Solar Probe Plus

A NASA Mission to Touch the Sun

SPP Spacecraft Autonomy

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NASA

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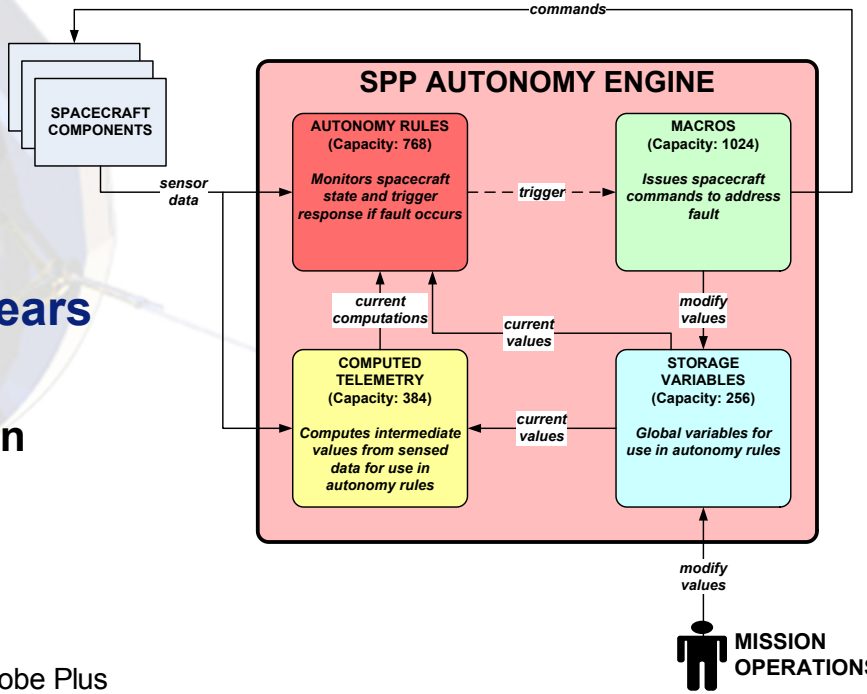
Spacecraft Autonomy Agenda

- Spacecraft Autonomy Overview
- Spacecraft Modes
- Instrument Autonomy Overview
  - EPI-Hi Instrument Autonomy
- Payload Autonomy Overview
- Instrument Heater Autonomy Overview
  - EPI-Hi Heater Autonomy

Spacecraft Autonomy System Overview

- The SPP Autonomy System is a Monitor→Response system where faults are detected and corrective actions are taken in response to the fault
  - All Monitors are evaluated at a 1 Hz rate
- The SPP C&DH Flight Software provides an on-board Autonomy Engine to facilitate the development of the Autonomy System. The Autonomy Engine supports four types of uploadable constructs that allow the Autonomy Engineer to independently develop the Autonomy System:
  - Autonomy Rules
  - Macros
  - Storage Variables
  - Computed Telemetry
- The Autonomy Engine has over 15 years of heritage.
  - Incremental enhancements have been made to the engine over the years



Spacecraft Autonomy System: Attributes Overview

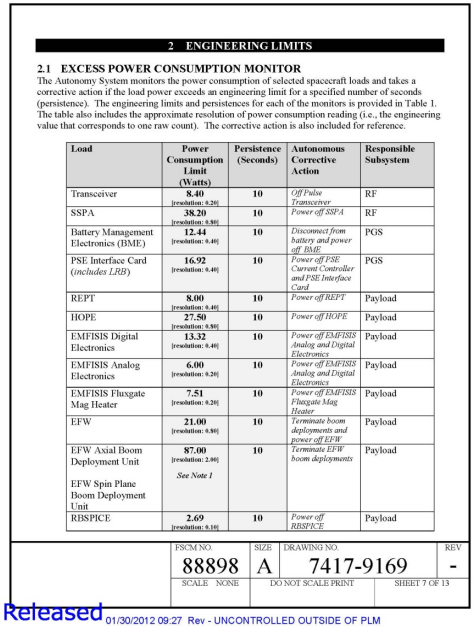
- **Autonomy Rules**
  - Autonomy rules specify the fault condition to be monitored. The fault condition (*autonomy rule expression*) may be a combination of any engineering telemetry and common arithmetic and logical operators
    - Example expression: `( SC_MODE == OPERATIONAL ) && (BUS_VOLTAGE * BUS_CURRENT < 350.0)`
  - Rule Attributes
    - ***Persistence:*** How long a fault must persist *(M of N seconds)*
    - ***Maximum Fire Count:*** How many times an autonomy rule can fire
    - ***Priority:*** Priority of the autonomy rule's response macro when running concurrently with other macros
    - Initial State: Whether the autonomy rule is enabled or disabled by default
- **Macros**
  - Macros specify a list of spacecraft commands designed to address a fault. They are invoked in response to the firing of an autonomy rule.
  - Macros may call other macros (like invoking a subroutine). This allows a level of modularity to be applied to the macro design. Also, in the spirit of modularity, multiple autonomy rules may trigger the same macro

Spacecraft Autonomy System: Attributes Overview

- **Computed Telemetry**
  - Computed Telemetry allow intermediate calculations to be defined from engineering telemetry (*i.e., derived telemetry*). The calculation results can then be used in autonomy rule expressions. Like autonomy rules, the expressions may be a combination of any on-board telemetry and common arithmetic and logical operators
    - Example computed telemetry definition to calculate spacecraft power: `BUS_VOLTAGE * BUS_CURRENT`
    - The resulting calculation can now be used in other autonomy rules
- **Storage Variables**
  - Storage Variables are global variables for the exclusive use of the Autonomy System. The values of the storage variables are typically used in the premise of autonomy rules.
  - Commands are available to modify storage variables. Storage variables can be:
    - Set to specific value (Ex: `STOR_VAR_X = 13`)
    - Incremented and decremented (Ex: `INCREMENT STOR_VAR_X`)
    - Assigned to existing value of telemetry point (Ex: `STOR_VAR_X = BUS_CURRENT`)
  - Commands to modify storage variables are used in autonomy macros and by MOPS ground command

Instrument Autonomy Requirements & Documentation

- Autonomy requirements applicable to all teams are captured in the General Instrument ICD, 7434-9066, rev B
- Instrument specific requirements are captured in the ISIS to Spacecraft ICD, 7434-9058, rev B
- All autonomy requirements are captured in the SPP Level 4 Autonomy Systems Requirements Document, 7434-9072, rev A
  - Specific limits (current, temperature, power, etc.) are captured in a separate document known as the SPP Autonomy Engineering Limits Specification, 7434-9116
  - All spacecraft and instrument subsystems that own any limits in the Autonomy System will be approvers on the document



2 ENGINEERING LIMITS

2.1 EXCESS POWER CONSUMPTION MONITOR

The Autonomy System monitors the power consumption of selected spacecraft loads and takes a corrective action if the load power exceeds an engineering limit for a specified number of seconds (persistence). The engineering limits and persistences for each of the monitors is provided in Table 1. The table also includes the approximate resolution of power consumption reading (i.e., the engineering value that corresponds to one raw count). The corrective action is also included for reference.

Load	Power Consumption Limit (Watts)	Persistence (Seconds)	Autonomous Corrective Action	Responsible Subsystem
Transceiver	**8.40** [resolution: 0.20]	10	*Off Pulse Transceiver*	RF
SSPA	**38.20** [resolution: 0.80]	10	*Power off SSPA*	RF
Battery Management Electronics (BME)	**12.44** [resolution: 0.40]	10	*Disconnect from battery and power off BME*	PGS
PSE Interface Card *(includes LRB)*	**16.92** [resolution: 0.40]	10	*Power off PSE Current Controller and PSE Interface Card*	PGS
REPT	**8.00** [resolution: 0.40]	10	*Power off REPT*	Payload
HOPE	**27.50** [resolution: 0.50]	10	*Power off HOPE*	Payload
EMFISIS Digital Electronics	**13.32** [resolution: 0.40]	10	*Power off EMFISIS Analog and Digital Electronics*	Payload
EMFISIS Analog Electronics	**6.00** [resolution: 0.20]	10	*Power off EMFISIS Analog and Digital Electronics*	Payload
EMFISIS Fluxgate Mag Heater	**7.51** [resolution: 0.20]	10	*Power off EMFISIS Fluxgate Mag Heater*	Payload
EFW	**21.00** [resolution: 0.80]	10	*Terminate boom deployments and power off EFW*	Payload
EFW Axial Boom Deployment Unit EFW Spin Plane Boom Deployment Unit	**87.00** [resolution: 2.00] *See Note 1*	10	*Terminate EFW boom deployments*	Payload
RBSPICE	**2.69** [resolution: 0.10]	10	*Power off RBSPICE*	Payload

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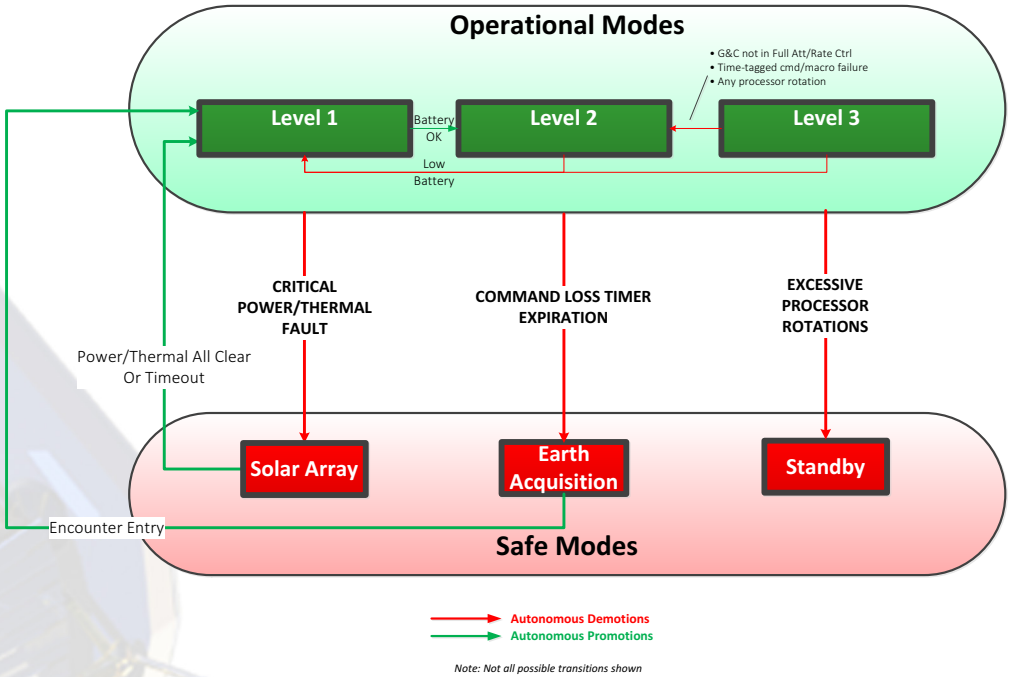
Example from Van Allen Probes

Spacecraft Modes

- There are six main spacecraft modes:
  - Operational Mode – Level 3
  - Operational Mode – Level 2
  - Operational Mode – Level 1
  - Safe Mode – Solar Array
  - Safe Mode – Earth Acquisition
  - Safe Mode - Standby
- SPP allows both autonomous mode demotions and promotions
- The intent of this overview is to provide simple definitions for the spacecraft modes since some autonomy rules are contingent upon mode



Operational Modes

- **There are three Spacecraft Operational Modes**
  - ***Operational Mode - Level 3***: **Highest mode of operation. All spacecraft operations allowed. Full science achievable.**
  - ***Operational Mode - Level 2***: **Demotion to this mode if G&C indicates less than full attitude and rate control, there is a command failure in a MOPS time-tagged sequence or there is a processor rotation. MOPS time-tagged sequences inhibited in this mode. Autonomy ensures full science still achievable (e.g., powering on instruments inside of 0.25 AU). TCMs, G&C Off Pointing and HGA downlink are not allowed.**
  - ***Operational Mode - Level 1***: **Demotion to this mode if there is a low battery state of charge. Instruments are powered off. Science not achievable.**
    - **Autonomous promotion to *Operational Mode - Level 2* once battery state of charge is nominal (science operations would then resume)**

Safe Modes

- **There are three Spacecraft Safe Modes**
  - ***Safe Mode – Solar Array***: **Demotion to this mode for critical power/thermal fault. Instruments are powered off. Science not achievable in this mode.**
    - **Autonomous promotion to *Operational Mode - Level 1* when power/thermal fault has cleared (or 10 minutes have elapsed). If battery state of charge returns to nominal levels, promotion would continue to *Operational Mode – Level 2* (science operations would then resume)**
  - ***Safe Mode – Earth Acquisition***: **Demotion to this mode if Command Loss Timer expires outside of 0.25 AU. Instruments are powered off. Science not achievable in this mode.**
    - **Autonomous promotion to *Operational Mode - Level 1* if spacecraft crosses 0.25 AU inbound while in this mode. If battery state of charge is nominal promotion would continue to *Operational Mode – Level 2* (science operations would then initiate)**
  - ***Safe Mode – Standby***: **Demotion to this mode if there are excessive processor rotations. Instruments are powered off. Science is not achievable in this mode.**
    - **No avenue to autonomously promote from this mode**

Spacecraft Mode Capabilities

Spacecraft Modes	SPP Spacecraft Modes Capability						
	Autonony Initiated Processor Rotations	X-band Downlink	Instrument Ops	Time-tags Cmds	Ka Band (HGA) Downlink	ΔV Maneuvers	G &C Off-Pointing
Operational Mode - Level 3	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Operational Mode - Level 2	Yes	Yes	Yes	No	No	No	No
Operational Mode - Level 1	Yes	No	No	No	No	No	No
Safe Mode - Solar Array	Yes	No	No	No	No	No	No
Safe Mode - Earth Acquisition	Yes	Yes	No	No	No	No	No
Safe Mode - Standby	No	Yes	No	No	No	No	No

Instrument Autonomy Overview

- **The Spacecraft Autonomy System provides overarching protection which can either:**
  - **Power On an instrument**
  - **Power Off an instrument**
  - **Power Cycle an instrument**
    - **i.e., power instrument off for predefined number of seconds and then power it back on**
- **Each instrument has its own internal safing**
  - **Discussed in following presentations**

Design Overview (1 of 3)

- **Each instrument sends Interface Transfer Frames (ITFs) to the Prime CDH at a 1 Hz (or higher) rate.**
  - **Each ITF contains an 8-bit sequence counter that is incremented by the instrument. The Prime CDH Flight Software monitors the sequence counter and declares a failed aliveness if the sequence counter fails to increment or if the ITFs are not valid.**
    - **This provides a mechanism for the Autonomy System to monitor instrument aliveness.**
  - **Each ITF also contains a pair of bits so that each instrument can self-request a power off or power cycle of the instrument.**
    - **A power off request trumps a power cycle request if both bits are asserted.**

- **Autonomy can send an individual instrument a shutdown warning prior to removing power from the instrument**
  - **In general, Autonomy will provide an instrument a 60-second shutdown warning if the power-down is not urgent**

Design Overview (2 of 3)

- **For each instrument the Autonomy System provides the following protection:**
  - ***Self-Power Down Request:*** **Power off an instrument that requests it**
  - ***Self-Power Cycle Request:*** **Power cycle an instrument that requests it**
  - ***Instrument Stale Aliveness:*** **Power off an instrument whose aliveness fails**
  - ***Instrument Excessive Power Consumption:*** **Power off an instrument if its power consumption exceeds limits**
  - ***Instrument LVDS Over-Voltage:*** **Power off an instrument if it applies LVDS over-voltage**

Design Overview (3 of 3)

- **Because of the mission criticality of keeping the instruments operating, the Autonomy System includes provisions for powering on instruments in Operational Mode – Level 2 or 3.**
  - **Instruments are powered on at 0.25 AU Inbound**
  - **"Second-chance" power-on after specific power-downs**
- **The Second-chance power-on in Operational Mode – Level 2 or 3 is selectively performed based on solar distance and based on the manner in which the instrument had been powered down.**

		SECOND CHANCE INSTRUMENT POWER-ON	
		Inside 0.25 AU	*Outside 0.25 AU*
Instrument Power-Down Cause	*Stale Aliveness*	POWER BACK ON ONCE	POWER BACK ON ONCE
	Excess Power	POWER BACK ON ONCE	POWER BACK ON ONCE
	LVDS Over-Voltage	POWER BACK ON ONCE	POWER BACK ON ONCE
	Power-Down Request	LEAVE POWERED OFF	LEAVE POWERED OFF
	Circuit Breaker Trip	LEAVE POWERED OFF	LEAVE POWERED OFF
	MOPS Command	LEAVE POWERED OFF	LEAVE POWERED OFF
	S/C Mode Demotion	POWER BACK ON ONCE †	LEAVE POWERED OFF
		† - *upon promotion to Op Level 2*	

ISIS EPI-Hi Requirements

AUT-19	Autonomy shall power off the EPI-Hi instrument if it is powered on and its flight software is not producing valid ITFs with incrementing sequence counts.
AUT-28	Autonomy shall power off the EPI-Hi instrument if the instrument requests to be powered down.
AUT-35	Autonomy shall power cycle the EPI-Hi instrument if the instrument requests to be power-cycled and is not simultaneously requesting to be powered down.
AUT-42	Autonomy shall power off the EPI-Hi instrument if its power consumption is above a pre-defined limit.
AUT-209	Autonomy shall power off the EPI-Hi instrument if its temperature is above a pre-defined limit.
AUT-336	Autonomy shall power off the EPI-Hi instrument if the voltage applied to an LVDS device is above 4.0V
AUT-466	Autonomy shall power on the EPI-Hi instrument when the spacecraft transitions inside 0.25 AU of the Sun (inbound) if the instrument is powered off and the spacecraft is in Operational Mode - Level 2 or Operational Mode - Level 3.
AUT-654	Autonomy shall provide the capability to autonomously restore power to the EPI-Hi instrument if was powered off due to a fault and its temperature is below a pre-defined value and the spacecraft is in Operational Mode - Level 2 or Operational Mode - Level 3.
AUT-168	Autonomy shall provide an EPI-Hi power-on macro that performs the following actions: * Power on the EPI-Hi survival/warm-up heaters * Indicate that EPI-Hi is being warmed-up for power-on * Wait until EPI-Hi's temperature is above a programmable low limit for power-on * Power off the EPI-Hi survival/warm-up heaters * Power on EPI-Hi * Power on the EPI-Hi operational heater * Indicate that EPI-Hi is no longer being warmed-up for power-on

Summary of EPI-Hi-*Specific* Spacecraft Autonomy

- **Autonomy will power off EPI-HI (with a 60 second shutdown warning) for:**
  - **EPI-Hi Stale Telemetry (*Static ITF Sequence Count Field*)**
- **Autonomy will immediately power off EPI-HI (no warning) for**
  - **EPI-Hi Excess Power Consumption**
  - **EPI-HI Requests Shutdown (*via ITF request*)**
- **Autonomy will power cycle EPI-HI for**
  - **EPI-HI Requests Power Cycle (*via ITF request*)**

Autonomy "Second Chance" for EPI-Hi

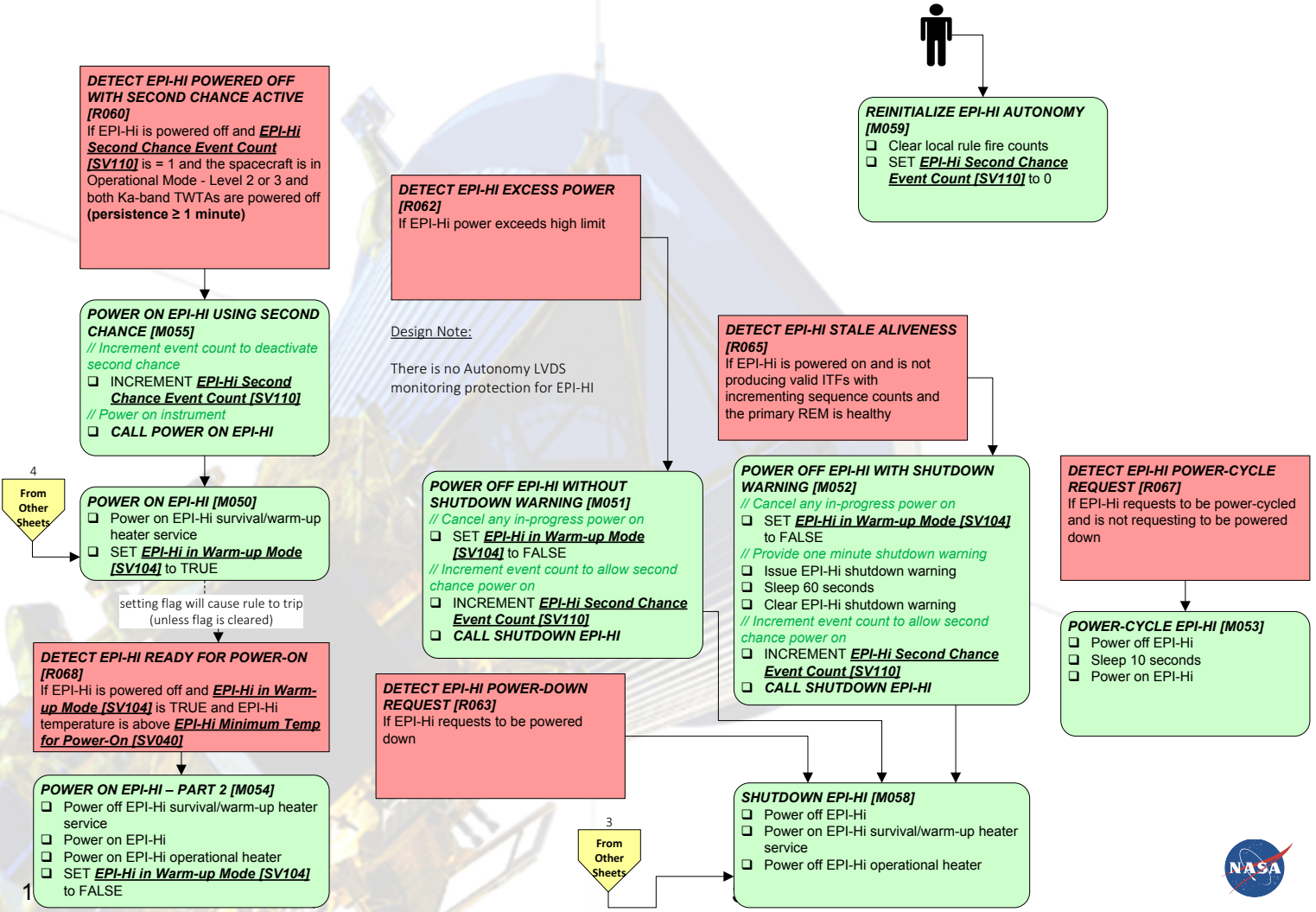
- The Autonomy System provides a mechanism to attempt a one-time powering back on of an instrument if it was powered off due to certain faults.
- The specific set of EPI-Hi faults that qualify for a second chance power on are:
  - EPI-Hi Stale Telemetry (*ITF Sequence Count Field*)
  - EPI-Hi Excess Power Consumption
- Once the "Second Chance" is exhausted for an instrument, there will be no further autonomous powering on of the instrument without ground intervention.

EPI-Hi Power-On Sequence

- **Before powering on EPI-Hi, the instrument must be warmed up using its survival/warm-up heaters to a temperature suitable for power-on**
- **The Autonomy System provides a macro that can be used by Mission Operations and Autonomy to perform the EPI-Hi power-on sequence**
  - **Power on the EPI-Hi survival/warm-up heaters**
  - **Wait until EPI-Hi's temperature is suitable for power-on**
  - **Power off the EPI-Hi survival/warm-up heaters (must be off while EPI-Hi is powered on)**
  - **Power on EPI-Hi**
  - **Power on the EPI-Hi operational heater**

EPI-Hi Design

Instrument - *ISIS EPI-Hi*

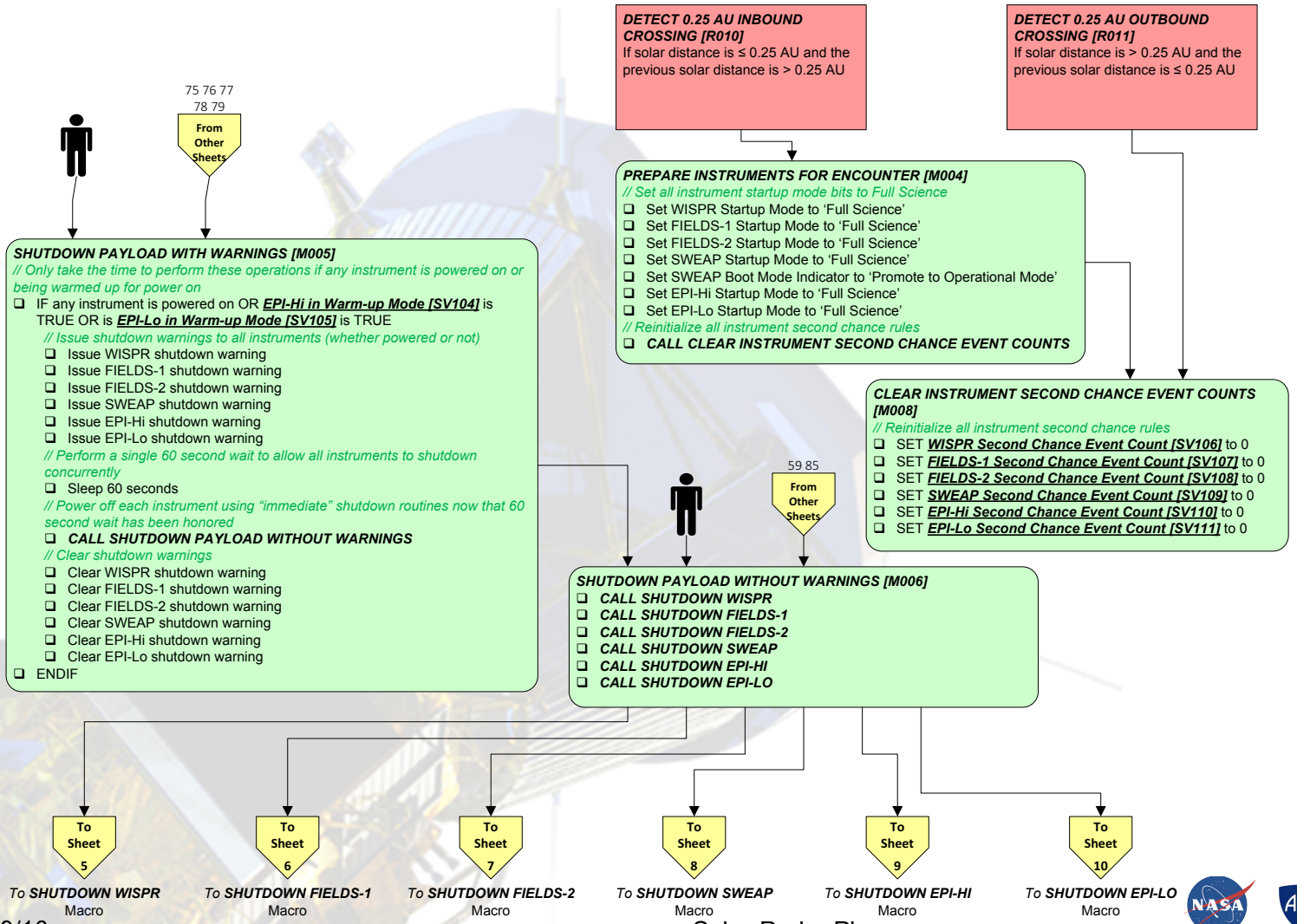


Summary of Payload-*wide* Autonomy

- **Autonomy will power off all instruments including EPI-Hi (with a 60 second shutdown warning):**
  - **Operational Mode – Level 2 at 0.25 AU Crossing Outbound**
  - **Operational Mode – Level 1**
  - **Safe Mode – Earth Acquisition Mode**
  - **Safe Mode – Standby Mode**
- **Autonomy will immediately power off all instruments including EPI-Hi (without warning):**
  - **Safe Mode – Solar Array Mode**
  - **If Ka-band TWTA is powered on concurrently with instrument (outside of 0.25 AU)**
    - **Inside of 0.25 AU, TWTA is powered off and instruments remain on**
- **Autonomy will power on all instruments including EPI-Hi:**
  - **Operational Mode – Level 2 at 0.25 AU Crossing Inbound**
  - **Operational Mode – Level 3 in the unlikely event that MOPS had not scheduled instruments to be powered on**

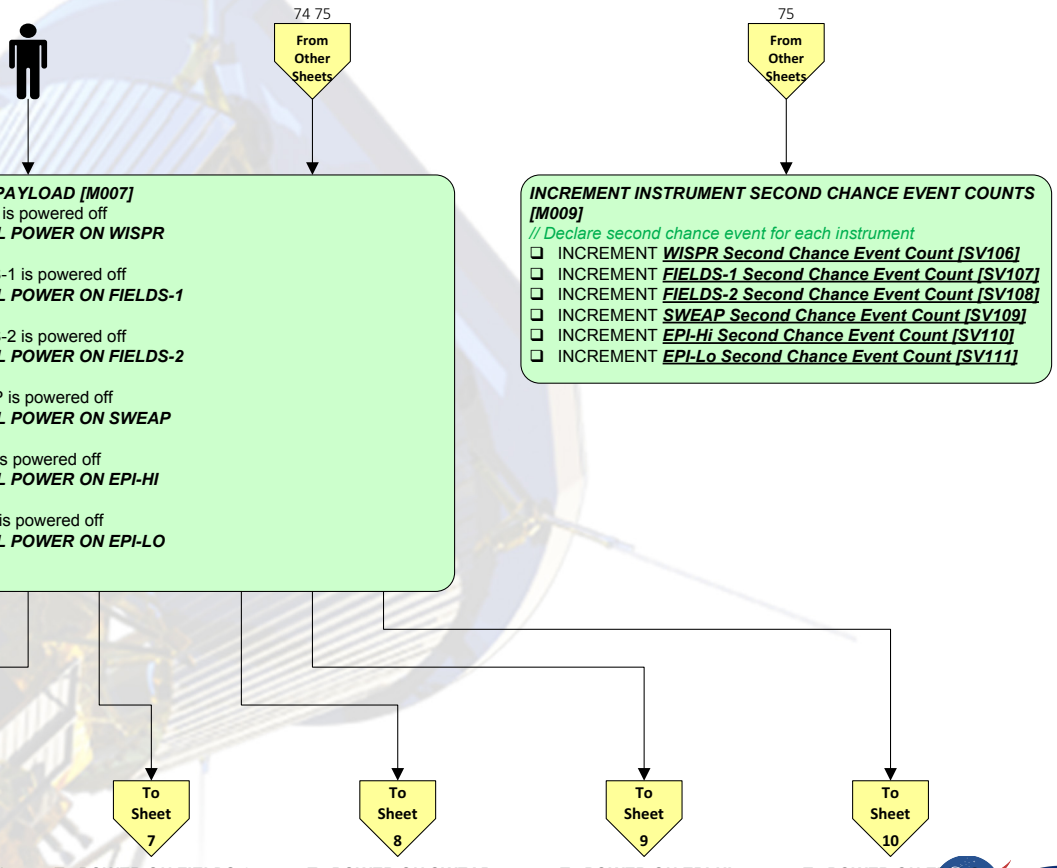
Payload Design (1 of 2)

Instrument Payload - *Shutdown*



Payload Design (2 of 2)

Instrument Payload – *Power On*



Instrument Heaters Overview

- Instrument heaters are single string
- EPI-Hi survival and warm-up heaters are software controlled
- Autonomy also enforces instrument heater ground rules (individually negotiated with each instrument team)
  - Instrument heater over-conductance rules eliminated post-Autonomy CDR with agreement from all instrument teams

Instrument Heater Service	INSTRUMENT ON		INSTRUMENT OFF	
	Inside 0.25 AU	Outside 0.25 AU	Inside 0.25 AU	Outside 0.25 AU
FIELDS 1 Op & Survival Heaters	ON ►►►			
FIELDS 2 Op & Survival Heaters	ON ►►►			
WISPR Survival Heaters	ON ►►►			
SWEAP SPAN A+ & B Survival Heaters	OFF	ON ►►►		
SWEAP SPC Survival Heater	OFF	ON	OFF	ON
ISIS EPI-Hi Survival and Warm-up Heaters	OFF ►►►		{Autonomy Thermostat}	
ISIS EPI-Lo Survival and Warm-up Heaters	OFF ►►►		{Autonomy Thermostat}	
ISIS EPI-Hi Operational Heaters	ON ►►►		OFF ►►►	
WISPR Operational Heaters	ON ►►►		OFF ►►►	

Instrument Heater Requirements

AUT-599	Autonomy shall power off the EPI-Hi operational heater service if its conductance is above a pre-defined high limit.
AUT-604	Autonomy shall power on the EPI-Hi operational heater service if it is powered off and the EPI-Hi instrument is powered on.
AUT-605	Autonomy shall power off the EPI-Hi operational heater service if it is powered on and the EPI-Hi instrument is powered off.

EPI-Hi Heater Power-On Sequence Details

- **EPI-Hi**
  - **When the instrument is off Autonomy operates the survival/warm-up heater service as a "software thermostat" between two programmable thresholds**
  - **When the instrument is in Warm-up mode, Autonomy turns the heaters on and drives up the temperature**
  - **Autonomy then waits until the instrument's temperature is safe for power-on before applying power to the instrument**
  - **When the instrument is powered, Autonomy powers off the survival/warm-up heaters (instrument's FSW will manage internal heaters)**
  - ***Note: Although the EPI-Hi survival/warm-up heater service includes a thermostat, it is only used only as a backup mechanism to mitigate a PDU failure. The primary temperature control is via Autonomy.***

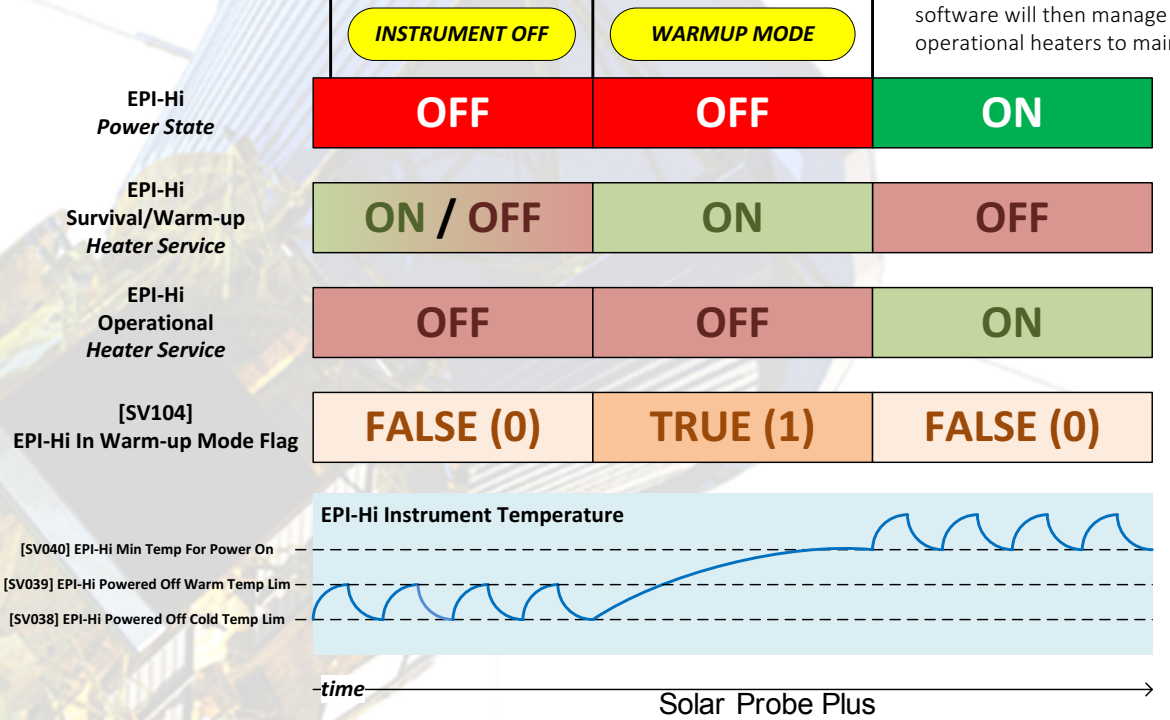
EPI-Hi Power On Sequence Diagram

EPI-Hi Power On Sequence

❶ When EPI-Hi is powered off, Autonomy Rules power on and off the Survival / Warm-up Heater Service to maintain the instrument temperature between two programmable set points (i.e., "software" thermostat).

❷ When Macro #50 ("Power On EPI-Hi") is executed, Autonomy leaves the Survival / Warm-up Heater powered on until the instrument reaches a programmable temperature that is safe for power on.

❸ After instrument reaches temperature, Autonomy powers on the instrument and powers off the Survival / Warm-up Heater Service. Autonomy then powers on the Operational Heater Service. The instrument flight software will then manage enabling and disabling operational heaters to maintain instrument temperature.



EPI-Hi Design – Operational Heaters

Instrument Heaters – *EPI-Hi Operational*

DETECT EPI-HI OPERATIONAL HEATER OVER CONDUCTANCE [R221]
If EPI-Hi operational heater conductance exceeds high limit

DETECT EPI-HI OPERATIONAL HEATER POWERED ON WHILE EPI-HI POWERED OFF [R222]
If EPI-Hi operational heater is powered on and EPI-Hi is powered off

DETECT EPI-HI OPERATIONAL HEATER POWERED OFF WHILE EPI-HI POWERED ON [R223]
If EPI-Hi operational heater is powered off and EPI-Hi is powered on and ***EPI-Hi Operational Heater Over-Conductance Fail Count [SV118]*** is ≤ 1

POWER OFF EPI-HI OPERATIONAL HEATER DUE TO OVER CONDUCTANCE [M161]
- ❑ Power off EPI-Hi operational heater
- ❑ INCREMENT ***EPI-Hi Operational Heater Over-Conductance Fail Count [SV118]***

POWER OFF EPI-HI OPERATIONAL HEATER [M160]
- ❑ Power off EPI-Hi operational heater

POWER ON EPI-HI OPERATIONAL HEATER [M162]
- ❑ Power on EPI-Hi operational heater

REINITIALIZE EPI-HI OPERATIONAL HEATER AUTONOMY [M164]
- ❑ Clear local rule fire counts
- ❑ SET ***EPI-Hi Operational Heater Over-Conductance Fail Count [SV118]*** to 0

EPI-Hi Design – Survival/Warm-Up Heaters

Instrument Heaters – *EPI-Hi Survival/Warm-up*

DETECT EPI-HI POWERED ON [R234]
If EPI-Hi survival/warm-up heater service is powered on -AND-
EPI-Hi is powered on

DETECT EPI-HI UNDER-TEMP WHILE POWERED OFF [R233]
If EPI-Hi survival/warm-up heater service is powered off -AND-
EPI-Hi is powered off -AND-
EPI-Hi temperature is below ***EPI-Hi Powered-Off Minimum Temp [SV038]***

DETECT EPI-HI OVER-TEMP WHILE POWERED OFF [R236]
If EPI-Hi survival/warm-up heater service is powered on -AND-
EPI-Hi is powered off -AND-
EPI-Hi in Warm-up Mode [SV104] is FALSE -AND-
EPI-Hi temperature is above ***EPI-Hi Powered-Off Maximum Temp [SV039]***

POWER ON EPI-HI SURVIVAL/WARM-UP HEATERS [M167]
- ❑ Power on EPI-Hi survival/warm-up heater service

POWER OFF EPI-HI SURVIVAL/ WARM-UP HEATERS [M165]
- ❑ Power off EPI-Hi survival/warm-up heater service

REINITIALIZE EPI-HI SURVIVAL/ WARM-UP HEATER AUTONOMY [M169]
- ❑ Clear local rule fire counts

Summary

- **Instrument autonomy needs are well understood**
- **Spacecraft autonomy team is staffed and ready to start rule development**
- **Key Milestones:**
  - **June 2015 FSW Build 1 Delivered and Available**
    - **Includes Autonomy Engine and FSW interfaces to components**
    - **Autonomy implementation and testing can proceed in earnest**
  - **January 2016 FSW Build 2 Delivered and Available**
    - **Includes most planned FSW functionality**
    - **Autonomy implementation and testing continues**
  - **July 2016 FSW Build 3 Delivered and Available**
    - **Includes all planned FSW functionality**
  - **August 2016 Delivery of Autonomy System to Spacecraft I&T**
    - **Autonomy implementation and unit testing should be complete**
    - **Start of autonomy testing on spacecraft and high fidelity simulators**
    - **Fault Management testing begins on spacecraft and simulators**