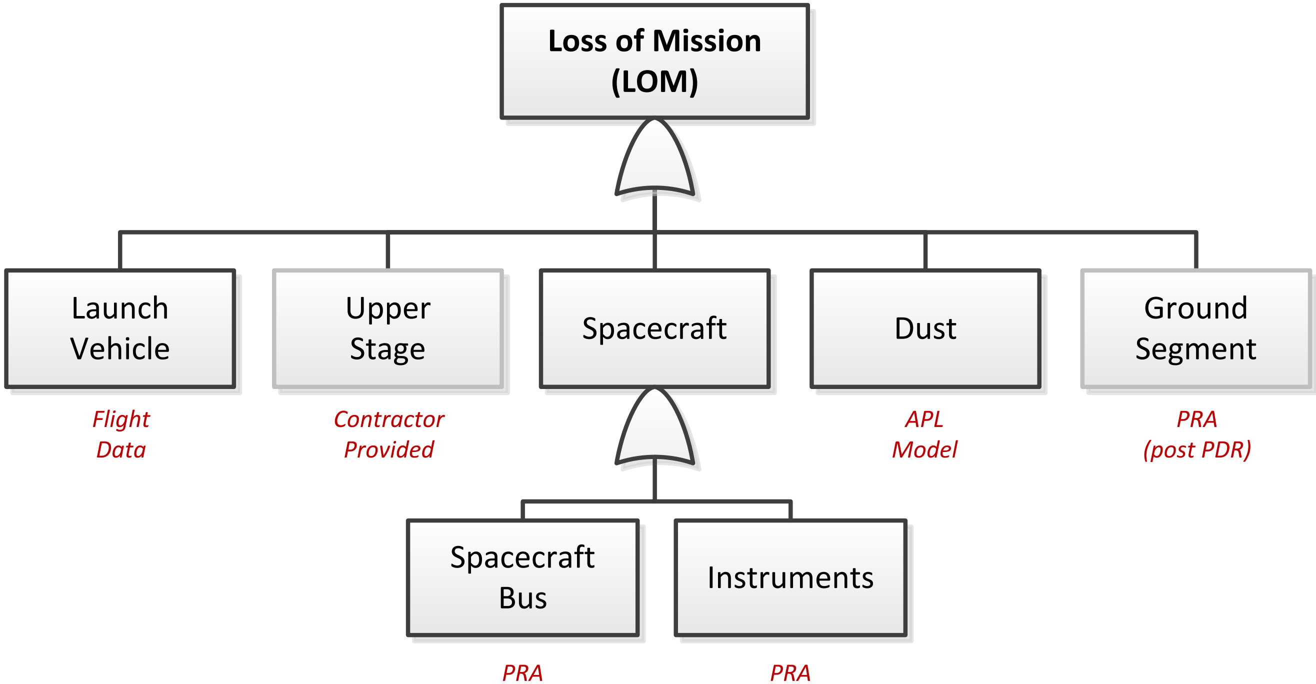
- **Started with functional block diagrams**
- **FMEA process lead to understanding of the failure modes and consequences**
- **Reviews**
  - Scenario selection
  - Fault Trees Science success criteria and fault trees with Science Working Group and instrument teams
  - Data methods
- **Applications**
  - Supported trade studies (cooling system, solar array launch locks, FIELDS redesign)
  - Supported FMEA activities
  - Verified Single Point Failure list

PRA Framework



PRA Framework

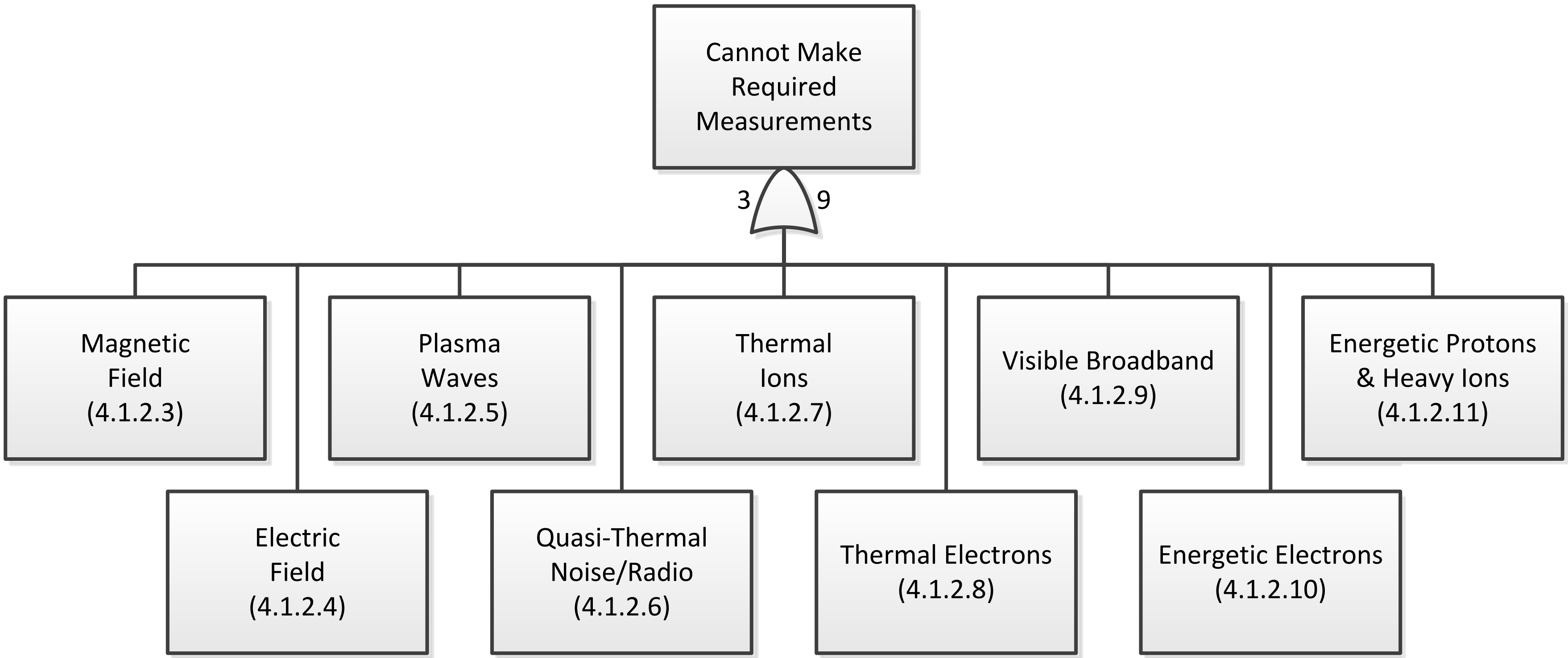
Top Level Modeling Structure



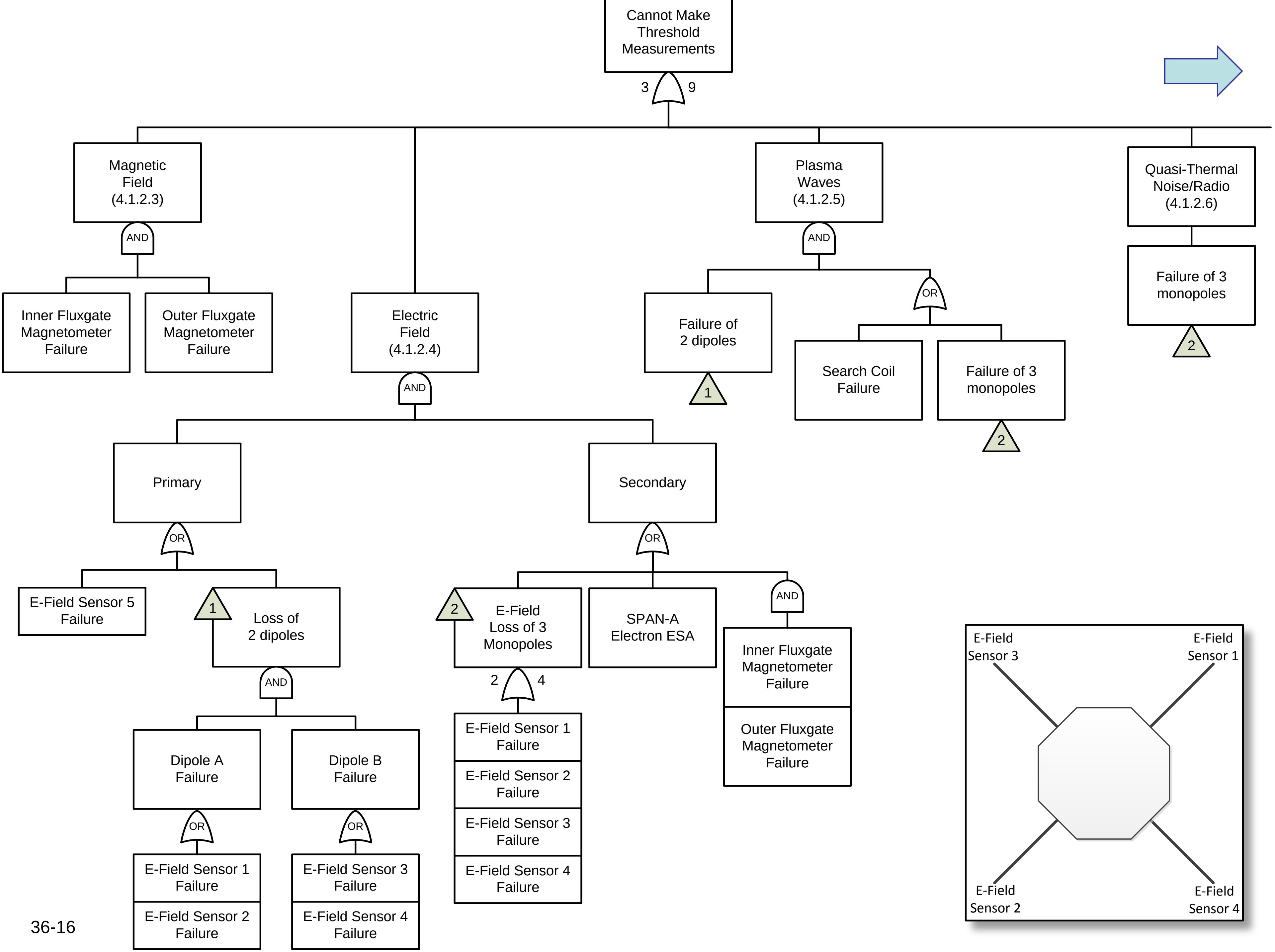
- **PRA encompasses various aspects of the mission**
- **Many analyses are performed off-line and incorporated at a top level**
- **Upper stage and Ground segment to be done after PDR**

PRA Framework

Science Measurements Fault Tree

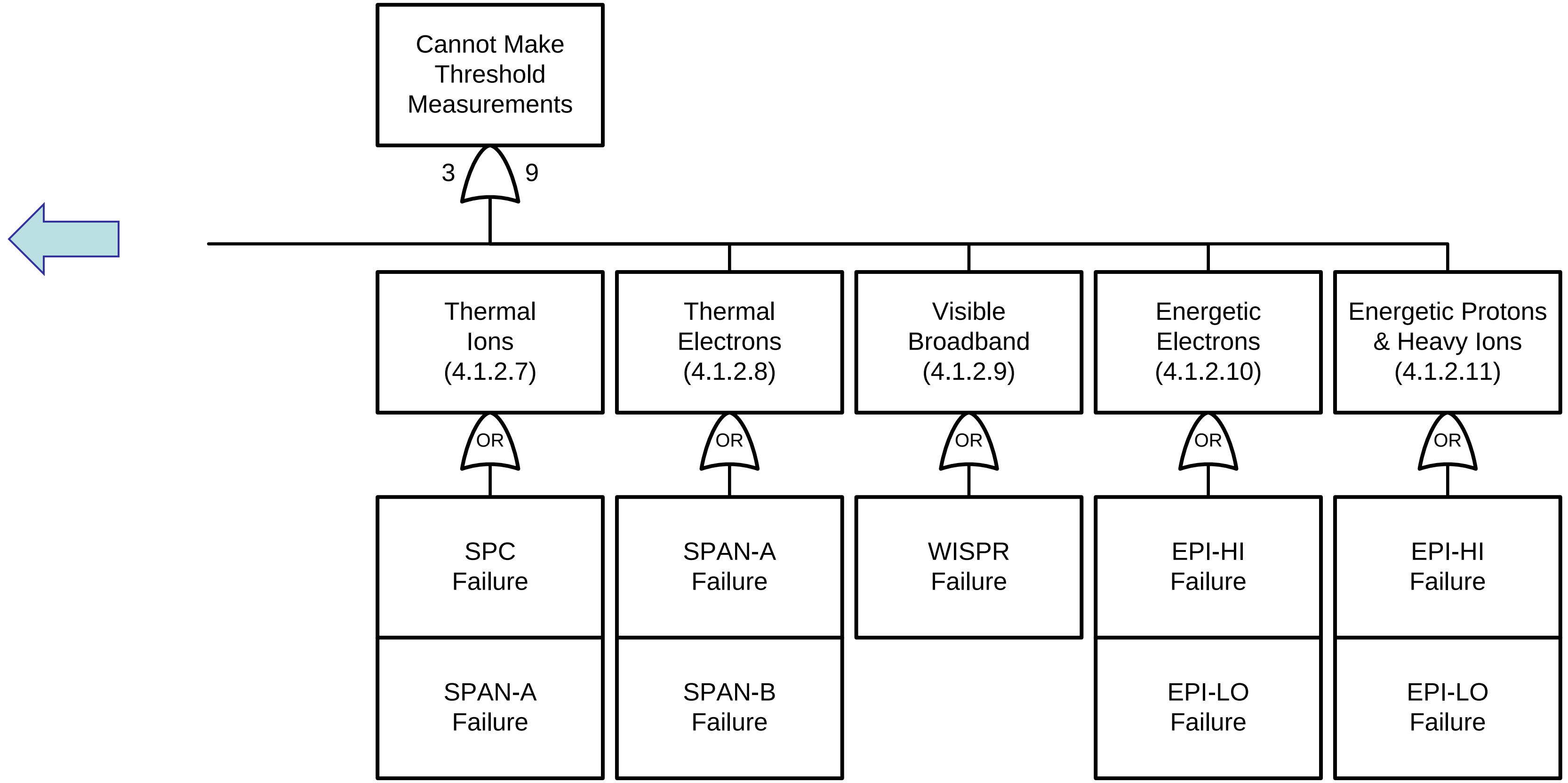


- **Logic for instruments reflects mission success criteria**
  - Vetted with project science team


Cannot Make Threshold Measurements
3
9
Magnetic Field (4.1.2.3)
AND
Inner Fluxgate Magnetometer Failure
Outer Fluxgate Magnetometer Failure
Electric Field (4.1.2.4)
AND
Primary
OR
E-Field Sensor 5 Failure
1
Loss of 2 dipoles
AND
Dipole A Failure
OR
E-Field Sensor 1 Failure
E-Field Sensor 2 Failure
Dipole B Failure
OR
E-Field Sensor 3 Failure
E-Field Sensor 4 Failure
Secondary
OR
2
E-Field Loss of 3 Monopoles
2
4
E-Field Sensor 1 Failure
E-Field Sensor 2 Failure
E-Field Sensor 3 Failure
E-Field Sensor 4 Failure
SPAN-A Electron ESA
AND
Inner Fluxgate Magnetometer Failure
Outer Fluxgate Magnetometer Failure
Plasma Waves (4.1.2.5)
AND
Failure of 2 dipoles
1
OR
Search Coil Failure
Failure of 3 monopoles
2
Quasi-Thermal Noise/Radio (4.1.2.6)
Failure of 3 monopoles
2
E-Field Sensor 3
E-Field Sensor 1
E-Field Sensor 2
E-Field Sensor 4

PRA Framework

Science Measurements Fault Tree



PRA Framework

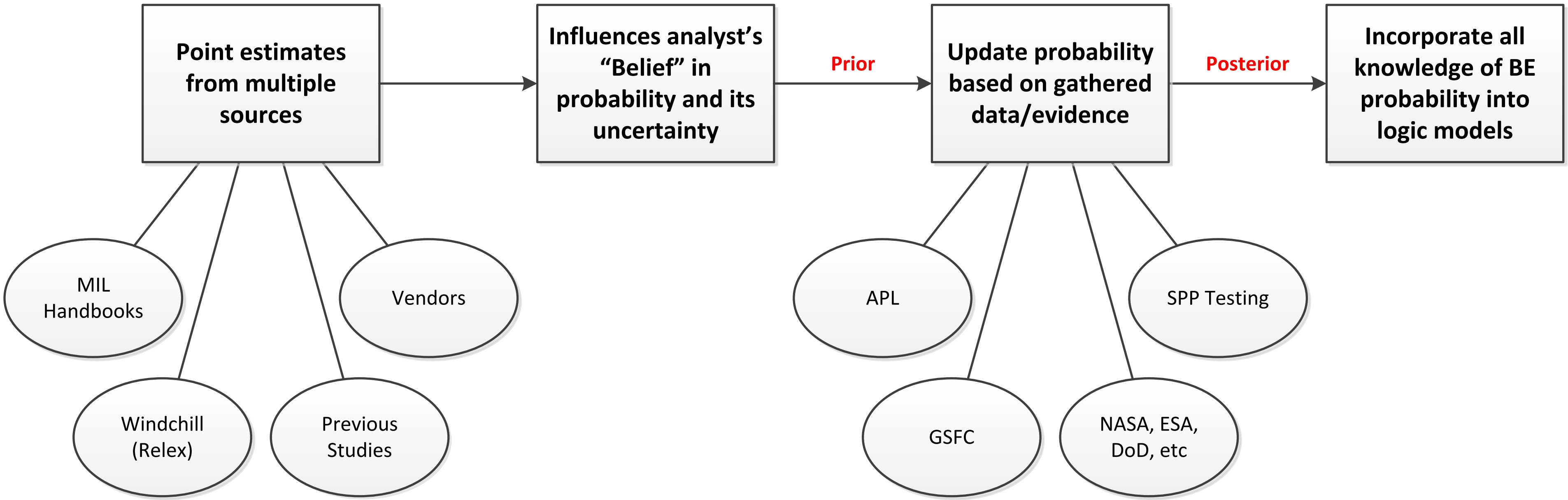
Scenarios

- **Nominal Operations Event Trees**
  - Launch
  - Commissioning
  - Cruise
  - Solar Encounter

- **Off-Nominal Event Trees**
  - Umbra Violation
  - Safe Mode – Solar Array (not yet incorporated)
  - Safe Mode – Standby (not yet incorporated)
  - Safe Mode – Earth Acquisition (not yet incorporated)

PRA Basic Event Quantification

Bayesian Updating



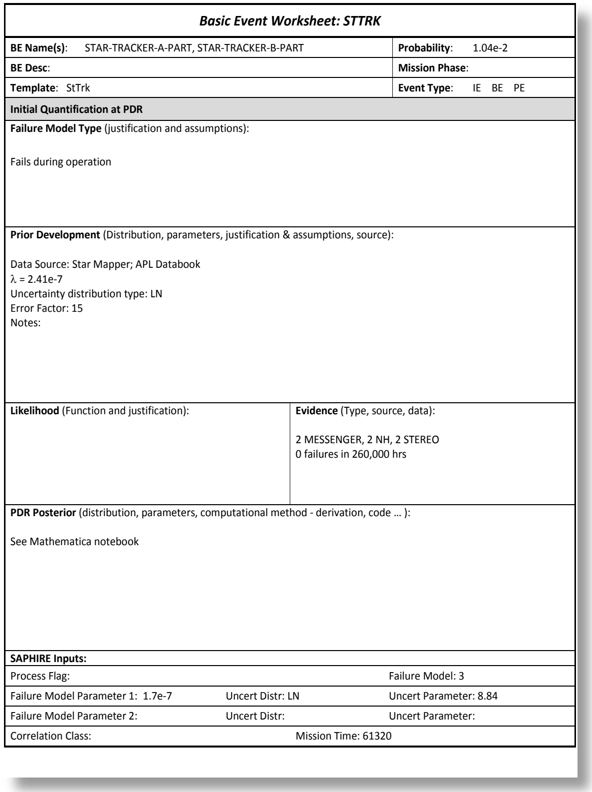
PRA Basic Event Quantification

Documentation

- **Each BE (~350) has a worksheet that describes how the probability was determined**
  - Lists assumptions and approximations
  - Data sources
  - Failure model used
  - Prior justification
  - Likelihood
  - Evidence used in updating process
  - Pointer to specific analysis file

- **BE templates for similar components**

- **PDF of worksheets for all BEs will be made available**



Basic Event Worksheet: STTRK

BE Name(s): STAR-TRACKER-A-PART, STAR-TRACKER-B-PART	**Probability:** 1.04e-2
BE Desc:	**Mission Phase:**
Template: StTrk	**Event Type:** IE BE PE

Initial Quantification at PDR

Failure Model Type (justification and assumptions):

Fails during operation

Prior Development (Distribution, parameters, justification & assumptions, source):

Data Source: Star Mapper; APL Databook
λ = 2.41e-7
Uncertainty distribution type: LN
Error Factor: 15
Notes:

Likelihood (Function and justification):	**Evidence** (Type, source, data): 2 MESSENGER, 2 NH, 2 STEREO; 0 failures in 260,000 hrs

PDR Posterior (distribution, parameters, computational method - derivation, code …):

See Mathematica notebook

SAPHIRE Inputs:

Process Flag:		Failure Model: 3
Failure Model Parameter 1: 1.7e-7	Uncert Distr: LN	Uncert Parameter: 8.84
Failure Model Parameter 2:	Uncert Distr:	Uncert Parameter:
Correlation Class:	Mission Time: 61320	

PRA Basic Event Quantification

Phenomenological Models

- **Phenomenological modeling techniques are used to complement and extend traditional reliability modeling methods by evaluating the nodes in a logic tree that are driven by physical processes**
  - Solar protons causing star tracker white-out
  - Dust causing damage to components

PRA Results

Top Level Probabilities

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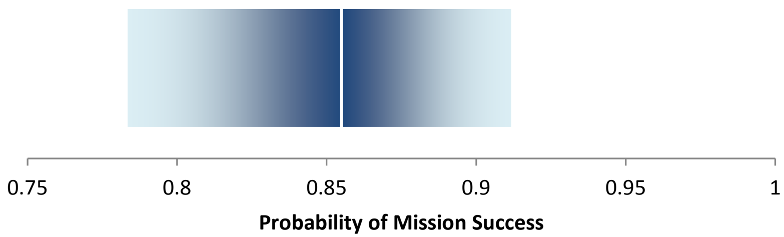
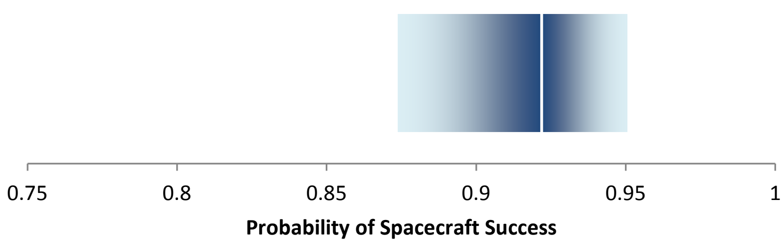
- **Mission Success = 0.88**



- **Spacecraft = 0.92**

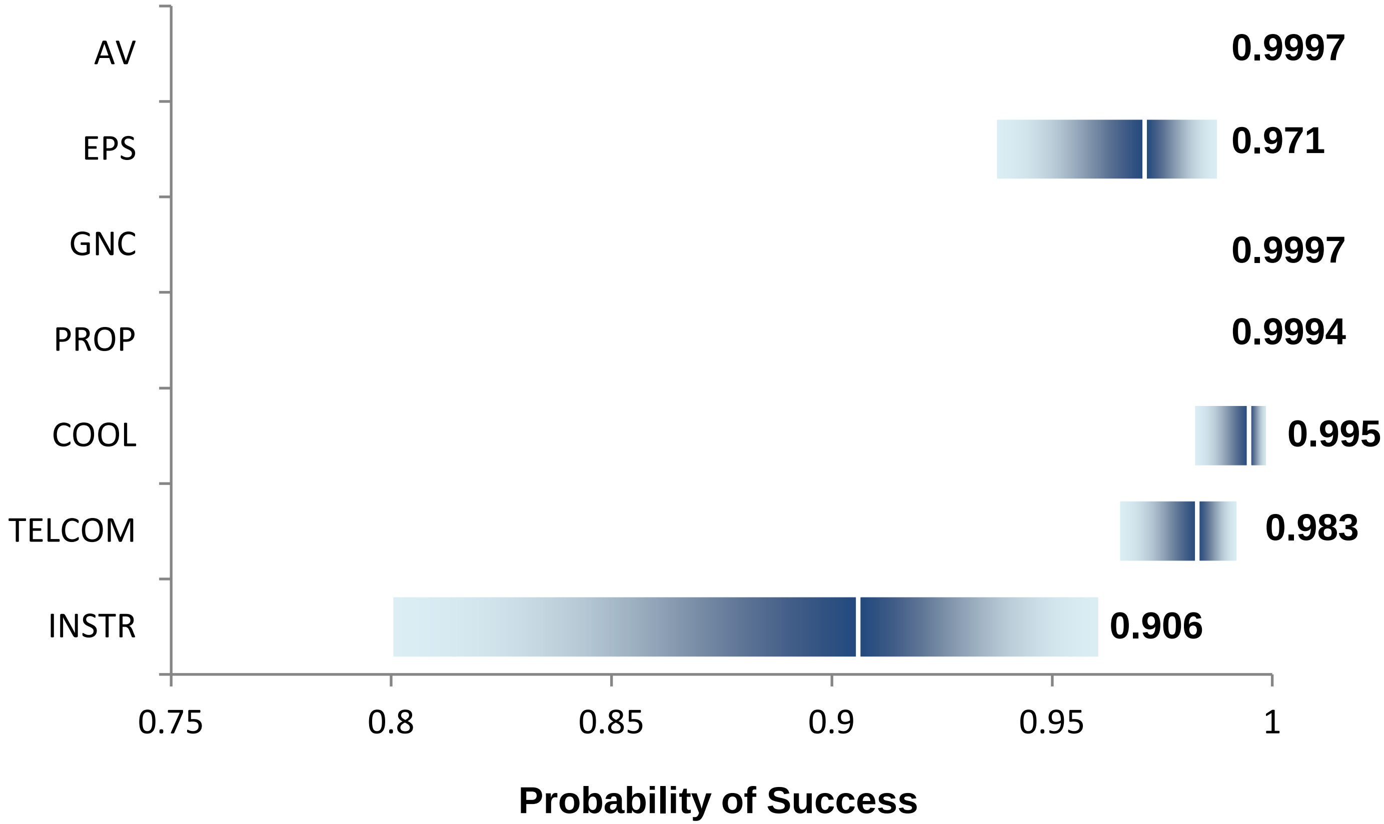


- **Mission level accounts for the Launch Vehicle, Spacecraft Bus, Instruments, and Dust only**

- **Hardware and functional redundancy together with robust responses to failures results in acceptable probability value**

PRA Results

System Probabilities



PRA Results

Cut Sets

- **Combinations of basic events leading to Loss of Mission (LOM)**
- **Following represent 60% of the LOM risk**
    - Battery
    - Both pumps fail (pump hardware failures)
    - Ka Hybrid
    - Main power bus junction
    - Solar array junction
    - HGA and SA actuators
    - Pump A hardware failure, pump B fails to start
    - Thruster assembly failures
    - One pump has a hardware failure, the other pump doesn't get power
    - Instrument failures (EPI-Hi and SWEAP)
    - One pump experiences a hardware failure, but the check valve is stuck blocking the other pump
    - Both sides of EPS fail
    - Both sides of telecom fail (Ka-band or X-band)

Conclusions

- **Reliability engineering is**
  - Participating in design trade studies
  - Developing analyses
  - Meeting required deliverables

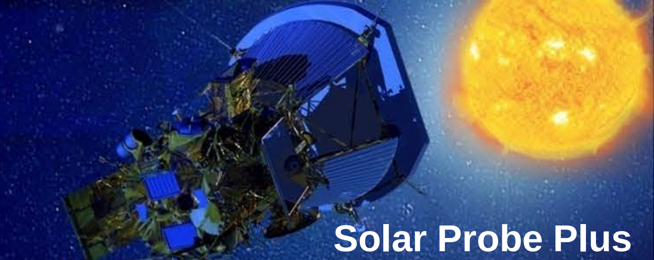
- **FMEA and PRA are current with SPP design maturity**
  - Configuration
  - Data collection

- **Analyses validates that the redundancy philosophy is significantly reducing risk**

Backup Slides

SPP Requirements

Science Measurements



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

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	$20^{\circ} \times 25^{\circ}$	1 Hz	None
4.1.2.8	Thermal Electrons	5 eV – 2 keV	< 30%	> 65% of the sky	$20^{\circ} \times 20^{\circ}$	1 Hz	n/a

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

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)

Failure Mode and Effects Analysis

Severity Categories

1	Catastrophic	Failure modes that could result in serious injury, loss of life, or loss of spacecraft.
1R		Failure modes of identical or equivalent redundant hardware or software elements that could result in Category 1 effects if all failed.
1S		Failure in a safety or hazard monitoring system that could cause the system to fail to detect a hazardous condition or fail to operate during such condition and lead to Category 1 consequences.
2	Critical	Failure modes that could result in loss of three or more mission objectives
2R		Failure modes of identical or equivalent redundant hardware or software that could result in Category 2 effects if all failed.
2S		Failure in a safety or hazard monitoring system that could cause the system to fail to detect a hazardous condition or fail to operate during such condition and lead to Category 2 consequences.
3	Significant	Failure modes that could cause loss to any mission objectives.
4	Minor	Failure modes that could result in insignificant or no loss to mission objectives

PRA Framework

Process

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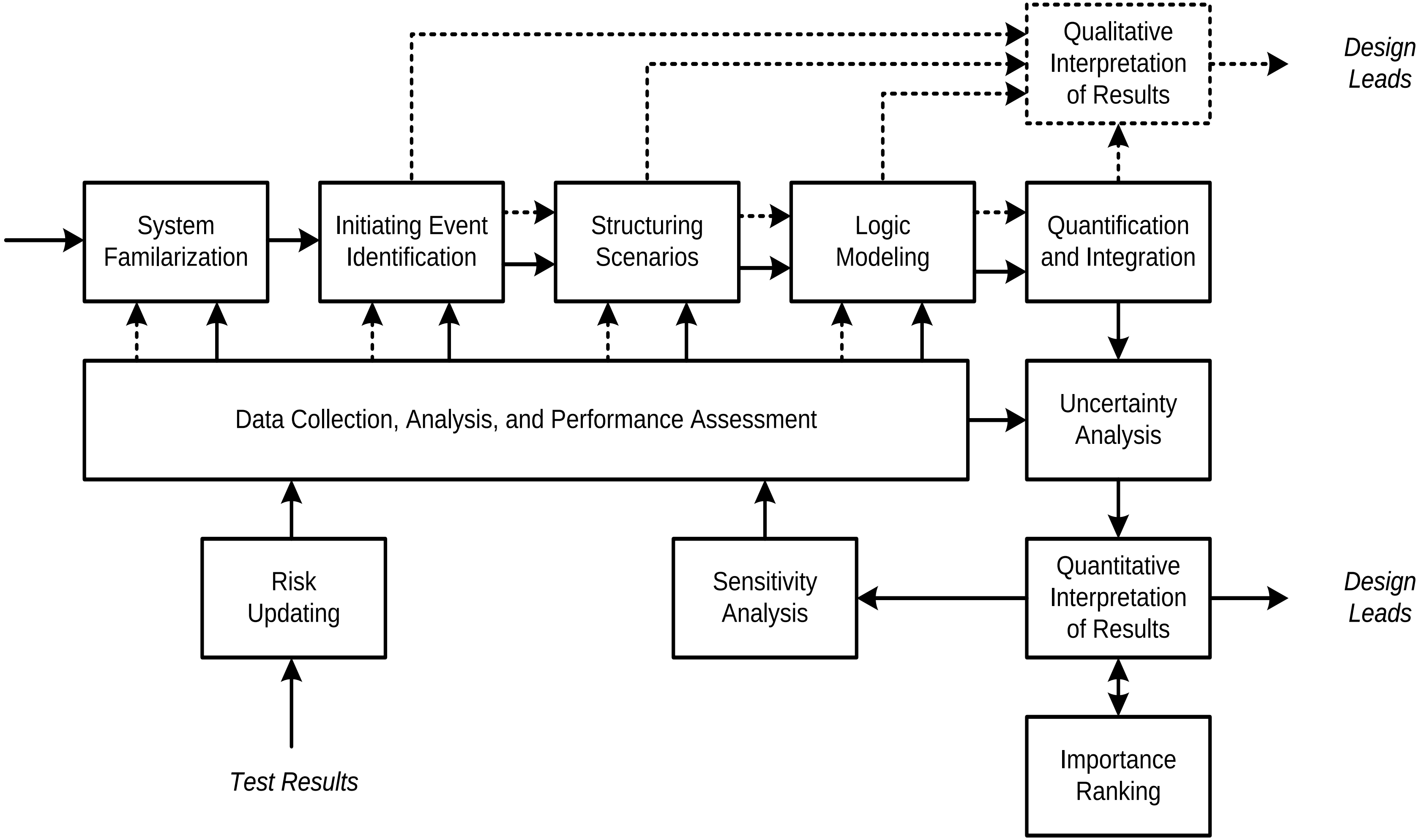

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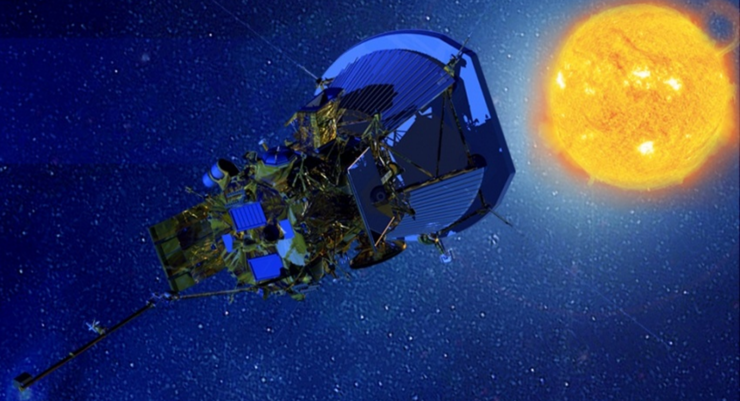

Ground System Hardware

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13 – 16 January 2014

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The Johns Hopkins University
APPLIED PHYSICS LABORATORY

Agenda

- Driving Requirements
- Networks and IT Security
- Ground System Configurations
- Data Backup
- Backup Power
- Testbeds and Hardware-In-The-Loop Simulators
- Verification

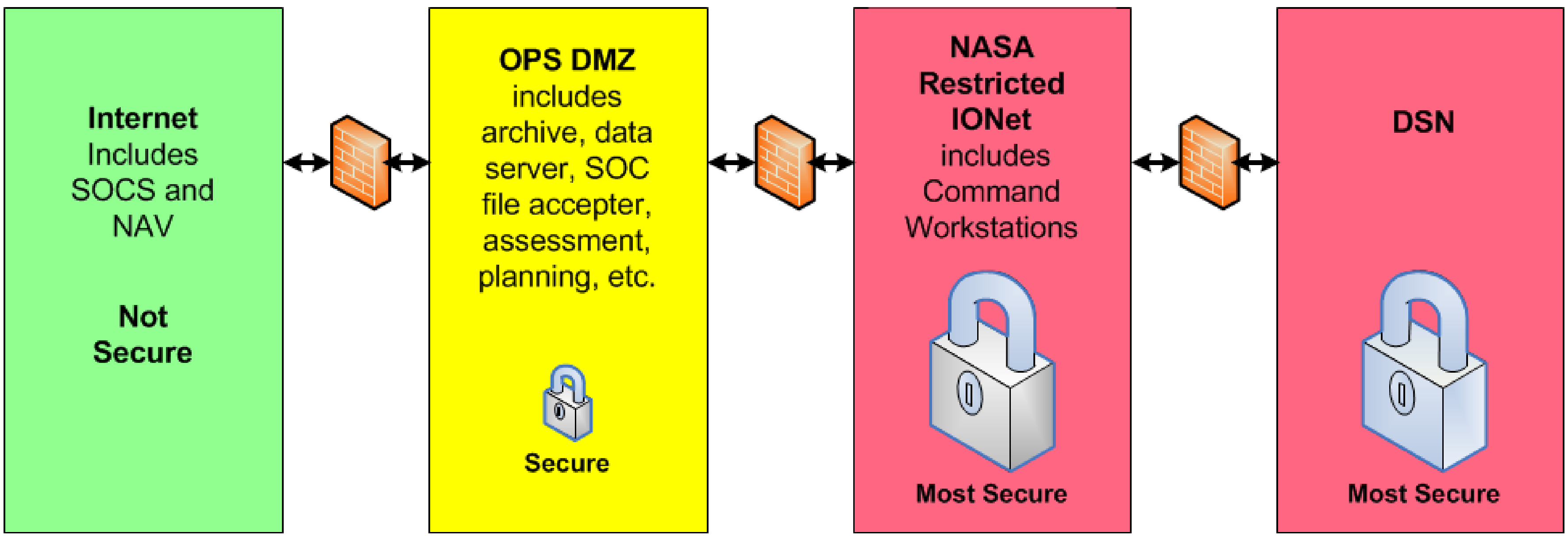
Driving Requirements

- 7434-7003 Ground Hardware Requirements Document (in PLM)
- The Ground Hardware shall:
  - Provide specified computers and equipment for Mini-MOCs, I&T, and Mission Operations
  - Support generation and transmission of command files to the spacecraft and commands to the GSE
  - Support processing, distribution, and storage of spacecraft and GSE telemetry
  - Support SOC commanding and access to telemetry and data products
  - Accommodate interfaces with all external systems applicable to I&T, Mission Operations, and simulator environments
  - Include Hardware-in-The-Loop (HIL) simulators
  - Include a faster-than-real-time software simulator
  - Provide long term storage for telemetry and data products
  - Provide data backup
  - Provide network and physical security
  - Include a Disaster Recovery Center (DRC)
  - Provide specified computer and network redundancy

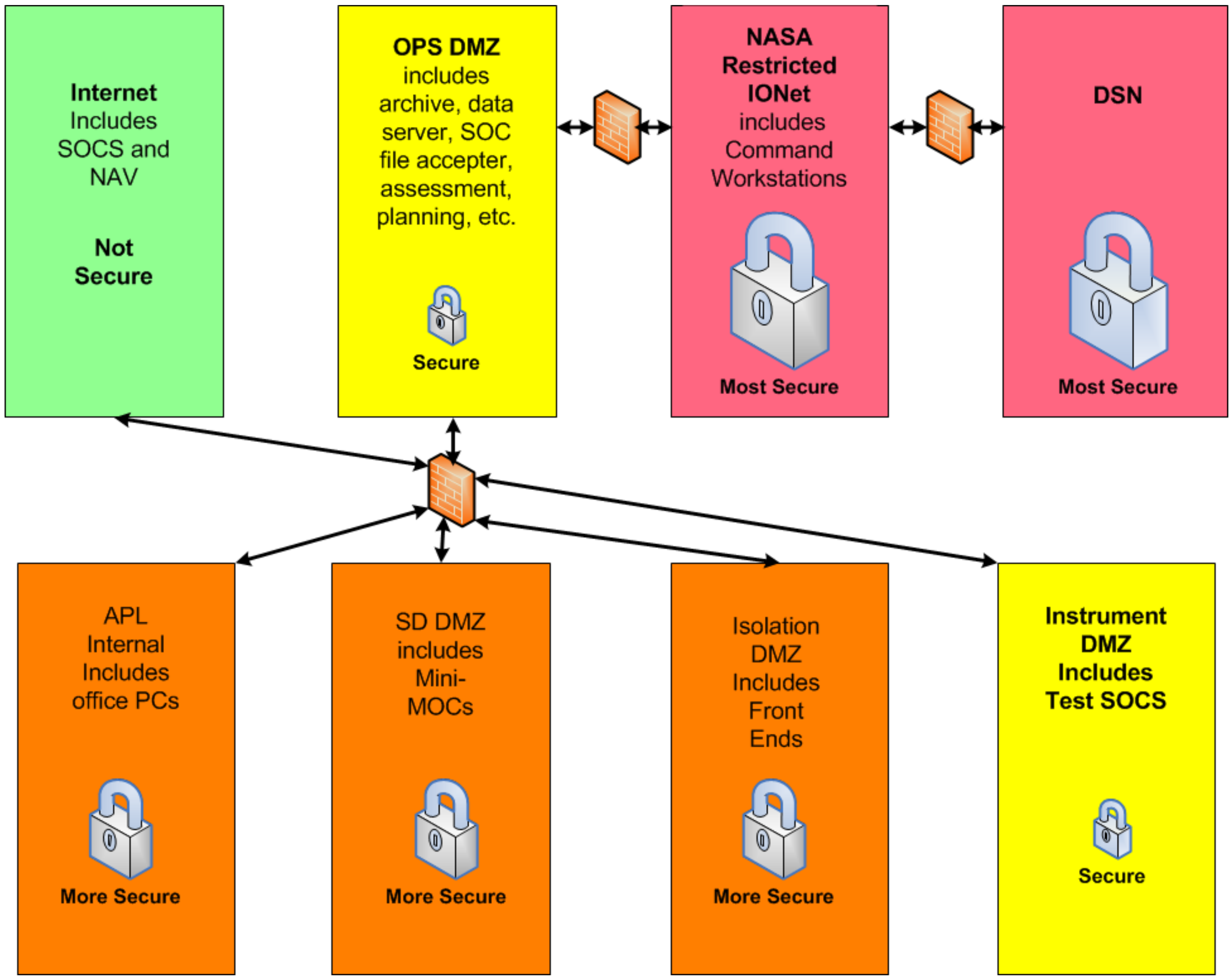
Ground Hardware Reviews

- Ground Hardware Requirements Review was held on August 5, 2013
  - All action items are in PIMS and have been closed
- Ground Hardware Pre-PDR Peer Review was held on October 22, 2013
  - All action items are in PIMS and have been closed
- Ground Hardware Pre-CDR Peer Review 5/9/2014
- HIL Simulator Requirements Review 1/15/2015
- HIL Simulator Design Review 7/15/2015

Networks and IT Security



Networks and IT Security



Networks and IT Security

- All networks: APL and SD IT Security Plans adhere to FISMA requirements
- IONet:
  - 7434-9033 SPP Ground System IONet Segment (GSIS) Security Plan is in PLM and shows how the SPP MOC will comply with NPR 2810.1 for Restricted IONet
  - From a user's point of view, this means:
    - IONet equipment for both I&T and Mission Operations is contained in facilities with badge readers on the doors (at APL and Astrotech) or with guards (at GSFC) – only approved badges have access
    - Each user who requires access to the IONet equipment will have received a National Agency Check with Inquiry (NACI) or have a DOD Secret clearance or higher
    - Each user who requires access to the I&T and Operations equipment or physical access to the area must sign and abide by an IONet Rules of Behavior form
    - NASA GSFC performs a scan of the Restricted IONet
- OPS DMZ: All users of the OPS DMZ are required to have the same clearance required for IONet (NACI or higher) and complete an IONet Rules of Behavior

Ground System Configurations: Pre-Launch

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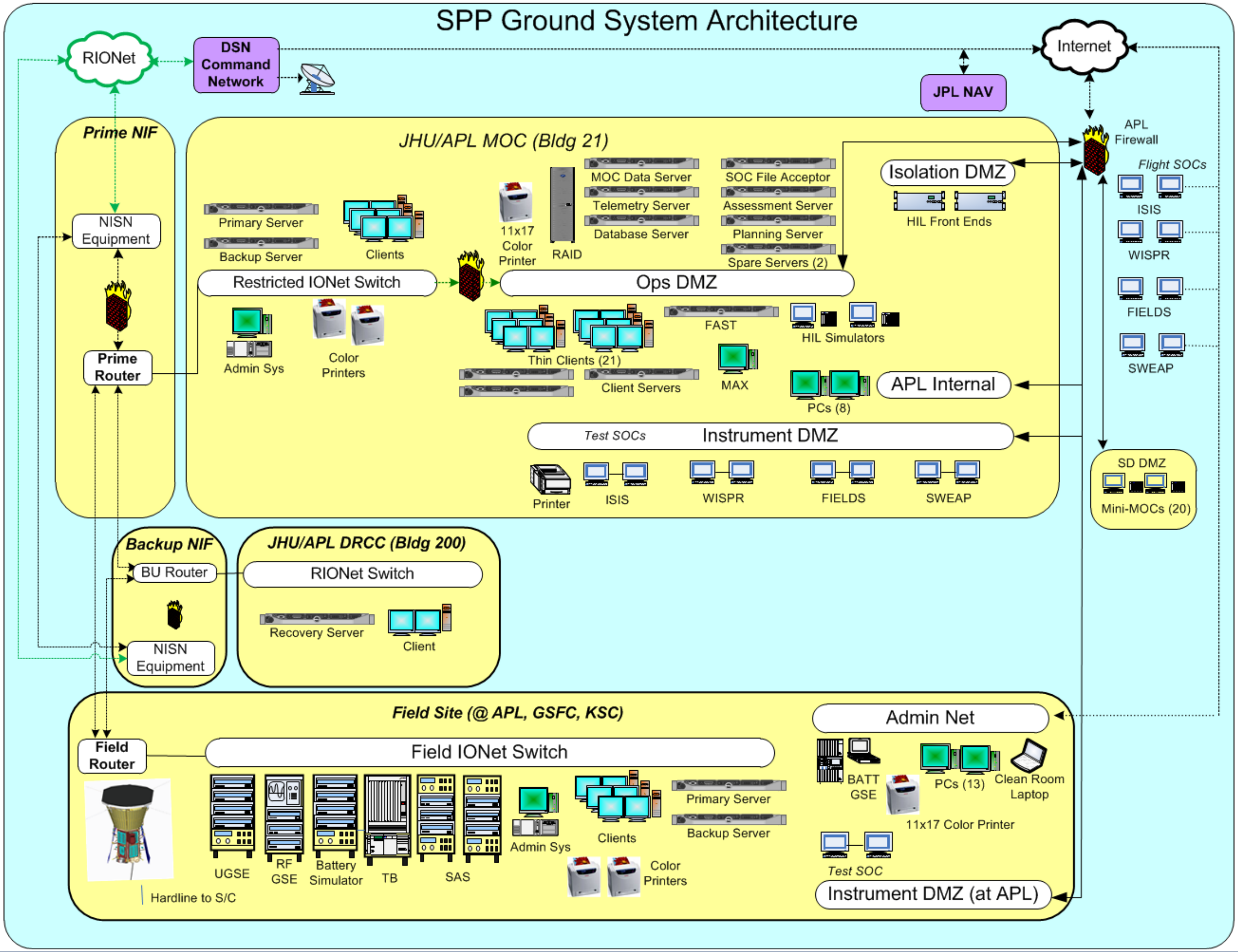
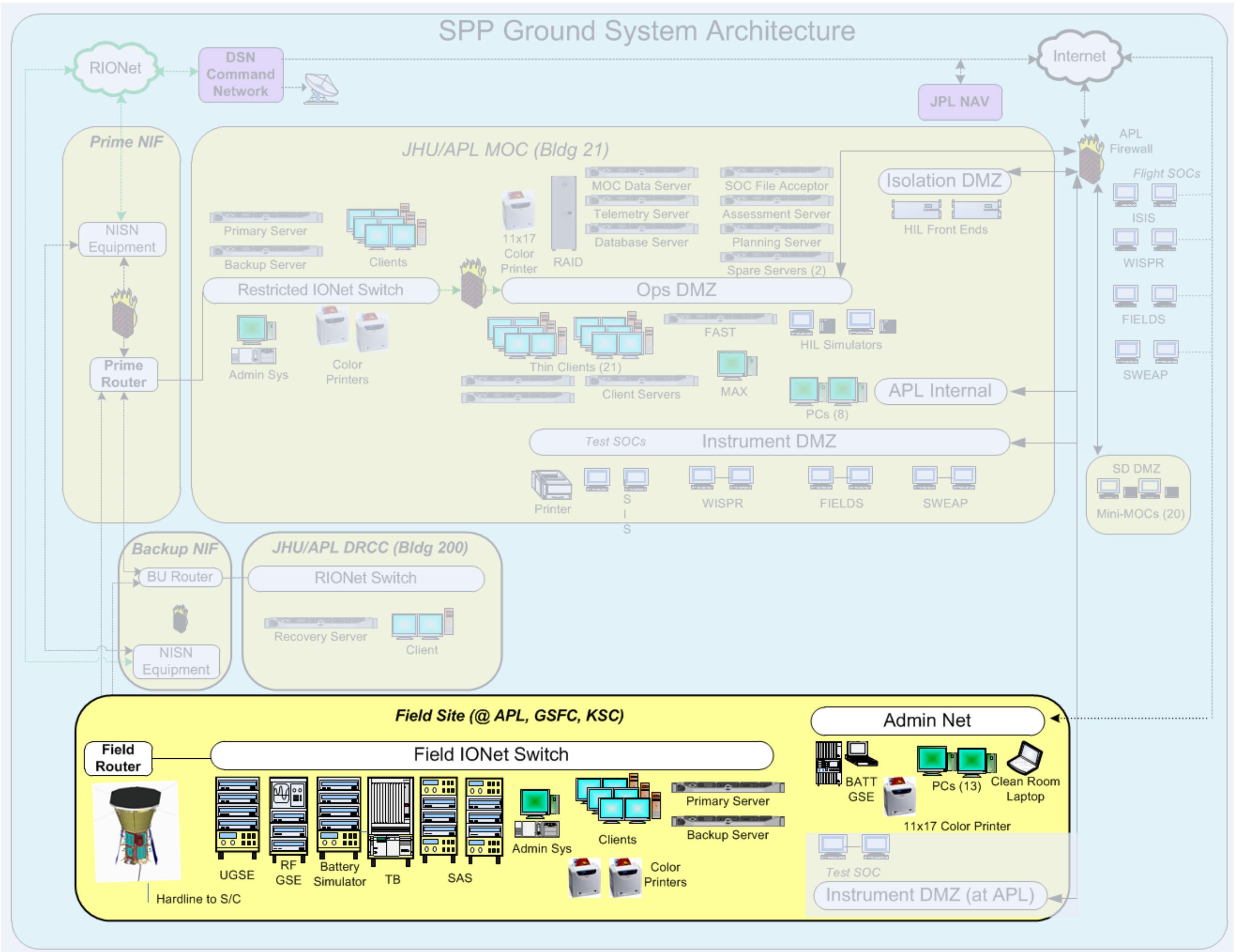


APL

Ground System Configurations: Pre-Launch, Field Site



Ground System Configurations: Pre-Launch: JHU/APL MOC

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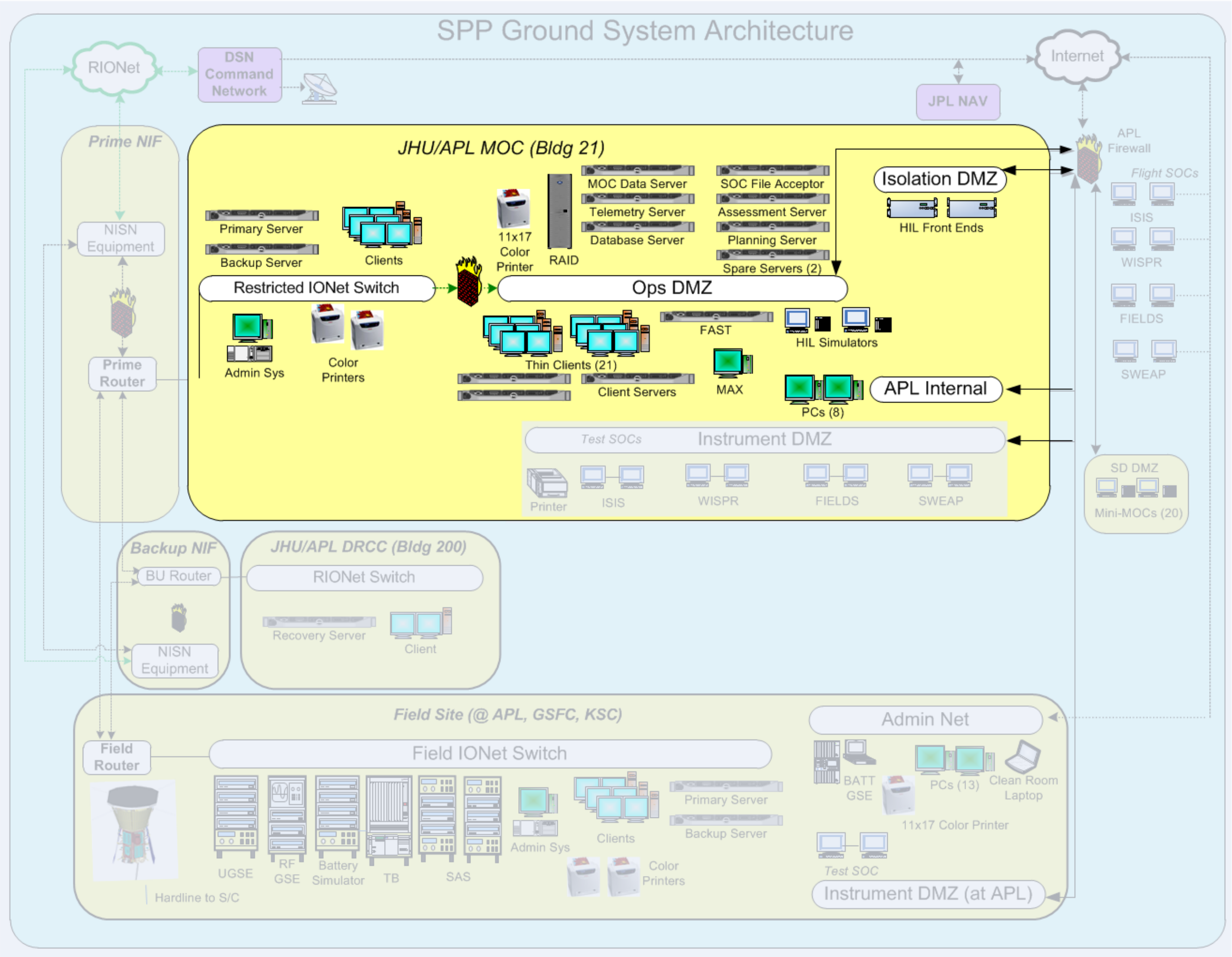
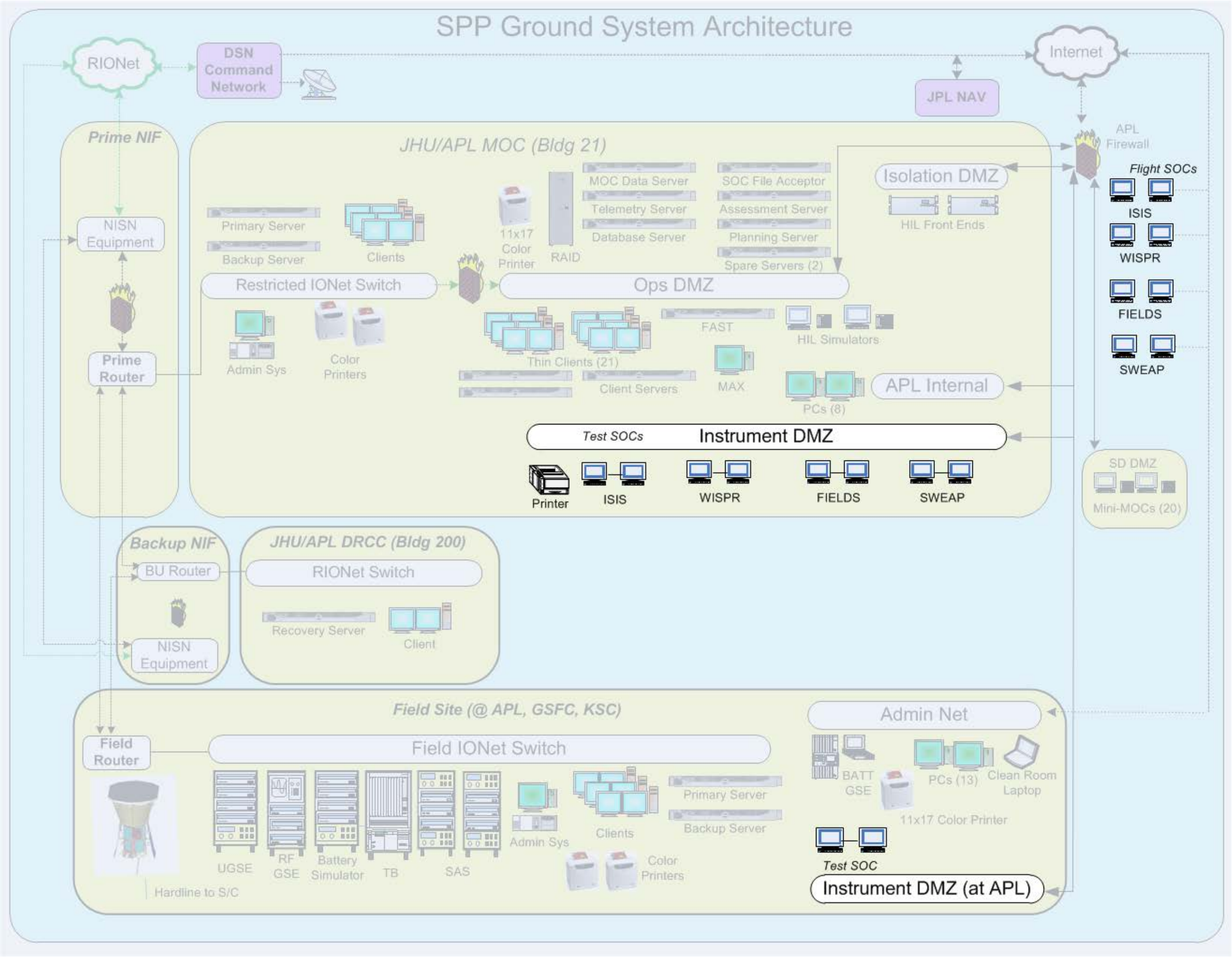
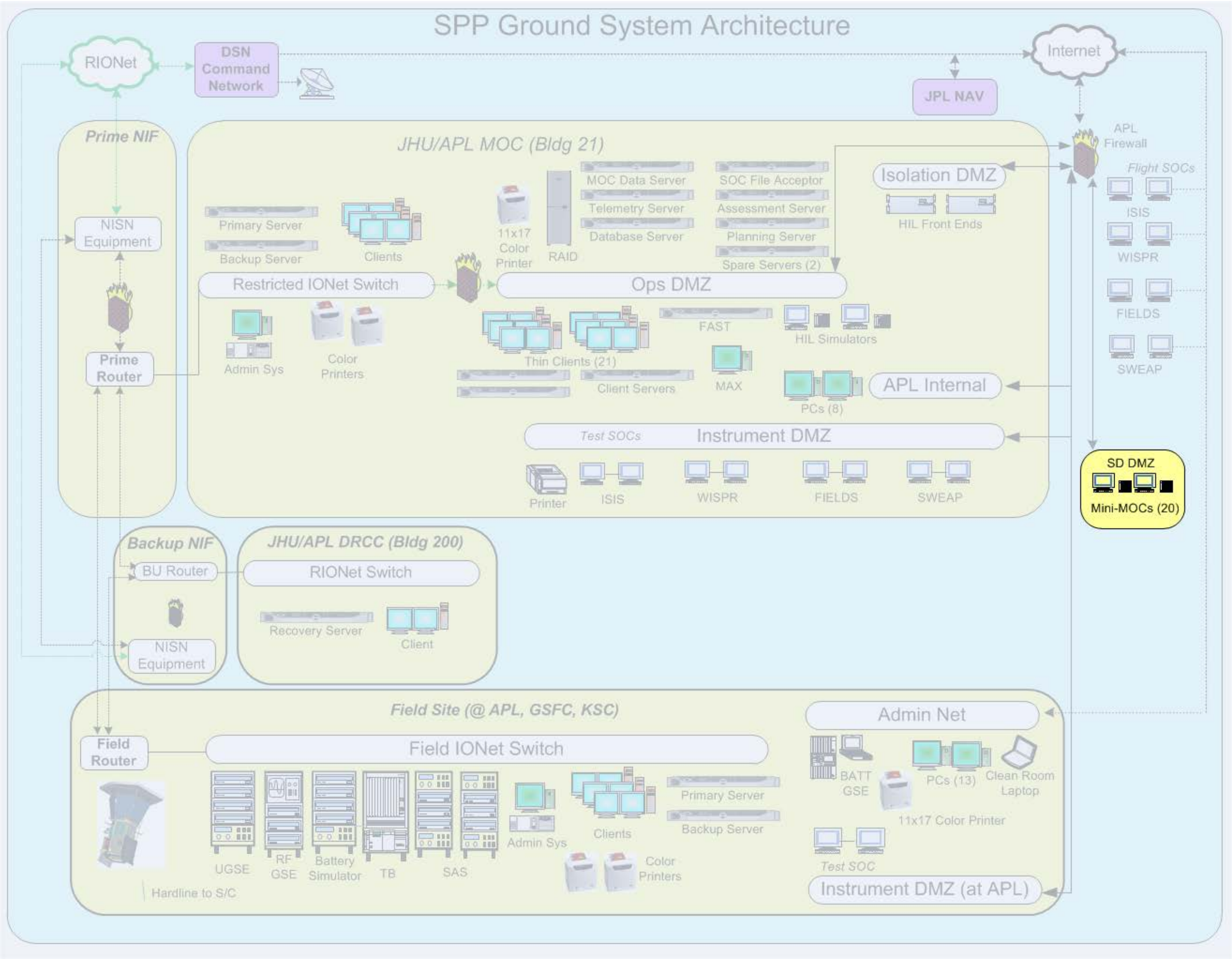


Ground System Configurations: Pre-Launch: SOCs



Ground System Configurations: Pre-Launch: Mini-MOCs



Mini-MOCs

- Since APL builds, integrates, and operates spacecraft such as SPP, we use the same basic ground hardware and software system for subsystem level testing, Integration and Test (I&T), and Mission Operations
  - The subsystem configuration is referred to as a Mini-MOC. There are Mini-MOCs for testbed development, avionics development, EPS subsystem development, PDU subsystem development, Flight Software development, etc.
  - I&T uses an I&T MOC configuration
  - Mission Operations uses a MOC configuration
- Using the same basic system at all three levels provides a number of benefits:
  - Subsystem engineers are familiar with the system when they support I&T and Mission Operations
  - Command and Telemetry Definition Databases are developed early in the program
  - Some display pages and automated procedures migrate from subsystem testing to I&T, and some migrate from I&T to Mission Operations
  - It facilitates the sharing of personnel between I&T and Mission Operations
  - The basic system matures well before launch

Ground System Configurations: Post-Launch

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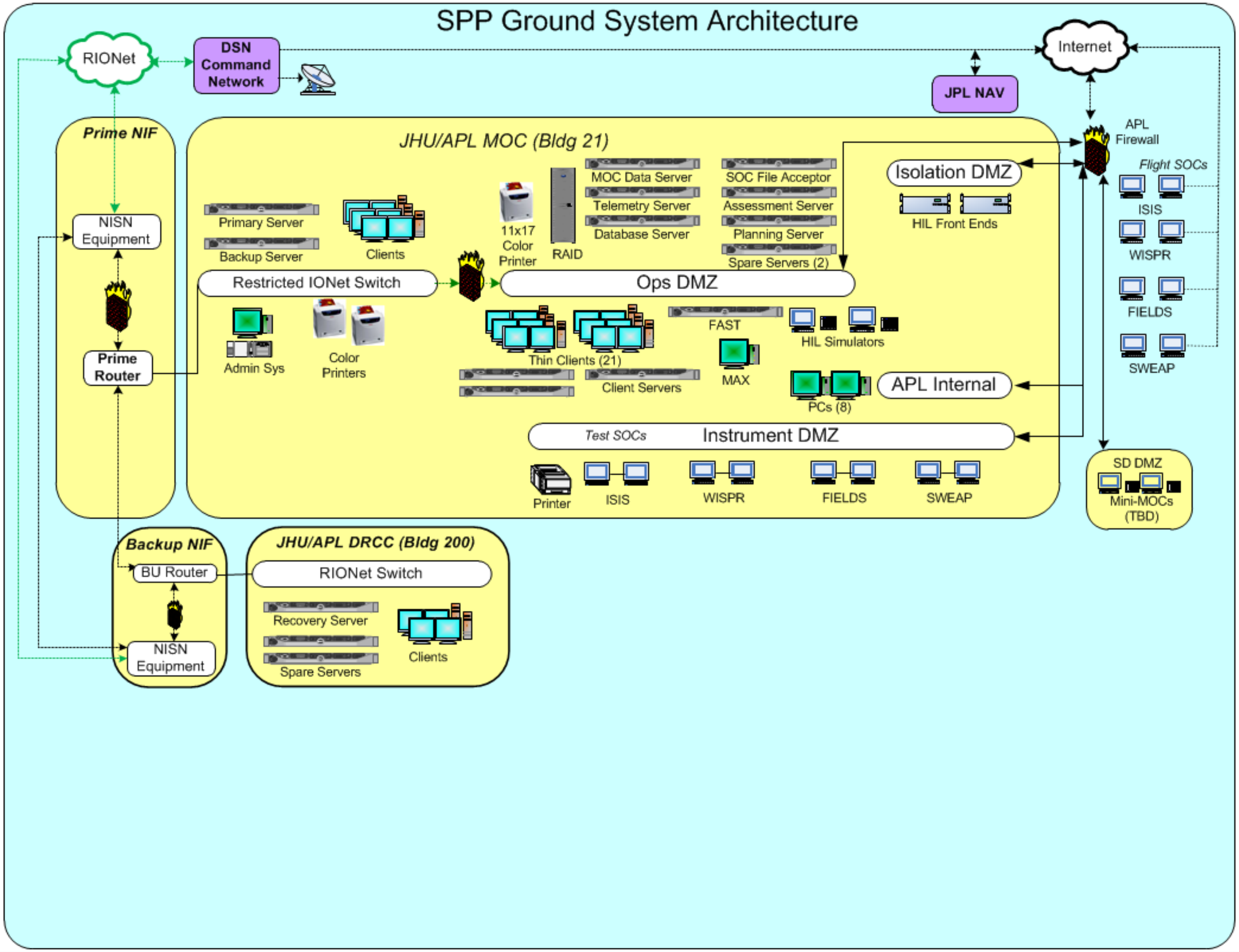

APL

Ground System Configurations: Post-Launch: Disaster Recovery Center

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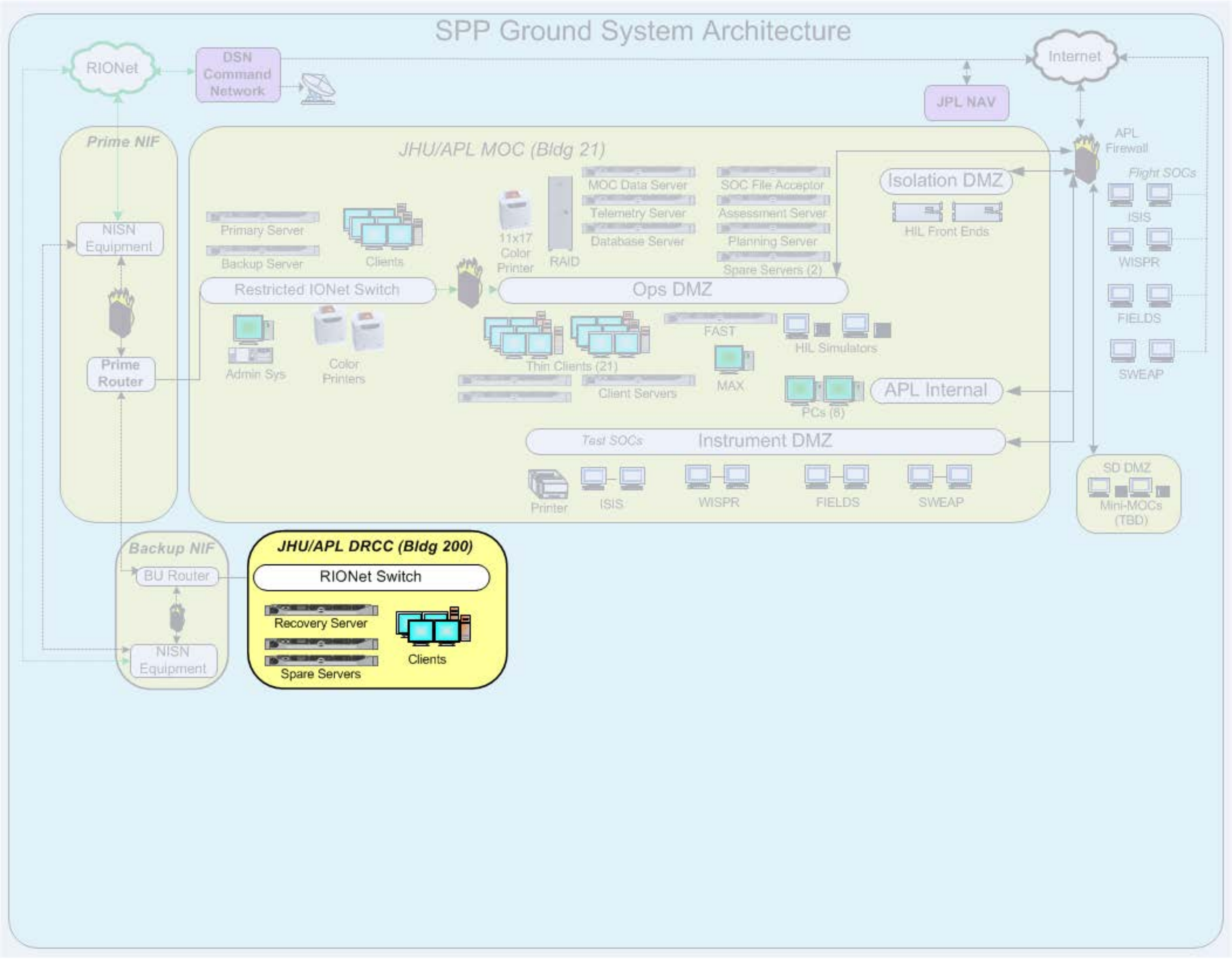


APL

Disaster Recovery Center

- APL will have an SPP Disaster Recovery Center (DRC) in Building 200 (on the south campus vs. the MOC in Building 21 which is on the main campus)
- The DRC will have the capability to command the spacecraft and receive telemetry if the MOC is unavailable
- The Disaster Recovery plan will be documented in 7434-7005, the Ground System Contingency and Disaster Recovery Document

Telemetry and Data Products Storage and Archival

- EMC RAID systems
- 30 TB MOC RAID (enough for all required data with margin)
- Separate 15 TB RAID systems for each SPPOPS
- Data is backed up to tape both in IONet and in the OPS DMZ
- Tapes are kept in buildings that are physically separate from the MOC (Building 36 for the OPS DMZ and Building 200 for IONet)
- Periodically tapes are put into a fire proof vault in Building 10

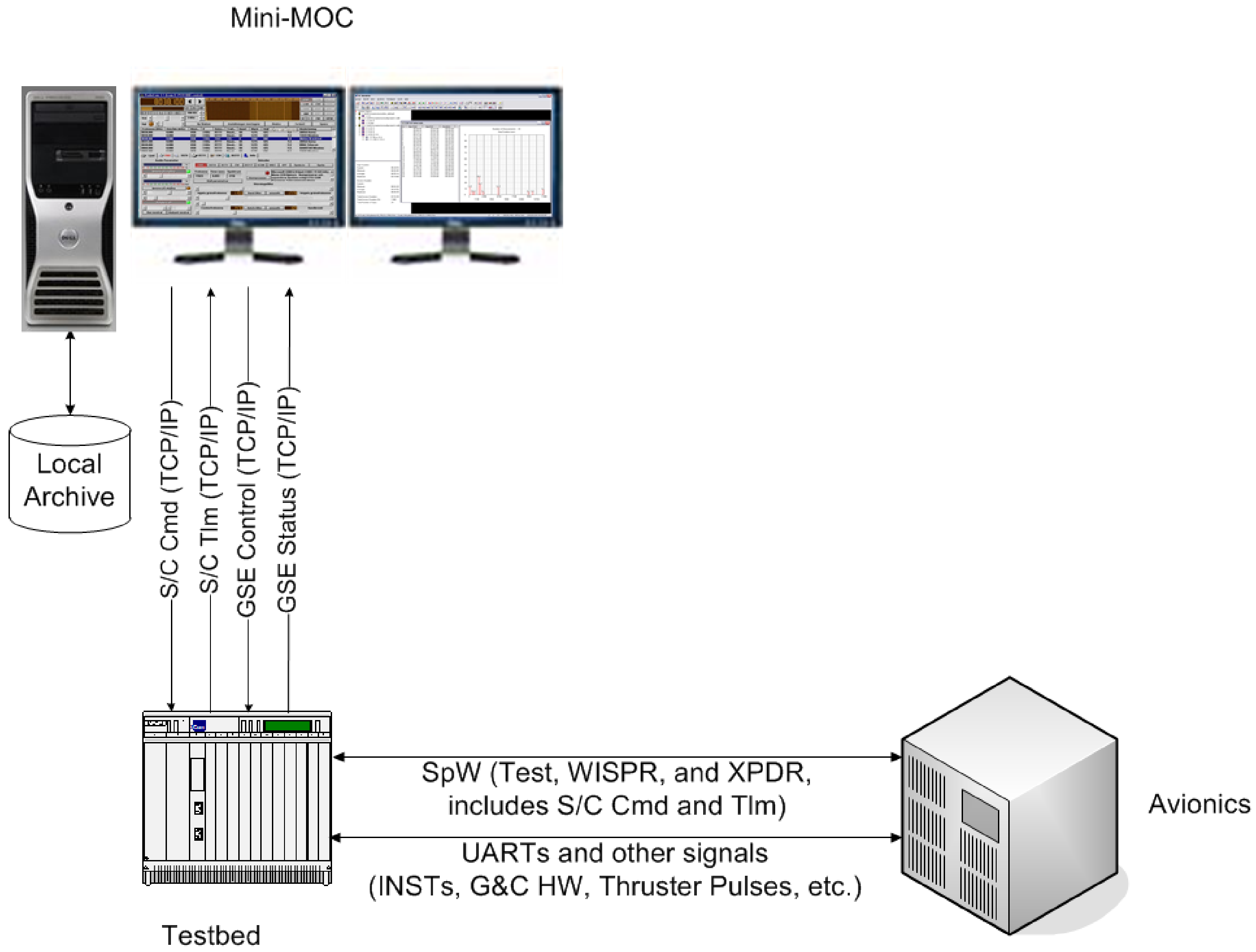
Backup Power

- The MOC and the DRC include an UPS and a generator so that they can continue to operate in the case of a power failure
- The APL I&T facility (both in the spacecraft assembly area and the environmental test facility) includes an UPS and a generator
- Astrotech has an UPS and a generator
- There is budget for a standalone UPS to power the GSE and selected workstations during I&T at GSFC
- This UPS will travel to the launch pad with the UGSE and the SAS when the spacecraft is moved to the launch pad

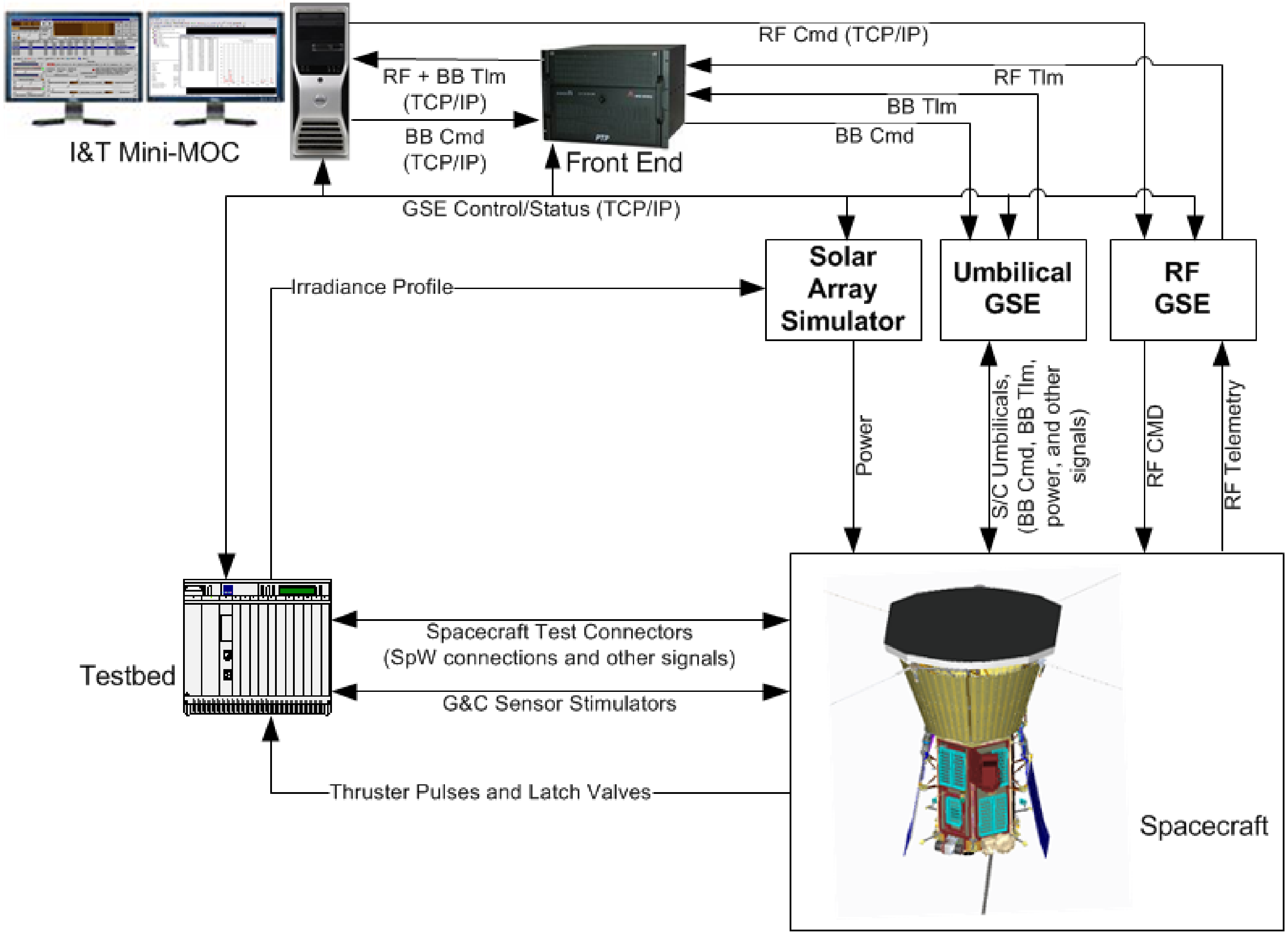
Testbeds and Hardware-In-The-Loop Simulators

- Testbeds are used along with Mini-MOCs to aid Flight Software development, avionics subsystem development, EPS subsystem development, PDU subsystem development, etc.
- Two Testbeds will transition into HIL Simulators (aka SPPOPS-1 and SPPOPS-2)
- Each HIL simulator will have a fully redundant avionics unit, 2 RF simulators, a testbed, a front end, a Mini-MOC, and a 15TB RAID
- One of the HIL simulators will be higher fidelity than the other in that it will have engineering model avionics vs. breadboard avionics
- The RF simulators will be high fidelity on the spacecraft facing side, but provide baseband only access on the ground facing side
- The testbed simulates the parts of the spacecraft that are not present
- HIL simulators will be used for vetting critical command sequences

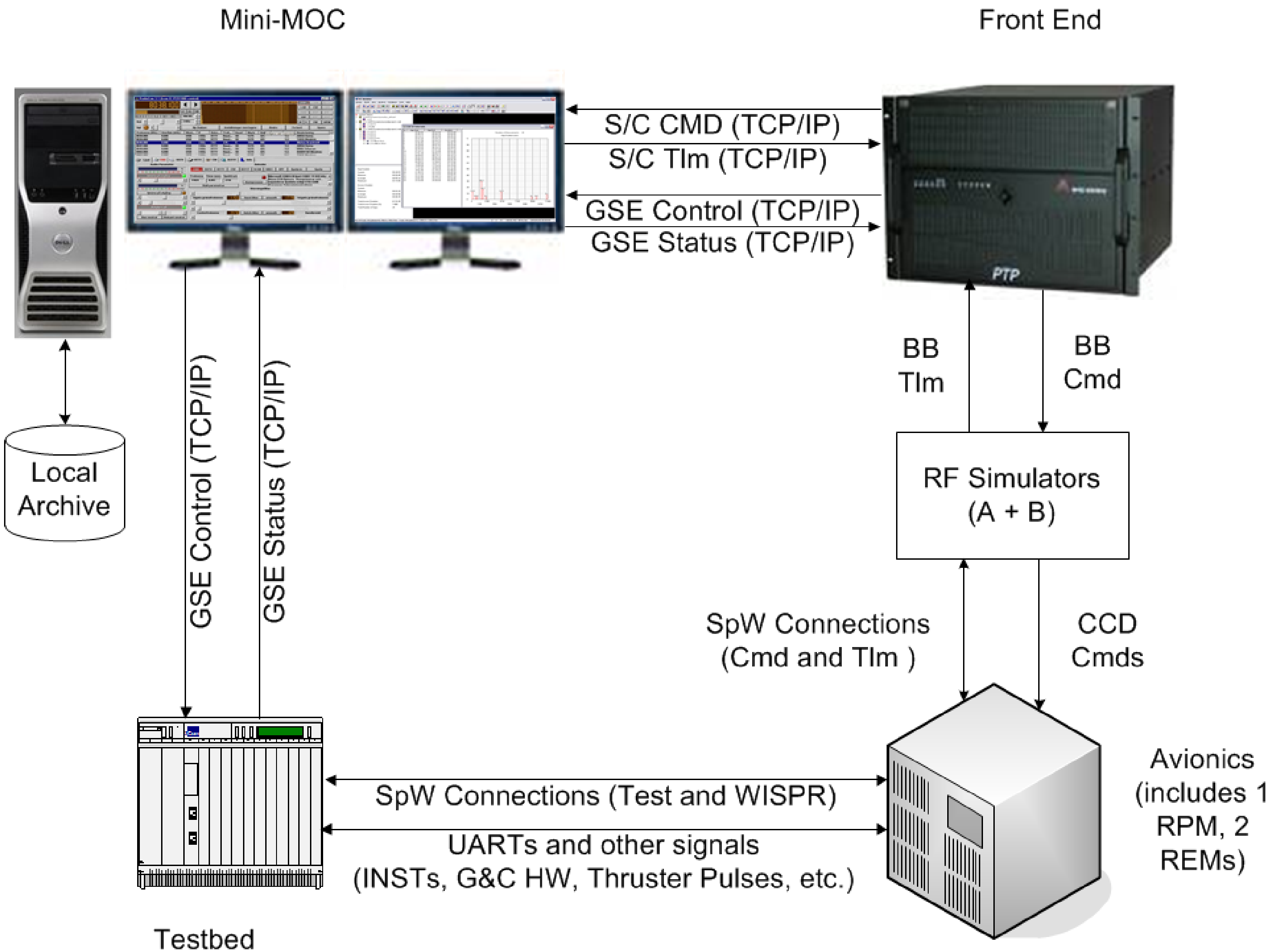
FSW Testbed (Conceptual)



I&T / Mission Sim Test Configuration (Conceptual)



Hardware-In-The-Loop Simulator (Conceptual)



Testbed Migration Diagram: Testbeds 1 - 5

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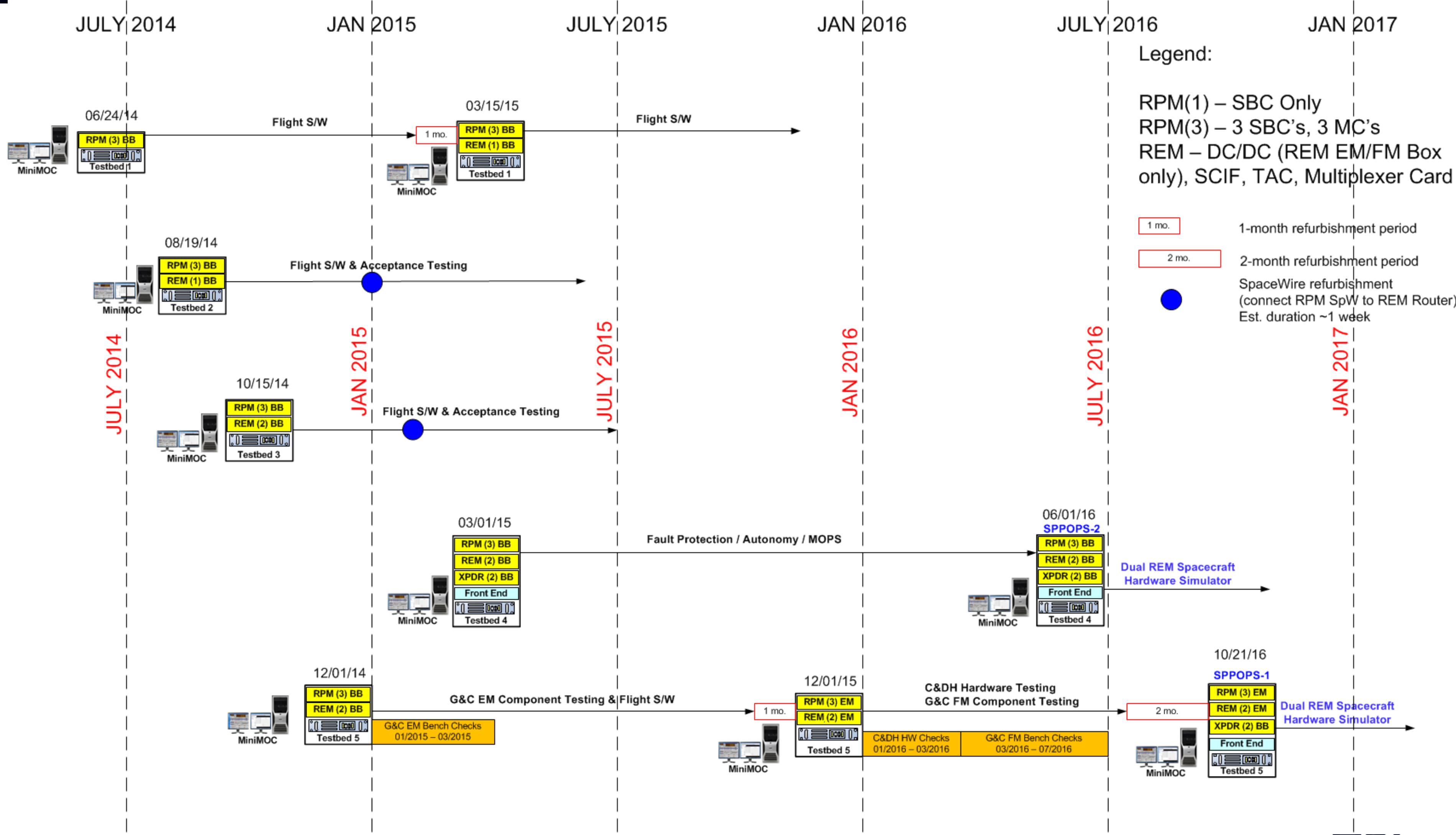

Testbed Migration Diagram: Testbeds 6, 7, 8 and Slice Testers

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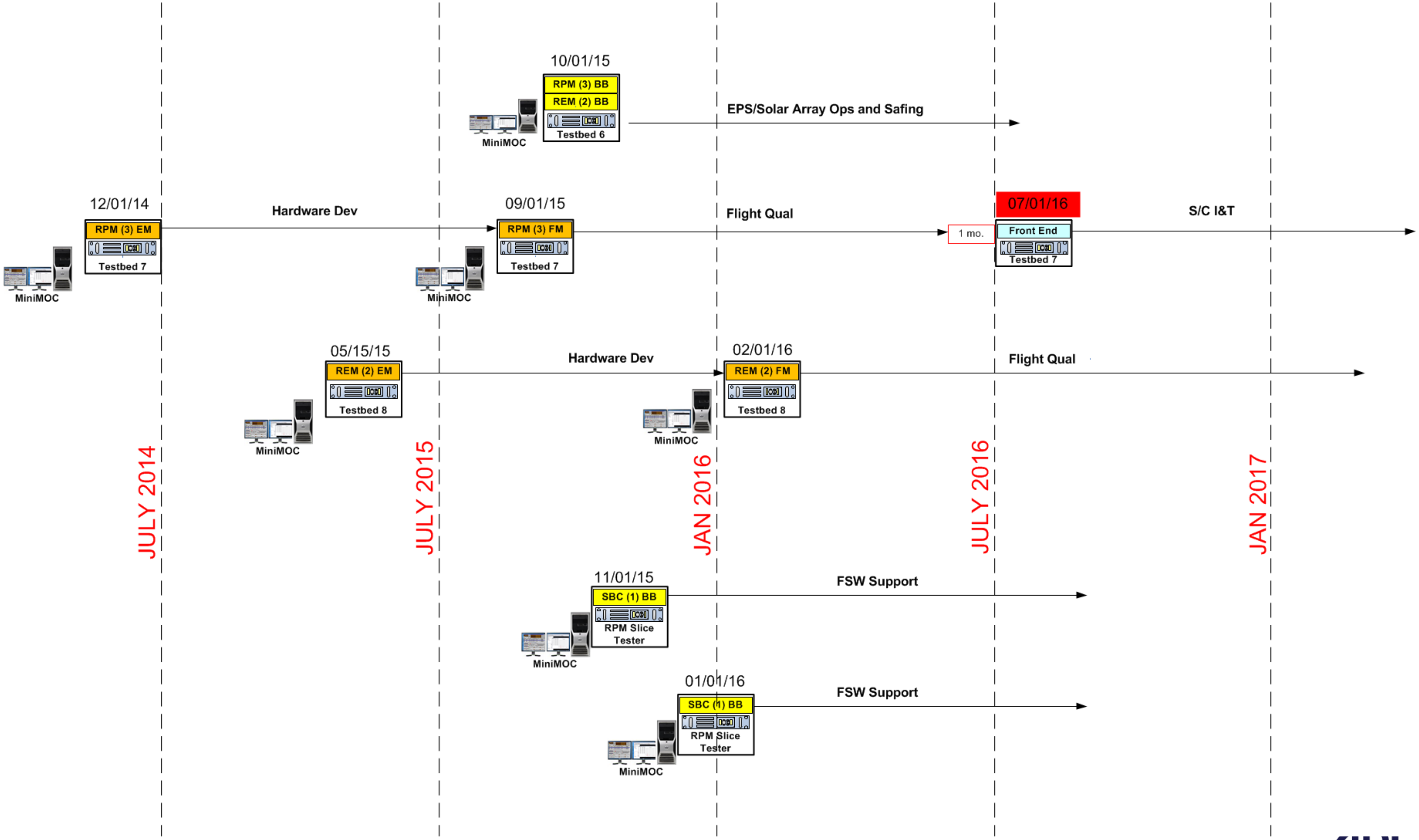

Verification

- Requirements verification will be documented in DOORS
- The Ground System Setup and Checklist Test procedure will be used to test the Ground System
  - when first delivered to I&T
  - when moved to the environmental test area at APL
  - when moved to GSFC
  - when moved to Astrotech
  - when first delivered to OPS

Ground System Hardware Summary

- **Level 4 Requirements**
  - **Completed Requirements Review (August 5, 2013)**
  - **Closed Action Items**
  - **Released the Requirements Document (7434-7003)**
- **Preliminary Design**
  - **Completed Pre-PDR Peer Review (October 22, 2013)**
  - **Closed Action Items**
  - **Released Preliminary Ground Operations Equipment Plan (7434-7002)**
- **Based on current testbed utilization estimates and the testbed development schedule there is a sufficient number of testbeds to support the project’s needs**
- **Ground System Hardware is ready for Phase C**

Backup Slides

Ground Hardware Documentation

- 7434-7002 Ground Operations Equipment Plan (Preliminary, in PLM)
- 7434-7003 Ground Hardware Requirements Document (in PLM)
- 7434-7004 Ground System Longevity Plan, draft
- 7434-7005 Ground System Contingency and Disaster Recovery Document, draft
- 7434-7006 Ground System Setup and Checkout Test Procedure
- 7434-9033 SPP Ground System IONet Segment Security Plan (in PLM)

Solar Probe Plus

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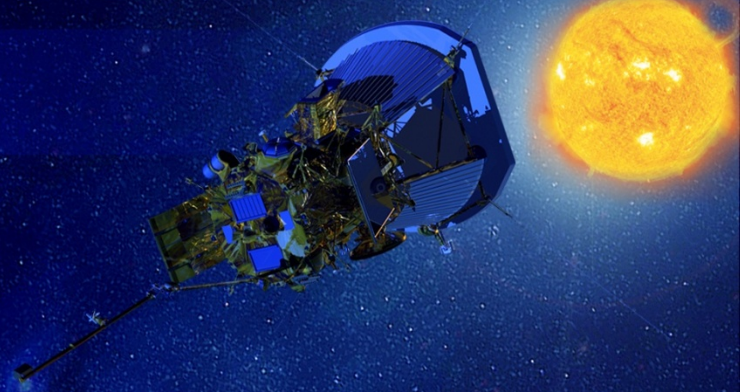

Ground System Software

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Lead Engineer

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13 – 16 January 2014

The Johns Hopkins University
APPLIED PHYSICS LABORATORY

Ground System Software Agenda

- **Driving Subsystem Requirements**
- **History**
- **Design Overview**
- **Build Plan**
- **Verification Plans**

Ground System Software Driving Requirements (1/2)

- **Requirements flow from Ground System Requirements (7434-9049 Rev -)** (GSYS)
- **Support full mission lifecycle** (GSYS-4)
  - **Includes hardware checkout, flight software development, ground subsystem testing, integration and test, mission operations, simulations**
- **Support external interfaces**
  - **Deep Space Network (DSN)** (GSYS-215,250,217)
  - **Science Operations Centers** (GSYS-359,11,39,40,41,42,43,54)
  - **Navigation** (GSYS-340)
  - **Ground Support Equipment** (GSYS-189,191,329,194,341)
- **Meet NASA IT Security Requirements** (GSYS-202)
- **Challenging Deep Space Communication Geometry**
  - **Support Short and Long Telemetry Frames** (GSYS-337)
  - **Use CFDP for both uplink and downlink** (GSYS-243)

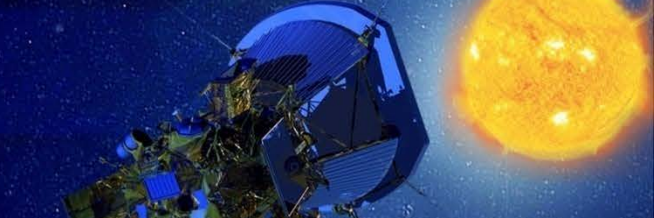
Ground System Software Driving Requirements (2/2)

- **Mission Planning**
  (GSYS-74,324,75,76,289,79,83,84,93)
- **Attitude**
  (GSYS-128,129,317,318)
- **Ground management of on-board memory**
  (GSYS-334,335,97,98,99,100,101,102,321)
- **Ground management of Solid State Recorder**
  (GSYS-85)
- **I&T**
  (GSYS-352,198,199,408,409,411,412)
- **Timekeeping**
  (GSYS-120,416)

Ground System Software Reviews

- **SPP Ground Software Requirements**
  - **Review held August 7, 2013**
  - **Review Board – Vicki Dulski, Mike Furrow, Paul Lafferty, Chris Monaco, Nick Pinkine, Randy Schlotterbeck, Deane Sibol**
  - **19 Action Items and 57 Recommendations**
  - **All Requirements Review Action Items Addressed**
  - **GSW Requirements Document 7434-7009_Rev_Dash in PLM (2013-10-31)**

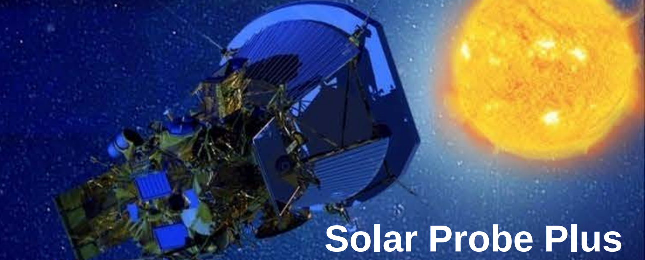
- **SPP Ground Software Preliminary Design**
  - **Review Held November 4, 2013**
  - **Review Board - Arthur Amador (SRB), Annette Dolbow, Mike Furrow, Chris Monaco, Nick Pinkine, Deane Sibol, Bill Stratton, Bob Schweiss**
  - **10 Action Items and 33 Recommendations**
  - **All Preliminary Design Review Action Items Addressed**
  - **SPP Ground Software Preliminary Design Slides added to PLM**



Ground System Software Distinguishing Features

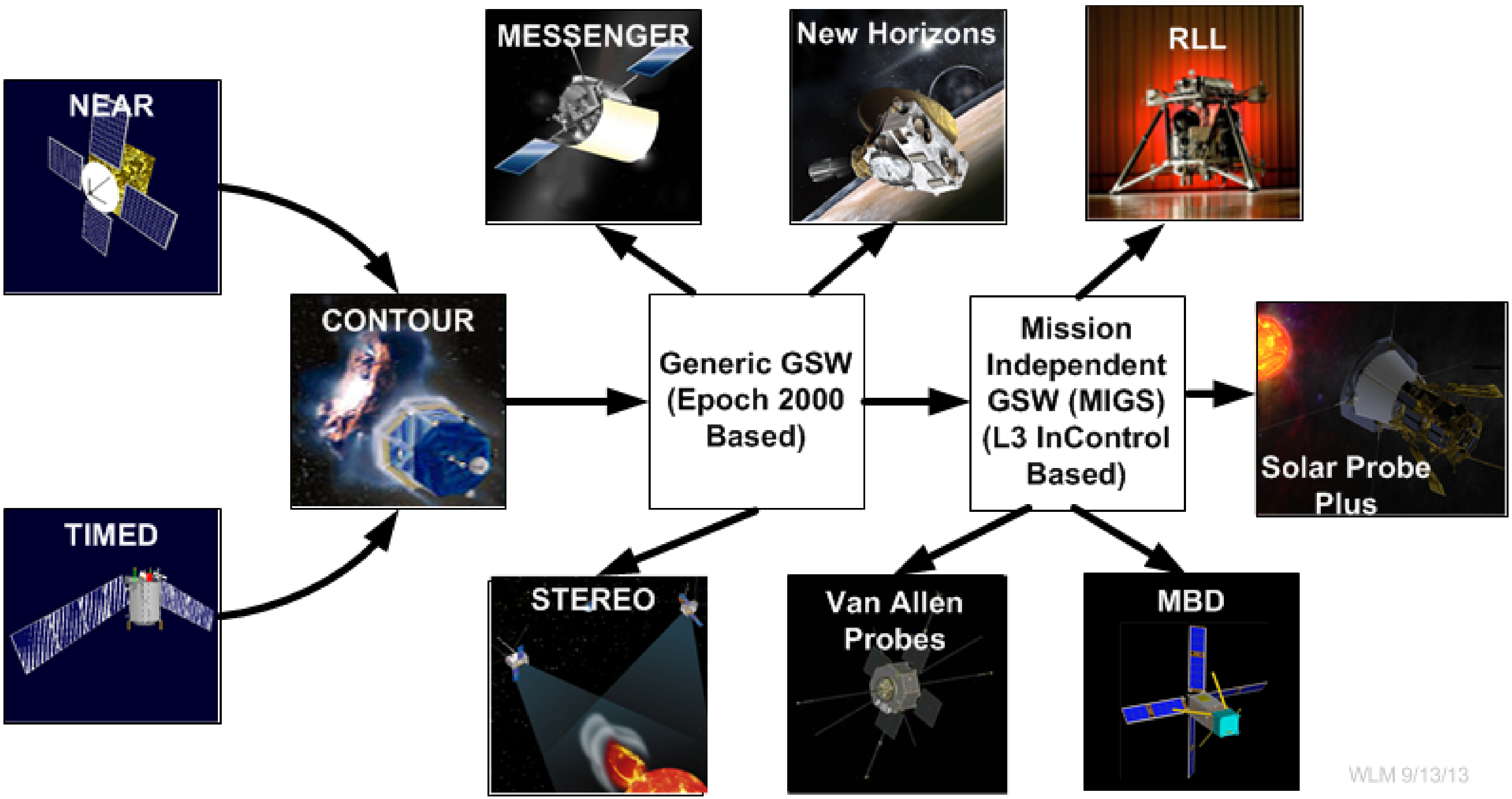
- Supports all phases of SC development including FSW development, Subsystem Test, Spacecraft I&T, Hardware Simulator Control, & Flight Operations Lifecycle
- Same software components; Different hardware configurations and software deployments throughout lifecycle
- Supports scripted operations of GSE as well as SC
- Supports status viewing & archiving of GSE as well as SC data
- Decoupled Payload Operations Approach (similar to TIMED, STEREO, Van Allen Probes)
  - Mission Planning Process more complicated than other APL decoupled missions
- S/C and Instrument File Commanding via guaranteed delivery CFDP uplink
  - Better suited to deep space mission than COP-1
  - Enables uplink bandwidth savings via copying load files across processors
- Significant Reuse from Van Allen Probes (~87% of CSCs are High or Full Reuse)
  - Reuse includes ground timekeeping architecture

Ground System Software
3 MOC Configurations



- **Ground Software Supports 3 MOC Configurations**
  - **Mini-MOC**
    - **Supports local test of a spacecraft processor subsystem and avionics**
    - **Provides primary user interface for the testbed (commanding and telemetry)**
    - **Local archive**
  - **I&T MOC**
    - **Supports spacecraft I&T, allowing users to send commands to and receive telemetry from the spacecraft under test and GSE**
    - **Central archive in the OPS DMZ**
    - **Other users may view status and telemetry information simultaneously from client workstations connected to controlling I&T MOC workstation and in the OPS DMZ**
  - **Flight MOC**
    - **Supports mission simulations, launch and operations, including via ground stations**
    - **Central archive in the OPS DMZ**
    - **Other users may view status and telemetry information simultaneously from client workstations connected to controlling Flight MOC workstation and in the OPS DMZ**
- **Same basic ground system software is used for all configurations**

Ground System Software Migration



Ground System Software Significant Deltas from Van Allen Probes (1/3)

- **Commanding**
  - **CFDP uplink used as replacement to COP-1 AD commanding**
  - **CFDP only used in reliable delivery configuration (Class 2)**
  - **File based SOC commanding interface**

- **Interfacing with NASA's Deep Space Network (DSN)**
  - **Creation of InControl based DSN interface**
  - **Automated IDR file delivery over internet**
  - **New Return Beacon Tone Interface for low bit rate tones**
  - **DSN Keyword Generation File Creation necessary to configure stations**

- **Min/Max Downlink Data Rate of (10 bps/ 1 Mbps) versus (1000 bps/2 Mbps) on Van Allen Probes**
  - **Use of short frame telemetry at low data rates**

Ground System Software Significant Deltas from Van Allen Probes (2/3)

- **SPP has 3 flight processors vs 1 flight processor**
  - **Memory to be tracked by both logical and physical SBC**
  - **APIDs used to track logical FSW and G&C data**
  - **InControl Metadata used to track physical SBC FSW and G&C data**

- **SPP has on-board G&C**
  - **Need for ephemeris_load**
  - **Need for tk_time_param_load**
  - **Need for Attitude History and SFF generation**

- **FAST Simulator**
  - **Includes G&C**
  - **Simulator will be Model Based (No longer closed loop simulation running full flight software)**

Ground System Software Significant Deltas from Van Allen Probes (3/3)

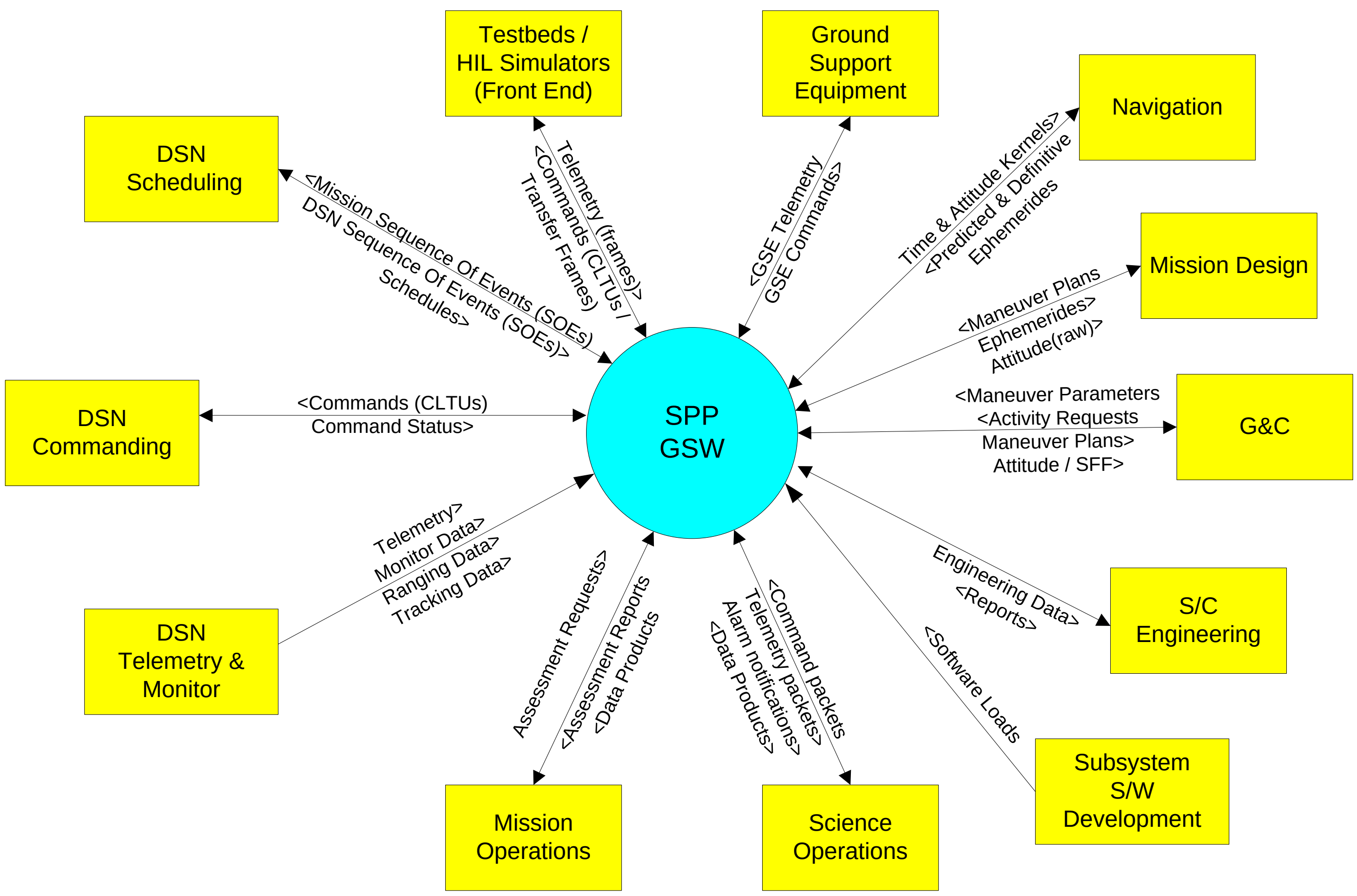
- **New orbit_planning software CSC**
- **SPP tailored activity_planner software (derived from Van Allen Probes scheduler)**

- **Archive Data**
  - **Recorded SSR telemetry files provided directly to SOCs**
  - **L0 files for real-time only (playback data via SSR telemetry files)**
  - **InControl configured to archive both playback and real-time packets.**
    - **Van Allen Probes would throw away duplicate content if same packet in real-time and recorded data file (non-deterministic if real-time or playback packet dropped).**
    - **This allows successful complete real-time or playback retrievals**

- **System configuration**
  - **Redhat Enterprise Linux vs SUSE Linux**
  - **DMZ Client VMs vs full client desktop computers**
  - **Remote InControl client instead of NFS cross-links**

Ground System Software Design Description: Context Diagram

SPP Ground Software Context Diagram



Ground System Software CSCIs

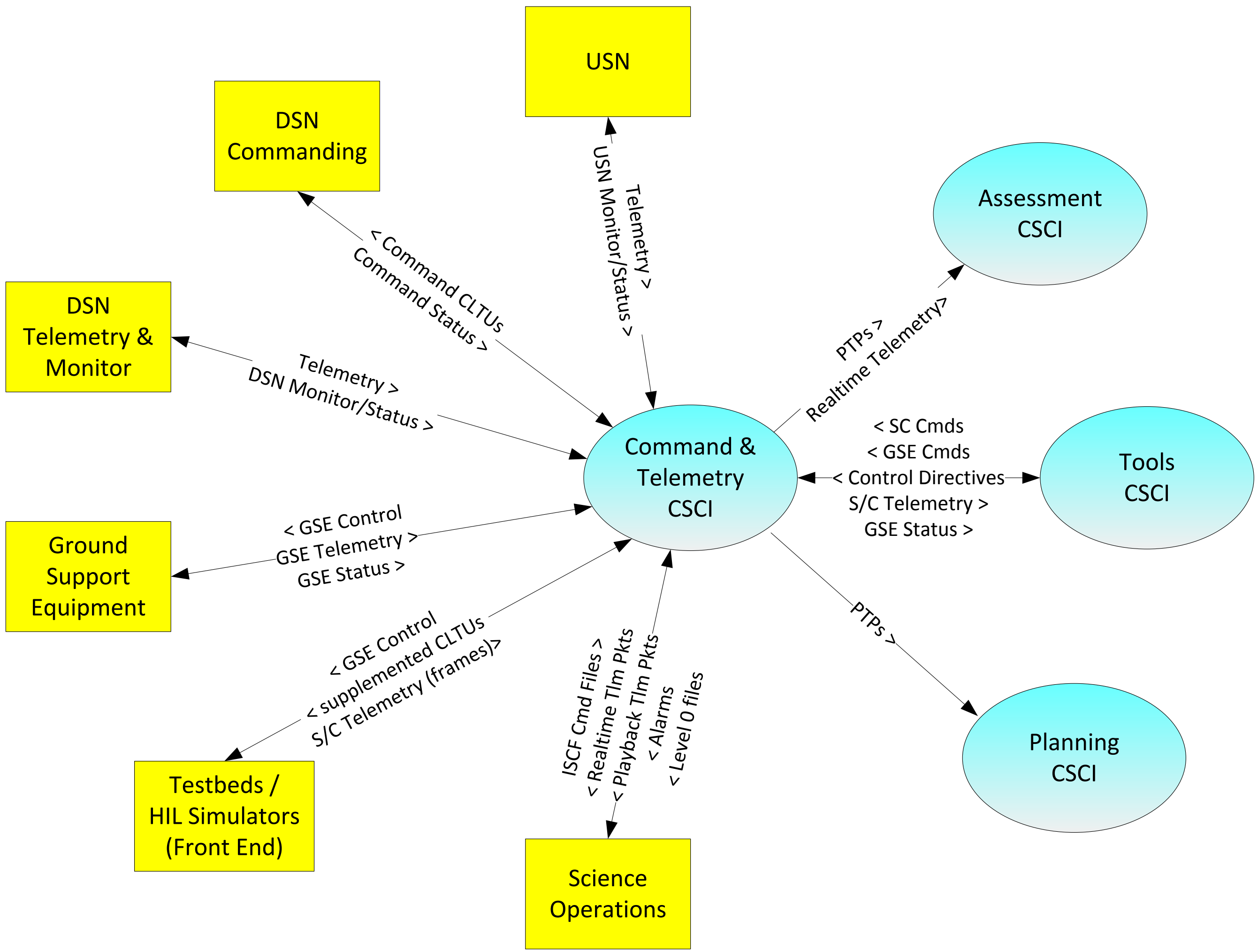
- **Commanding & Telemetry – Delivery of commands to the spacecraft and GSE, routing, processing, & monitoring of real-time telemetry, CFDP**

- **Planning – Generation of command loads, software loads, DSN Antenna setup, etc.**

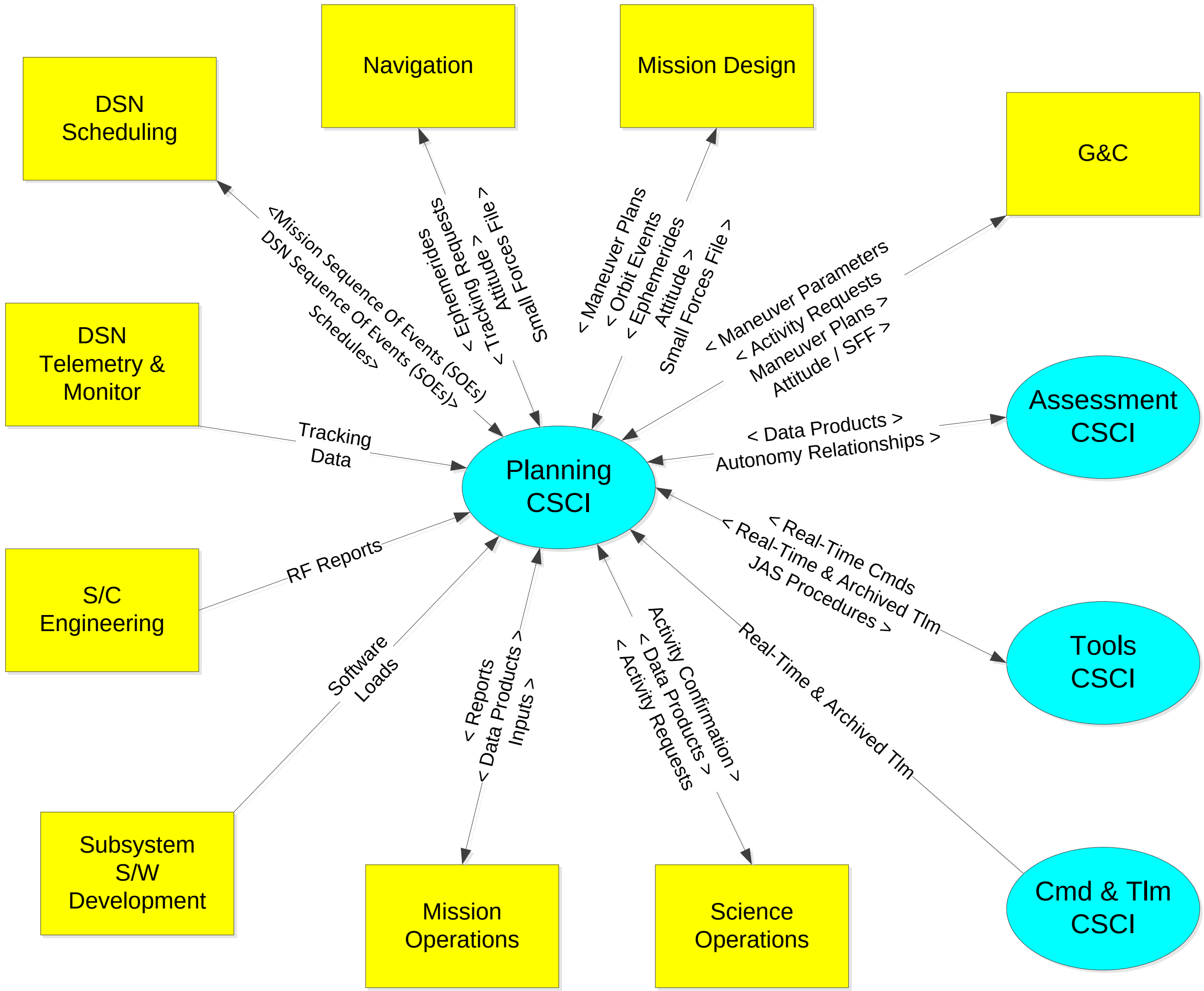
- **Assessment – Offline assessment of S/C housekeeping telemetry, Time-keeping, Data Accounting, etc.**

- **Tools – COTS MOC Core Software (InControl) which provides Core Telemetry, Commanding, Assessment, GUI, and scripting functionality. Software Based S/C Simulator. MOC Monitoring, Remote Access, etc.**

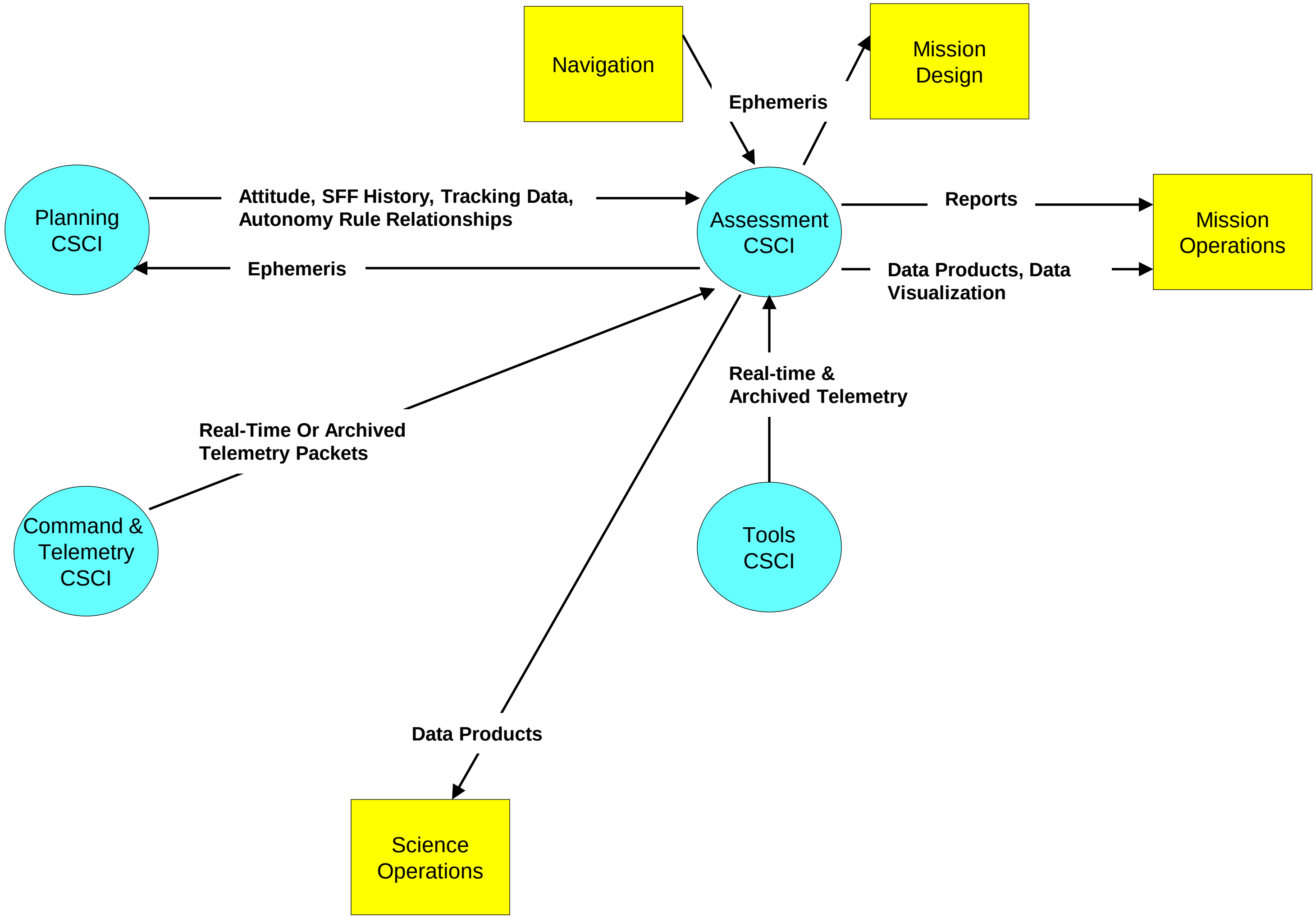
Ground System Software Commanding & Telemetry Context



Ground System Software Planning Context



Ground System Software Assessment Context



Ground System Software Design Description: MOC Core Software

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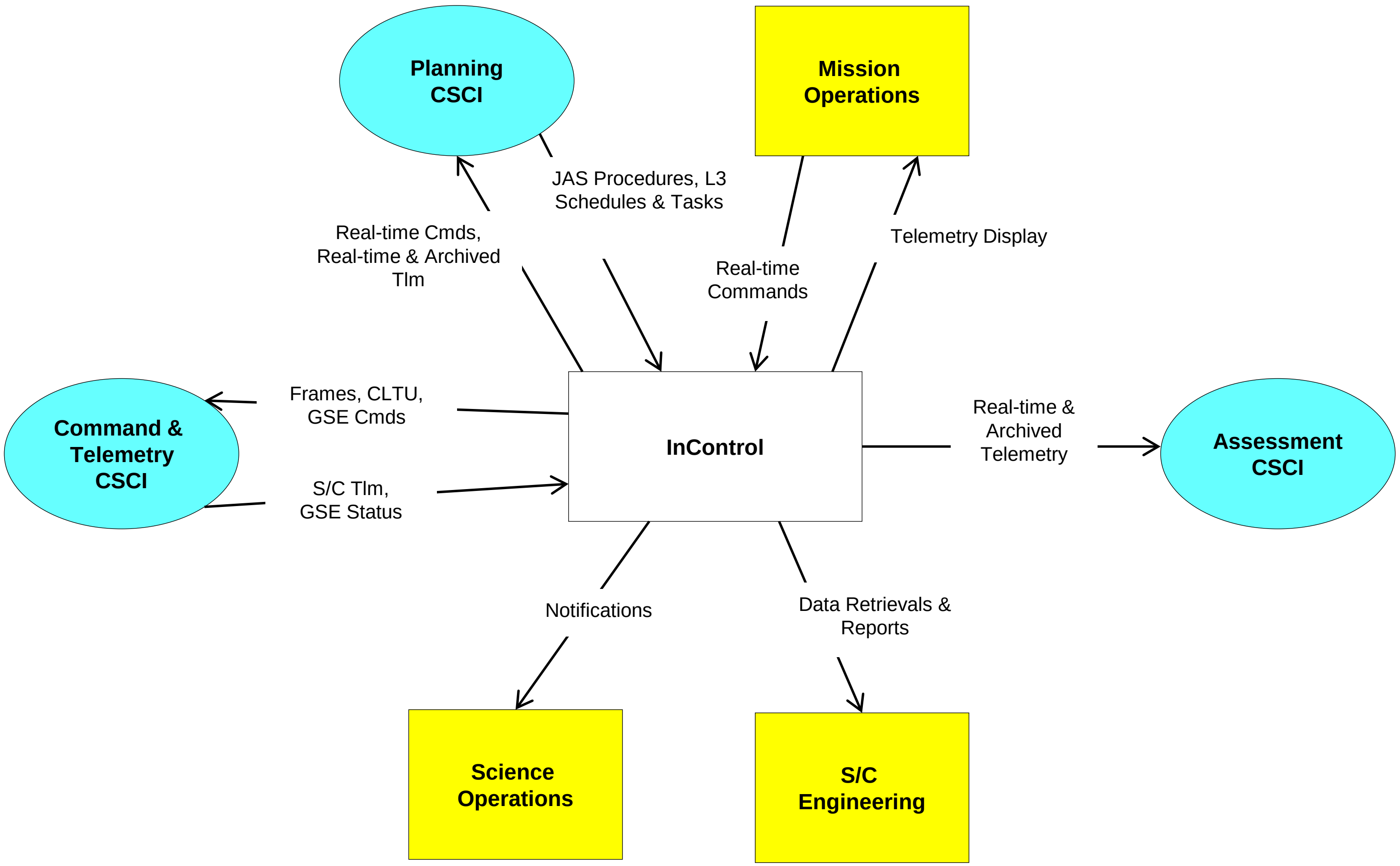
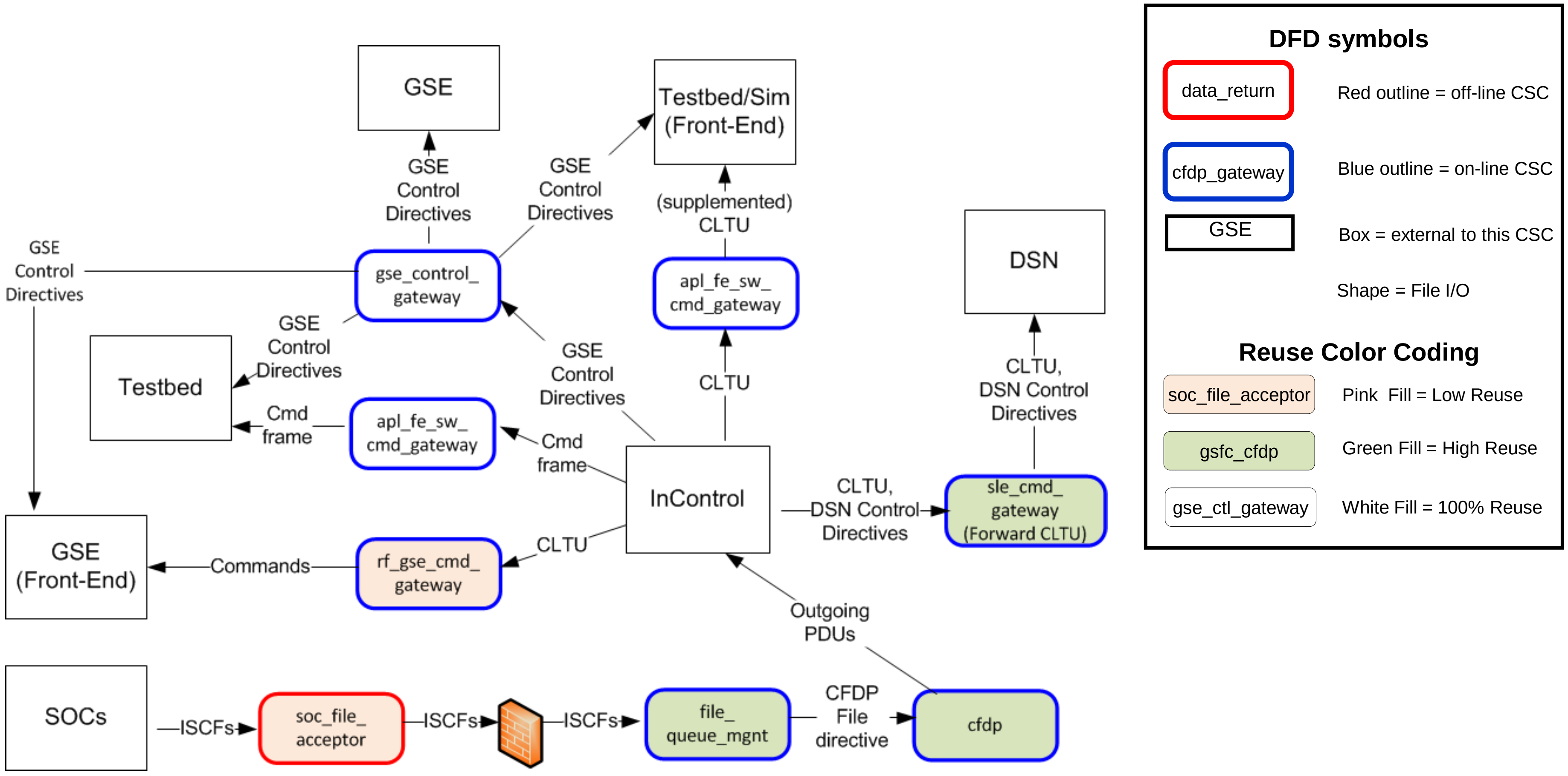


Ground System Software
Design Description: Command Data Flow



Ground System Software Design Description: Telemetry Data Flow

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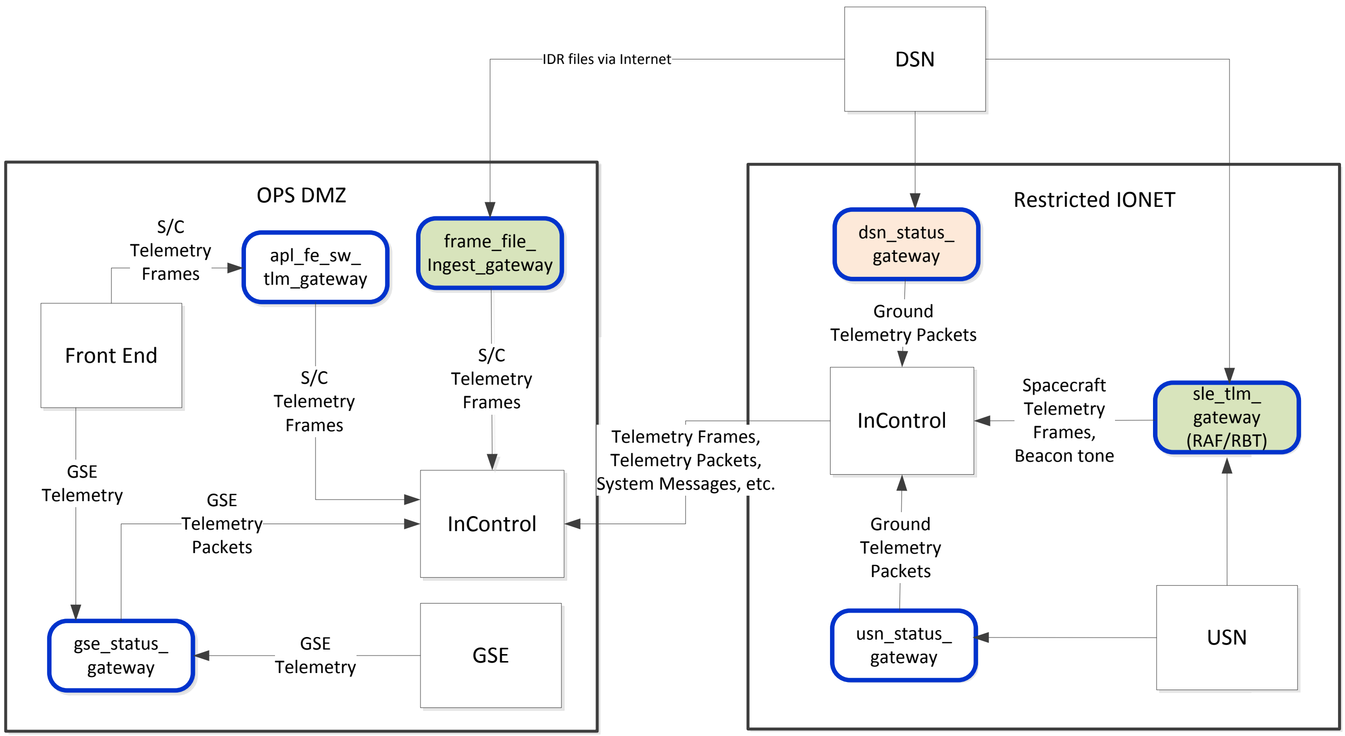

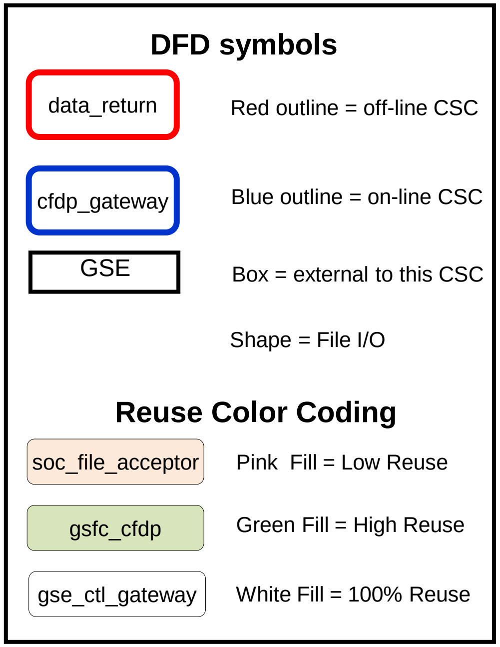

Ground System Software Design Description: Scheduling Flow

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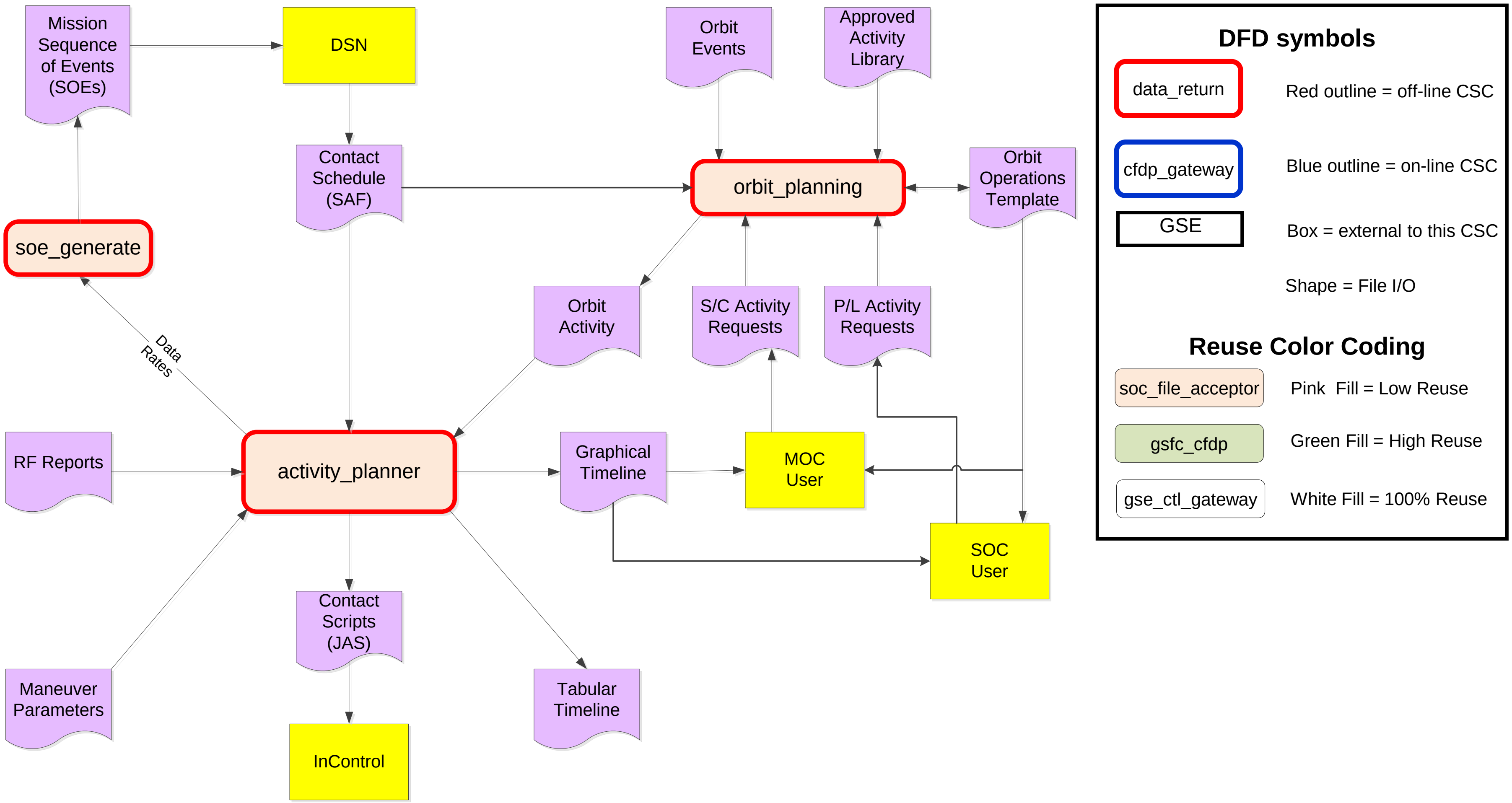

Ground System Software Memory Management Flow

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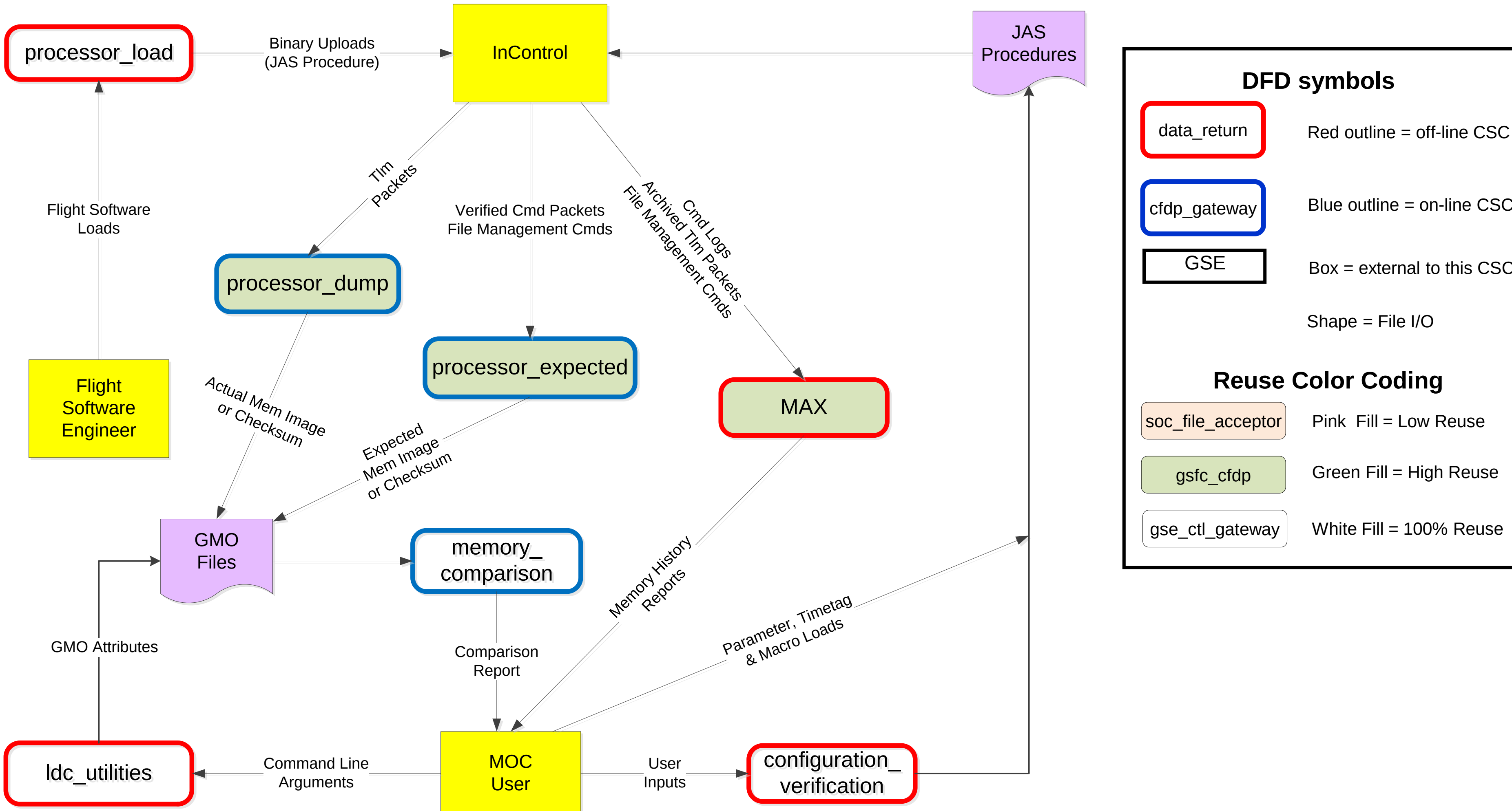


Ground System Software Build Plan

- **Build 0 (Jan 2013)** — **FSW Development, GSE Development – Deployed and in use**
- **Build 1 (May 2014)**
  - **Target:** **FSW Development, GSE Development**
  - **Deployment:** **Mini-MOC configuration**
    Individual (standalone) workstations on SD-DMZ Network
- **Build 2 (July 2015)**
  - **Target:** **FSW Development, GSE Development**
  - **Deployment:** **Mini-MOC configuration**
    Individual (standalone) workstations on SD-DMZ Network
- **Build 3 (June 2016)**
  - **Target:** **Early Spacecraft I&T**
  - **Deployment:** **I&T configuration**
    OPS DMZ Network, Restricted IONet
- **Build 4 (March 2017)**
  - **Target:** **Spacecraft I&T, Pre-Mission Simulation 2**
  - **Deployment:** **I&T, Hardware Simulator, Flight MOC Configurations**
    OPS DMZ Network, Restricted IONet
- **Build 5 (December 2017)**
  - **Target:** **Spacecraft I&T, Mission Simulations 3-5, Launch**
  - **Deployment:** **I&T, Hardware Simulator, Flight MOC Configurations**
    OPS DMZ Network, Restricted IONet

Ground System Software Verification Plans

- Developer Verification
  - Requirements traced to CSC
  - Application testing is performed on each CSC
  - System and applicable integration/interface testing is performed on each Build
- Independent Acceptance Verification
  - Performed on ‘critical’ requirements implemented in Builds (‘critical’ requirements involve functionality such as: commanding the spacecraft, spacecraft attitude determination and maneuvers)
  - Test methods
    - Requirements based (involves both positive and negative testing of the requirement)
    - Scenario (incorporates GSW and FSW in end-to-end tests)
    - Stress
- Regression test suite will be established

Ground System Software Summary

- Requirements
  - Completed Requirements Review (Aug 7, 2013)
  - Closed Action Items
  - Released Requirements
- Design
  - Completed Preliminary Design Review (Nov 4, 2013)
  - Closed Action Items
  - Released Preliminary Design Documentation
- Software Team
  - Phase B – team of 6 members in place
  - Phase C – team increases to 9 members
- Ground System Software Team is ready to proceed to Phase C

Backup

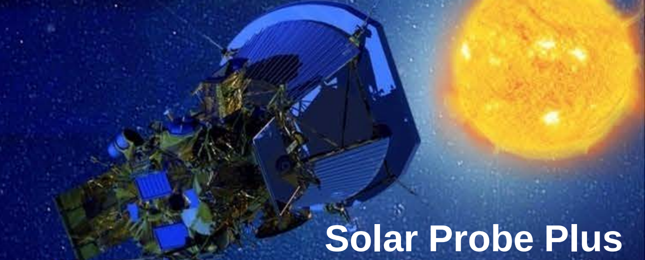
Ground System Software Lessons Learned from Van Allen Probes (1/3)

- Provide significant amounts of memory for InControl as performance in presence of limited resources is poor (design is enough resources must be available at all times)
- Ensure Development Virtual Machines are configured to have sufficient resources (RAM and processing)
- Van Allen Probes has experienced problems with broken functionality in new releases of InControl. Mitigations are
  - Provide SPP InControl Configuration to L-3 for testing
  - Develop automated tests of core InControl functionality used by SPP to be used as verification tests prior to APL receiving System
  - Bi-Weekly meeting with L-3 about development roadmap and current software issues
- Plan for staffing level to support the timing of the user of the software (versus the release date)
- Provide text field in JIRA to allow engineer and/or tester to provide assistance for gathering comprehensive release notes

Ground System Software Lessons Learned from Van Allen Probes (2/3)

- **Ensure all newly developed CSCs validate input (user mistake can cause invalid data to get into the system)**
- **Enforce early use of nightly builds and static analysis tools**
- **GSW Information Security Awareness – All new development should consider information security in design and implementation.**
- **Limit number of NFS cross-mounts between systems as this caused performance problems and was hard to maintain**
- **Reduce the number of physical machines in DMZ / IONET to reduce cost of maintenance and replacements**
- **Use mini-MOC configuration for JAS script development**

Ground System Software Lessons Learned from Van Allen Probes (3/3)

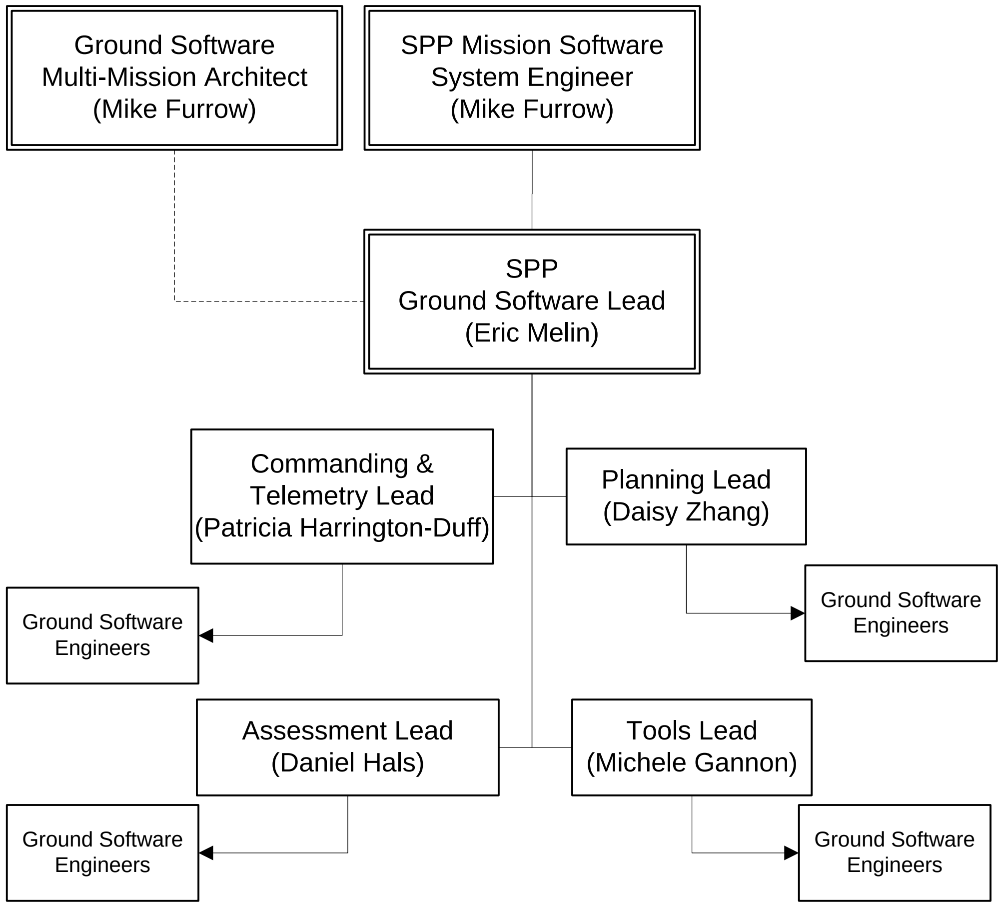


- **Create a separate InControl mission per unique hardware unit being tested**
  - **This allows for easy tracking of qualification data when the hardware is used on different mini-MOCs**
- **Software Simulator (FAST) should have a dedicated team with a single project lead.**
- **Heritage APL flight software is designed for flight functionality and not well suited for Faster than Real-time Execution**
  - **SPP FAST approach involves models written and maintained by FSW developers (will not run G&C FSW directly)**
- **Van Allen Probes FAST experienced problems with performance in Flight to ground communication**
  - **SPP FAST will not send telemetry to ground component**

Ground System Software Interface Control Documents (ICDs)

PLM Number	Document	Current Revision	Revision for CDR (2015-03)
7434-9054	SPP GSW-to-FSW ICD	Draft planned 2014-01	2014-11
7434-9078	SPP MOC to SOC ICD	Preliminary Rev-a - 2013-10-31	2014-11
7434-9079	SPP MOC to NAV/MD ICD	Draft - 2013-10	2014-11
7434-9163	SPP MOC Data Products Document	Draft - 2013-10	2014-11
DOORS	Multi-Mission MOC to GSE ICD	Draft - 2013-10	2014-11
TBD	SPP Space Asset Protection Requirements	TBD	TBD
7434-9016	Concept of Operations	Rev A – 2013-09-10	Rev A – 2013-09-10
DSN Document (870-462)	SPP DSN Service Agreement (DSA)	2013-10 rev3	TBD
DSN Document	SPP Operational Interface Control Document (OICD)	TBD	TBD

Ground System Software Team



Ground System Software
CSC Development Summary (Release where most functionality is available)

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Assessment	C&T	Tools	Planning
autonomy_visualizer	cfdp_core	**InControl**	**activity_planner**
concord_ingest	cfdp_gateway	FAST	attitude_history
concord_web_client	cfdp_packet_file_ingest_gateway	auto_test	attitude_prediction
concord_web_service	**dsn_status_gateway**		autonomy_labels
data_return	file_queue_mgmt		countdown_clock
level_zero	frame_file_ingest_gateway		dkf_generate
moc_data_server	frame_gse_cmd_gateway		ephemeris_load
time_convert_service	frameview		get_tlm
tk_data_mgr	gsfc_cfdp		max
tk_history_file	rf_gse_cmd_gateway		**orbit_planning**
tk_time_param_load	**sle_cmd_gateway**		processor_dump
	sle_tlm_gateway		processor_expected
	soc_file_acceptor		sff_merge
	space_asset_protection		sff_predict
			sff_reconstruct

Most CSC Features Available
Build 1 - 5/2014
Build 2 - 7/2015
Build 3 - 6/2016
Build 4 - 3/2017
Build 5 - 12/2017
BOLD when most features available before completed release

Ground System Software CSC Completion Summary

Assessment	C&T	Tools	Planning
autonomy_visualizer	cfdp_core	InControl	activity_planner
concord_ingest	cfdp_gateway	FAST	attitude_history
concord_web_client	cfdp_packet_file_ingest_gateway	auto_test	attitude_prediction
concord_web_service	dsn_status_gateway		autonomy_labels
data_return	file_queue_mgmt		countdown_clock
level_zero	frame_file_ingest_gateway		dkf_generate
moc_data_server	frame_gse_cmd_gateway		ephemeris_load
time_convert_service	frameview		get_tlm
tk_data_mgr	gsfc_cfdp		max
tk_history_file	rf_gse_cmd_gateway		orbit_planning
tk_time_param_load	sle_cmd_gateway		processor_dump
	sle_tlm_gateway		processor_expected
	soc_file_acceptor		sff_merge
	space_asset_protection		sff_predict
			sff_reconstruct

CSC Complete
Build 1 - 5/2014
Build 2 - 7/2015
Build 3 - 6/2016
Build 4 - 3/2017
Build 5 - 12/2017

Solar Probe Plus

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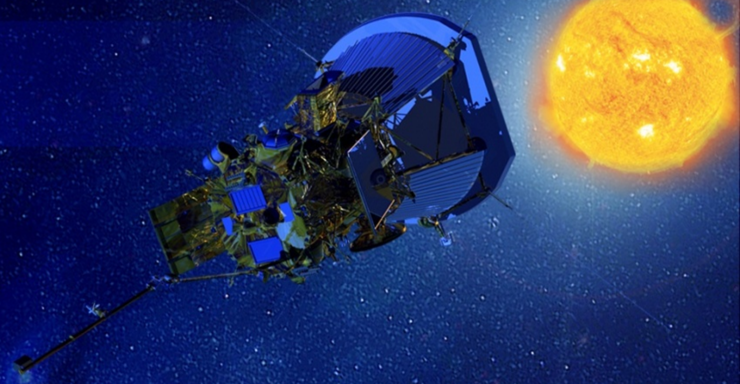

Mission Operations

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13 – 16 January 2014

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Outline

- Mission Operations Driving Requirements
- Previous Reviews & Action Item Status
- Mission Operations Key Characteristics
- Mission Operations Interfaces & Data Products
- Orbit Planning & ConOps
- Mission Operations Pre-Launch Testing
- Early Operations Timeline
- DSN Support Profile
- Mission Operations Development Plan

Mission Operations

DRIVING REQUIREMENTS

Mission Operations Driving Requirements

ID	Requirement	Impact
GSYS-255	Launch Readiness Date of July 2018	Drives the overall Mission Operations Development & Test Plan
GSYS-6	Post-Launch Design Life of 7 Years	Impacts Operations Staffing Profile, DSN User Loading Profile (ULP) & Ground System Maintenance Plan
GSYS-11 GSYS-39	Decoupled Payload Operations Instrument Command Handling	Impacts operations planning, ground software, data flow & interfaces
GSYS-14 GSYS-61	CFDP Utilization CFDP Downlink	CFDP will be used for commanding (new functionality) and data downlink
GSYS-62 SCRD-232	Downlink an average of 127 Gbits of data per orbit (HK & Science)	Impacts DSN profile, orbit planning process & overall ConOps
GSYS-324	Orbit Planning	Requires detailed orbit planning process/software to support spacecraft & instrument activity coordination
GSYS-92 GSYS-93	TCM Planning & Implementation	Frequent maneuvers require detailed end-to-end maneuver implementation process with MD/Nav/GC/MOPs

Mission Operations

PREVIOUS REVIEWS & ACTION ITEMS

Previous Reviews & Action Item Status

- **Ground System & MOC Requirements Review (6/24/13 – 6/25/13)**
  - Number of Action Items 34 Open Action Items 3
  - All Action Items documented online in PIMS

- **Concept of Operations Peer Review (10/3/2013)**
  - Number of Action Items 7 Open Action Items 3
  - All Action Items documented online in PIMS

Mission Operations

KEY CHARACTERISTICS

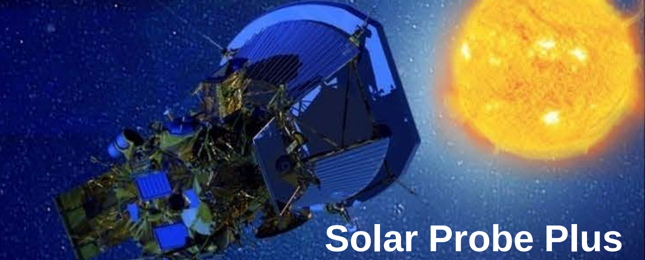
Mission Operations Key Characteristics

- **<u>Trajectory Maintenance</u>**
  - **7 Venus Flybys with one or more TCMs each orbit**
    - **Upwards of 42 TCMs over the course of the mission**
  - **Some TCMs may require “tight” turnaround times between final OD data cut-off and execution time**
  - **No optical navigation requirements for OD significantly simplifies required flight and ground operations**

End-to-End TCM implementation process has been defined composed of elements from:

- ***Navigation Mission Design***
- ***Spacecraft Engineering (G&C/Prop)***
- ***Mission Operations***
- ***DSN***

Mission Operations Key Characteristics



- <u>**Spacecraft Attitude Management**</u>
  - **Expect spacecraft attitude changes to be relatively infrequent**
    - **Not doing intensive, targeted pointing for instrument operations**
  - **During solar encounter operations there is no requirement to change spacecraft attitude**
  - **During cruise/downlink operations there is a finite number of specific spacecraft orientations defined in spacecraft requirements documentation & EDTRD**

Highly constrained attitude simplifies operations and enables decoupled spacecraft & payload commanding concept

Mission Operations Key Characteristics

- **<u>Solar Array & Power System Operations</u>**

  - **Available power varies over the course of an orbit as a function of solar distance and solar array flap angle**
  - **Need to configure spacecraft per power configurations defined in spacecraft requirements document**
  - **Solar array performance monitoring expected**
    - **Periodic solar array tests to track performance/degradation**
  - **Autonomous solar array control supported via flight software**
    - **May require parameter maintenance from operations**

Need to predict and track available power over each orbit to support activity planning

- ***Facilitates coordination with instrument teams for when instruments can be powered on/off outside of solar encounters***

Mission Operations Key Characteristics

- **Data Management**
  - **Deep Space Network (DSN) used for communications (34m)**
  - **X-band for command uplink and housekeeping data downlink**
  - **Ka-band for science data downlink**
    - **High-rate science data downlink opportunities are constrained**
      - **Function of sun distance and SPE angle**
  - **SSR file system supports reliable data downlink via CFDP**
  - **Each instrument has a configurable allocation of space on SSR**
  - **Some science data is stored on instruments and transferred to SSR**
  - **Instrument teams responsible for determining what instrument data to transfer or store to SSR**

Requires coordination between mission operations and instrument teams to support data downlink, data management and transfer requests

Mission Operations Key Characteristics

Instrument Operations – Decoupled Payload Commanding Approach

Used on TIMED, STEREO, Van Allen

- **Instrument SOCs command and manage their own instruments**
  - Coordination with MOps to determine instrument power on/off periods, available instrument commanding opportunities, SSR data transfers, packet filter table (PFT) changes, etc.
- **Instrument SOCs forward command files to their SOC queue prior to the pass needed for uplinking**
  - Safeguards in ground system to ensure instrument commands come from a valid source
  - Mission Ops does not have instrument commands in database
- **Instrument teams cannot command the S/C bus (i.e., cannot control S/C attitude or power switching)**
  - Mission operations is responsible for powering instruments on & off
  - Instrument operating periods determined during orbit planning
- **Instrument SOCs will monitor their own instrument’s health & safety**
  - MOC can monitor some high-level instrument health & status telemetry
- **Onboard Fault Management provides a status message to instruments indicating they should perform a graceful shutdown**
  - In the event of over-current conditions and spacecraft bus anomalous conditions, instruments will be powered down without warning
- **Fault management will power on instruments during recovery from a fault in solar encounter**

Mission Operations Key Characteristics

• Additional Features Affecting Operations & Planning

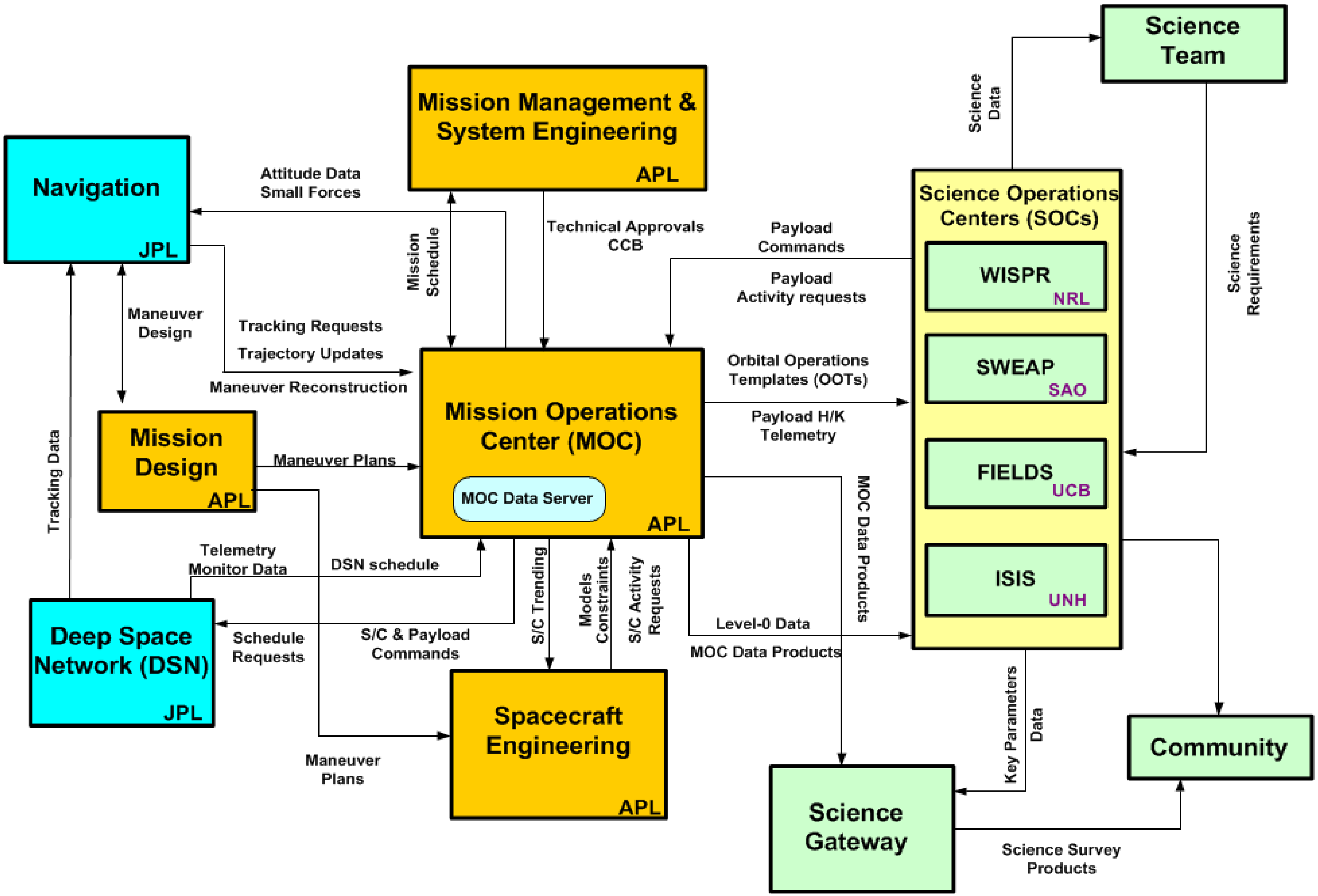
- **Commanding via CFDP uplink** (file based commanding for s/c & instruments) This is a new capability.
- **Three flight processors**
  - More complex parameter management/synchronization
  - Telemetry access by logical & physical processor configuration
  - SSR management complexities
- **Instrument Operations outside encounters**
  - Mission Planning Process more complicated than TIMED, STEREO, Van Allen Probes but not as complicated as MESSENGER, New Horizons
  - Orbit Planning Software tool will be developed to facilitate orbit planning process
    - Orbital Operations Template Development

Mission Operations

INTERFACES & DATA PRODUCTS

Mission Operations Functional Interfaces

Solar Probe Plus
A NASA Mission to Touch the Sun



SPP MOC
Data Products

Flight Data | Planning Data | Navigation Data

OPS
- Anomaly History Report
- As Flown Contact Report
- Archive Change Report
- Span Report
- Gap Report
- Command History Report
- Event History Report
- Instr Cmd History Report
- Instr Telem Alarm Notice
- Level 0 RT Telemetry
- Raw SSR Files
- SC/Gnd Telem Dictionary
- Weekly MOC Status
- Att Hist Report
- Ops SCLK Kernel
- Time History File

PLANNING
- Contact Plan
- DSN Keyword File (DKF)
- Graphical Timeline
- Orbit Ops Template
- FAST/Sched reports
- Att Short Term Predict
- Att Metakernel
- Leap Second Kernel

ENG
- S/C Activity Request
- RF Scheduler Inputs
- Maneuver Parameters
- Small Forces File
- Att Long Term Predict
- Frame Kernel (FK)

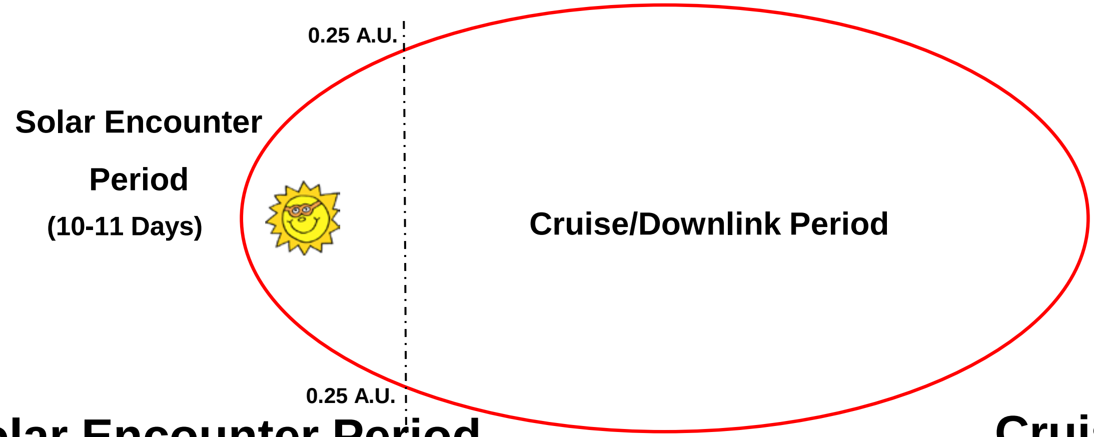
NAV/MD
- Planetary Ephem
- Predicted S/C Ephem
- Mission S/C Ephem
- Reconstructed S/C Ephem
- Orbit Events Predicts
- Maneuver Plan

SOC
- Instr Telem Dictionary
- Weekly Inst Status

DSN
- Stn Allocation File (SAF)
- Tracking Data

Mission Operations
ORBIT PLANNING & CONOPS

Orbital Operations Concept



24 Solar Encounter Orbits

Orbital Periods Vary (168 days to 88 days)

Solar Encounter Period

Encounter Operations

- Primary science data collection phase – All instruments will be powered on
- Fanbeam antenna periodically available for communications (aliveness check) & navigation tracking data collection
- Minimal commanding expected
- G&C Maintains shade-to-sun attitude
- No SSR Playbacks

Cruise/Downlink Period

Cruise Operations

- Instruments Can Be Powered On (Sun Distance < 0.82 AU)
  - Instruments off during some activities
- Fanbeam for communications – (X-Band, H/K data only)
- Commanding as needed to support spacecraft & instruments
- Spacecraft Attitude Changes Permitted
- No SSR Playbacks

Science Downlink Operations

- All instruments powered off
- HGA for communications (Ka-Band, Science & HK data)
- Commanding as needed to support spacecraft maintenance
- Spacecraft Attitude Changes Permitted
- SSR Playbacks Supported

Orbit Planning Activities

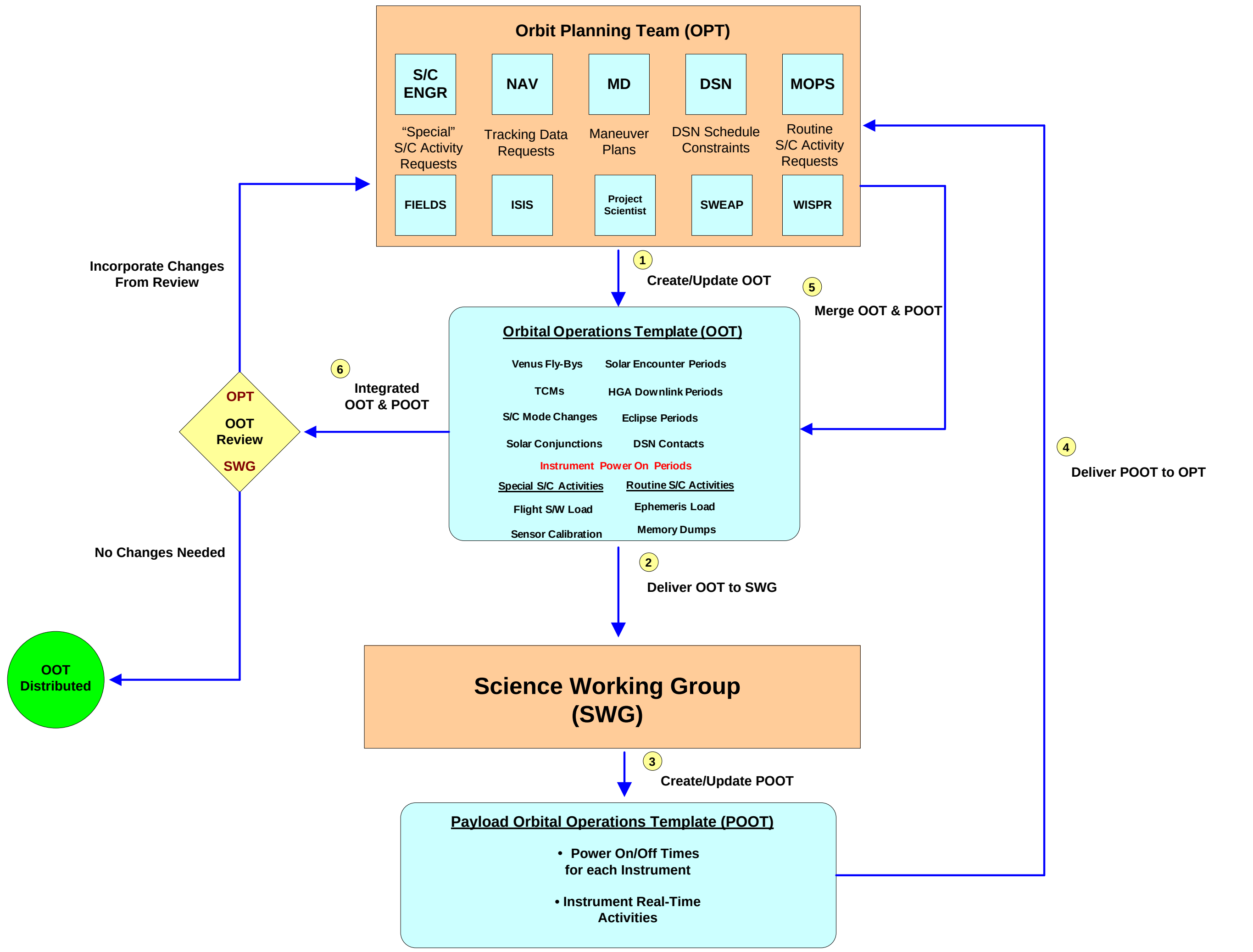
- **Detailed operations planning performed for each orbit**
  - **24 total orbits (Orbital period varies between 168 - 88 days)**

- **Key operations planning required for each orbit include:**
  - **Venus Flyby Events**
  - **TCMs**
  - **Spacecraft Slews**
  - **HGA downlink opportunities**
    - **High priority downlink periods each orbit**
    - **Dictates SSR management scheme**
    - **Slews will be required for some downlinks**
  - **Spacecraft housekeeping & maintenance activities**
    - **Flight software loads**
    - **Command Sequence Uplinks**
    - **Pump Speed Changes**
    - **Autonomy loads**
    - **Parameter maintenance**
    - **Special sub-system and/or payload tests**
  - **Eclipse & solar conjunction periods**
  - **Doppler range & Delta-DOR tracking requirements**
  - **Instrument Operations (During Cruise)**
    - **Power On/Off, Data Transfers, Command File Uplinks**
  - **Solar encounter operations (SOCs)**
- **Orbital operations template created to capture and schedule these activities**
- **Orbit activity planning process under development to coordinate s/c activities with instrument teams**

Orbit Activity Planning Process

Solar Probe Plus

A NASA Mission to Touch the Sun



Orbital Operations Template
(Orbital View)

Solar Probe Plus
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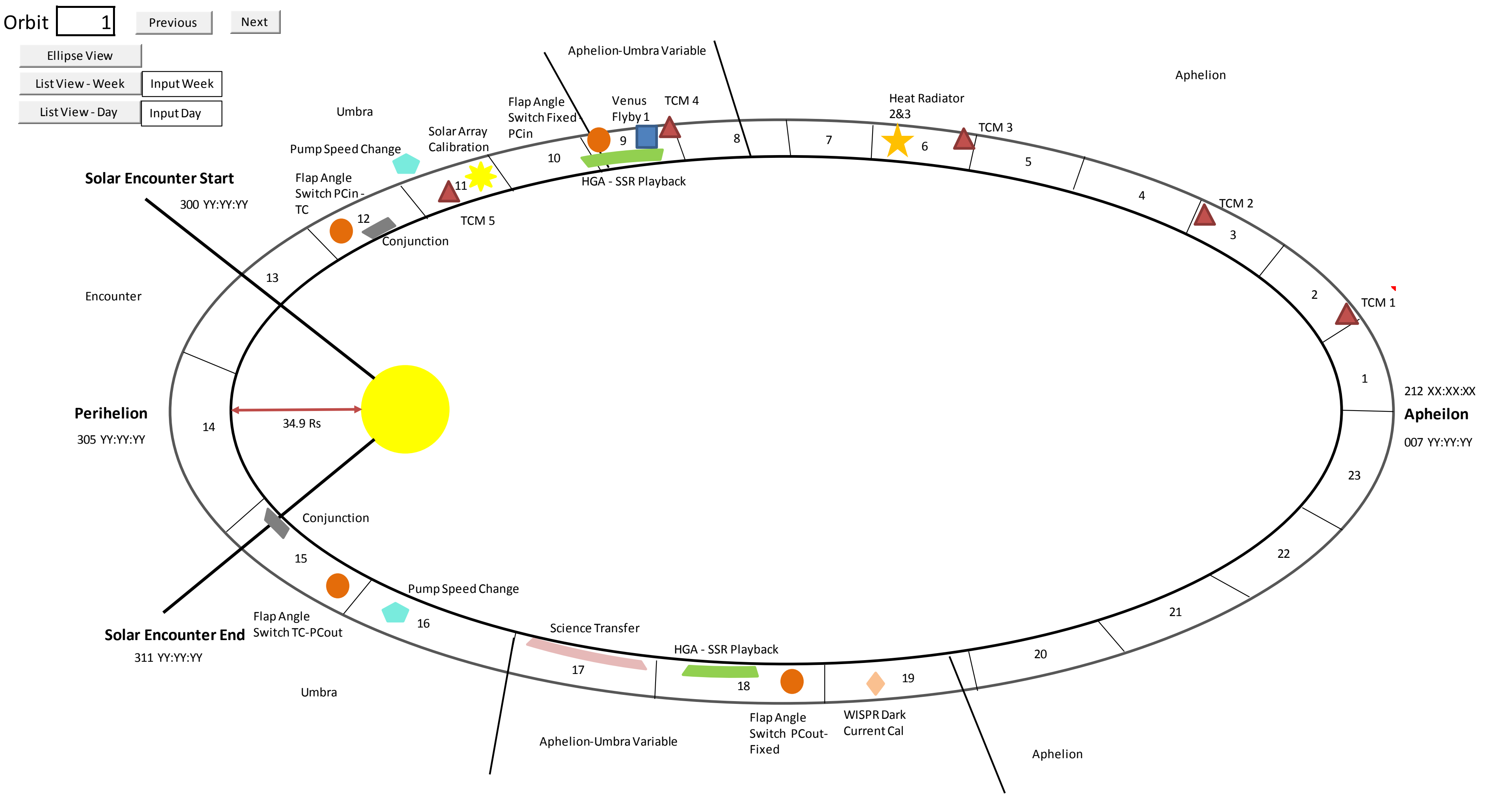

Orbital Operations Template

(Weekly View)

Solar Probe Plus

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Orbit 1							
Week 9	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday	Sunday
Mission Day	57	58	59	60	61	62	63
Orbit Day	57	58	59	60	61	62	63
DOY, UTC	267	268	269	270	271	272	273
Solar Distance	0.76	0.75	0.74	0.73	0.72	0.71	0.69
Attitude	Aphelion	Aphelion-Umbra Variable	Aphelion-Umbra Variable	Aphelion	Aphelion-Umbra Variable	Aphelion-Umbra Variable	Aphelion-Umbra Variable
Solar Array Flap Mode	Fixed	Fixed	Fixed	Fixed	Fixed	Fixed	PC Inbound
Power Configuration							
Command Load	18XXX	18XXX	18XXX	18XXX	18YYY	18YYY	18YYY
S/C Activities							
G&C			TCM Prep 269 XX:XX:XX Activiy Name	Flyby Prep 270 XX:XX:XX Activiy Name	Flyby Cleanup 271 XX:XX:XX Activiy Name		
RF			TCM Prep 269 XX:XX:XX Activiy Name	Flyby Prep 270 XX:XX:XX Activiy Name			
Power			TCM Prep 269 XX:XX:XX Activiy Name	Flyby Prep 270 XX:XX:XX Activiy Name	Flyby Cleanup 271 XX:XX:XX Activiy Name		
Thermal			TCM Prep 269 XX:XX:XX Activiy Name	Flyby Prep 270 XX:XX:XX Activiy Name			
CDH			TCM Prep 269 XX:XX:XX Activiy Name	Flyby Prep 270 XX:XX:XX Activiy Name			
Prop		TCM 3 Prep 268 xx:xx:xx Activity Name	TCM 3 269 xx:xx:xx Activity Name				
Payload Activities							
Instrument On Times							
FIELDS			TCM & Flyby Prep 269 XX:XX:XX Activiy Name				
SWEAP			TCM & Flyby Prep 269 XX:XX:XX Activiy Name				
WISPR			TCM & Flyby Prep 269 XX:XX:XX Activiy Name				
ISIS			TCM & Flyby Prep 269 XX:XX:XX Activiy Name				
DSN Schedule							
DSN Station	DSN XX Start Time: 267 XX:XX:XX End Time: 267 XX:XX:XX	DSN XX Start Time: 268 XX:XX:XX End Time: 268 XX:XX:XX	DSN XX Start Time: 269 XX:XX:XX End Time: 269 XX:XX:XX	DSN XX Start Time: 270 XX:XX:XX End Time: 270 XX:XX:XX	DSN XX Start Time: 271 XX:XX:XX End Time: 271 XX:XX:XX	DSN XX Start Time: 272 XX:XX:XX End Time: 272 XX:XX:XX	DSN XX Start Time: 273 XX:XX:XX End Time: 273 XX:XX:XX
Ka-Band						DSN XX Start Time: 272 XX:XX:XX End Time: 272 XX:XX:XX	DSN XX Start Time: 273 XX:XX:XX End Time: 273 XX:XX:XX
X-Band	DSN XX Start Time: 267 XX:XX:XX End Time: 267 XX:XX:XX	DSN XX Start Time: 268 XX:XX:XX End Time: 268 XX:XX:XX	DSN XX Start Time: 269 XX:XX:XX End Time: 269 XX:XX:XX	DSN XX Start Time: 270 XX:XX:XX End Time: 270 XX:XX:XX	DSN XX Start Time: 271 XX:XX:XX End Time: 271 XX:XX:XX		
Instrument Uplink Window							
Science Downlink	Instrument Uplink Start Time: 267 XX:XX:XX End Time: 267 XX:XX:XX	Instrument Uplink Start Time: 268 XX:XX:XX End Time: 268 XX:XX:XX		Instrument Uplink Start Time: 270 XX:XX:XX End Time: 270 XX:XX:XX	Instrument Uplink Start Time: 271 XX:XX:XX End Time: 271 XX:XX:XX	Science Downlink Start Time: 272 XX:XX:XX End Time: 272 XX:XX:XX	Science Downlink Start Time: 273 XX:XX:XX End Time: 273 XX:XX:XX
MOT Uplink Window	MOT Uplink Start Time: 267 XX:XX:XX End Time: 267 XX:XX:XX	MOT Uplink Start Time: 268 XX:XX:XX End Time: 268 XX:XX:XX	MOT Uplink Start Time: 269 XX:XX:XX End Time: 269 XX:XX:XX	MOT Uplink Start Time: 270 XX:XX:XX End Time: 270 XX:XX:XX	MOT Uplink Start Time: 271 XX:XX:XX End Time: 271 XX:XX:XX		
Orbital Events							
Solar Encounter							
Solar Conjunction							
TCM			TCM 3 269 xx:xx:xx Burn Type				
Venus Flyby				Venus Flyby 1 Closest Approach: 270 XX:XX:XX			
Eclipse				Eclipse Entry: 270 xx:xx:xx Eclipse Exit: 270 xx:xx:xx			

APL

Orbital Operations Template

(Daily View)

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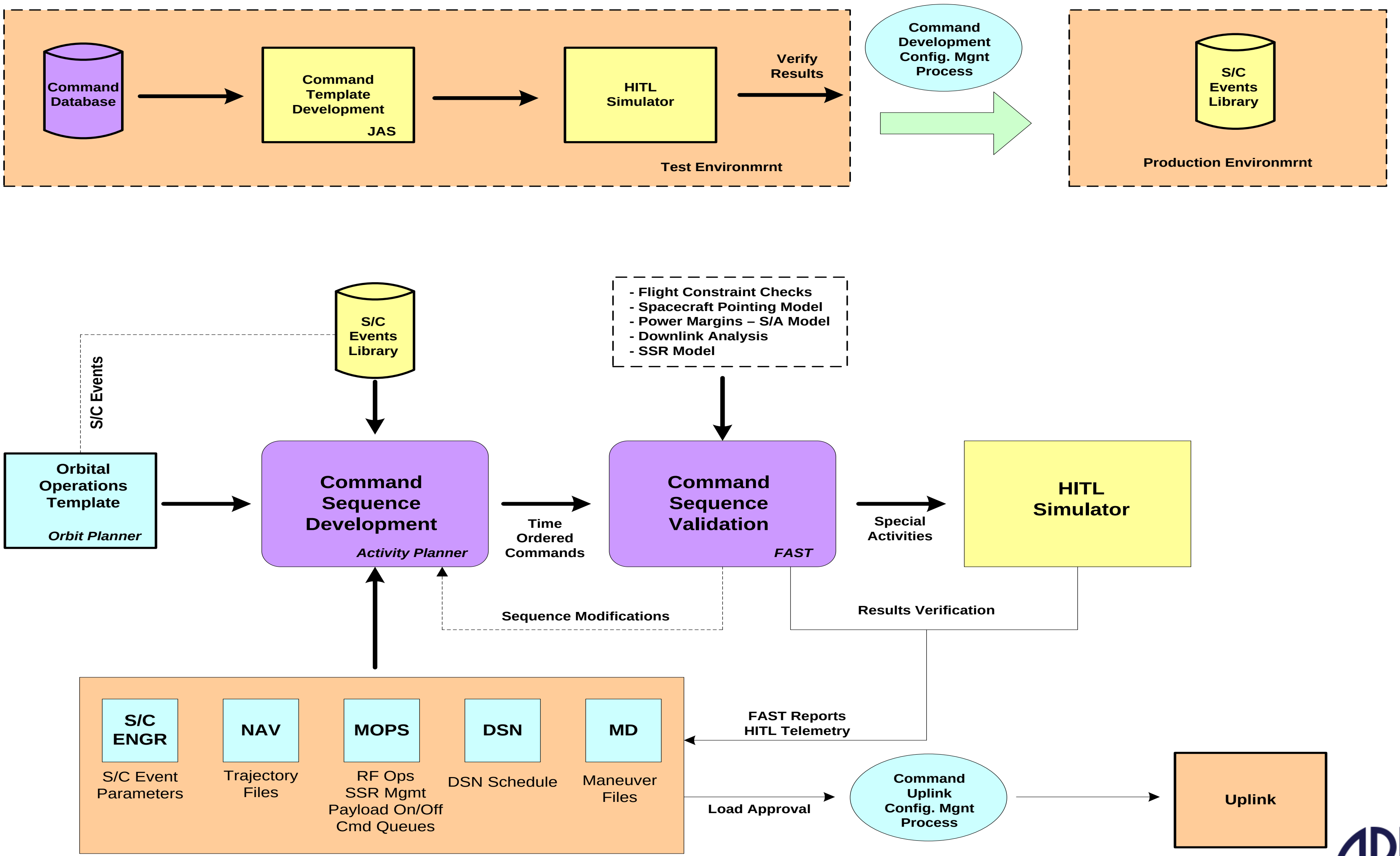
Orbit Day	XXX																							
DOY, UTC	YYY																							
Hour, UTC	0:00	1:00	2:00	3:00	4:00	5:00	6:00	7:00	8:00	9:00	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00	18:00	19:00	20:00	21:00	22:00	23:00
Activity																								
S/C Phase	Cruise																							
Command Load	18YYZ																							
S/C Activities																								
G&C				CMD	PNTG OPT								DNLINK										PNTG OPT	
RF													Ka				X-band					X-band		
Power								SA Cal					PWR Dwn					PWR Up						
Thermal																								
CDH													Daily Files											
Prop				CMD																				
Payload Activities																								
Instrument On Times																								
FIELDS						On - Data Transfer						Off								On				
SWEAP	On - Data Transfer											Off								On				
WISPR								On - Data Transfer				Off								On				
ISIS										On - Data Transfer		Off								On				
DSN Schedule																								
DSN Station													DSN XX				DSN XX					DSN XX		
Ka-Band													DSN XX											
X-Band																	DSN XX					DDOR		
Instrument Uplink Window																								
Science Downlink																								
MOT Uplink Window																								
Orbital Events																								
Solar Encounter																								
Solar Conjunction																								
Venus Flyby																								
TCM																								
Eclipse																								

Activity start/stop times are not necessarily representative of actual activity start/stop times

Command Sequence Development & Validation



Command Sequence Development & Validation

Commanding & Sequence Validation

- Majority of spacecraft bus activities executed from onboard command sequences
  - Command sequence durations may vary
  - All command sequences are validated on faster than real-time software simulator (FAST)
    - Automatic flight constraint checking is performed
- All non-routine activities tested on HITL simulator, at a minimum:
  - TCMs
  - Spacecraft Attitude Changes
  - Software & Autonomy Loads (3 Processors)
  - Non- Routine sub-system Activities
  - Recovery procedures
  - Onboard Memory Updates (3 Processors)
- Real-Time commanding utilized when necessary
  - Command Sequence Uplink
  - Interactive sub-system or instrument checkout
  - Software/Autonomy/Memory Uploads
  - Recovery procedures

Mission Operations
PRE-LAUNCH TESTING

Mission Operations Pre-Launch Testing

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Test Type	Date	Test Description
Mission Ops Testing 1	**Dec 2016**	Test Data Flow between spacecraft, MOC, testbeds Routine Commanding & Telemetry processing
Mission Simulation Data Flow Test	**Dec 2016**	Test Data Flow between spacecraft, MOC, testbeds Routine Commanding & Telemetry processing
Mission Simulation 1	**Jan 2017**	Launch, Separation, First Contact Activities G&C Commissioning, Early TCMs Routine Mission Operations Activities
DSN Compatibility Testing	**Feb 2017**	Test commanding & telemetry interfaces via the DSN compatibility test trailer(CTT), RF sub-system testing
Mission Ops Testing 2	**Feb 2017**	Spacecraft Subsystem Routine Activities Mission Operations Routine Activities
Mission Ops Testing 3	**May 2017**	Spacecraft Subsystem Routine Activities Mission Operations Routine Activities
Mission Simulation 2	**May 2017**	Instrument Commissioning Activities S/C Subsystem (Non-G&C) Commissioning Activities Data Product Verification

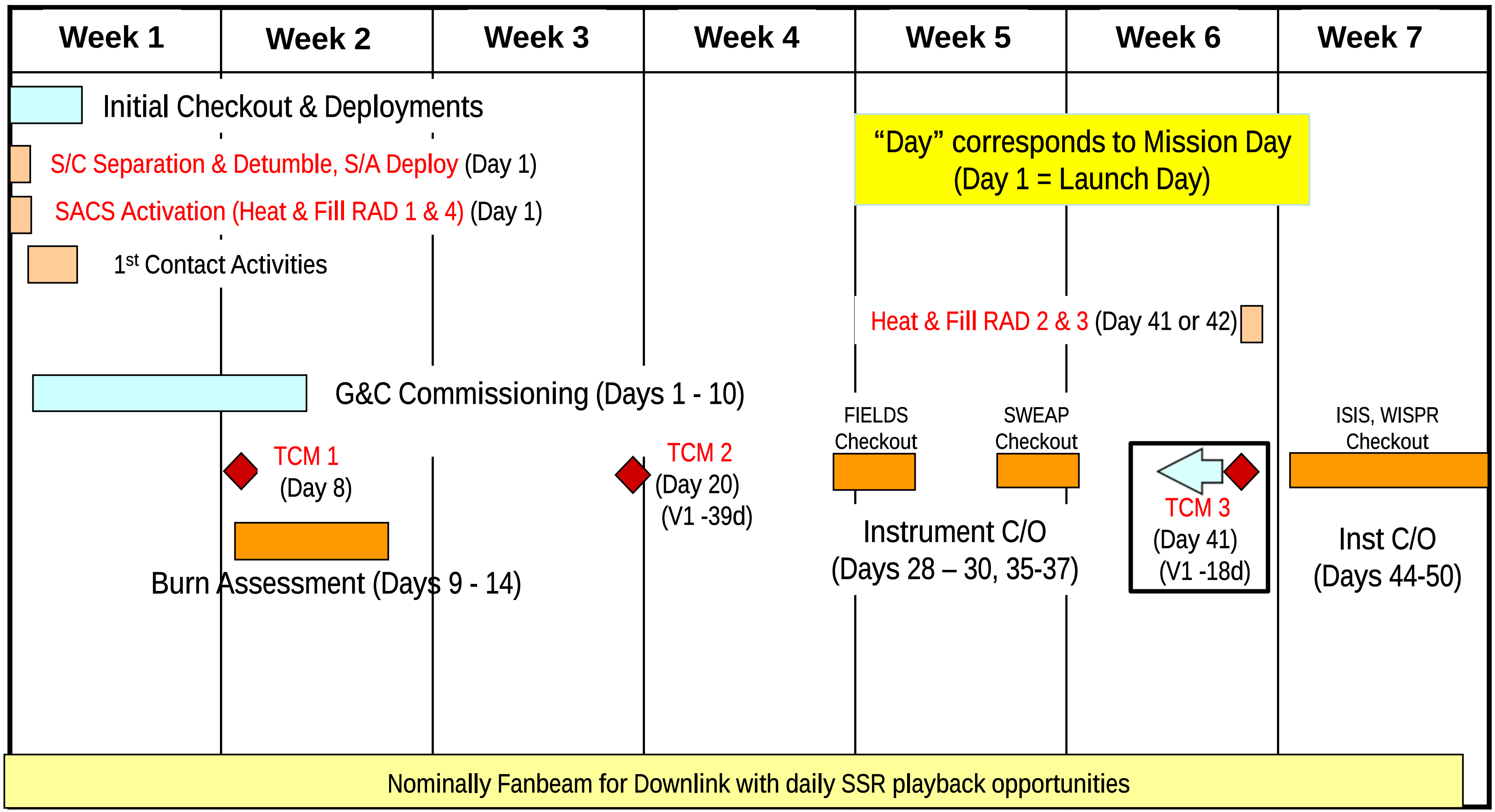
Mission Operations Pre-Launch Testing

Test Type	Start Date	Test Description
Mission Ops Testing 4	**Fall 2017**	Solar Encounter Preparations & Operations Science Downlink Operations Contingency Operations
Mission Simulation 3	**Jan 2018**	Multi-Day Operations Flow Test Orbit Planning Process, Command Sequence Execution Data Product Verification
Mission Simulation 4	**Apr 2018**	Launch, Separation, First Contact Activities G&C Commissioning, Early TCMs Contingency Operations
Launch Rehearsals	**May –Jul 2018**	Pre-launch countdown activities and spacecraft launch configuration script testing, Pre-launch contingencies

Mission Operations

EARLY OPERATIONS TIMELINE

Early Operations Timeline



LGA for Critical Activities (Red)

Early Operations Timeline

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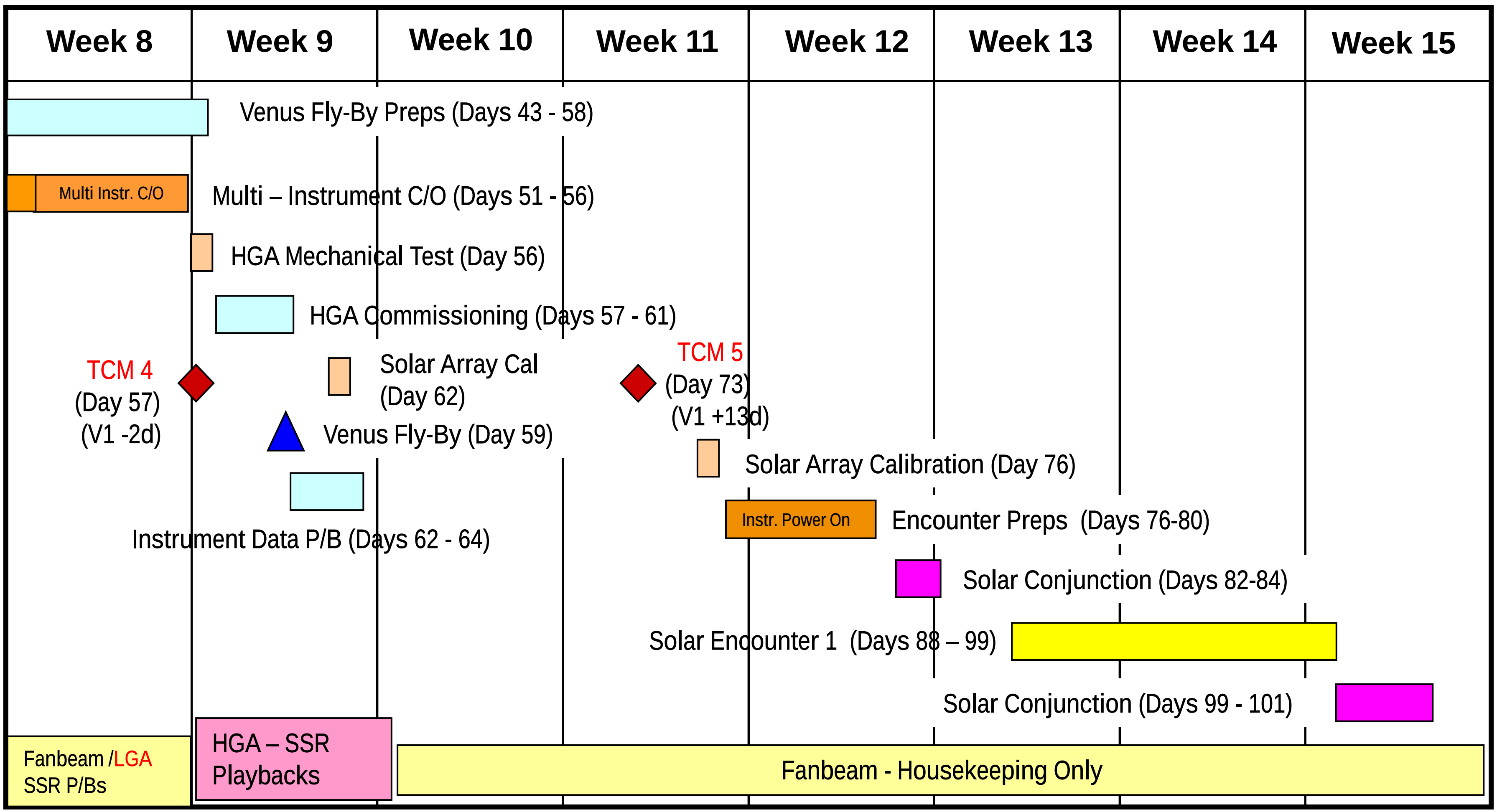

LGA for Critical Activities (Red)

Instrument Commissioning DL Data Rates

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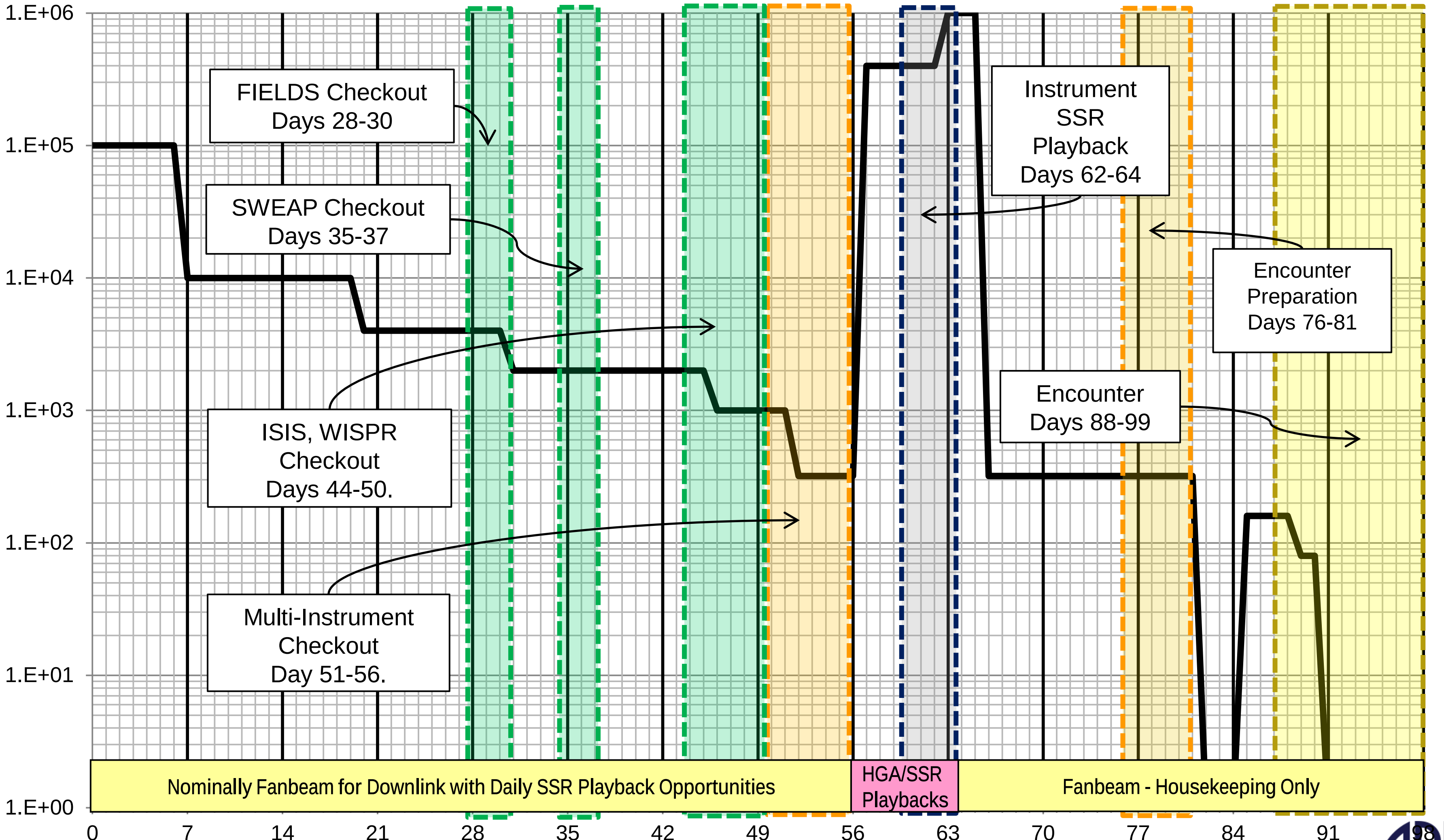

Mission Operations

DSN SUPPORT PROFILE

DSN Support Profile (All 34m Support)

Mission Phase	Contact Frequency	Duration
Launch & Initial C/O Spacecraft	Continuous 16 hrs/day	1 week 1 week
Early Commissioning	5 x 10 hr (per week)	4 weeks
Cruise Operations	3 x 8 hr (per week)	Weekly
Science Downlink	10 hr/day	Entire science downlink period (Varies each orbit leg, ~ 4 - 21 days)
Solar Encounter Phase	3 x 4 hr (per week)	Entire solar encounter period (~ 2 weeks)
Venus Fly-Bys	5 x 10 hr (per week) 10 hr/day	V-5 to V-1 weeks V-1 to V+1 weeks

DSN Support Profile (Early Operations)

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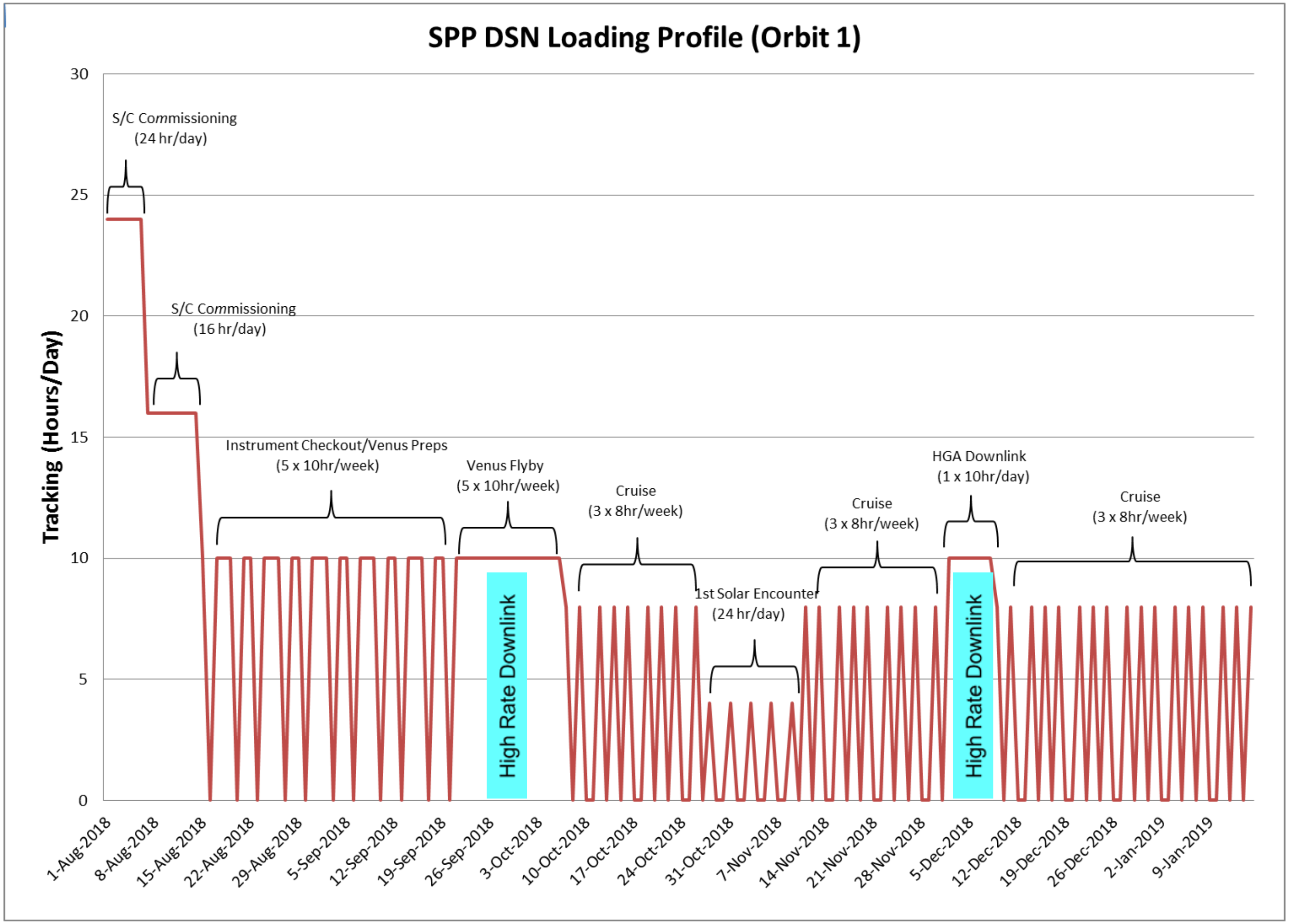

Mission Operations

DEVELOPMENT PLAN

Mission Operations Development Plan (Phase B/C)

Solar Probe Plus

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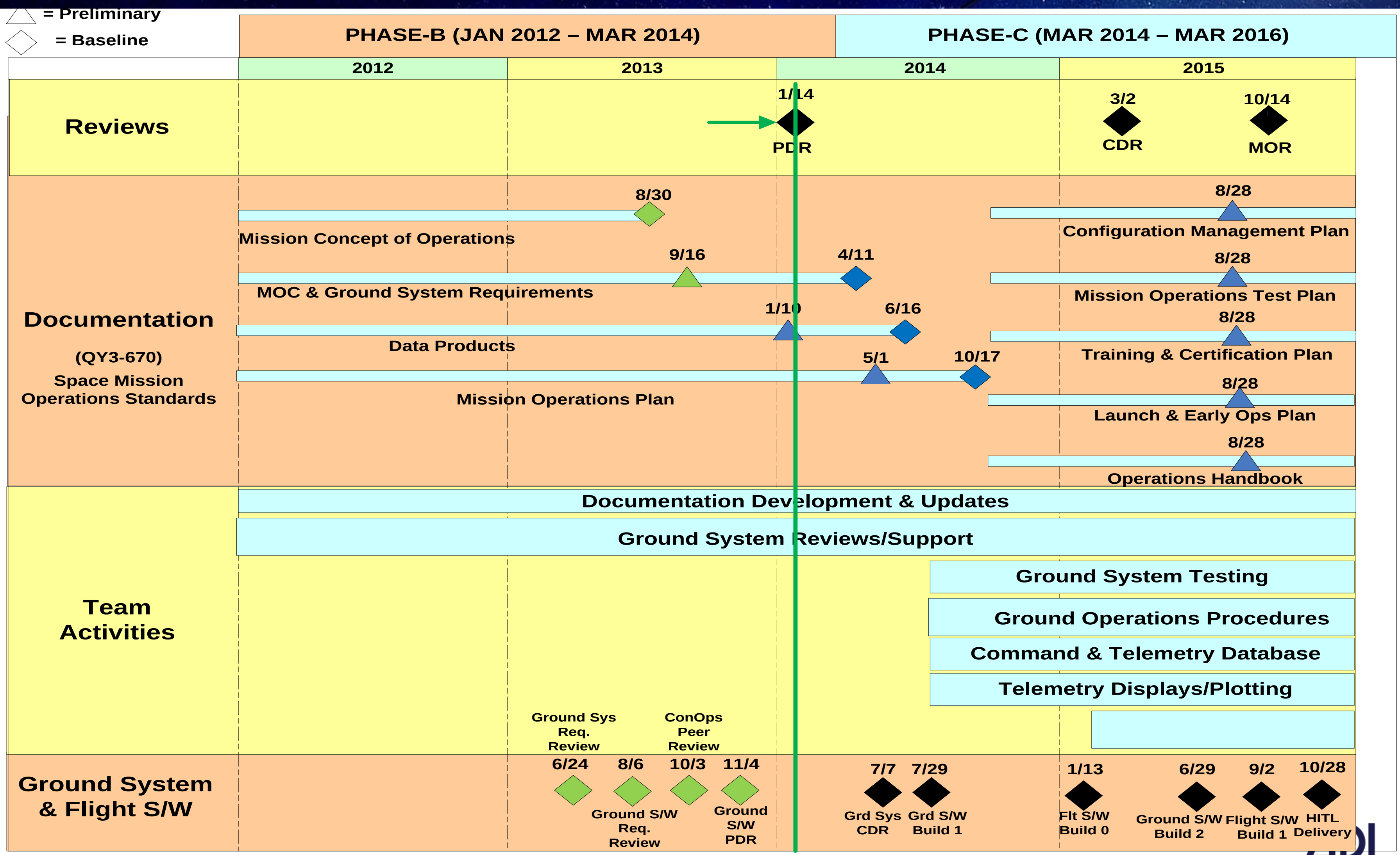

Mission Operations Development Plan (Phase D)

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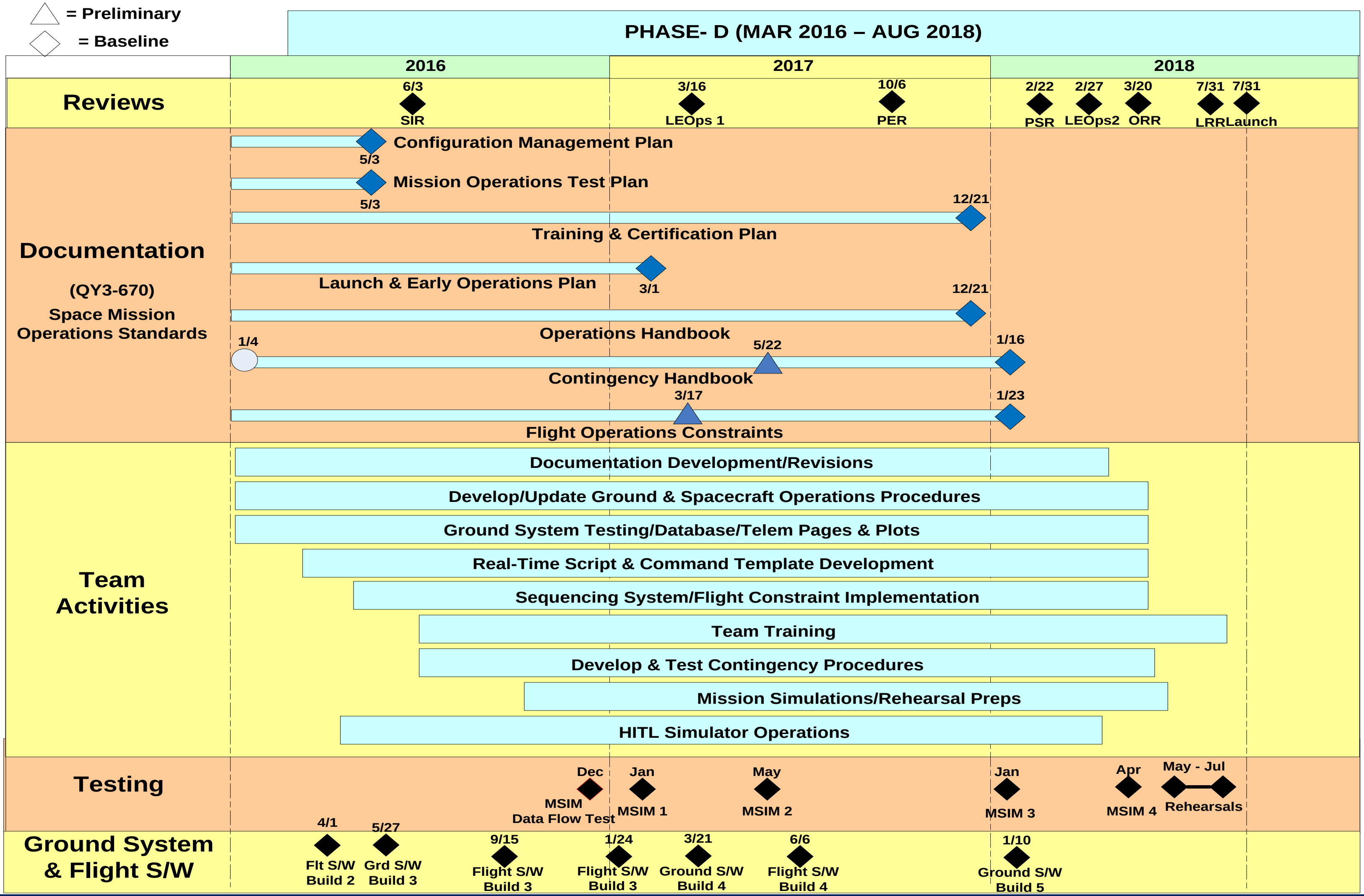


Mission Operations Key Deliverables

- Documentation
  - 7434-9016 Concept of Operations Document
  - 7434-9162 Ground System Requirements Document
  - 7434-9163 Mission Operations Center (MOC) Data Products Document
  - 7434-9164 Mission Operations Plan
  - 7434-9165 Mission Operations Flight Constraints and Requirements (FC&R) Handbook
  - 7434-9166 Mission Operations Configuration Management Plan
  - 7434-9167 Mission Operations Training and Certification (T&C) Plan
  - 7434-9168 Mission Operations Standard Operations Handbook
  - 7434-9169 Mission Operations Contingency Operations Handbook
  - 7434-9170 Mission Operations Launch and Early Operations (LEOPS) Plan
  - 7434-9171 Mission Operations Test Plan

Conclusion

- **Key ground system & mission operations requirements defined**
  - **Level 3 Ground System & MOC Requirements Document released**

- **Spacecraft and Instrument Concept of Operations has been defined**
  - **Mission Concept of Operations Document released**
  - **Mission Operations Plan under development**

- **Mission Operations Interfaces & Data Products are defined**
  - **Further refinement during Phase-C**

- **Mission Operations Development & Testing schedule defined**

- **Mission Operations is ready to proceed to Phase C.**

Backup

TCM Implementation

Baseline TCM Schedule (2013 RefTraj) (1/2)

Maneuver	Date	Placement wrt/ Vn	Placement wrt/ Sn-1	Placement wrt/ Sn	Earth Range [AU]	Sun Range [AU]	SEP [deg]
TCM-01	08/07/2018	V1-51d		S01-85d	0.05	1.02	92.62
TCM-02	08/19/2018	V1-39d		S01-73d	0.14	1.00	81.34
TCM-03	09/09/2018	V1-18d		S01-52d	0.27	0.90	59.69
TCM-04	09/25/2018	V1-2d		S01-36d	0.36	0.76	39.31
TCM-05	10/11/2018	V1+13d		S01-20d	0.48	0.55	15.50
TCM-06	12/05/2018	V2-381d	S01+34d	S02-115d	1.63	0.73	15.97
TCM-07	05/12/2019	V2-223d	S02+42d	S03-107d	1.01	0.81	47.10
TCM-08	10/10/2019	V2-72d	S03+43d	S04-106d	1.15	0.82	44.15
TCM-09	12/03/2019	V2-18d	S03+97d	S04-52d	1.40	0.88	38.38
TCM-10	12/18/2019	V2-3d	S03+112d	S04-37d	1.35	0.76	33.55
TCM-11	01/05/2020	V2+14d	S03+130d	S04-19d	1.19	0.54	26.38
TCM-12	03/09/2020	V3-118d	S04+44d	S05-84d	1.72	0.82	15.96
TCM-13	06/18/2020	V3-17d	S05+16d	S06-96d	0.56	0.48	12.65
TCM-14	07/03/2020	V3-2d	S05+31d	S06-81d	0.44	0.70	34.41
TCM-15	08/11/2020	V3+36d	S05+70d	S06-42d	0.28	0.78	29.01
TCM-16	12/23/2020	V4-54d	S06+91d	S07-20d	1.26	0.57	26.03
TCM-17	01/26/2021	V4-20d	S07+13d	S08-88d	1.40	0.45	7.83
TCM-18	02/14/2021	V4-1d	S07+32d	S08-69d	1.67	0.72	9.24
TCM-19	03/02/2021	V4+14d	S07+48d	S08-53d	1.72	0.78	12.28
TCM-20	05/10/2021	V5-154d	S08+15d	S09-86d	0.85	0.50	29.95
TCM-21	08/20/2021	V5-52d	S09+15d	S10-88d	0.71	0.50	27.03

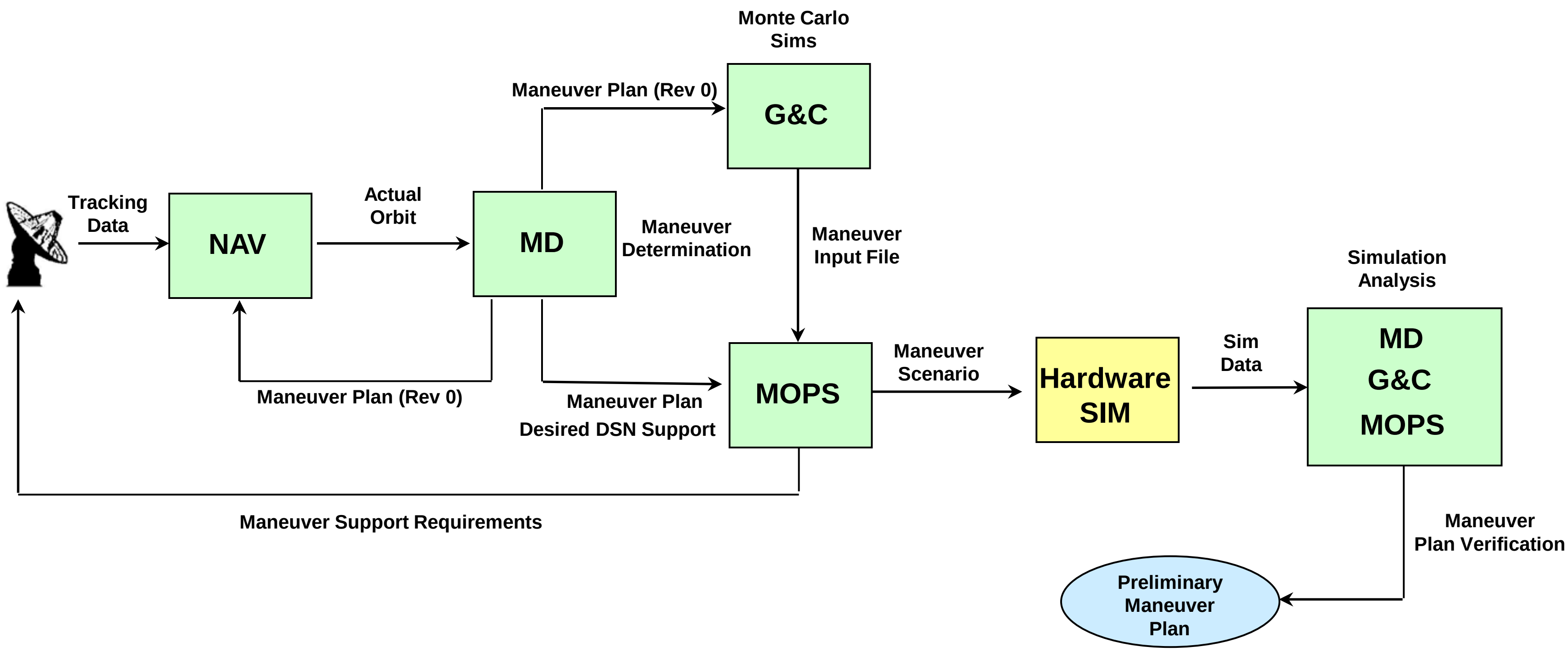
TCM Planning General Schedule (1 of 2)

- **Baseline TCM schedule released to project prior to launch**
  - **Ensure the TCM schedule being integrated into the mission operations activity schedule**
- **TCM Request, T–4 weeks (TBR)**
  - **MD and Nav will determine a TCM is needed based on current OD solution and trajectory re-optimization**
  - **A TCM will be requested, along with the TCM execution date, at least 4 weeks before the TCM execution time**
  - **MOps will confirm the DSN tracks needed for supporting the TCM**
- **Preliminary TCM Plan, T- 2 weeks**
  - **Preliminary TCM planning will start 2 weeks before the TCM execution time**
  - **It will include TCM design, implementation, and ground tests including HITL simulator**
  - **A preliminary TCM plan will be produced and verified**

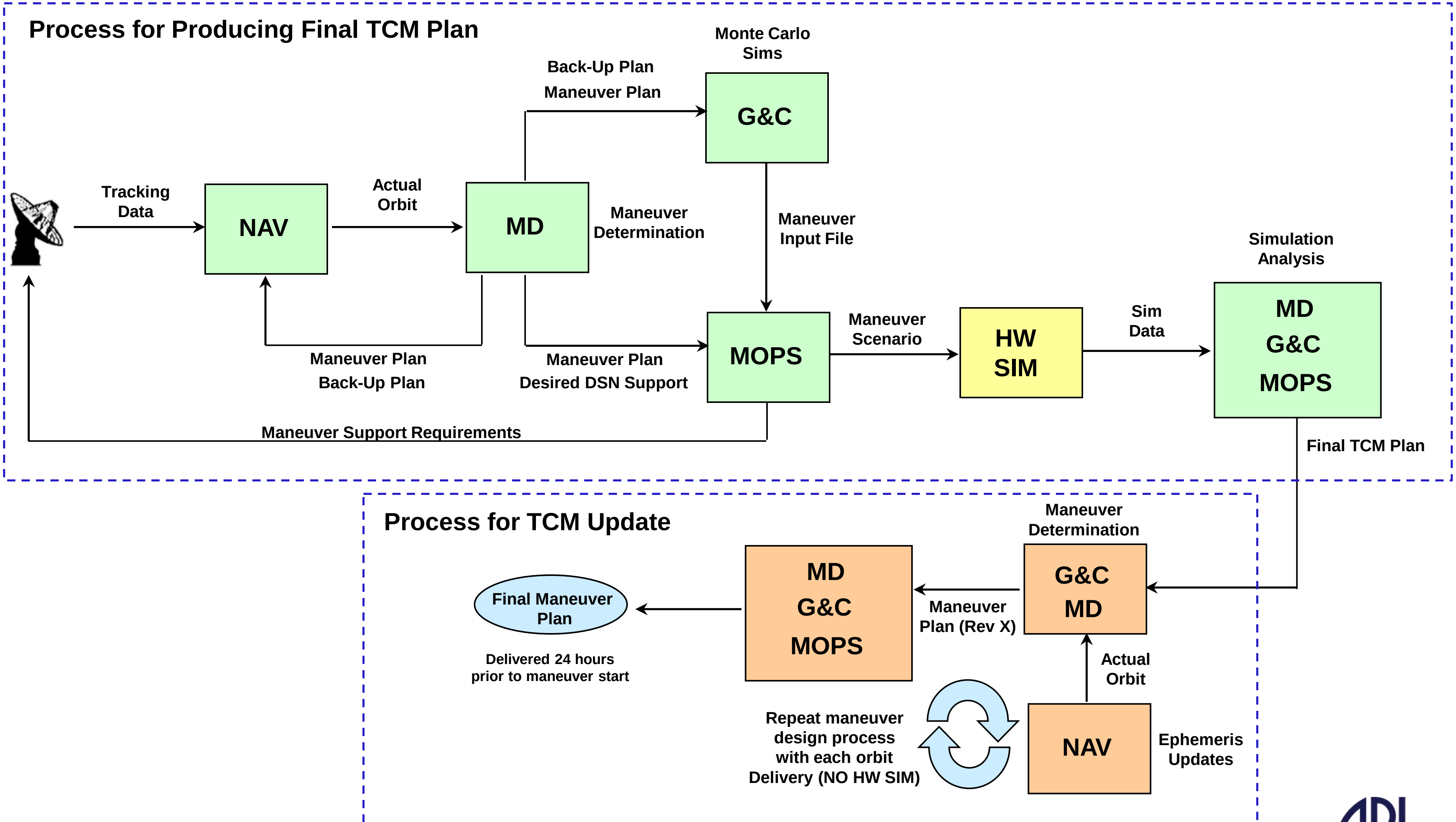
TCM Planning General Schedule (2 of 2)

- **Final TCM Plan, T-1 week**
  - **MD and Nav will re-compute the TCM based on the latest OD solution and trajectory re-optimization**
  - **The TCM values may not be the same as computed a week ago, and the TCM values will be updated, new ground tests may or may not be required depending on the changes**
- **Final TCM Update, T-1 day (TBR)**
  - **The majority of the TCMs are not expected to require this update**
  - **TCM Update may be needed for special situations, for example, the last TCM prior to a Venus flyby**
  - **This update is limited to a few TCM parameters (TBD)**
  - **Hardware SIM (HW SIM) is not included for TCM Update**
- **The TCM planning for TCM-1**
  - **will be different and on a more compressed schedule**
  - **Process will be similar to the T-1 week final TCM planning**
  - **Details to be worked out**

TCM Planning: T-2 Weeks
Preliminary TCM Plan



Final TCM Planning: Final TCM Plan (T-1 Week) and TCM Update



Ground System Requirements

- Ground System (Level 3) requirements review held on 6/24 & 6/25

- SPP Ground System is comprised of Ground Hardware, Ground Software and **Mission Operations** facilities & personnel to support the following high level functional areas:

  - Commanding
  - Telemetry Processing
  - Data Storage & Retrieval
  - Mission Planning

  Assessment
  Simulation & Validation
  Integration & Test

  - Heritage – Van Allen Ground System Requirements
  - SPP Mission Requirements Document – Level 2
  - SPP Spacecraft Requirements Document – Level 3
  - SPP Concept of Operations Document
  - Team Experience

- Mission Design and Navigation Requirements captured in a separate Level 3 document

Mission Operations Planning & Scheduling Requirements

- **The Mission Operations Team shall:**
  - **Support orbit activity planning**
      - **Generate Orbital Operations Templates (OOTs)**
  - **Schedule and Implement spacecraft activities:**
    - **Activities include but are not limited to the following:**
      - **Ephemeris Loads, Flight S/W Loads, Autonomy Loads**
      - **S/C Pointing Changes, Instrument Power On/Off, TCMs**
      - **RF Configuration Changes, SSR Playbacks**
      - **Non-Autonomous Momentum Dumps**
      - **Onboard Memory Object Maintenance**
      - **Routine H/K activities**
      - **Instrument data transfer requests**
  - **Perform Command Sequence Creation, Validation & Testing**
  - **Support Trajectory Correction Maneuver (TCM) planning**
  - **Perform Solid State Recorder Management**
  - **Support DSN Contact Scheduling for all activities**

Mission Operations
Real-Time Operations Requirements

- **The Mission Operations Team shall:**
  - **Perform real-time commanding of the spacecraft bus (not the instruments)**
  - **Perform real-time monitoring of telemetry and DSN monitor data**
  - **Perform DSN interfacing during real-time contacts**
  - **Perform command sequence uploads**
  - **Perform software image uploads**
  - **Perform autonomy object uploads**
  - **Perform spacecraft ephemeris uploads**
  - **Perform spacecraft recovery procedures (as necessary)**
  - **Develop and test real-time command scripts**
  - **Assuming staffed contacts for real-time operations**

Mission Operations Assessment Requirements

- **The Mission Operations Team shall:**
  - **Perform early detection of anomalous spacecraft behavior**
  - **Perform routine short-term analysis of sub-system telemetry**
  - **Perform long-term trending of critical parameters**
  - **Provide anomaly investigation & resolution**
  - **Side Note – Spacecraft & Instrument long-term health & performance monitoring supported by the spacecraft and instrument engineers throughout the mission**
  - **Side Note 2 – Sustained spacecraft & instrument engineering teams support anomaly resolution and recovery procedures**

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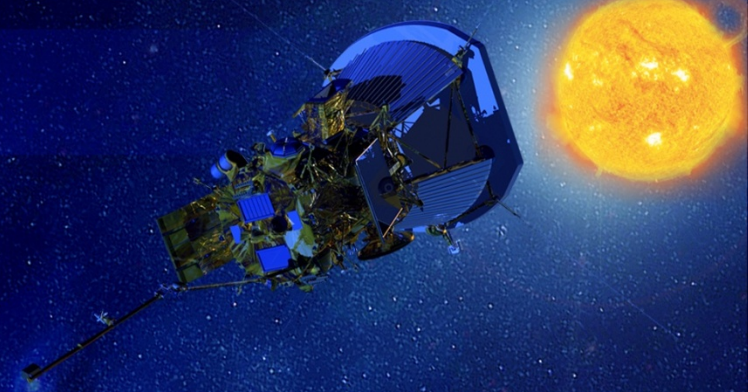

Navigation

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13 – 16 January 2014

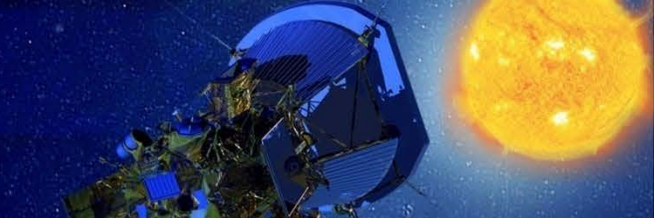
Acknowledgement to
Jessica Williams, Paul Thompson, and Eunice Lau

APL
The Johns Hopkins University
APPLIED PHYSICS LABORATORY

Overview

- **MDNAV Requirements Review held August 6, 2013**
- **MDNAV Peer Review held November 15, 2013**
- **Requirements**
- **NAV analysis of the 2018 Baseline (Launch July 31)**
  - **Orbit Determination**
    - **Prediction, Reconstruction**
    - **Challenges: tracking and prediction of**
      - **Momentum Dumps**
      - **Solar Radiation Pressure**
  - **Flight-Path Control**
    - **ΔV99**
    - **TCM placement studies, $P_{I/F}$, ΔV implementation penalty**
- **Files & Interfaces**
- **Phase C Plans**

Current Requirements



- **as listed in *7434-9061 Solar Probe Plus Level 3 Mission Design & Navigation Requirements Document***

Ref	Requirement	Verify
MDNR-24	Spacecraft Ephemeris Knowledge Inside Science Phase Navigation shall provide a reconstructed spacecraft ephemeris with uncertainty in spacecraft position relative to the center of the Sun that is no greater than 1200km (TBR) (3-sigma) in any direction when solar distance is less than or equal to 0.25 AU.	Ana., Met
MDNR-25	Predicted Spacecraft Ephemeris Inside Science Phase Navigation shall provide a predicted spacecraft ephemeris with an uncertainty in spacecraft position relative to the center of the Sun that is no greater than 1200 km (3-sigma) in any direction for the time spans that spacecraft solar distance is less than or equal to 0.25 AU. This ephemeris will be delivered to the spacecraft team no later than 48 hours prior to the track start time of the final uplink and verification opportunity before the spacecraft solar distance drops below 0.25 AU.	Ana., Met

Pending Revisions

Ref	Requirement	Verify
MDNR-26	Predicted Spacecraft Ephemeris Outside Science Phase Excluding Venus Flybys Navigation shall provide a predicted spacecraft ephemeris with uncertainty in spacecraft position relative to the center of the Sun that is no greater than 8500 km (3-sigma) in any direction when solar distance is greater than 0.25 AU at times that are greater than 5 days from Venus closest approach for any of the Venus flybys.	Ana., Met
MDNR-74	Predicted Spacecraft Ephemeris Outside Science Phase Around Venus Flybys Navigation shall provide a predicted spacecraft ephemeris that constrains errors in knowledge of the direction of Earth center relative to the spacecraft to no more than 4 arcmin (3-sigma) (TBR) at times that are less than or equal to 5 days from Venus closest approach for any of the Venus flybys.	Ana., In-work

Current Requirements

Ref	Requirement	Verify
MDNR-27	Spacecraft Heliocentric Velocity Uncertainty Navigation shall provide each predicted spacecraft ephemeris with uncertainty in the spacecraft velocity relative to the center of the Sun that is no greater than 0.1 km/s (3-sigma) in any direction.	Ana., Met
MDNR-73	DSN Predicts Accuracy Navigation shall provide the predicted ephemeris of the Flight System to the DSN that maintains a 1-sigma accuracy of 1.0 m/s (TBR) for Doppler, 0.1 sec (TBR) for range, and an angular accuracy of 0.004 degrees (TBR).	Ana., In-work

Current Requirements

Ref	Requirement	Verify
MDNR-22	Statistical Delta-V Navigation shall determine the post-launch statistical delta-V required, to 99% confidence, to not exceed 170 m/s (TBR).	Ana., Met
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

Current Requirements

Ref	Requirement	Verify
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

Tracking Data

1. **Tracking Schedule used for NAV analysis**
   - **Launch and Early Operations:**
     - **L to L+1 week: continuous**
     - **L+1 to L+2 weeks: 16 hours per day**
     - **L+2 to L+4 weeks: five 10-hour passes per week**
   - **At Each Venus Flyby**
     - **V-5 to V-1 week: five 10-hour passes per week**
     - **V-1 to V+1 week: one 10-hour passes per day**
   - **Other Times**
     - **3 passes per week**
   - **Delta-DOR measurements around Venus flybys**
     - **V-3 to V+2 week: 2 points per week**
     - **Other times: 1 point per week (TBR)**
     - **Future work: adjust Delta-DOR schedule to reflect loss of DSN capability below -25° declination (peer review AI)**
   - **Gaps…**

Tracking Data

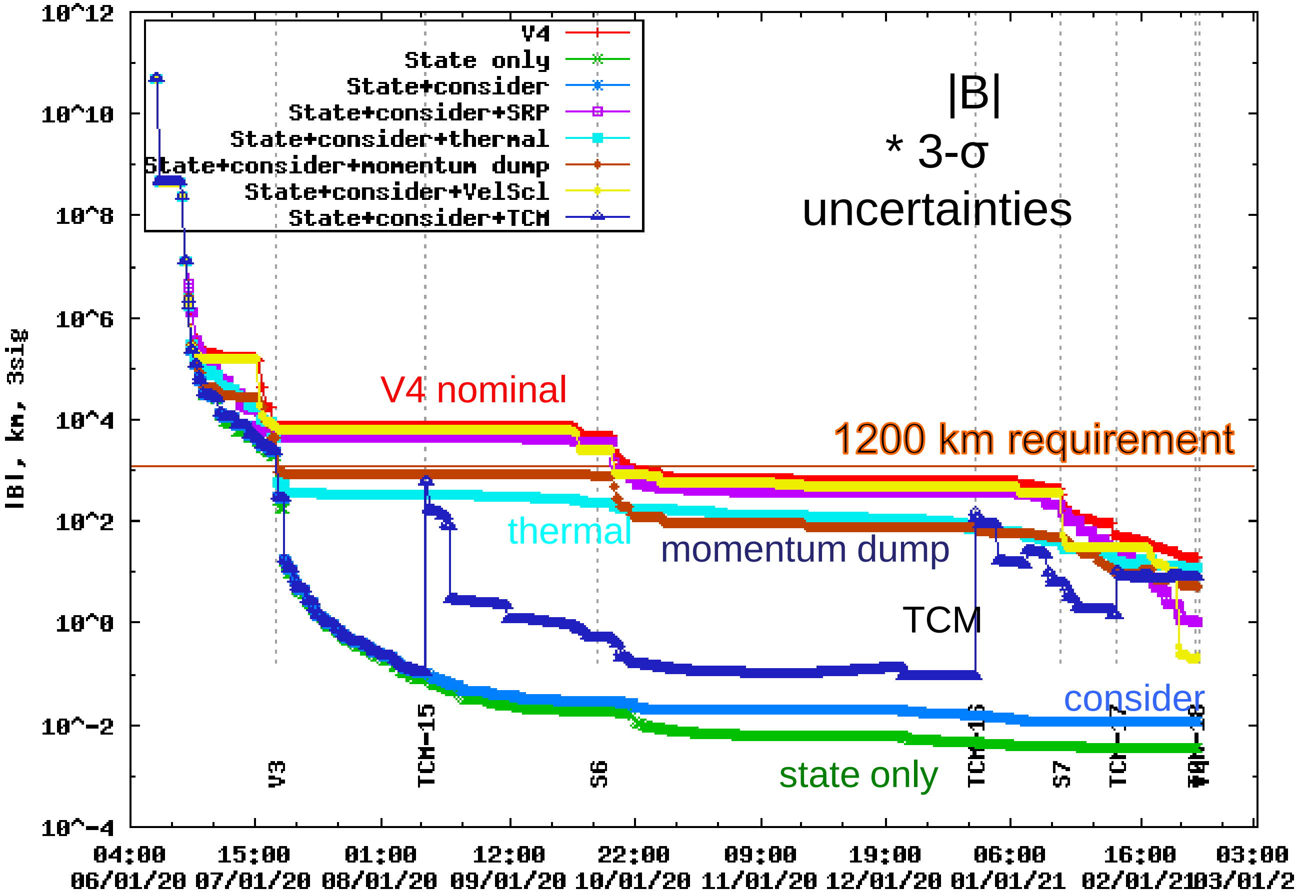
1. **Schedule Gaps**
   - **Tracking gaps due to low SEP angle, TPS blocking antenna, etc**
   - **Recovery of pre-V4 tracking gap for Doppler only (Phase B change)**
     - **31-Jan-2021 to 13-Feb-2022**
     - **Between TCM-17 and TCM-18**
   - **Ranging gaps (Phase B change)**
     - **Approximately 475 tracks of range removed and made into Doppler-only**
     - **This leaves 1113 Doppler tracks, 642 Range**
     - **Trade study showed acceptable performance**
2. **Weighting**
   - **Primary data types: 2-way coherent X-Band Doppler and range, and ∆DOR.**

Doppler	0.2 mm/s	1□
Range	10.0 m	1□
∆DOR	0.06 nsec	1□

   - **Solar Plasma Effects: low SEP**
     - **Historically, other missions frequently deleted all data below 5°-10° SEP. SPP can not afford to ignore that much tracking data.**
     - **In OD modeling, accounted for noise and some of the biased error via down weighting for smaller Sun-Earth-Probe (SEP) angles.**

OD Error Decomposition: Map V4 B-Plane

- **dump frequency (VelScl) and solar radiation pressure are the dominant error sources.**



Momentum Dumps: Filter Setup

- **Individual events placed at nominal frequency. Delta-V and errors in S/C frame. Significant deterministic component over time.**
  - **X: 10 mm/s +/- 3 mm/s (1σ)**
  - **Y: 0 mm/s +/- 0.5 mm/s (1σ)**
  - **Z: 13 mm/s +/- 2 mm/s (1σ)**
- **Generally, no dumps beyond 0.82 AU, up to 7 per day around 9.86 R_S**
- **Uncertainty in frequency of events accounted for with velocity scale factor (VelScl).**
  - **A priori uncertainty of 1.0. Freq. of 3-sigma case ~3 times nominal.**
  - **Stochastic batch of 10 days used to cover the time span roughly equivalent to how long a science phase lasts (inside 0.25 AU)**
  - **White noise – while an increase or decrease in frequency would be correlated by a common cause, our uncertainty in that frequency will be "reset" as communication and telemetry is re-established**

Solar Radiation Pressure

- **Dominant error source for predictions when range < 0.25 AU**
- **Single-sided plate, sun-pointed, representing the thermal protection shield along +Z axis**
  - **4.454 m^2**
  - **Converted APL-provided material properties into corresponding JPL definitions**
- **Estimate SRP scale factor as stochastic**
  - **3-day batch, 7-day time constant, 10% error**
  - **Numbers based on recent experience with Juno. SRP uncertainty was the dominant error source. Juno trajectory errors were highly sensitive to changes attitude, power utilization, solar range, etc.**
- **Future work: SRP as a function of solar range to account for solar panel flap angle variability, shadowing and more complicated thermal effects (in plan)**
- **Future Work: include a thermal balance in nominal modeling for axial force (peer review AI)**

Thermal forces

- **Additional non-radial error not accounted for any other models (e.g., SRP)**
  - **SRP model assumes sun-pointed and produces force in –Z direction of spacecraft frame (directly opposite of sun point)**
  - **Off sun-pointed attitude or attitude errors as a consequence of nominal deadbanding**
  - **Non-axisymmetric dumping of heat, e.g., by radiators**
- **Modeled as stochastic acceleration**
  - **12-hour batches, 7-day time constant**
  - ***A priori* error of 0.2 mm/sec/day, all three axes**

OD Delivery Schedule

- **116 ephemeris updates scheduled with following guidelines:**
  - **TCM final design DCOs**
  - **Immediately before and immediately after Venus flybys. On the order of a 2-5 days before and another one 2-5 after a Venus flyby**
  - **Immediately before entry and after exit of solar range < 0.25 AU**
  - **Maximum gap between DCOs of ~4 weeks**
  - **Schedule accounts for outages**

Predicted OD error: Position

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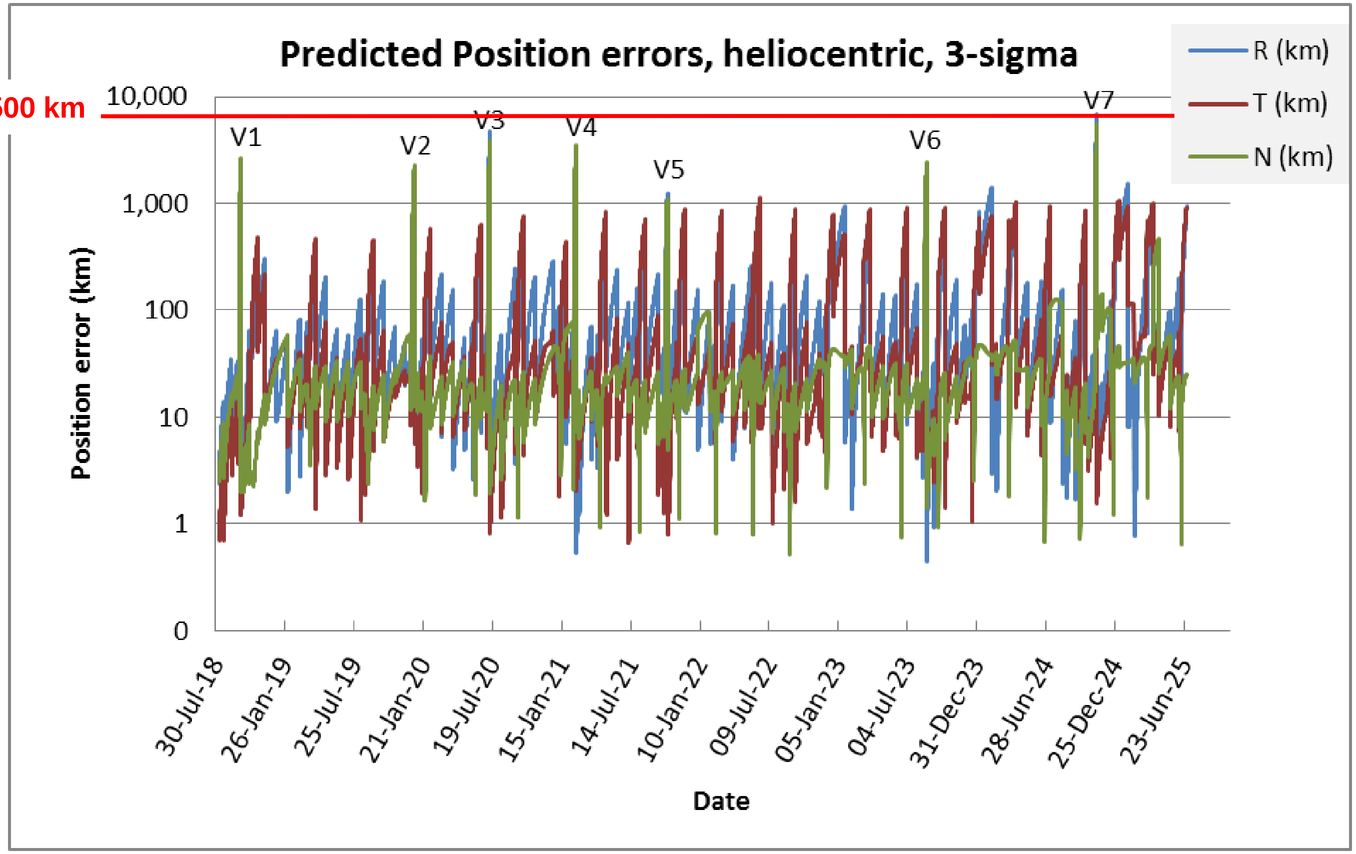
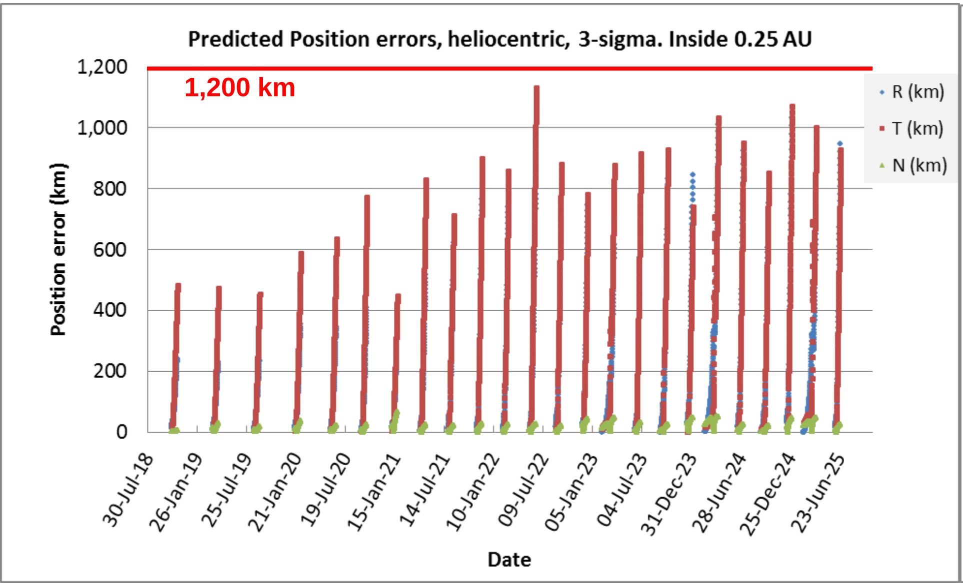


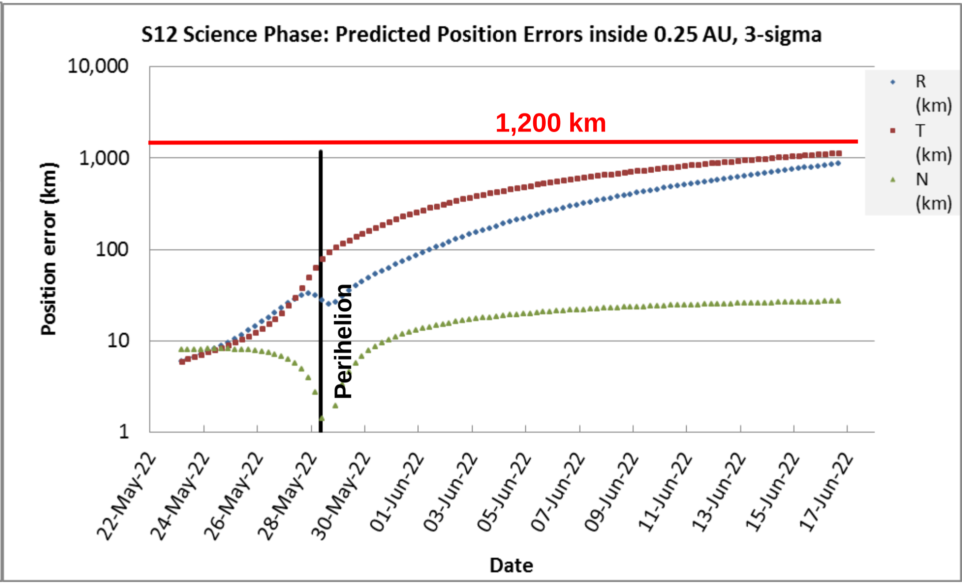
MDNR-26: Predicted heliocentric position errors no greater than 8500 km, 3-sigma in any direction for solar range > 0.25 AU and greater than 5 days from Venus encounter.

Predicted OD error: Inside 0.25 AU

All Periapse Passages: S1-S24



Example: Solar Periapse 12



MDNR-25: Predicted heliocentric position errors no greater than 1200 km, 3-sigma for solar ranges <= 0.25 AU.

Reconstruction OD Error: Current State

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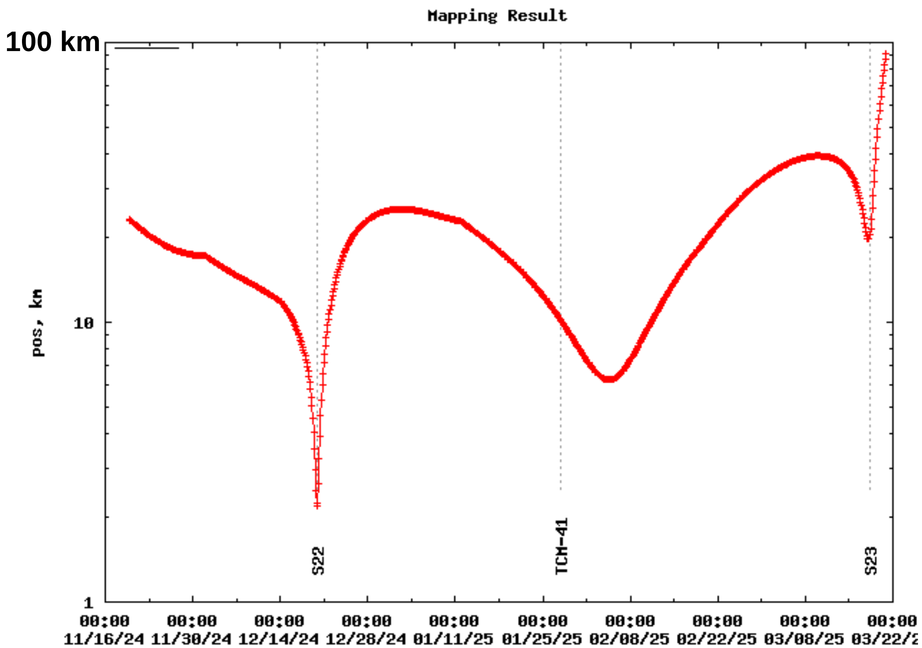
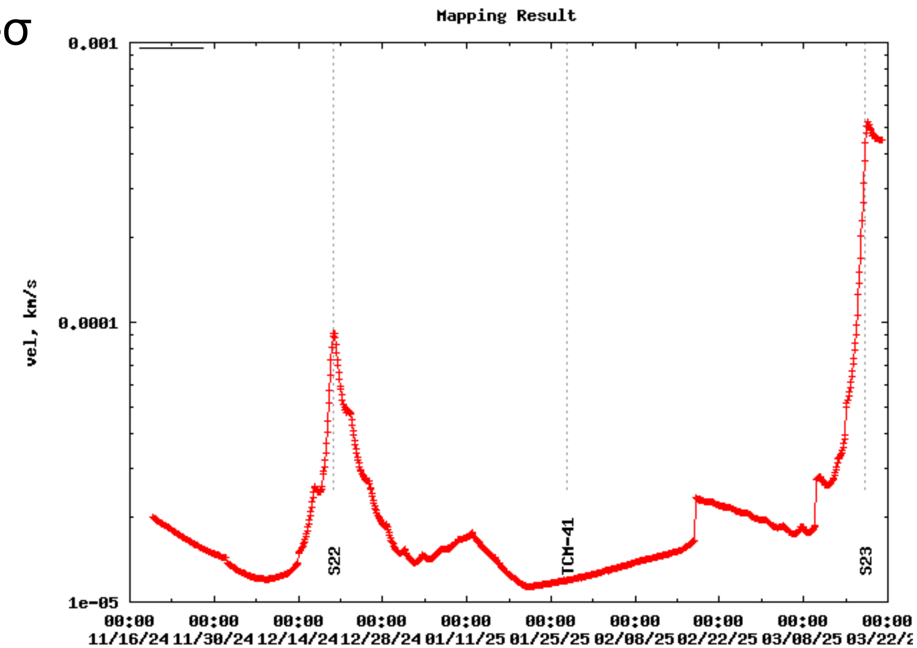


3-σ

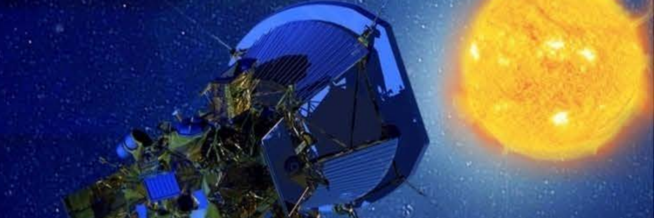


- **Statistics of S23 Arc as example**
  - **Includes 40-day gap**
  - **S22: 19-DEC-2024; S23: 18-MAR-2025**
  - **TCM-41 at 27-JAN-2025 18:00**
- **Requirement MDNR-24: Reconstructed spacecraft ephemeris with uncertainty in spacecraft position relative to the center of the Sun is no greater than 1200 km, 3-sig in any direction during the science phase for solar distance less than 0.25 AU**

TCM Assumptions

- Injection Covariance Matrix (ICM): Orbital 2nd ICM(Oct. 2013)
  - Rotated via flight path angle matching
- Maneuver schedule
  - Considered TCM capability using partial derivatives (CAPEL s/w)
  - SEP angle > 3°
  - Commandability of spacecraft prior to maneuver (ex: TCM-18)
  - Availability of tracking data pre- and post-maneuver
  - 5-day data-cutoff (DCO) prior to maneuver execution
  - 2 post-launch (cleanup) 2 pre-Venus, 1 post-Venus, 1 per solar orbit (42 TCMs)
- No minimum / maximum ΔV imposed
- Maneuver execution error model (Gates Model)
  - $\Delta V < 0.15$ m/sec:
    - Fixed magnitude error: 1 mm/sec (3σ)
    - Proportional pointing error: 0.02 rad (3σ)
  - $\Delta V > 0.15$ m/sec
    - Proportional magnitude error: 2% (3σ)
    - Proportional pointing error: 0.02 rad (3σ)
- Future Work:
  - ICM, execution-error model updates (in plan)
  - TCM cancellations, TCM back-up opportunities (in plan)

TCM Assumptions



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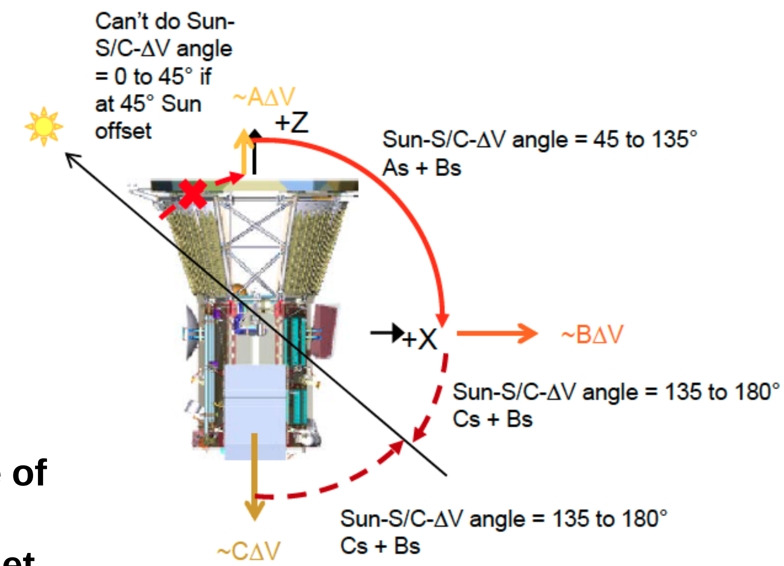
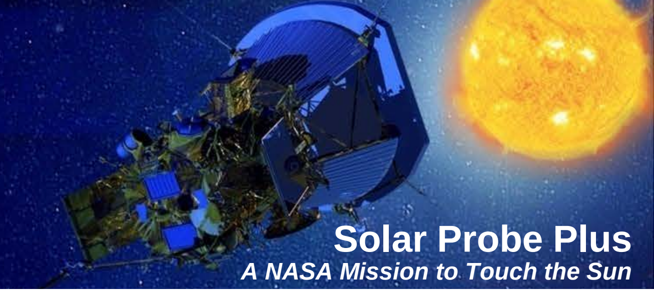
- Maneuver Requirements imposed:
  - Minimum distance = 0.3 AU (MDNR-70)
  - TCMs > 20 hours apart if duration > 7200 seconds (MNDR-71, MDNR-72)
  - ΔV angle > 45° for maneuvers ≥ 0.82 AU (MNDR-69)
    - implement with a cone angle constraint, or
    - move, for distance < 0.82 AU
    - TCM-9 (V2-18d, 3-Dec-2019) performed in two burns to satisfy pointing constraint
- Maneuver Targeting
  - Optimization chains within each Venus leg
  - Last & penultimate TCMs target final Venus aimpoint
    - Increases chance of cancelling last TCM
    - Decreases chance of needing a maneuver in case of safing
  - Future Work: investigate reoptimization of Venus-1 target (peer review)
- Statistical maneuver analysis performed using Monte LAMBIC software

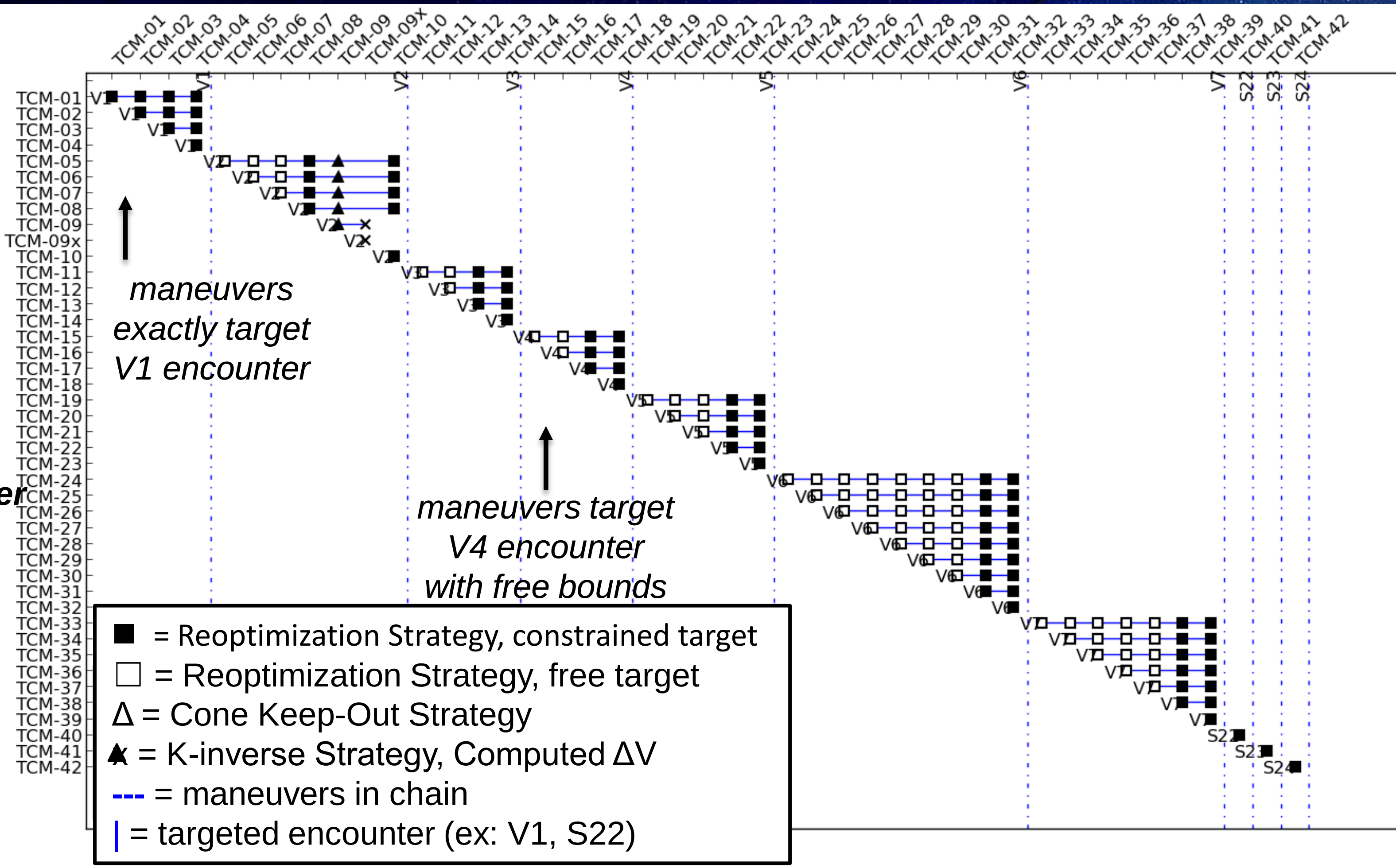


APL

Targeting Strategy



***y-axis*: maneuver**



***x-axis*: downstream maneuver(s) used in "chain" in Lambic optimization strategy**

Lambic Results: ΔV99

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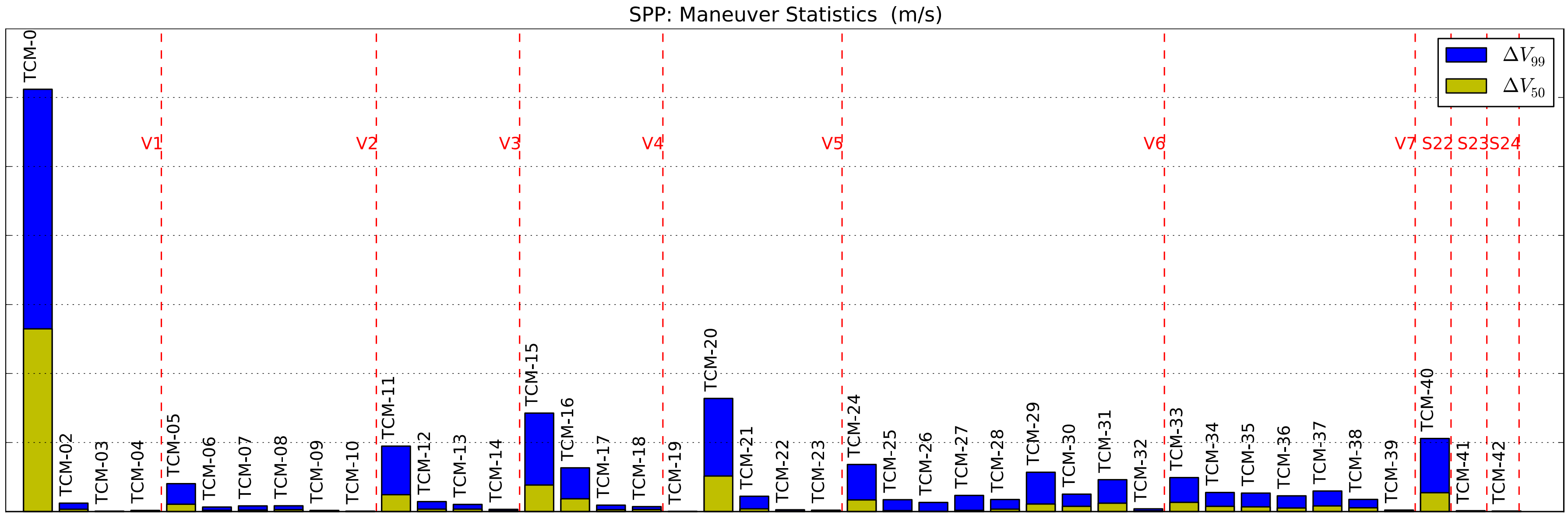
Lambic statistical ΔV results, using Orbital ICM (Oct 2013) and Phase B Baseline OD assumptions, is 121.6 m/s.



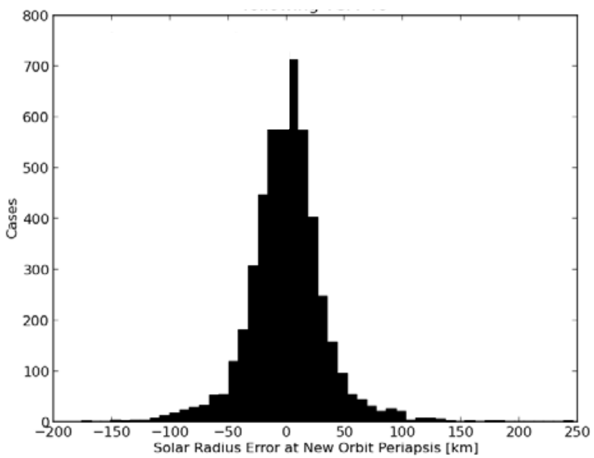
MNDR-22 Requirement	Lambic Result
ΔV 99% < 170 m/s	121.6 m/s

Lambic Results: Solar Distance

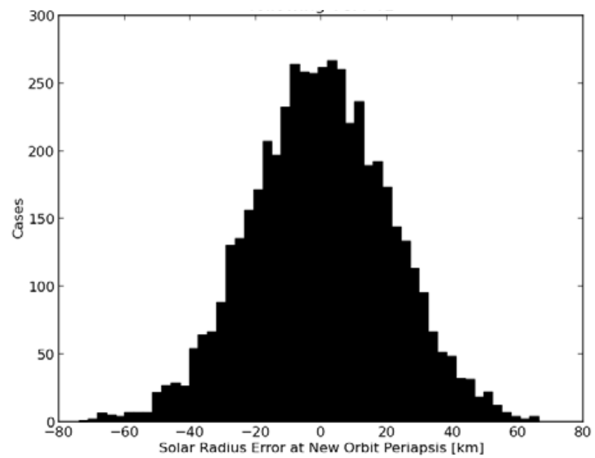
Maneuver	Date	Target	99% ΔV [m/s]
TCM-40	11/20/2024	S22 (Periapsis)	10.6
TCM-41	01/27/2025	S23 (Periapsis)	0.1
TCM-42	04/16/2025	S24 (Periapsis)	0.1

Periapsis Range Error [km], 1%ile	Periapsis Range Error, [km], 99%ile
-98 km	102 km
-50 km	50 km
-43 km	41 km

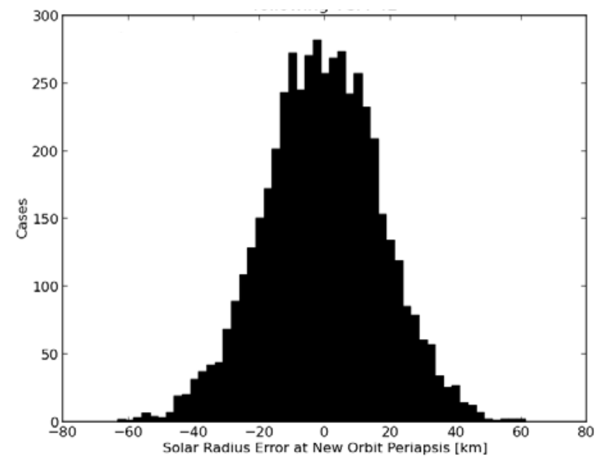
Error in Solar Radius (S22 Periapsis) following TCM-40 Nominal Distance = 9.86 Rs



Error in Solar Radius (S23 Periapsis) following TCM-41 Nominal Distance = 9.86 Rs



Error in Solar Radius (S24 Periapsis) following TCM-42 Nominal Distance = 9.86 Rs



Files & Interfaces

Interface Configuration Item	Description	Data Flow
MOCNAV-ICI- 101	Operations SCLK Kernel	MOC > NAV
MOCNAV-ICI- 201	Spacecraft Reconstructed Ephemeris	NAV > MOC
MOCNAV-ICI- 203	Spacecraft Attitude Predicts	MOC > NAV
MOCNAV-ICI- 204	Thruster Firing History	MOC > NAV
MOCNAV-ICI- 205	Spacecraft Attitude History	MOC > NAV
MOCNAV-ICI- 206	Navigation Tracking Requests	NAV > MOC
MOCNAV-ICI- 207	Spacecraft Predicted Ephemeris	NAV > MOC

File interfaces for the maneuver-design process will be determined in Phase C

Phase C Tasks

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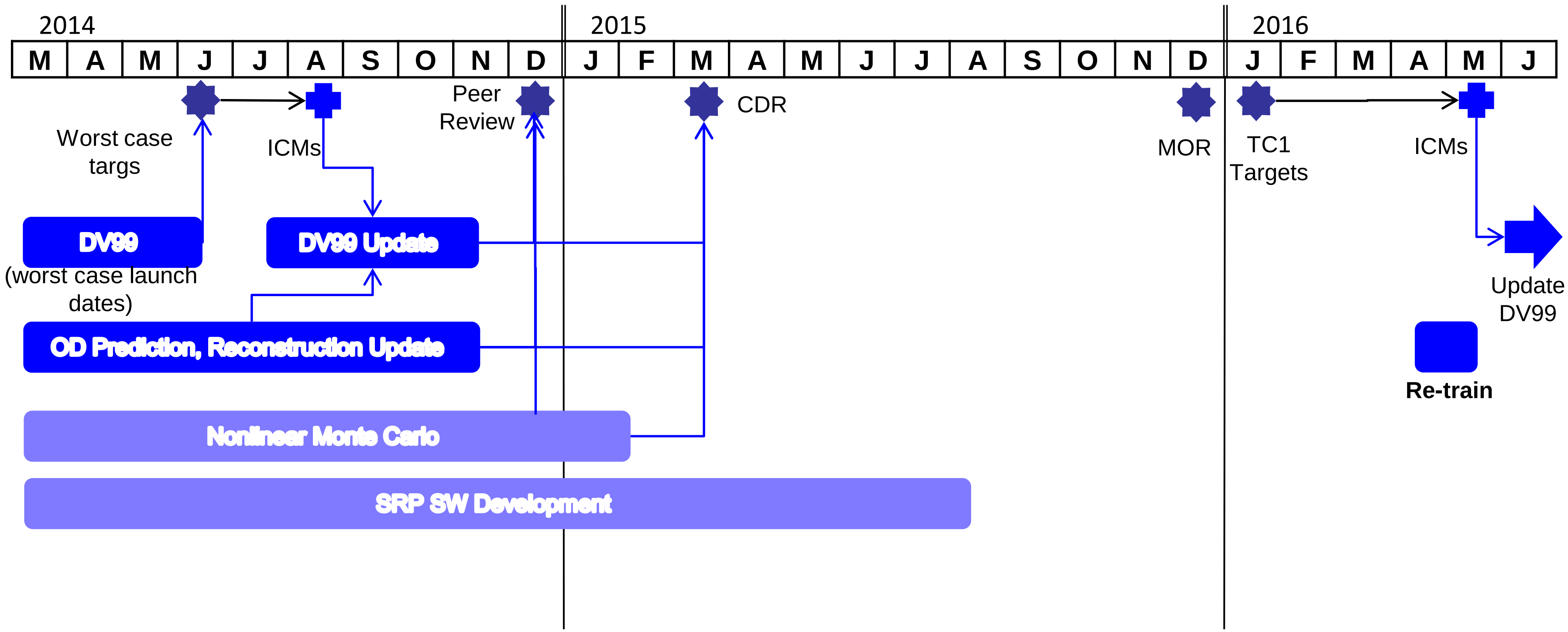

The project is working to assess staff levels for Navigation, phases C, D, & E

Summary

- **NAV analysis uses the latest baseline**
- **Key requirements are met**
- **Work identified for Phase C and beyond**
- **NAV is ready for Phase C**

Navigation Backup Slides

Reference Trajectory

- **June 2013 RefTraj: SPP20180731P2_ephem.xsp**
- **Only spacecraft portion used by NAV.**
- **Used in conjunction with planetary ephemeris DE424**
- **Differences from mission design vs. NAV reference trajectory**
  - **Lower fidelity solar radiation (SRP) model**
  - **Includes nominal delta-V of momentum dumps**
- **Match maneuvers introduced to reduce differences in position.**

Data Weighting vs SEP angle

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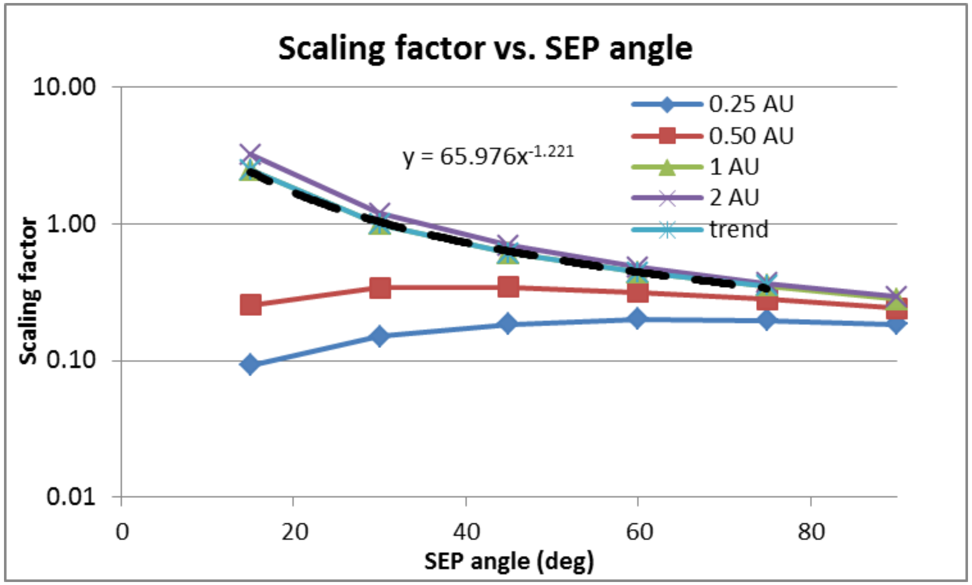
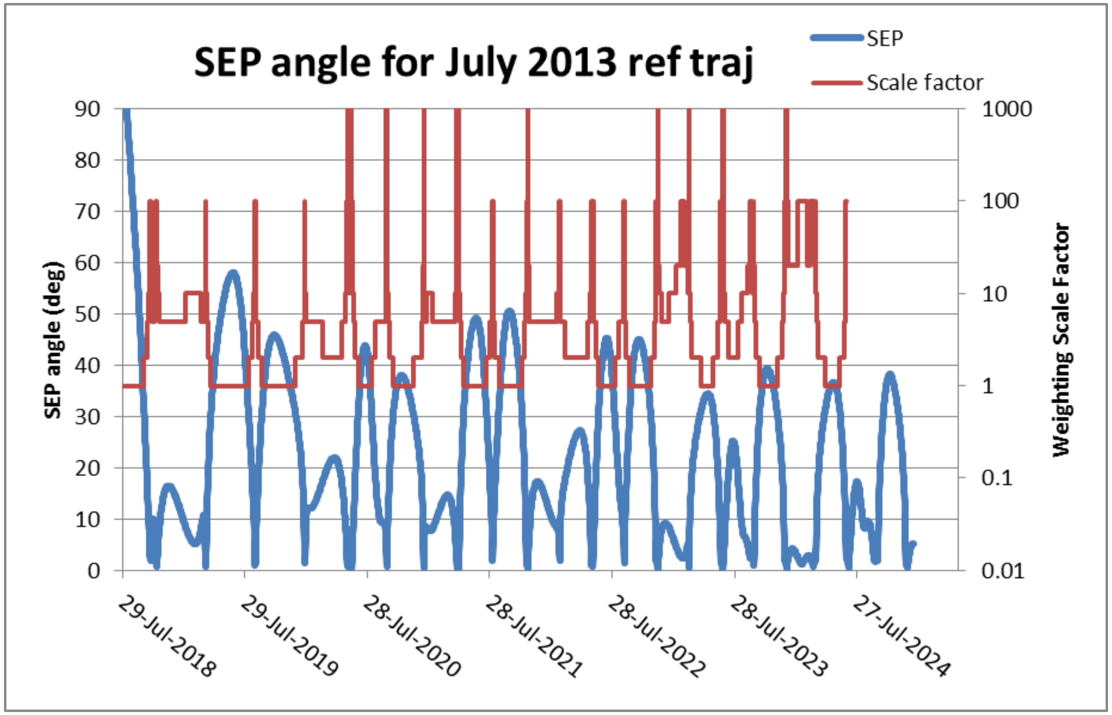
Combination of sources* provided weights as function of Earth range and SEP angle



- **Ranges experienced by SPP will tend to be 1-2 AU.**
- **Developed power law as function of SEP angle for those ranges**
- **Note that extrapolation is required for SEP angles lower than approx. 15 deg**

* e.g., Anderson, J.D., et al. "Study of the anomalous acceleration of Pioneer 10 and 11", Phys. Rev D, 65, 2002.

Weights vs SEP



	SEP angle (deg)	
Scale factor	from	to
1	--	> 31
2	31	17
5	17	8.3
10	8.3	4.7
20	4.7	2.8
100	2.8	0.7
1000	0.7	0

Implemented as discretized scale factor levels applied to nominal weight (multiplication factor for nominal sigmas) for Doppler and range. In most cases, for very low SEP angles there were other conditions that resulted in a data gap, e.g., TPS blockage.

Momentum Dumps

- **Momentum dumps will largely be autonomous**
  - **Around 0.25 AU time periods (science phase) there will be little to no communication. No ability to monitor wheel rates, update ephemeris, or command momentum dumps. Time between momentum dumps can be as little as a couple of hours.**
  - **Away from sun, there will be the ability to monitor, plan, and in some cases be proactive in placing momentum dumps in less painful areas, e.g., away from Venus encounters. The time between momentum dumps in these regions can be many days to weeks.**
- **Frequency of momentum dumps based on Phase B kickoff (Jan 2013)**
  - **October 2012 G&C analysis by Robin Vaughn, *Inputs to SPP Phase-B Navigation Study*, 8 Jan 2013**
  - **Current baseline trajectory (June 2013) has a higher periapse: lower frequency**
  - **Results given for nominal and 3-sigma cases: 260 and 670 total, respectively**
  - **Updated Monte Carlo analysis for current reference trajectory and design TBD**
- **Magnitudes and errors per momentum dump based on updated Phase B thruster configuration model (July 2013)**
  - **Presentation: Robin Vaughn, *SPP Momentum Dump Residual DV Update*, 5 July 2013**
  - **Based on updated spacecraft thruster configuration and usage**
  - **Variations for full, medium, and near empty fuel tank**
  - **Introduces net delta-V in specific direction over time**

Momentum Dumps: Nominal Frequency

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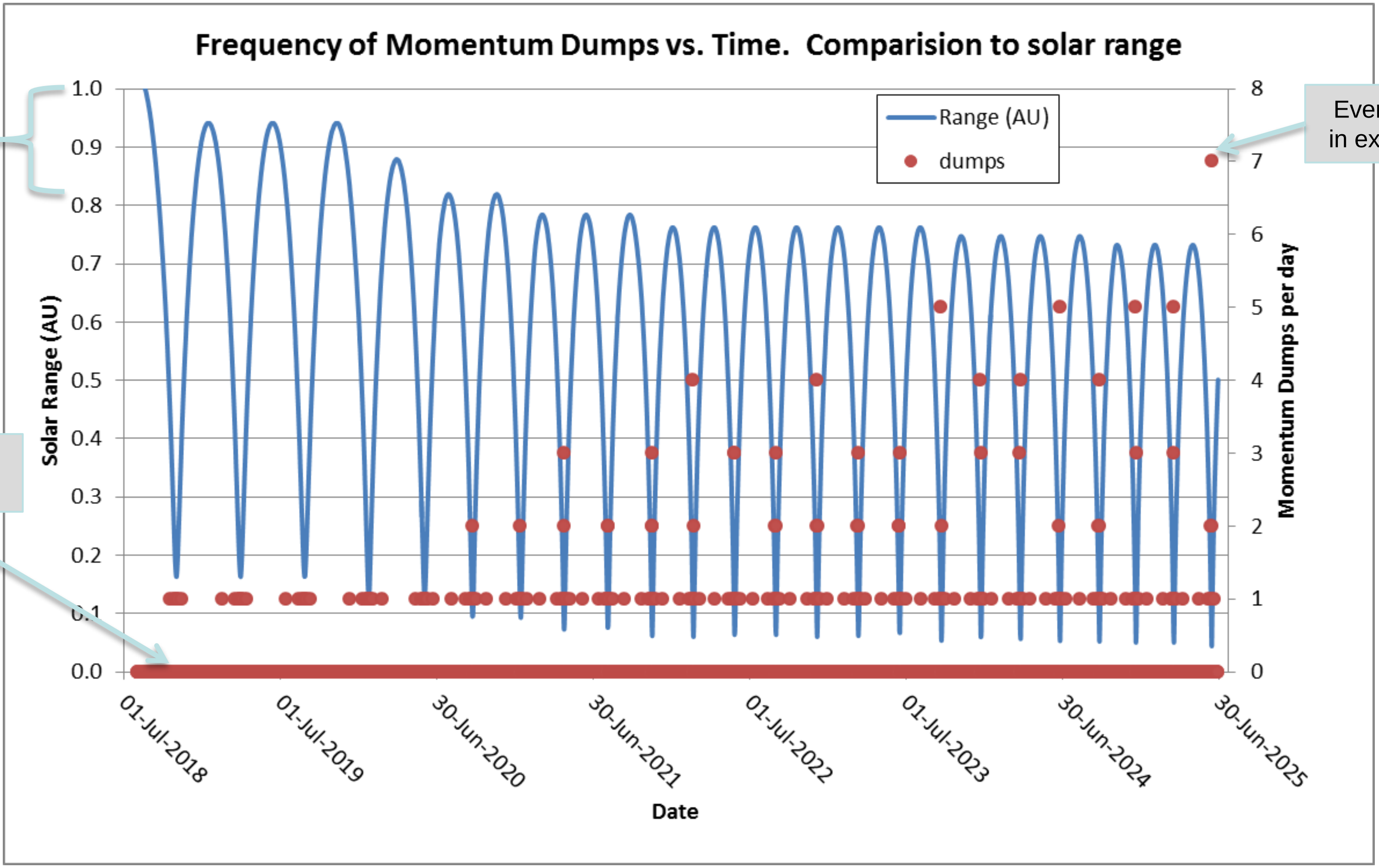
None > 0.82 AU

Every few hours in extreme cases

Days to weeks far from sun



Predicted OD error: Velocity

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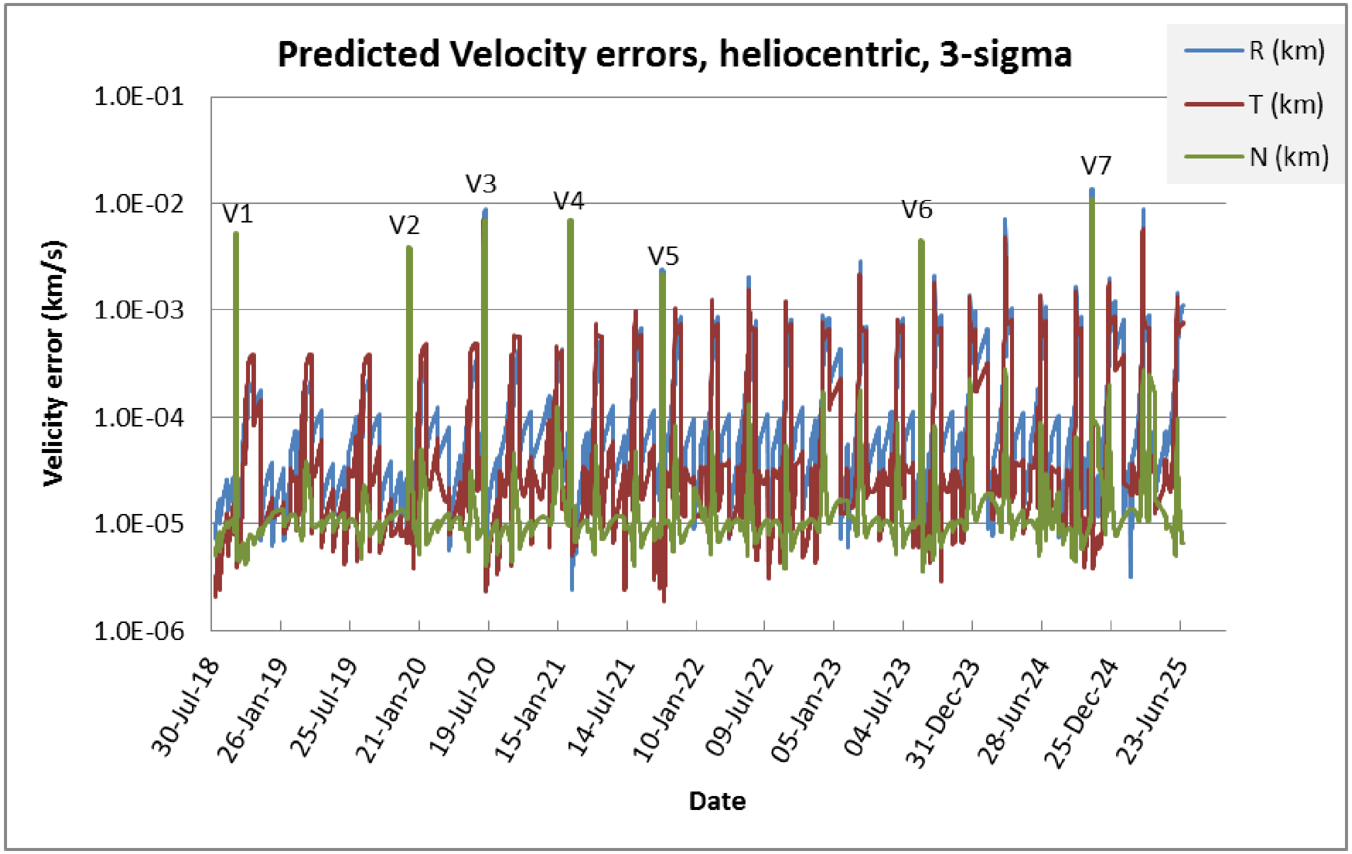

MDNR-27: Predicted heliocentric velocity of 0.1 km/s, 3-sigma in any direction.

Results: Predicted OD errors

- **Requirements met:**
  - **MDNR-25: Predicted heliocentric position errors no greater than 1200 km, 3-sigma for solar ranges <= 0.25 AU.**
  - **MDNR-26 (proposed): Predicted heliocentric position errors no greater than 8500 km, 3-sigma in any direction for solar range > 0.25 AU and greater than 5 days from Venus encounter.**
  - **MDNR-27: Predicted heliocentric velocity of 0.1 km/s, 3-sigma in any direction.**
  - **Additionally, predicted heliocentric position errors around Venus flybys are < 10,000 km.**

Ranging Trade Study

- **Study was performed on Phase A trajectory with Phase A assumption**
  - **Ranging contacts were reduced from 1113 contacts to 642 contacts**
  - **Degraded ranging at 10m accuracy**
- **The combination of reduced ranging and degraded ranging had little impact on the navigation performance**
- **There is sufficient link margin to meet current requirements with our navigation baseline assumptions.**
- **Documented study in memorandum dated 26-August-2013**
- **Subsequent Phase B analysis adopted these criteria with reduced ranging schedule and degraded ranging.**

OD Error Decomposition: Map V4 Time of Flight

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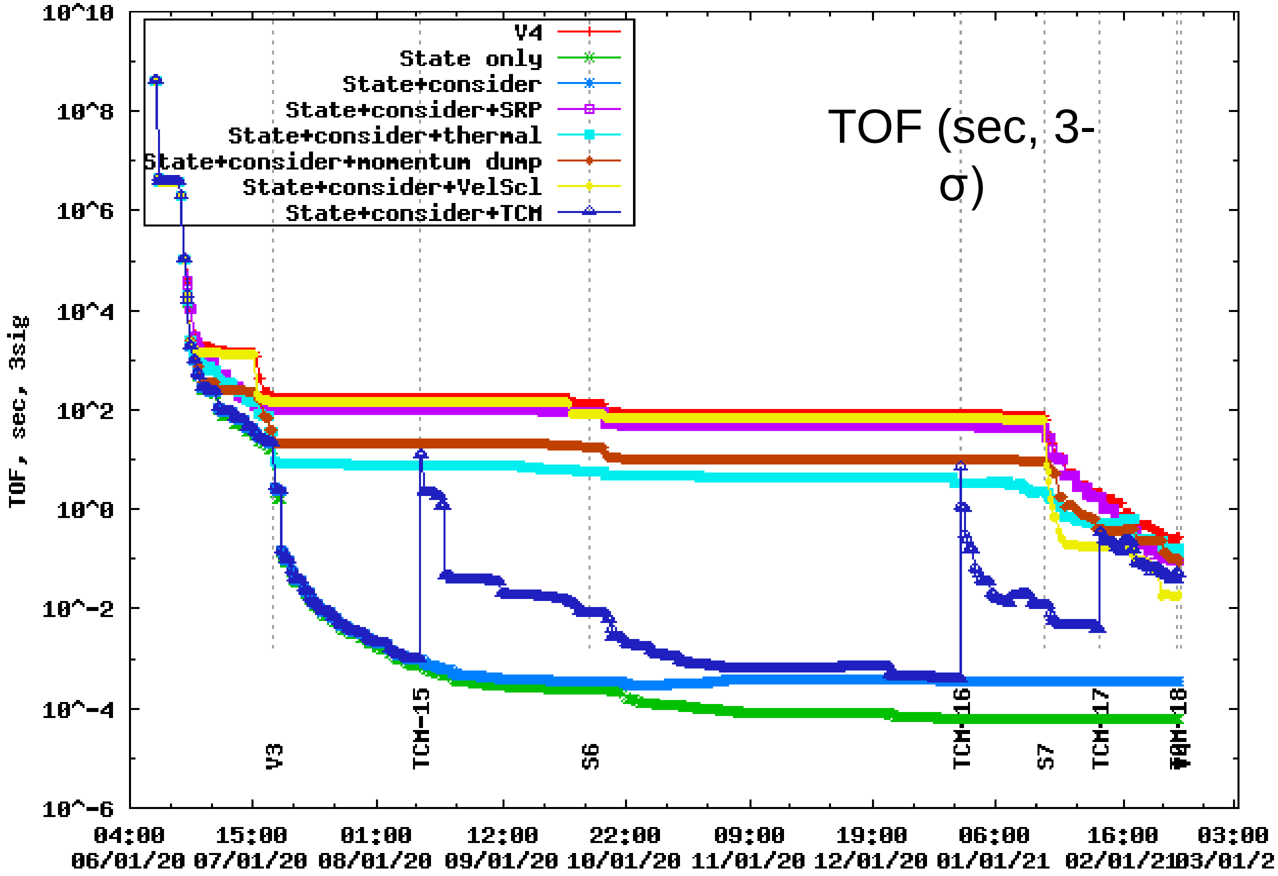

Reconstruction V1-V4

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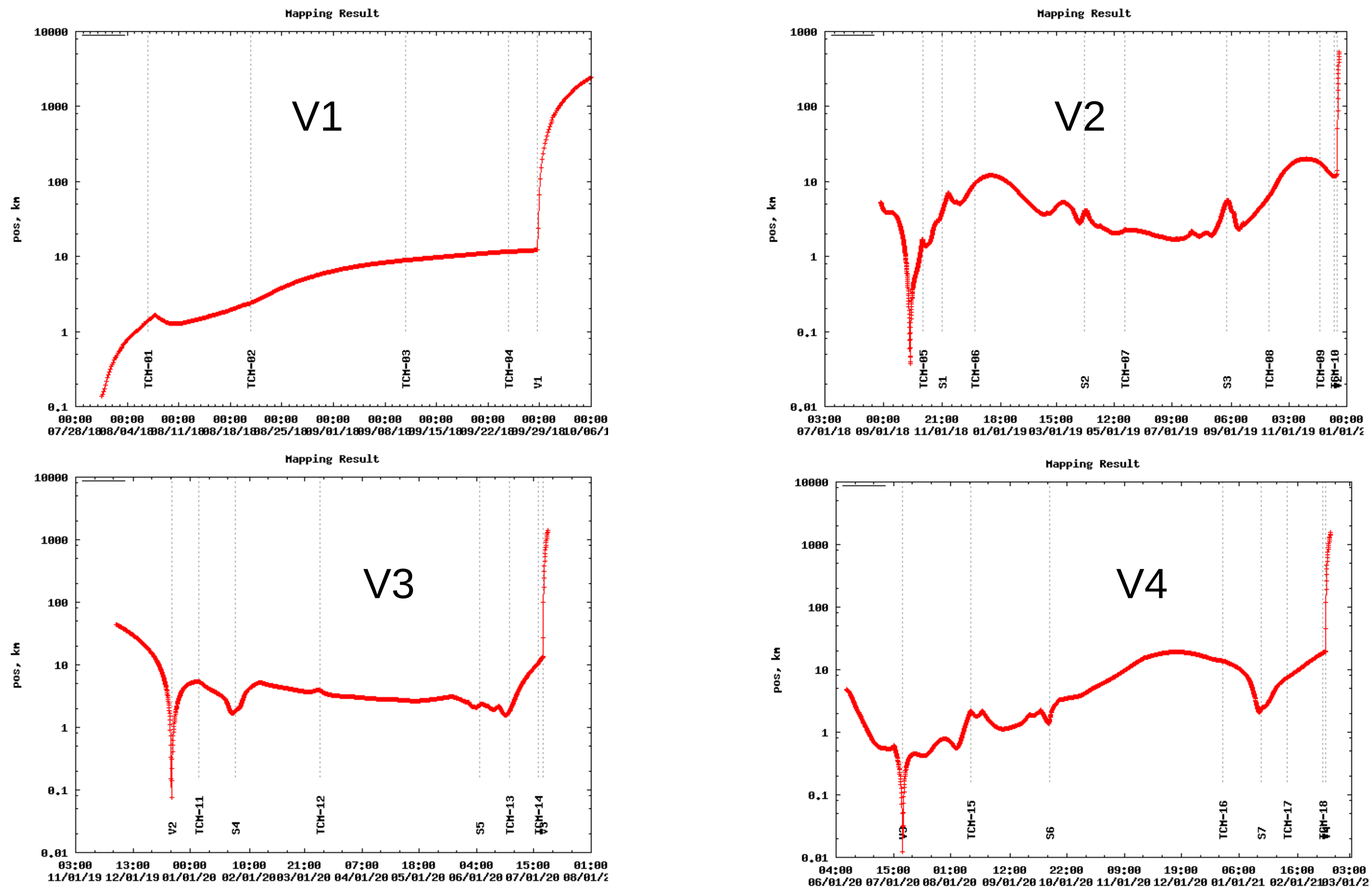

APL

Reconstruction V5-V7

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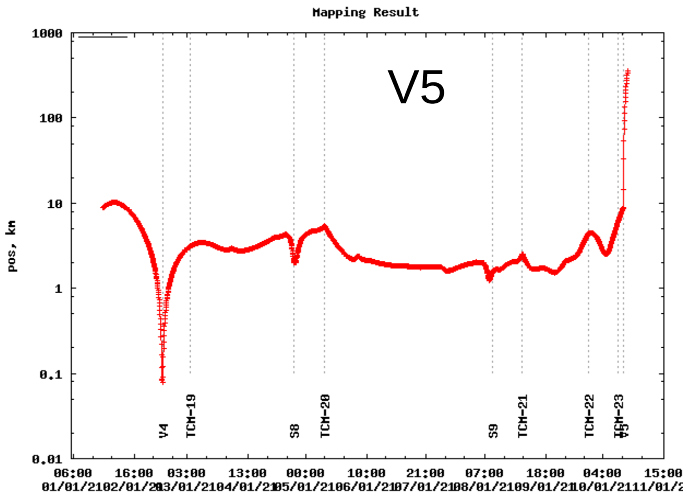
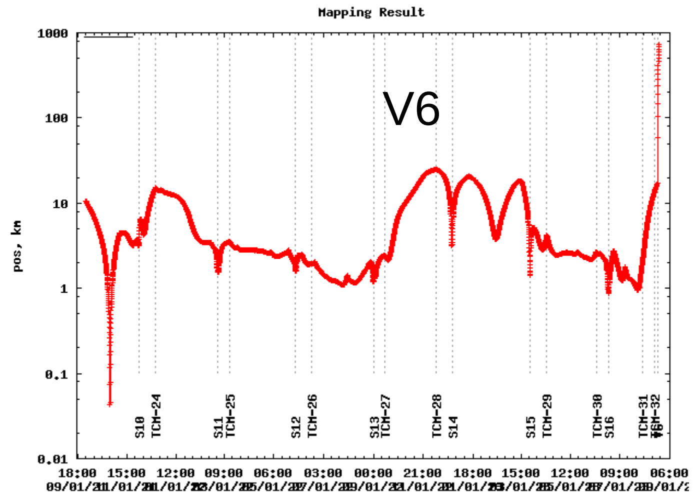
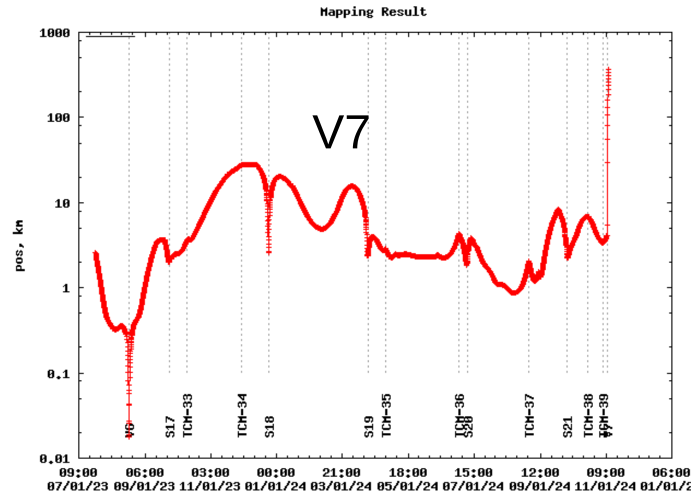


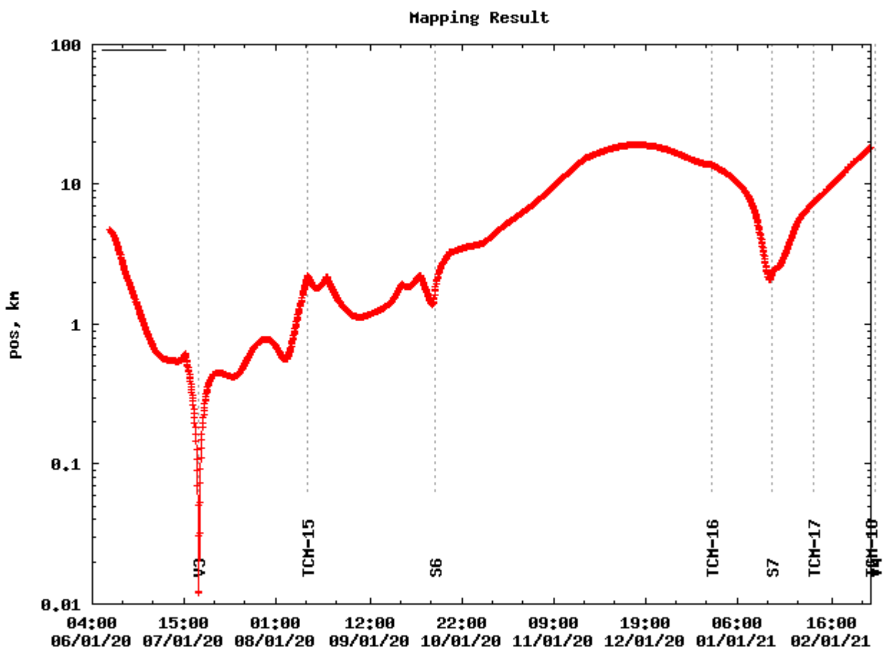


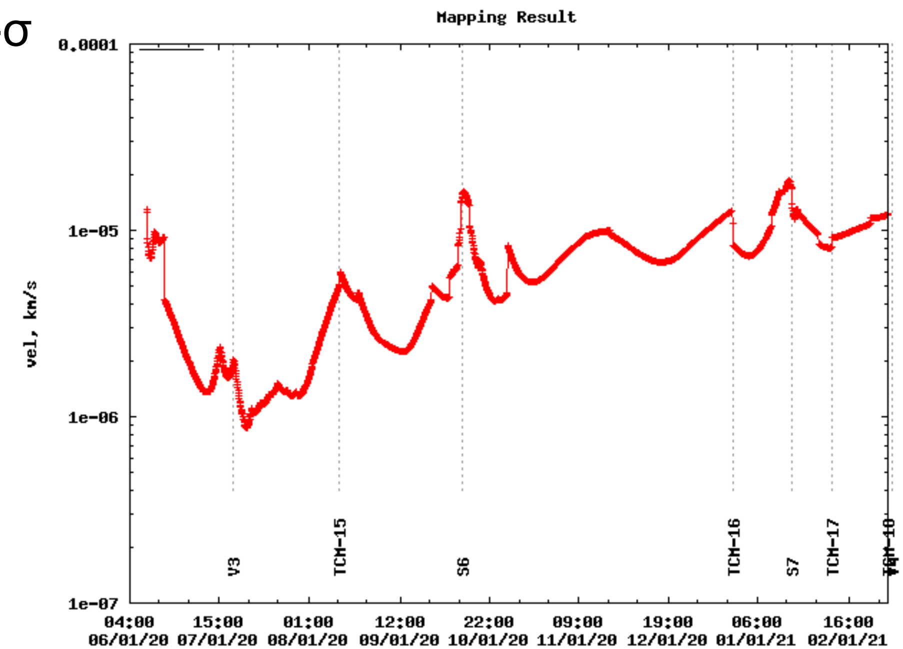


APL

Reconstruction, Current-State Statistics of V4 Arc

3-σ





3-σ	TCM-15 dco	TCM-16 dco	TCM-17 dco	TCM-18 dco
Position	0.78 km	14.6 km	5.5 km	14.7 km

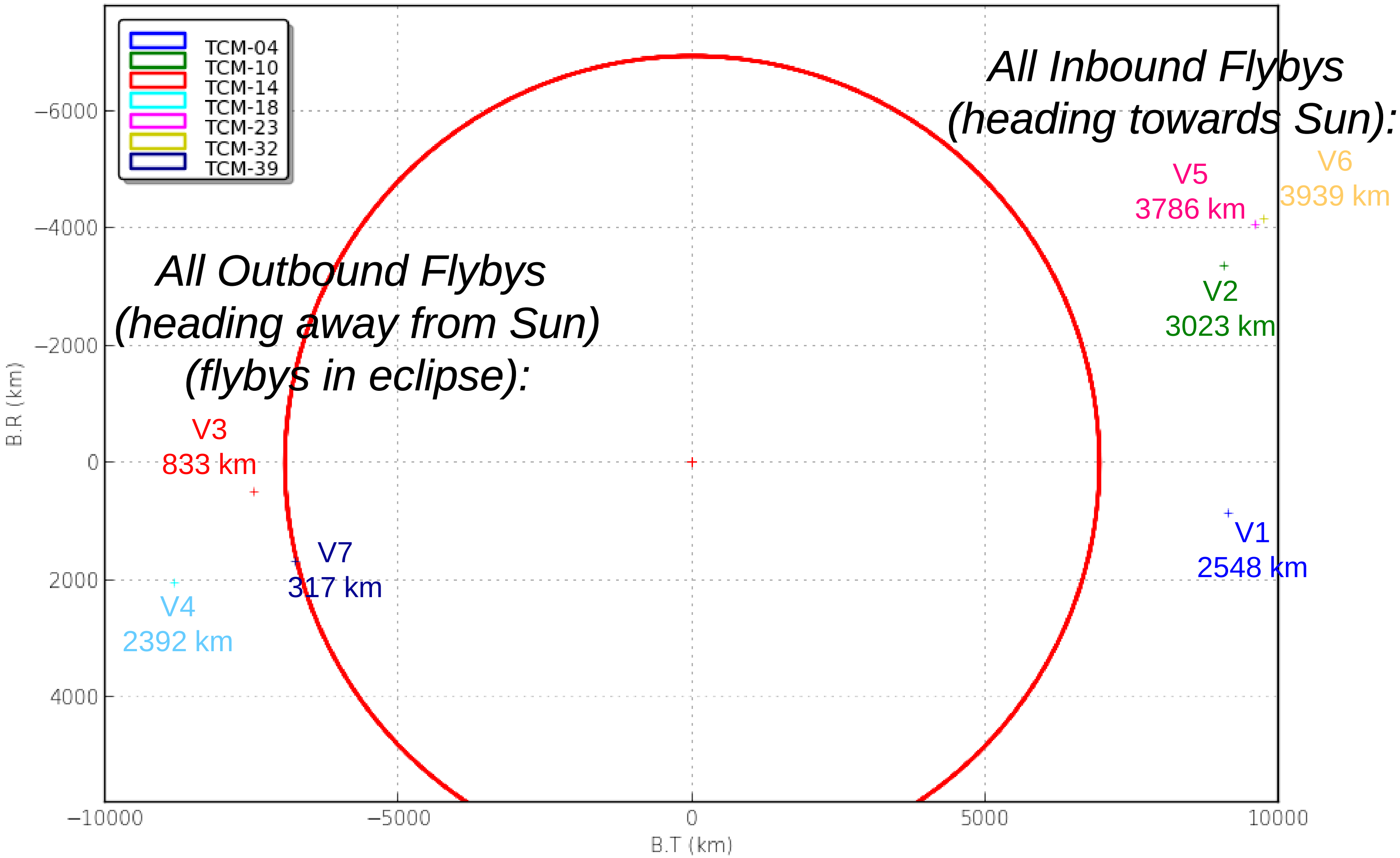
Trade Studies and Sensitivity Analysis

Changes were introduced into original Phase A setup one at a time in order to verify change and test any sensitivities to that change

- Small force model updated from Phase A version
  - Phase A assumed a spacecraft that used thrusters only for attitude control; a much “noisier” spacecraft. Phase B assumes use of wheels for attitude control
- SRP updated from Phase A version
  - Phase A used a bus model with large non-radial errors
  - Phase B replace it with plate model, sun-pointed along with an additional thermal acceleration
- SRP acceleration produced by variable solar panel angle
  - Currently magnitude of that additional acceleration << SRP errors
- Nominal vs. SEP angle based weights
- Tracking schedule variations
  - Gaps, reduced range

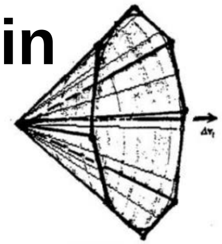
Venus Aimpoints

B-Plane Targets

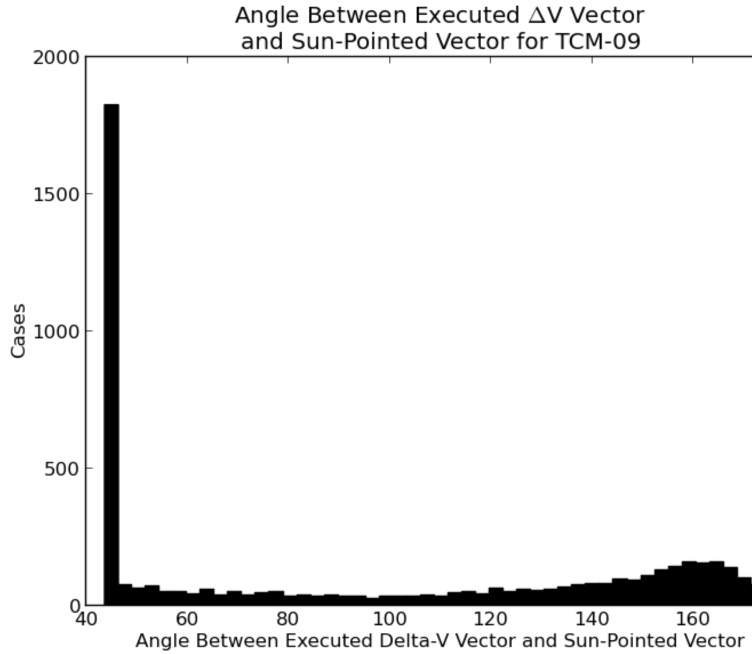


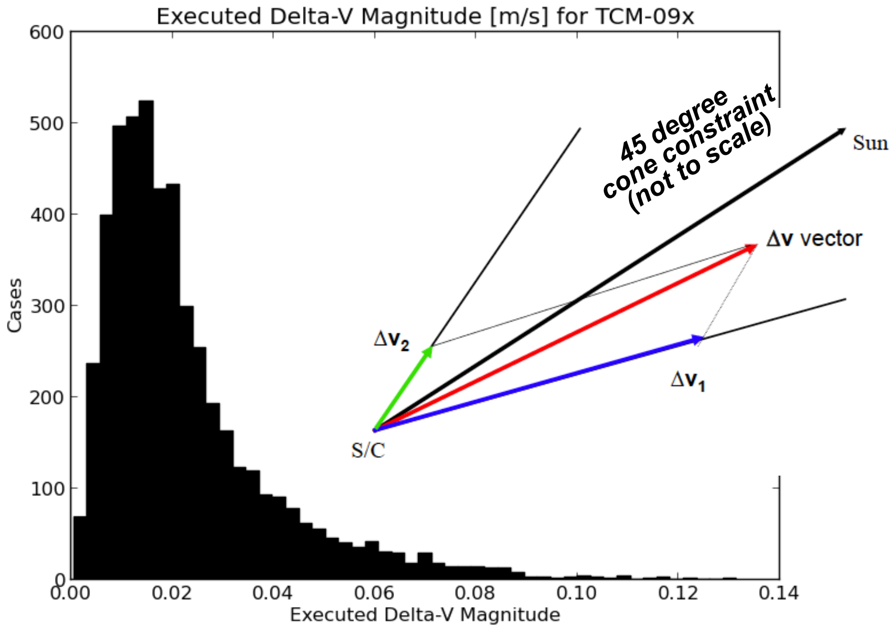
Lambic: TCM-09/09x

TCM-09 at Sun-probe range > 0.82 AU (45 degree Sun-ΔV cone angle constraint). Cone constraint implemented in Lambic.



- **TCM-09x 99% = 0.08 m/s**
- **TCM-09x maneuver may be skipped, w/ small penalty**





Lambic Targeting Strategy (2/3)

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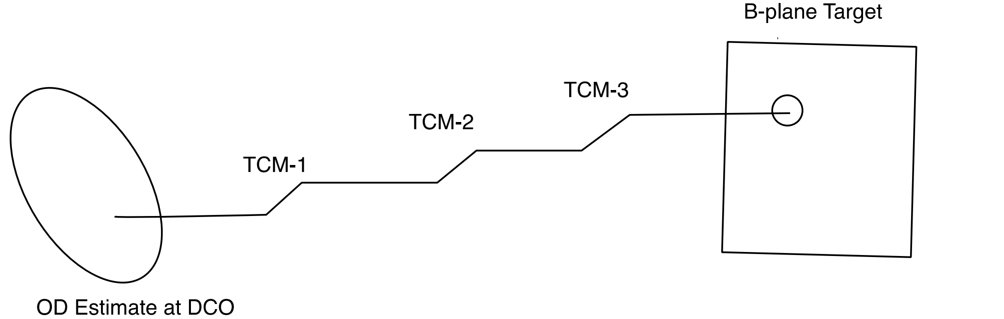
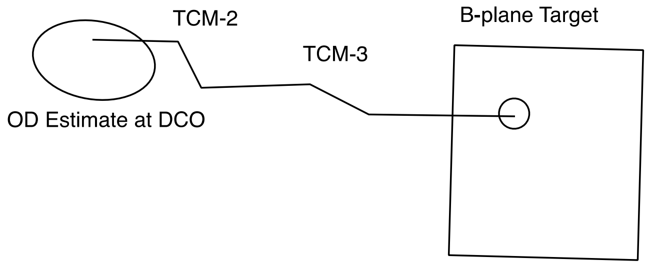
Maneuver "chains" are used in Lambic for Venus targeting to reduce the total simulation ΔV99:

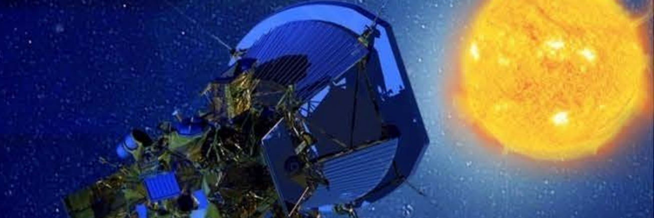
- Each TCM is designed to minimize the total ΔV of the chain of maneuvers.
- Only the first maneuver's design is used.
- The last maneuver is always targeted to the nominal aimpoint.

Design of TCM-1 in a 3-maneuver chain



Design of TCM-2…:





Lambic Results: ΔV

Mnvr	Date	Mean ΔV [m/s]	99% ΔV [m/s]
TCM-01	08/07/2018	27.73	61.20
TCM-02	08/19/2018	0.38	1.20
TCM-03	09/09/2018	0.02	0.06
TCM-04	09/25/2018	0.07	0.16
TCM-05	10/11/2018	1.26	4.05
TCM-06	12/05/2018	0.20	0.65
TCM-07	05/12/2019	0.24	0.81
TCM-08	10/10/2019	0.29	0.83
TCM-09	12/03/2019	0.06	0.16
TCM-10	12/18/2019	0.02	0.05
TCM-11	01/05/2020	2.94	9.48
TCM-12	03/09/2020	0.41	1.44
TCM-13	06/18/2020	0.38	1.03
TCM-14	07/03/2020	0.12	0.31
TCM-15	08/11/2020	4.50	14.26
TCM-16	12/23/2020	2.14	6.34
TCM-17	01/26/2021	0.31	0.92
TCM-18	02/14/2021	0.30	0.70
TCM-19	03/02/2021	0.00	0.00
TCM-20	05/10/2021	5.75	16.41
TCM-21	08/20/2021	0.49	2.23

Mnvr	Date	Mean ΔV [m/s]	99% ΔV [m/s]
TCM-22	09/23/2021	0.09	0.26
TCM-23	10/08/2021	0.07	0.20
TCM-24	12/06/2021	1.99	6.84
TCM-25	03/07/2022	0.34	1.71
TCM-26	06/16/2022	0.07	1.32
TCM-27	09/15/2022	0.43	2.33
TCM-28	11/17/2022	0.44	1.74
TCM-29	04/02/2023	1.51	5.70
TCM-30	06/02/2023	0.85	2.52
TCM-31	07/29/2023	1.43	4.61
TCM-32	08/13/2023	0.11	0.38
TCM-33	10/09/2023	1.57	4.92
TCM-34	11/29/2023	0.86	2.77
TCM-35	04/10/2024	0.82	2.67
TCM-36	06/17/2024	0.63	2.28
TCM-37	08/21/2024	0.94	2.97
TCM-38	10/15/2024	0.62	1.76
TCM-39	10/29/2024	0.08	0.20
TCM-40	11/20/2024	3.27	10.59
TCM-41	01/27/2025	0.02	0.11
TCM-42	04/16/2025	0.02	0.06

ICM TCM-01 FOM = 30.5 m/s

ΔV99 = 121.6 m/s

TCM Trade Studies

- TCM-11(TCM-11 moved earlier)
  - There is a certain penalty to be paid for correcting V3 errors at TCM-11
  - Downstream ΔV99 savings for performing TCM-11 earlier
  - Make no move of TCM-11 at this time
- TCM-18 sensitivity study is performed (TCM-18 moved earlier)
  - Earlier date enabled by removing data gap
  - Earlier TCM-18 reduces TCM-18 99% without reducing V4 delivery accuracy
  - Earlier maneuver is operationally advantageous
  - Commandability of spacecraft prior to TCM-18 is under
- TCM-19 sensitivity study performed by moving TCM-19 date:
  - TCM-19 ΔV ~ 0 m/s until TCM-19 placed at V4 + 28d
  - Post-V4 geometry is unfavorable for V5 B-plane corrections
  - NAV will recommend removing TCM-19

Probability of Impact

- Even at Venus-7, the last maneuver has negligible $P_{I/f}$

Flyby	Mnvr	Peri. Alt.	Delivery 3σ (km)	*Prob. Impact*
V1	TCM-04	2,548 km	18.63 x 7.57, 92°	Nil
V2	TCM-10	3,023 km	14.45 x 2.10, 63°	Nil
V3	TCM-14	833 km	20.22 x 13.35, 167°	Nil
V4	TCM-18	2,392 km	22.32 x 13.12, 40°	Nil
V5	TCM-23	3,786 km	13.48 x 8.44, 14°	Nil
V6	TCM-32	3,939 km	18.68 x 5.70, 83°	Nil
V7	TCM-39	317 km	23.47 x 18.62, 149°	Nil

TCM Implementation Penalty

To support the ΔV budget tally, NAV Monte Carlo results have been processed sample-by-sample to assess the implementation penalties

- The vector-mode penalty is component-wise execution versus hypotenuse: $|\Delta V_X| + |\Delta V_Z|$ versus *sqrt*$(\Delta V_X^2 + \Delta V_Z^2)$
- The cant-angle penalty is computed for angles of 20°, 10°, and 30° depending on thruster set (described earlier)

- It is *invalid* to add or subtract ΔV_{99}, the above tally of ΔV_{99} is combined via Monte Carlo
- This tally does not account for momentum dumps

Item	ΔV_{99} (m/s)	Comment
TCM-1	61	
TCM-1 penalty	4	20° cant
Other TCMs	78	
Other penalties	23	vector + cant
All the above	147	Monte Carlo

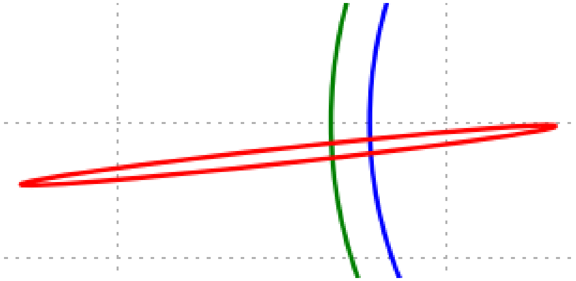
Venus Flyby Accuracy

- **SPP doesn't have a Planetary Protection Requirement for Venus**
- **No science at Venus, leaving ΔV_{99} to govern flyby accuracy**
  - **Only remaining concern for Venus impact is between the last maneuver and the nominal flyby**
  - **For all 7 Venus flybys, this probability is *Nil* (< 10^{-6})**

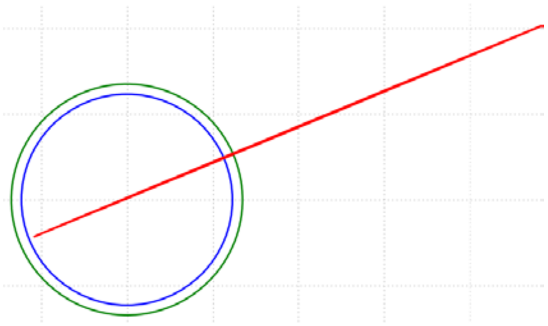
Probability of Impact

Occasionally, the mission will be on an impacting trajectory, a few examples:

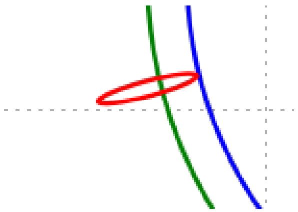
- TCM-11 has a relatively small dispersion, but it is close to Venus-3. ($P_{I/f}$ = 0.43)



- TCM-28 is further from Venus-6, but has a large dispersion ($P_{I/f}$ = 0.30)

- 

dispersion but closer to Venus-7. ($P_{I/f}$ = 0.49)



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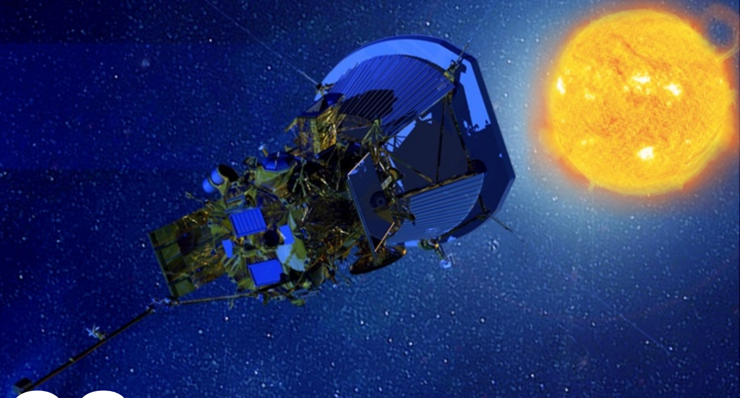

Science Planning/SOC

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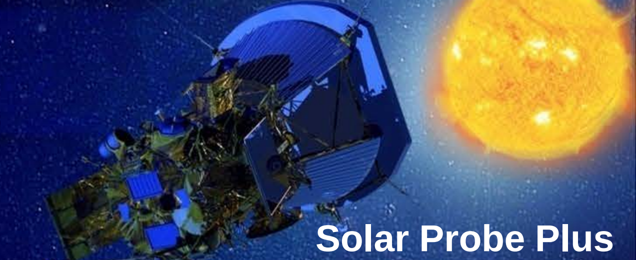
13 – 16 January 2014

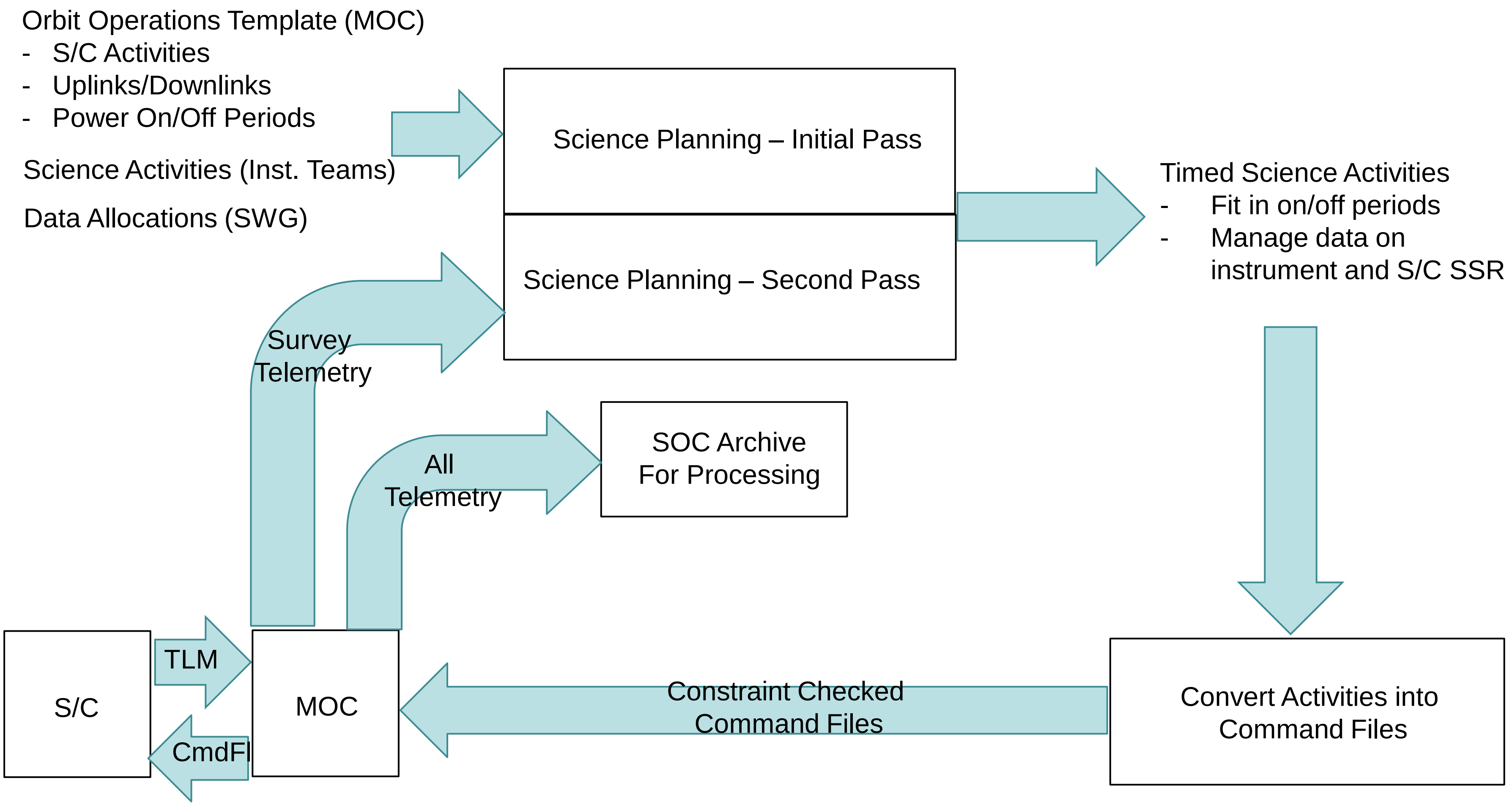
The Johns Hopkins University
APPLIED PHYSICS LABORATORY

Science Planning

- **Science Planning Steps**
- **Challenges**
- **Solution**
- **Next Steps**
- **Conclusion**

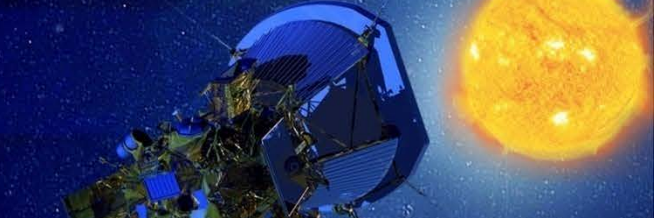
Science Planning Steps





Challenges for Science Planning on Solar Probe Plus

- **Managing the data on the instrument SSR (i-SSR) and instrument part of the spacecraft SSR (s/c-SSR)**
- **Limited uplink and downlink (DL) opportunities on some orbits**
- **Limited time to react to survey data and create commands to transfer data from the i-SSR to the s/c-SSR on some orbits**



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 would maximize the reaction time that the instrument teams have to analyze data and create commands to transfer over the data from the i-SSR to the s/c-SSR**
- **If the downlinks available during the orbit do not support the downlink survey, analyze, transfer selected data scheme, then the instruments would record data up to their data allocation and transfer it to the s/c-SSR during the encounter.**

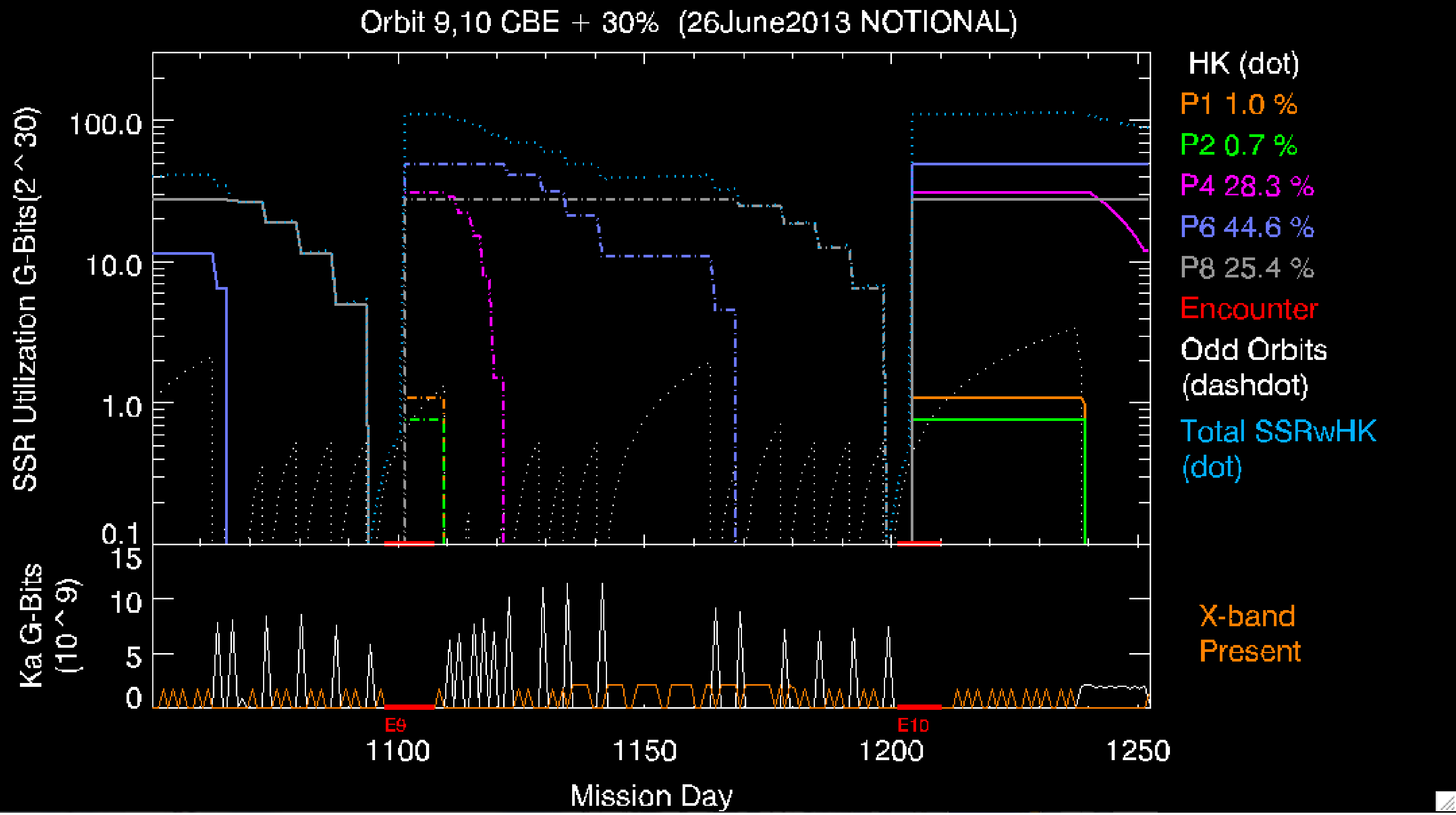
File Priority Scheme

Pr.	% 85 Gbits	Type	FIELDS (20 Gbits/orbit)	ISIS (12 Gbits/orbit)	SWEAP (20 Gbits/orbit)	WISPR (23 Gbits/orbit)
0		High Priority Usage / Commissioning / I&T				
1	1 % (not S/C HK)	S/C HK & Inst. High Priority HK	1 %	1 %	1 %	1 %
2	0.7 %	Quicklook & Survey	1 %	1 %	1 %	
3		Acclaimed Science	All teams agree			
4	28.3 %	Survey & Inst. HK	50 %		50 %	6 %
5		Place Holder				
6	44.6 %	Science & Inst. HK		98 %		93 %
7		Place Holder				
8	25.4 %	Science & Inst. HK	48 %		48 %	
9		Cruise Science & Inst. HK				

Orbit Types CBE + 30%

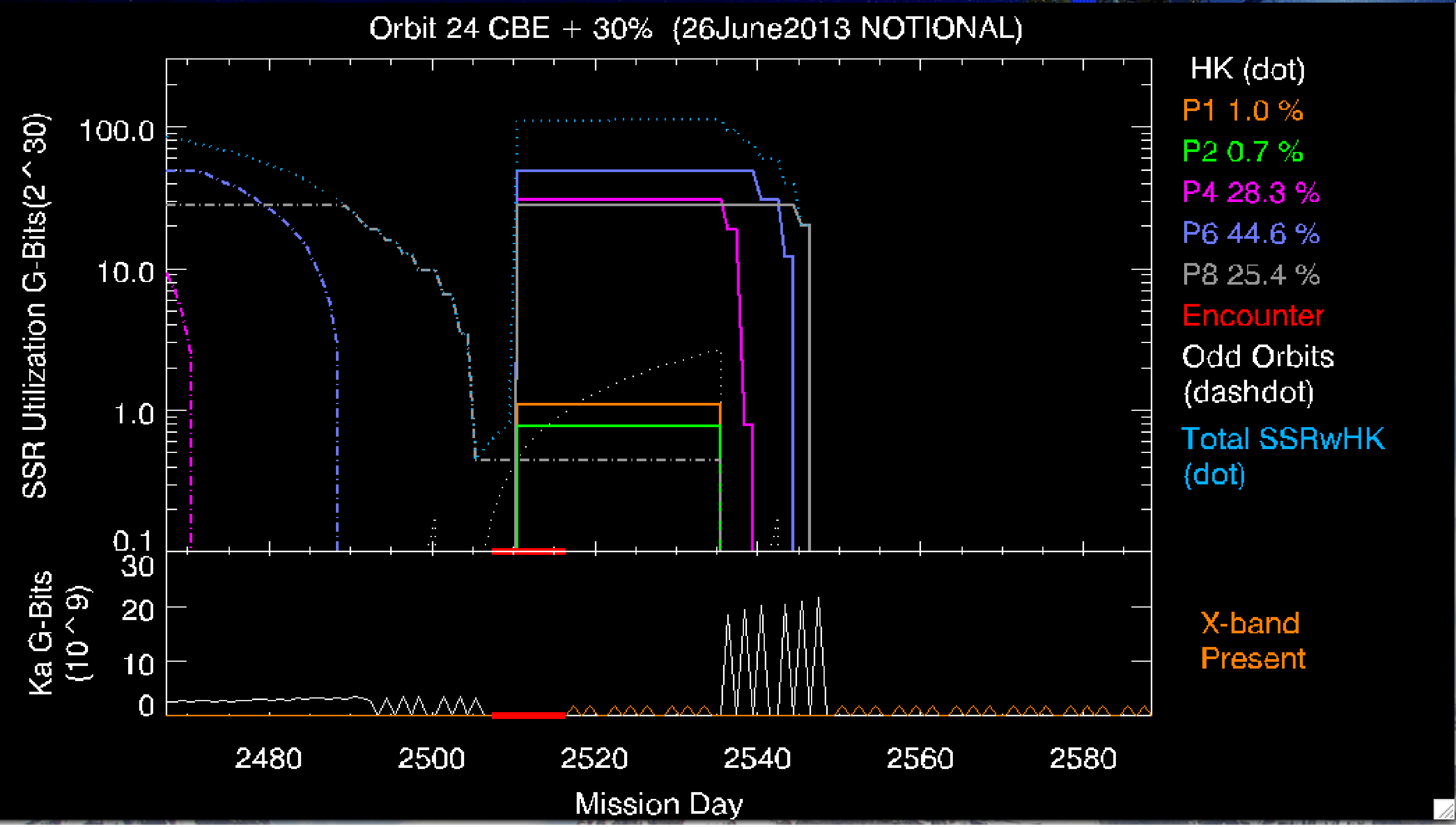
Orbit Type	Description	Orbits
Good	Time to analyze survey, and select data for DL * = most data DL in 1 orbit	2*, 3*, 6, 8, 9, 12, 13
Fast Downlink	No time to analyze survey and select data for DL	5, 7, 24
Limited Transfer Time	Limited opportunity to transfer from i-SSR to sc-SSR since must do between Ka-band DL	15, 17, 19, 21, 22, 23
Little or No Command Time	Little time to command after survey DL	14, 18
Downlink in Following Orbit	Little or no Ka-band downlink so data is downlinked in the following orbit	1, 4, 7, 10, 11, 14, 16, 20, 22

Good Orbit



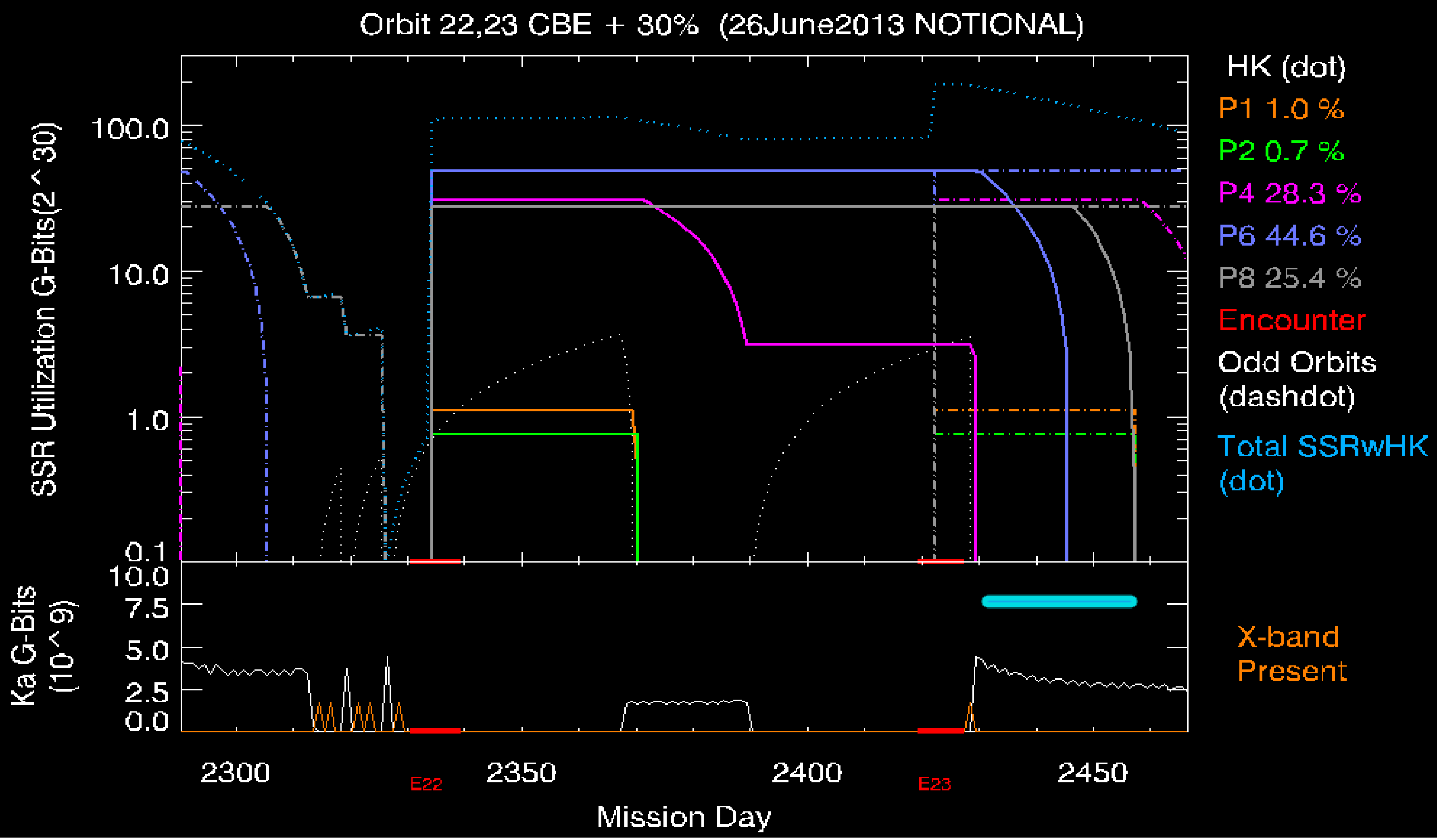
Plenty of time to analyze the survey data (pink), send commands and transfer the selected data (grey) from the i-SSR to the s/c-SSR

Fast Downlink – No Time for Survey/Selected



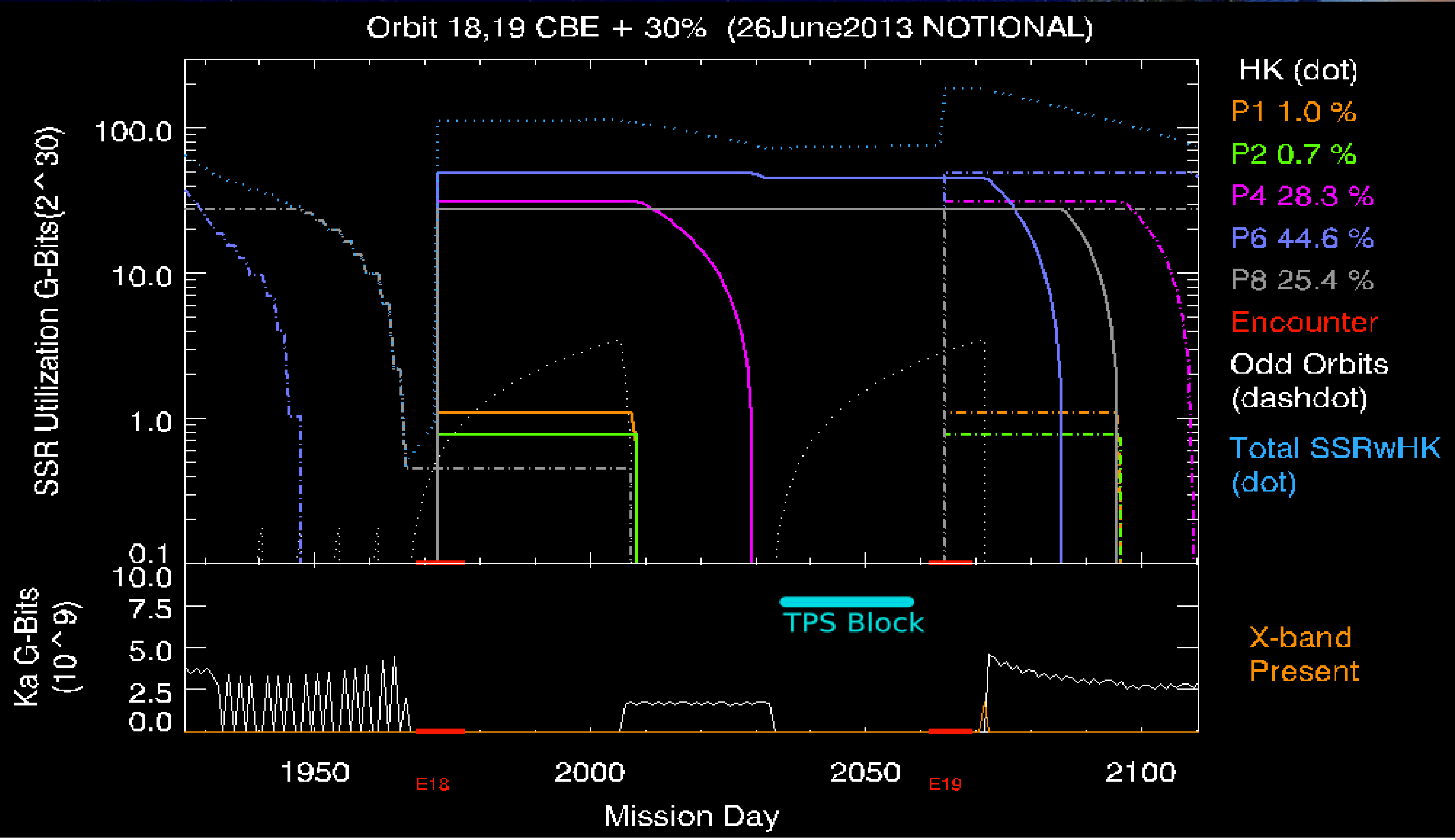
Science can accommodate this approach. All science data would be transferred to the s/c-SSR during the encounter.

Limited Transfer Time



Analysis of survey data (pink), commanding and transfer of selected data from i-SSR to s/c-SSR is done during periods of 16 +-8 hours between the Ka-band daily contacts. The Ka-band period is noted with a turquoise line.

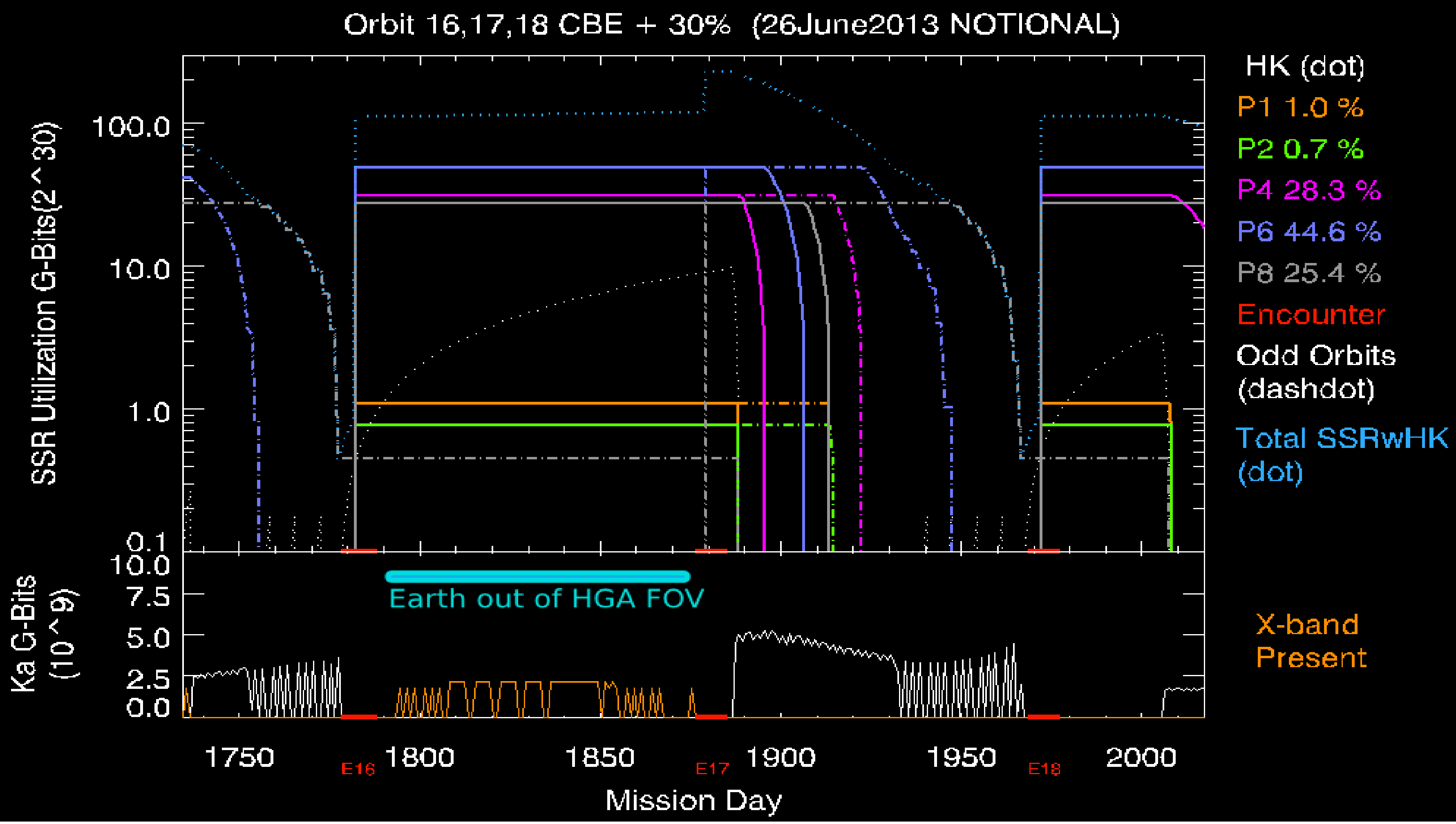
Little or No Command Time



There is time to analyze the survey data (pink) after it is received but due to the TPS blockage period, no commanding or data transfer can take place until after the next encounter.

Downlink in the Following Orbit

Solar Probe Plus



Due to the period when the Earth is out of the HGA FOV, downlink of the science data would be postponed until after the following encounter

Next Steps

- **The Science Working Group (SWG) will fine tune the file priority scheme as the operations concept is developed further**

- **Start development of an interactive display and analysis tool to integrate orbit operations template information with instrument specific information as an aid to planning**

Conclusion

- **We are ready for Phase C**

Backup Slides

File Priority Data Orbit Plot Legend

- The file priority data orbit plots are generated by a notional prototype using the cost constrained downlink profile
- The top plot is the science data available on the s/c-SSR in G-Bits (2^30) versus mission day for the CBE +30% margin
- The science data for each priority type, is added to the s/c-SSR at the center of the encounter for this notional prototype
- The bottom plot is the Ka-band in G-Bits (10^9) and an indication when X-band may be present versus mission day
- The solid horizontal red line is an encounter
- File priority data P1-P8 for odd orbits is plotted in dashed lines
- File priority data P1-P8 for even orbits is plotted in solid lines
- S/C housekeeping data is plotted in white dotted lines
- Total data (s/c housekeeping + all science) is plotted in blue dotted lines