EXPLORESPACE TECH
TECHNOLOGY DRIVES EXPLORATION

NASA: New Approaches Toward Advanced Data Handling for Space Products

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To be presented at the 2024 IEEE Space Mission Challenges for Information Technology - IEEE Space Computing Conference, Mountain View, CA, USA, July 15-19, 2024

Agenda

- NASA’s varied needs for onboard computing
- General themes for avionics/computing needs
- Examples for avionics/computing needs
- Key avionics/computing attributes
- Ecosystem needs

NASA’s Varied Onboard Computing Needs

- Onboard computing needs vary widely across NASA missions
  - Across NASA Mission Directorates and Divisions
  - Across Mission Size
  - Across Mission Environments
  - Across Mission Classes

NASA use cases driving onboard needs - Science

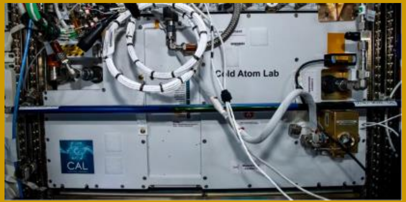
- Earth Science
  - High performance processing for onboard data reduction, as sensor bandwidth > downlink bandwidth
  - Increased onboard autonomy to enable sensor web
- Planetary Science
  - Increased autonomy, for navigation, fault management, precision navigation and timing (PNT), spacecraft/surface system control, instrument data collection, and science data prioritization for downlink
  - Harsh thermal and radiation environments
  - High performance processing for onboard data reduction, as sensor bandwidth >>> downlink bandwidth
- Astrophysics
  - High performance processing for adaptive wavefront sensing and control
  - High performance processing for onboard data reduction, as sensor bandwidth > downlink bandwidth
  - Avionics architectures to enable robotic servicing
- Heliophysics
  - Avionics and instrument miniaturization for smallsat constellations enabling multipoint in-situ measurements
- Biological and Physical Sciences
  - Avionics to enable autonomous operation of biological and physical science experiments on commercial LEO platforms

ICESat-2

Psyche

Roman Space Telescope

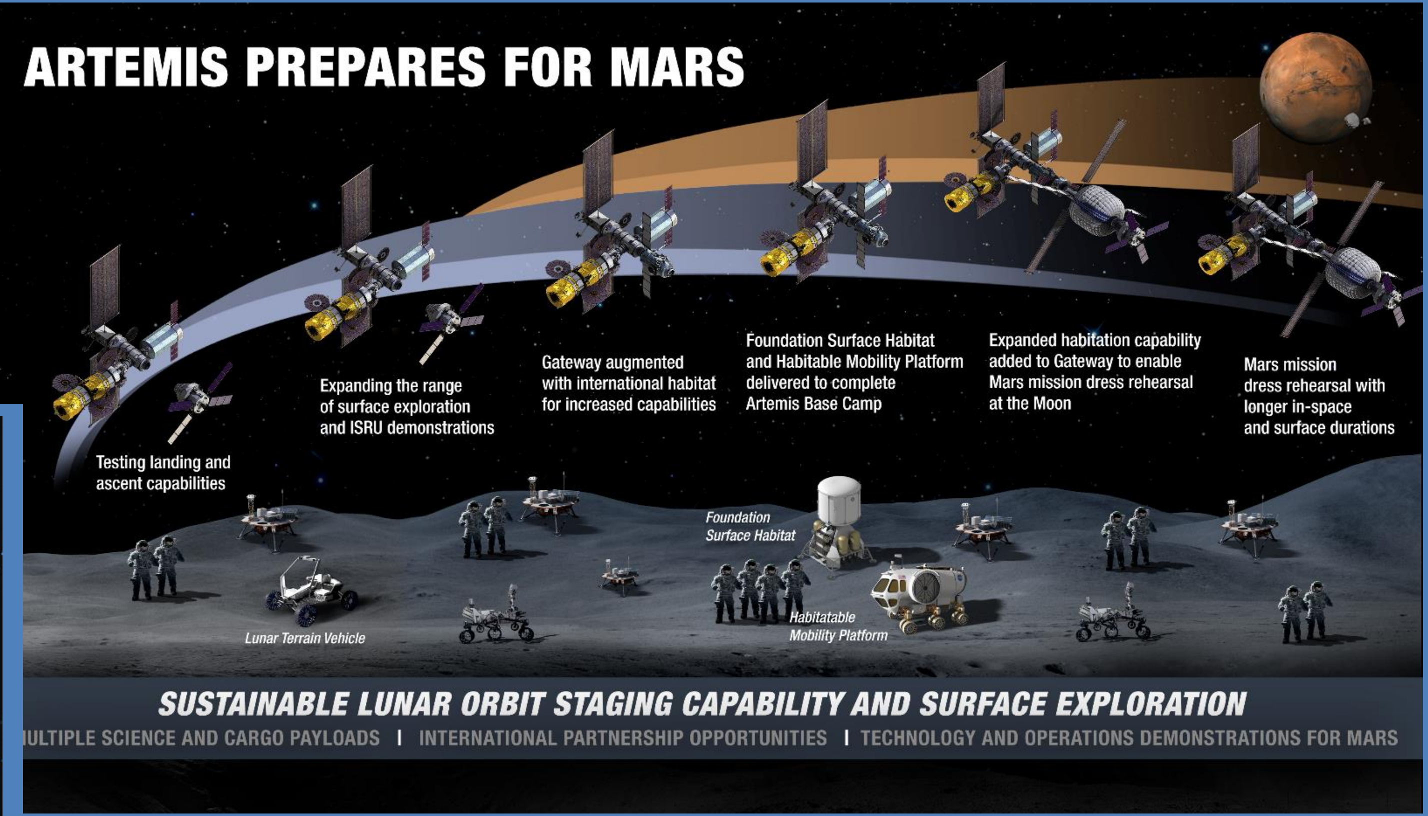
Magnetospheric Multiscale (MMS) Mission



Cold Atom Lab (CAL)

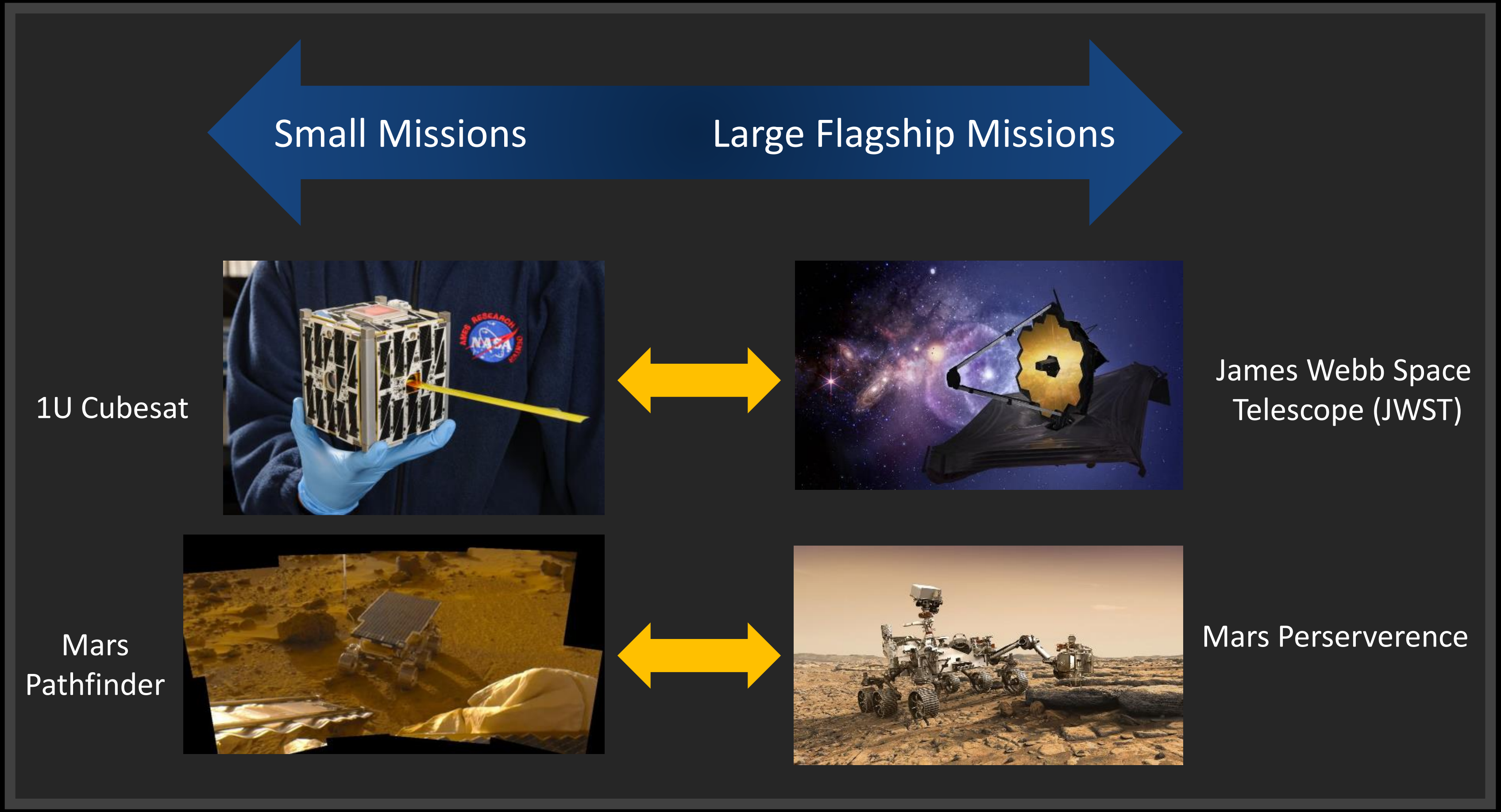
NASA use cases driving onboard needs - Crewed exploration

- Increased autonomy as missions extend beyond LEO to Cis-Lunar space, and beyond
- Robotics both working independently and collaboratively with crew
- Longer duration missions
- Harsh thermal environments
- Serviceability and maintainability



Gateway - Full Configuration in Orbit

Mission Size Variation



Small Missions

Large Flagship Missions

1U Cubesat

James Webb Space Telescope (JWST)

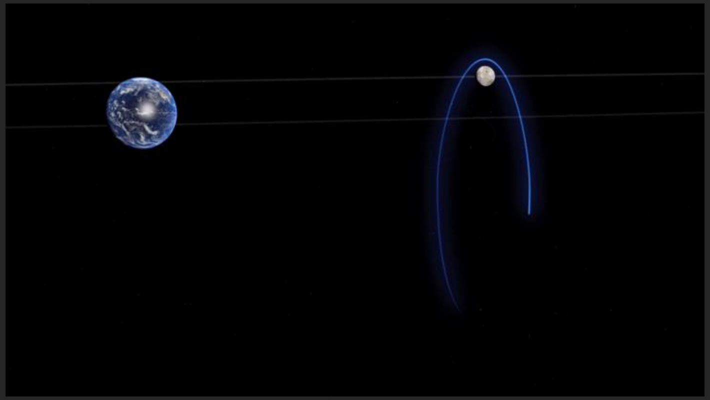
Mars Pathfinder

Mars Perserverence

Can influence
- Cost
- Risk tolerance
- Expected mission life
- SWaP-C sensitivity
- Part grade selection
- Redundancy

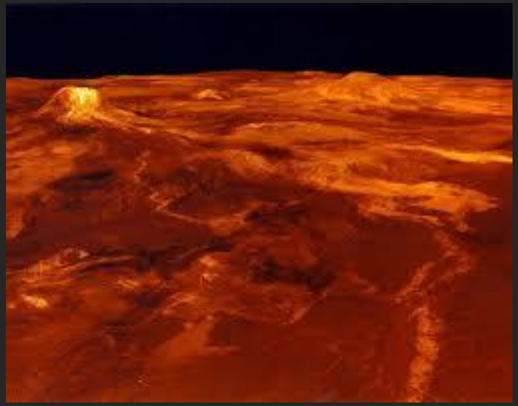
Mission Environment Variation


Low Earth Orbit


Cis Lunar

Lagrange Points


Lunar


Venus


Mars


Europa

Can influence temperature and Radiation

Mission Class Variation

	NASA Mission Classes			
	Class A	Class B	Class C	Class D
Priority	Very High	High	Medium	Low
Primary Mission Lifetime	> 5 Years	3 – 5 Years	1 – 3 Years	< 1 Year
Complexity and Challenges	Very High	High	Medium	Medium – Low
Life Cycle-Cost	High	Medium - High	Medium	Medium – Low

Can influence

- Part grade selection
- Redundancy

Applications

Application	Description	Key Challenges
Science spacecraft avionics	• Spacecraft health/safety management • Station keeping • Subsystem/instrument control and data handling	• Varies by mission size, environment, and class
Crewed vehicles avionics	• Spacecraft health/safety management • Station keeping • Environmental Control and Life Support System (ECLSS) management • Crew interface • Subsystem control and data handling	• Fault tolerance, ranging from 2 FT and 1 FT to single string, based on application criticality • Mission life • Serviceability
Crewed habitat avionics	• Spacecraft health/safety management • Station keeping • ECLSS management • Crew interface • Subsystem control and data handling	• Fault tolerance, ranging from 2 FT and 1 FT to single string, based on application criticality • Mission life • Serviceability • High sensor count • Earth independent operations

PACE Spacecraft

Gateway

Lunar Habitat Concept

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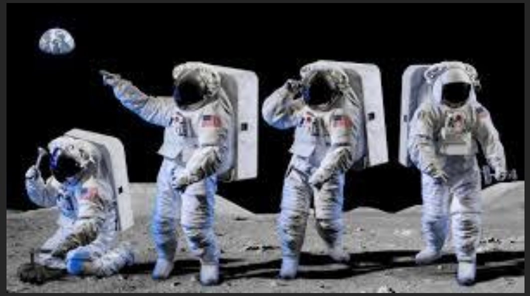
Applications

Application	Description	Key Challenges
Rover avionics	• Rover health/safety management • Situational awareness • Traverse path planning • Mobility control • Subsystem/instrument control and data handling • Crew interface (for crewed exploration rovers)	• Processing performance for autonomous driving • Fault tolerance • Power efficiency • Operational flexibility • Harsh environments
Planetary aerobot avionics	• Aerobot health/safety management • Situational awareness • Path planning • Flight control • Subsystem/instrument control and data handling	• SWaP efficiency • Processing performance for autonomous flight • Fault tolerance • Operational flexibility • Harsh environments
Space suit avionics	• Suit health/safety management • Crew health/safety management • Crew interface	• SWaP efficiency • Resource efficient graphics processing • Fault tolerance


Spirit Rover


Mars Ingenuity Helicopter


Space Suits

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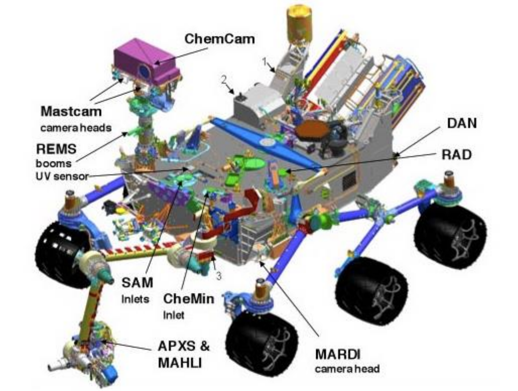
Applications

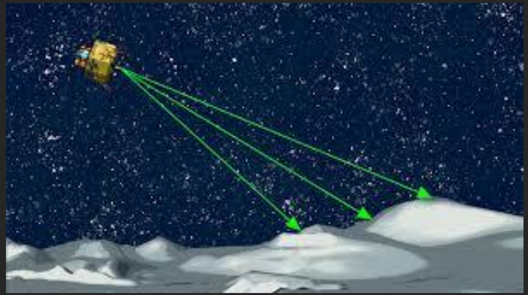
Application	Description	Key Challenges

Science Instrument Data Processing and Control	• Land imagers
	• Telescopes
	• Mass specs
	• Lidar
	• Radar
	• Cameras
	• Radiometers
	• Magnetometers
	• Biological and physical science experiments
		• Varies by instrument, but can include:
		  • Adaptive wavefront sensing and control
		  • Data reduction
		  • Low-latency alert generation
		  • SWaP sensitivity
		  • Harsh environments
		  • Autonomous operations

Landing systems	• Autonomous landing and hazard avoidance • Terrain relative navigation • Hazard detection and avoidance	• Fault tolerance (based on mission class), ranging from 2 FT to 1 FT • Operate through faults • Performance for terrain mapping and path planning
Communication relay	• In-space or surface relays for crewed and/or science missions using Delay Tolerant Networking (DTN) • Navigation and timing signals	• High bandwidth I/O • High bandwidth encryption/decryption • Onboard storage for buffering



Instruments on Curiosity Rover



ALHAT Concept

TDRSS Satellite

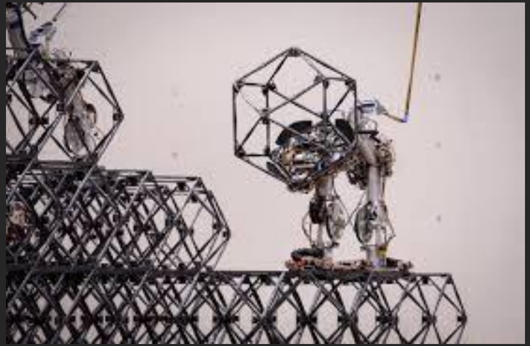
Applications

Application	Description	Key Challenges

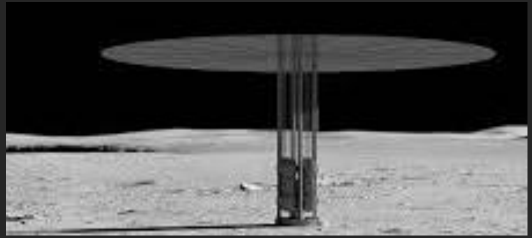
Robotics	• In-space and surface robotics, including:
	  • Rendezvous, Proximity Operations & Capture (RPOC)
	  • Servicing
	  • Assembly
	  • Construction
	  • Manufacturing
	  • Maintenance
		• Fault tolerance and safety for crew collaboration
		• Processing performance
		• Leveraging for industry standard interfaces
		• Leveraging for industry standard software tools (ROS support)
		• Mapping robotics applications to avionics requirements
		• Harsh environments

Surface systems and infrastructure for crewed presence	• Excavation and construction • In-Situ Resource Utilization (ISRU) • Surface power systems	• Processing performance to support robotics • Harsh environments
Space cloud computing	• Disaggregation of onboard processing applications to across multiple spacecraft or surface systems	• Communication overhead • Use cases identification and analysis needed

Integrated System for Autonomous and Adaptive Caretaking (ISAAC)



Automated Reconfigurable Mission Adaptive Digital Assembly Systems (ARMADAS)



Fission Surface Power

Avionics/computing needs – General Themes

Support increased autonomy

Enable closed loop onboard control systems requiring high bandwidth processing

Handling increased sensor bandwidth and sensor count

Examples - Support increased autonomy

- Earth Independent Medical Operations (EIMO)
  - Transition crew medical care and decision making from terrestrial to space-based assets to address unique risks for crewed missions to Mars
    - Long mission duration
    - Zero consumables resupply
    - Communication delays and blackouts
    - No evacuations possible
  - Onboard computing and data storage needed to support diagnostics and acute and emergent decision making

- Lunar Excavation to for ISRU
  - Large scale excavation of regolith is needed to feed IRSU plants
  - Removing the human-in-the-loop for low-level tasks is needed to increase the speed of operations
    - Regolith Excavation
    - Traverse to plant
    - Offloading regolith at plant
    - Anomaly detection and handling

Extending Crew Medical Care to Mars

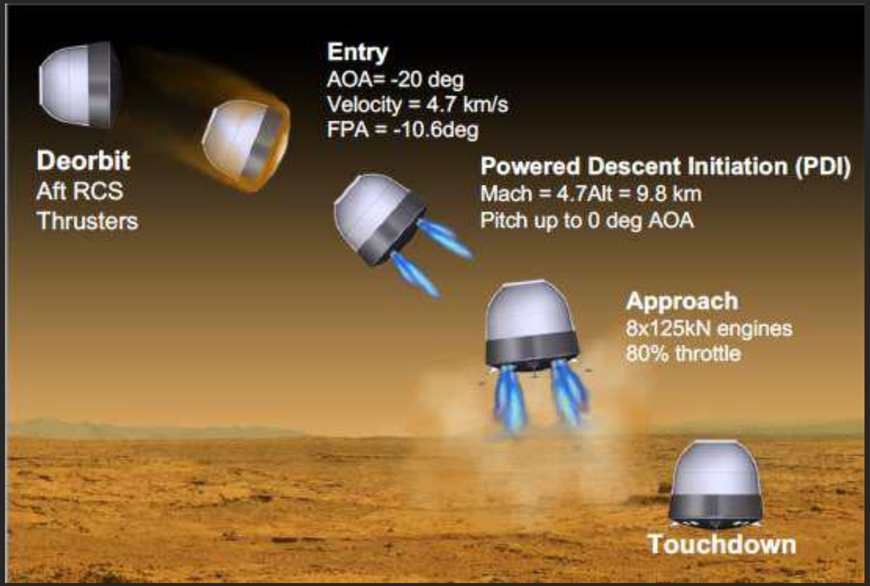
Regolith Advanced Surface Systems Operations Robot (RASSOR)

ISRU Plant Concept

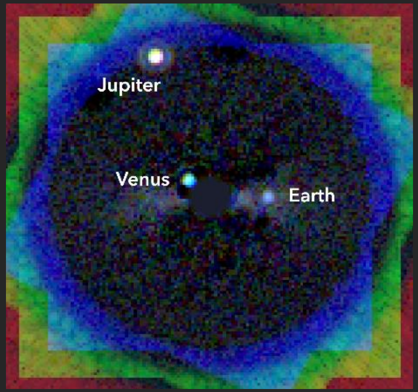
Examples - Enable closed loop onboard control systems

- Autonomous landing
    - Needed for both crewed and science missions (both lunar and Mars)
    - Must accommodate a variety of surface lighting conditions
    - One of the most challenging use cases for high performance onboard computing
        - High performance image processing is needed within a tight control loop
        - Mission critical application
        - Abort is not possible
        - Must operate through faults

- Adaptive wavefront sensing and control
    - Enable starlight nulling for direct imaging of exoplanets
    - Stabilize the wavefront from a large segmented mirror during an exposure time of a few hours
    - High performance image processing is needed within a tight control loop



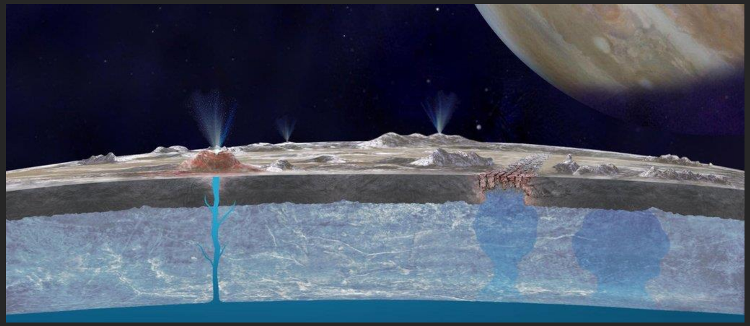
Autonomous Landing at Mars



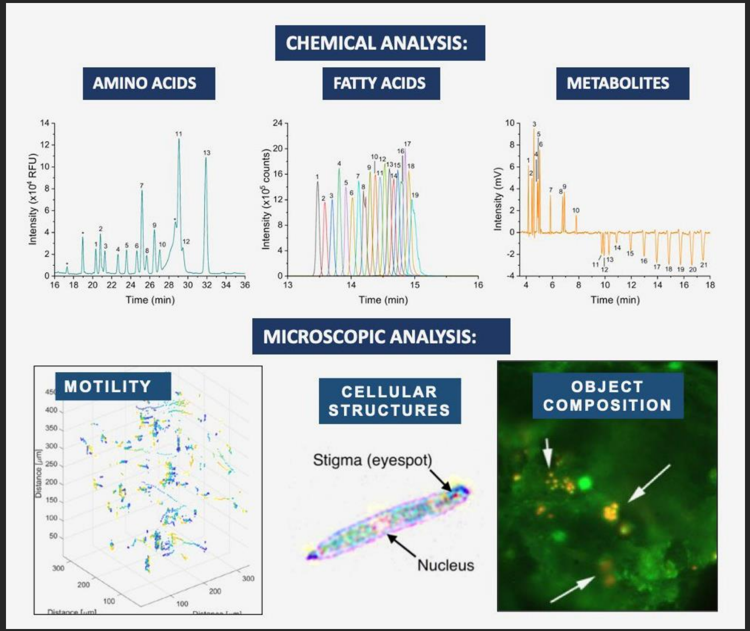
Simulated Image of the Solar System with Starlight Nulling

Examples - Handling increased sensor bandwidth

- Ocean Worlds Life Surveyor (OWLS)
  - Integrated, portable, and autonomous life-detection instrument suite designed to identify and characterize life on ocean worlds
  - Performs chemical and microscopic analysis of collected samples, which requires significant onboard processing
  - Requires a 1000X reduction in data volume
  - Will utilize onboard science autonomy algorithms to achieve this



Artist Depiction of Ocean World

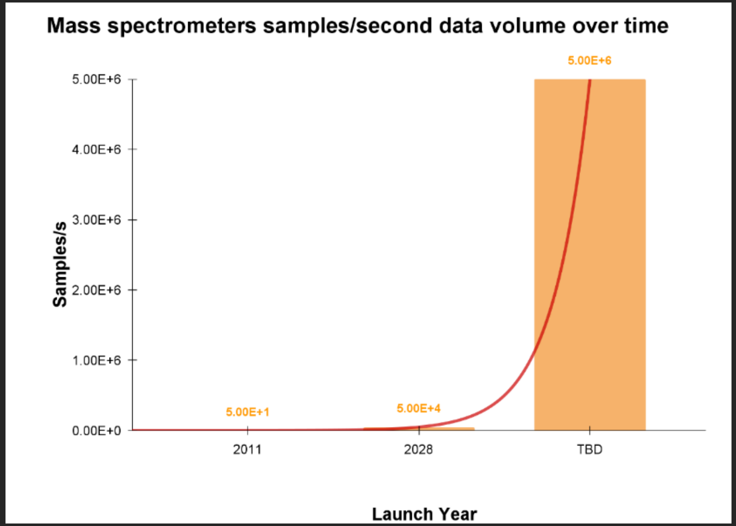


OWLS Data Analysis

Examples - Handling increased sensor bandwidth

- Mass spectrometers
  - Data bandwidths from outer planetary missions are exceedingly small
  - Dragonfly Mission will return < 20 Gbytes/year
  - Newer, high resolution mass spectrometer designs produce vastly more data
  - May require 100X onboard data reduction
  - Missions will rely on science autonomy to prioritize data for downlink

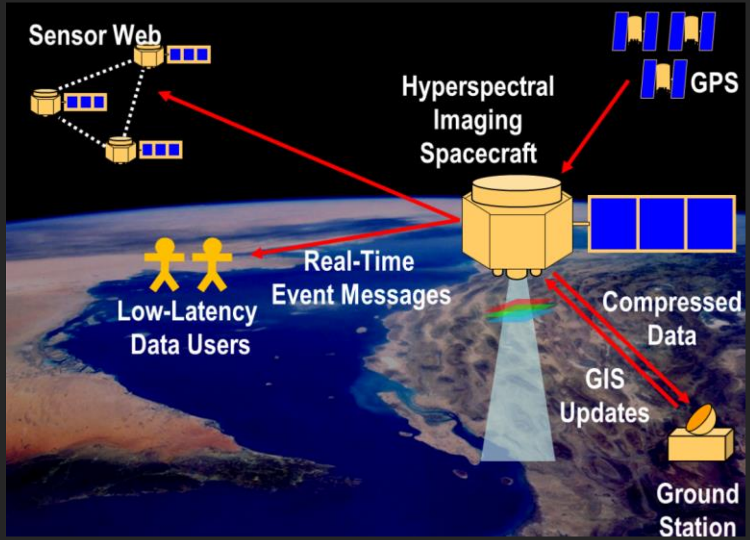
Sample Analysis at Mars (SAM) Instrument



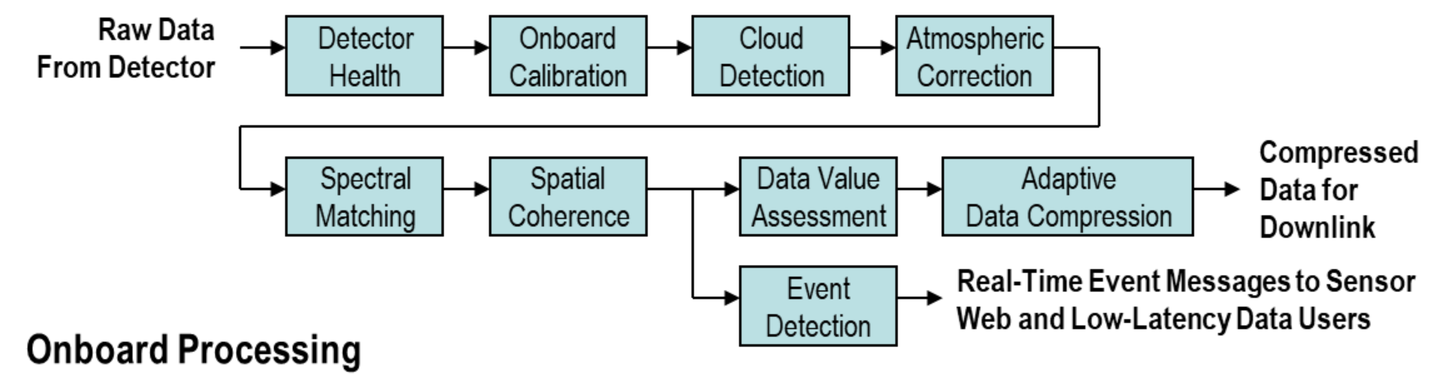
Mass Spectrometer Trends

Examples – Handling increased sensor bandwidth

- Hyperspectral land imagers
  - Sensor data rates far exceed downlink rates
  - Onboard data assessment (potentially using AI/ML) to prioritize data
  - Adaptive compression to maximize priority science downlink
  - Event detection to provide low latency notification to users and other observational assets
    - Fire
    - Flood
    - Volcanic activity



Conceptual Hyperspectral Imaging Mission



Raw Data From Detector → Detector Health → Onboard Calibration → Cloud Detection → Atmospheric Correction → Spectral Matching → Spatial Coherence → Data Value Assessment → Adaptive Data Compression → Compressed Data for Downlink

Spatial Coherence → Event Detection → Real-Time Event Messages to Sensor Web and Low-Latency Data Users

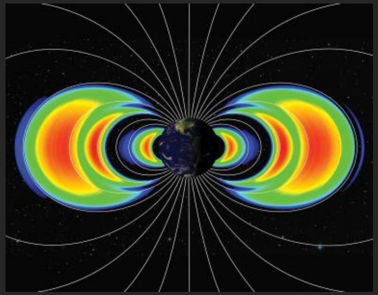
Onboard Processing

Key Avionics/Computing Attributes – Radiation Tolerance

- Specific radiation requirements will vary based on Mission, Application, Environment, and Lifetime (MEAL)
- Total Ionizing Dose (TID) requirements can range from <30 krad at LEO to >2-3 Mrad at Europa
- Total Nonionizing Dose (TNID) requirements are levied on bipolar, electro-optical and detector technologies and also vary many orders of magnitude for different mission environments and durations
- Destructive Single Event Effects (SEE)
  - Immunity to Single-Event Latchup (SEL) and other destructive SEE are typically needed
- Nondestructive Single Event Effects (SEE)
  - Single Event Upset (SEU)
  - Single Event Transient (SET)
  - Single Event Functional Interrupt (SEFI)
  - Levels of mitigation depend mission and the application criticality
- What about shielding?
  - Shielding can be used to mitigate TID, but can exacerbate single event effects

Natural Space Radiation Sources


Solar Energetic Particles


Trapped Protons and Electrons


Galactic Cosmic Rays (GCRs)

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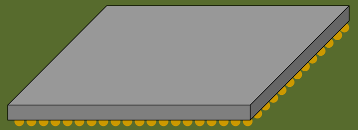
Key Avionics/Computing Attributes – Fault Tolerance

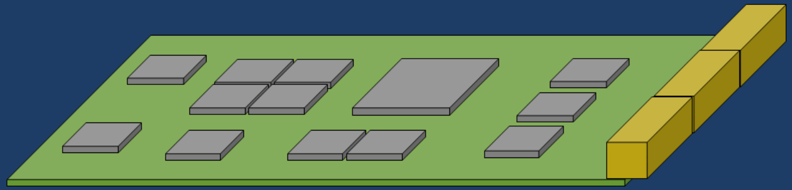
Component-level

- Foundry selection
- Cell library selection
- Circuit implementation (parity, ECC, redundancy)
- Microarchitecture (fault isolation/containment)



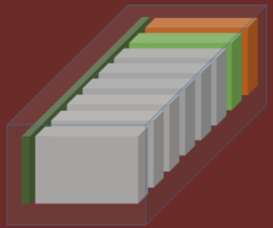
Board-level

- Component redundancy
- Local watchdog timers
- EDAC
- Power fault management



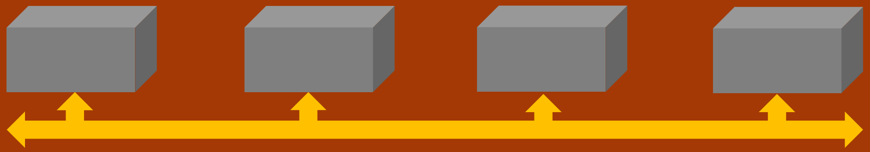
Chassis-level

- Fault isolation/containment
- Board redundancy
- Chassis management for fault tolerance
- Power fault management



Avionics-level

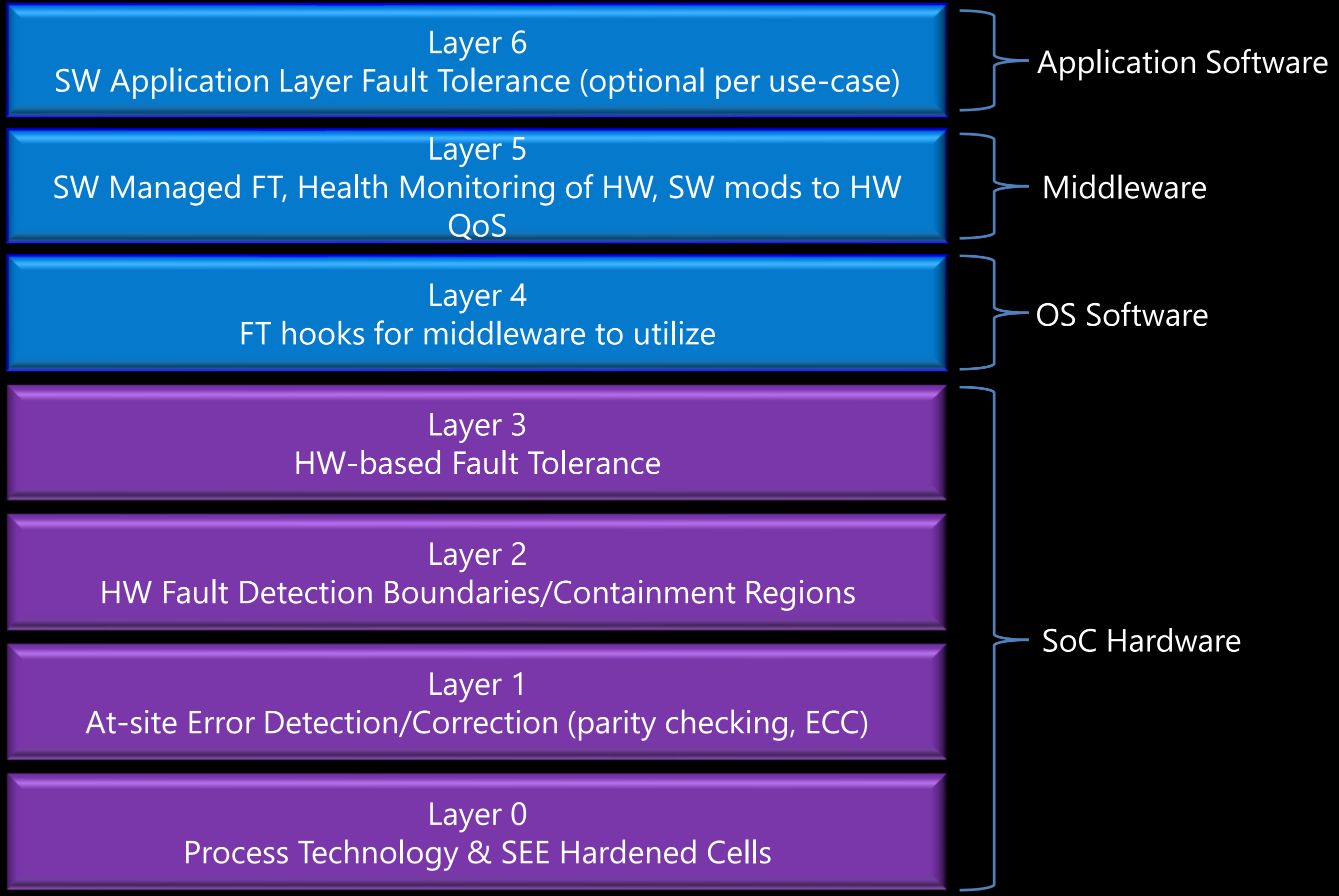
- Fault isolation/containment
- Interconnect ECC
- Interconnect Link redundancy
- Byzantine fault tolerance



Specific fault tolerance approaches may be mission dependent

Key Avionics/Computing Attributes – Fault Tolerance

- Another perspective



Layer 6
SW Application Layer Fault Tolerance (optional per use-case)

Layer 5
SW Managed FT, Health Monitoring of HW, SW mods to HW QoS

Layer 4
FT hooks for middleware to utilize

Layer 3
HW-based Fault Tolerance

Layer 2
HW Fault Detection Boundaries/Containment Regions

Layer 1
At-site Error Detection/Correction (parity checking, ECC)

Layer 0
Process Technology & SEE Hardened Cells

Application Software

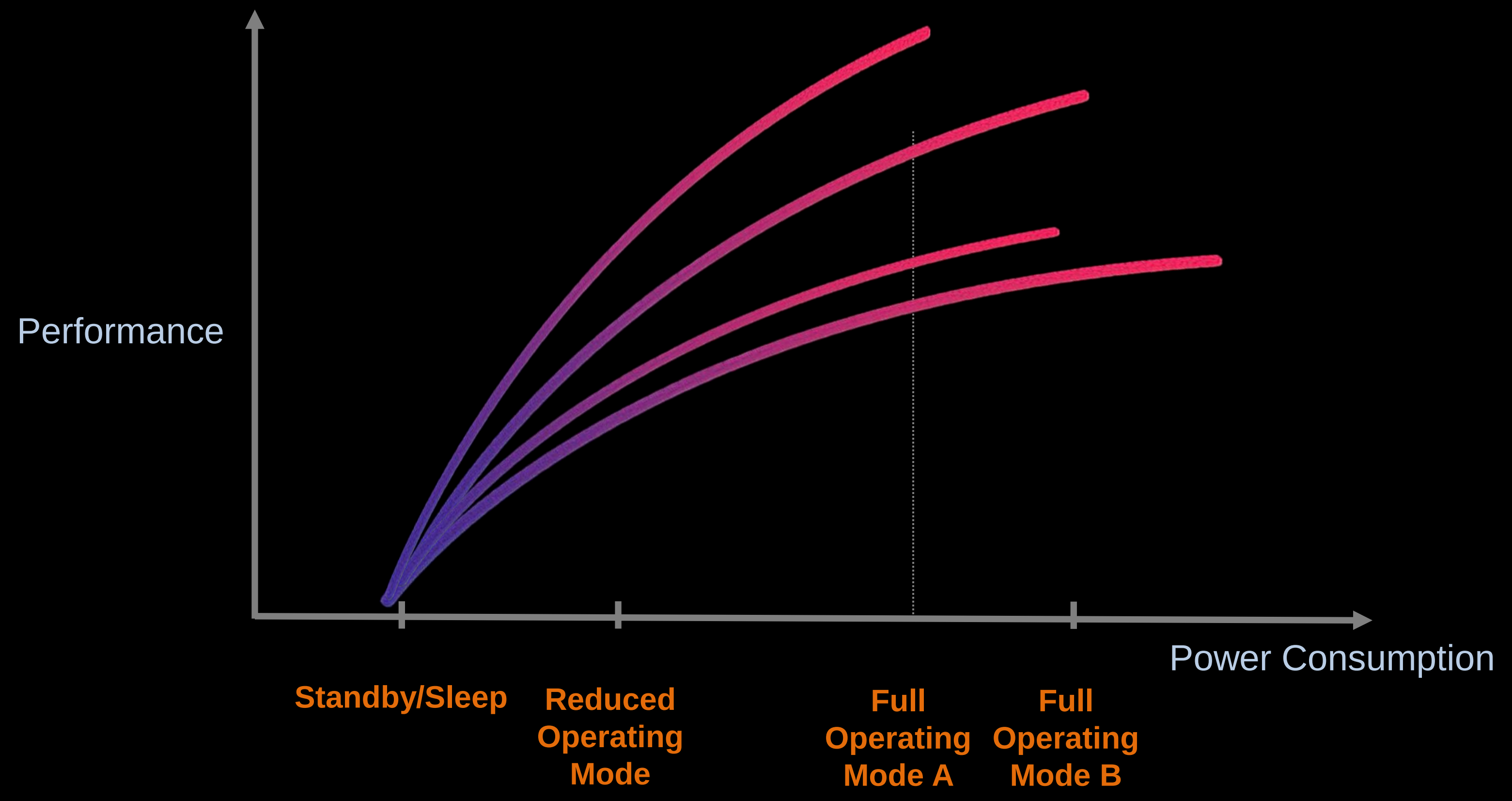
Middleware

OS Software

SoC Hardware

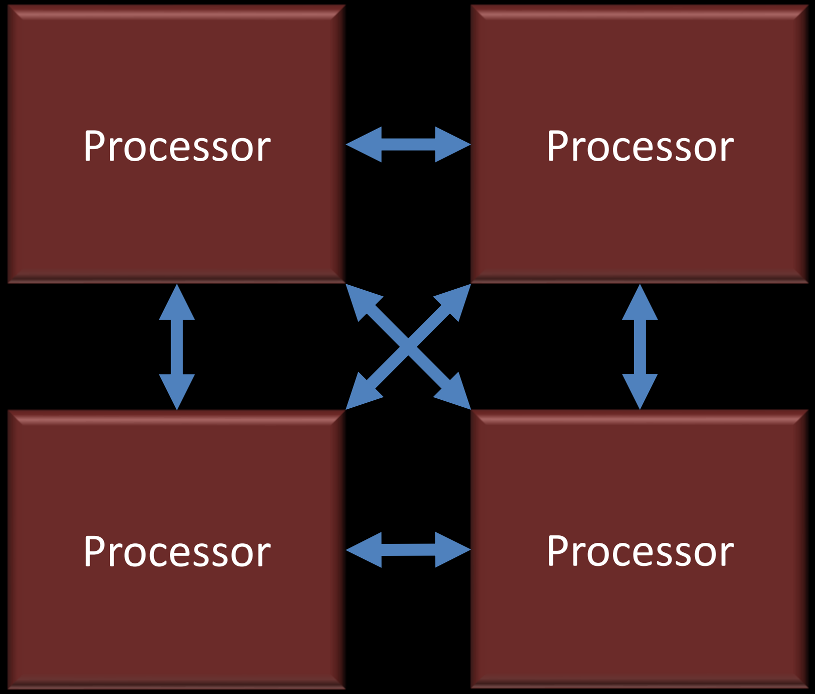
Key Avionics/Computing Attributes – Scalability

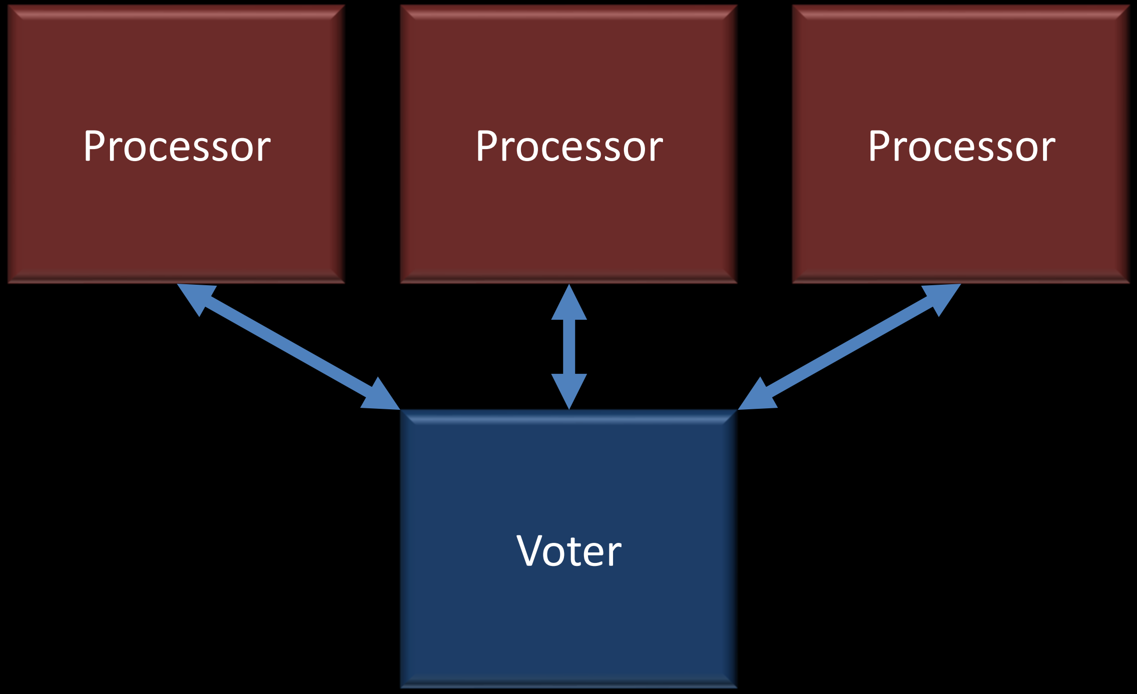
Power, Performance, Fault Tolerance and other Functions: Scalable via Software Control



Key Avionics/Computing Attributes – Expandability

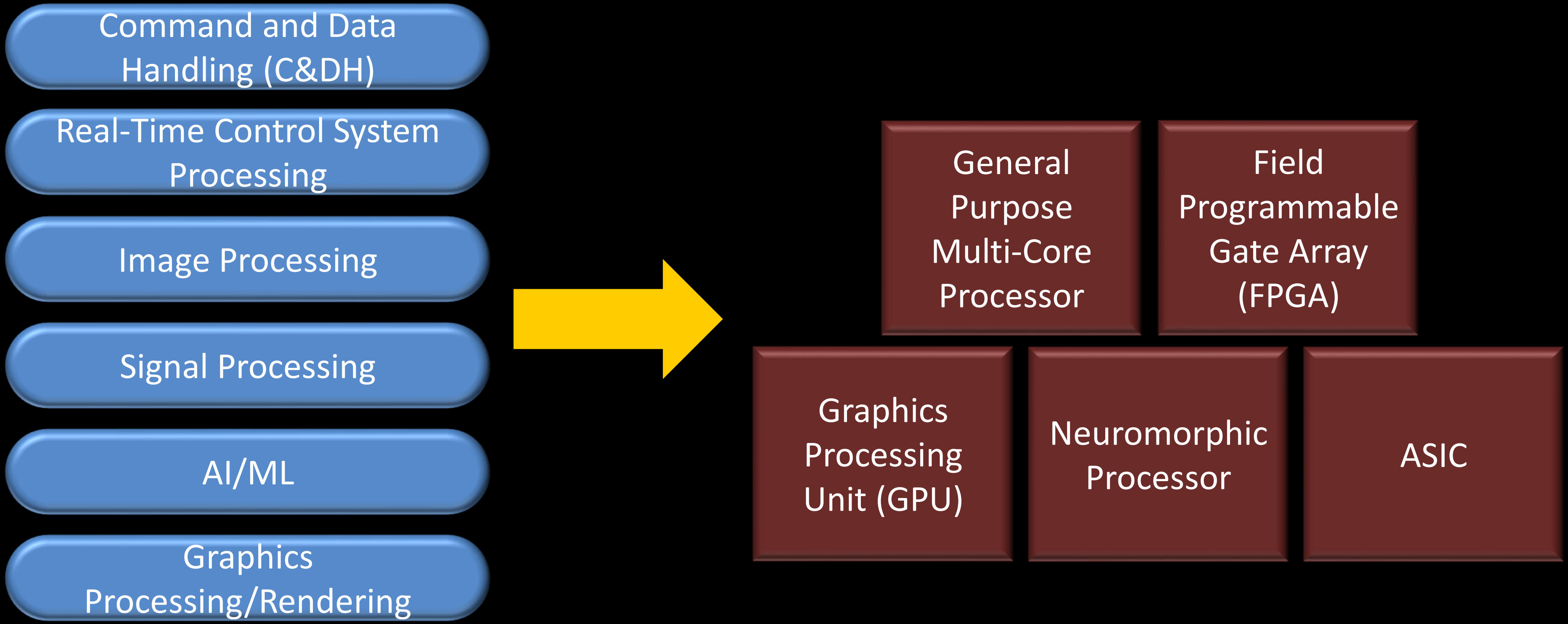
- For applications requiring processing bandwidth or fault tolerance beyond what a single processor can provide, extensibility enables implementation of multi-processor-HPSC systems





Key Avionics/Computing Attributes – Extensibility

- Diverse computing needs will drive needs for different processing device
- It's expected that avionics will often be hybrid systems that are extensible to employ multiple computing architectures



Command and Data Handling (C&DH)

Real-Time Control System Processing

Image Processing

Signal Processing

AI/ML

Graphics Processing/Rendering

General Purpose Multi-Core Processor

Field Programmable Gate Array (FPGA)

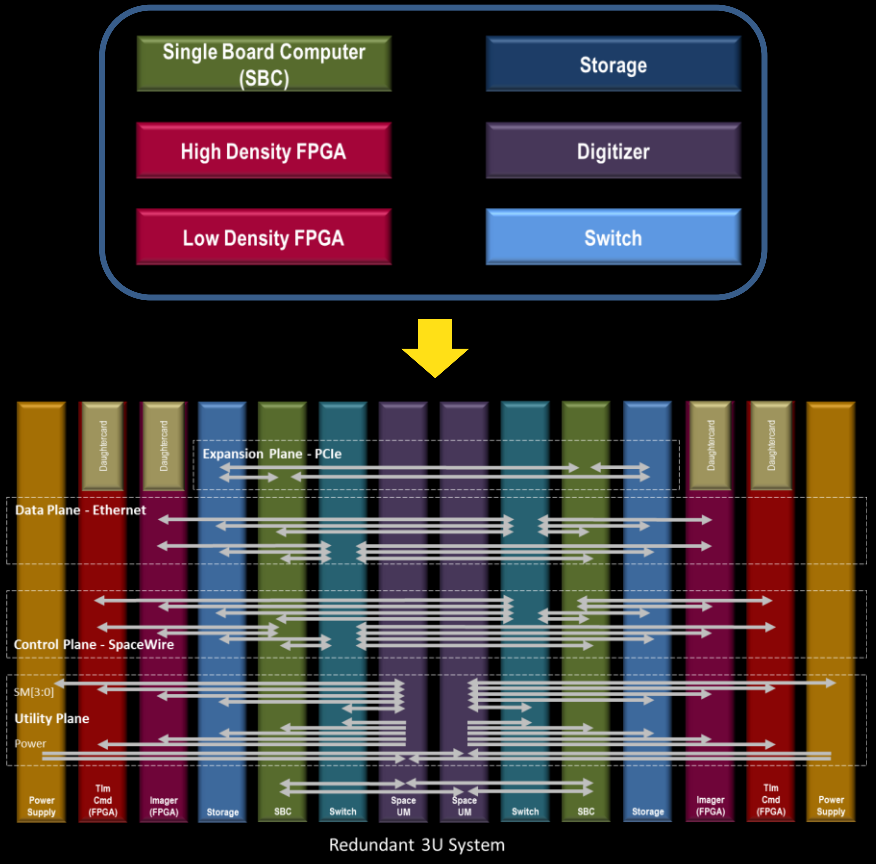
Graphics Processing Unit (GPU)

Neuromorphic Processor

ASIC

Key Avionics/Computing Attributes – Interoperability

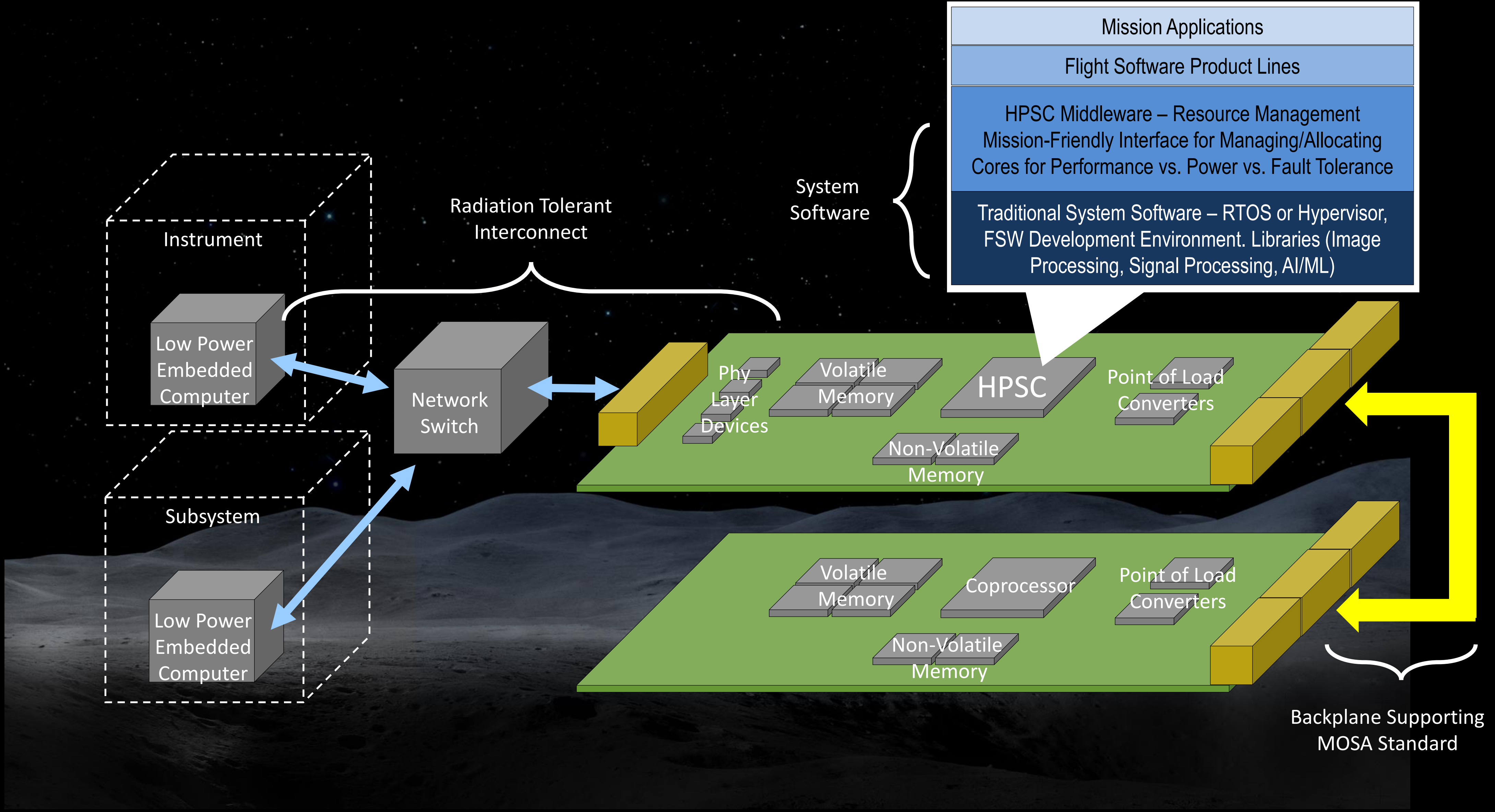
- NASA is currently working with industry to establish interoperable SpaceVPX standards at the avionics card level
- Allows a system developer to compose a system using an ecosystem of cards from multiple vendors that can interoperate



Redundant 3U System

SpaceVPX Concept

HPSC Ecosystem - A Deep Dive



Mission Applications

Flight Software Product Lines

HPSC Middleware – Resource Management
Mission-Friendly Interface for Managing/Allocating
Cores for Performance vs. Power vs. Fault Tolerance

Traditional System Software – RTOS or Hypervisor,
FSW Development Environment. Libraries (Image
Processing, Signal Processing, AI/ML)

System Software

Radiation Tolerant Interconnect

Instrument

Low Power Embedded Computer

Network Switch

Subsystem

Low Power Embedded Computer

Phy Layer Devices

Volatile Memory

HPSC

Point of Load Converters

Non-Volatile Memory

Volatile Memory

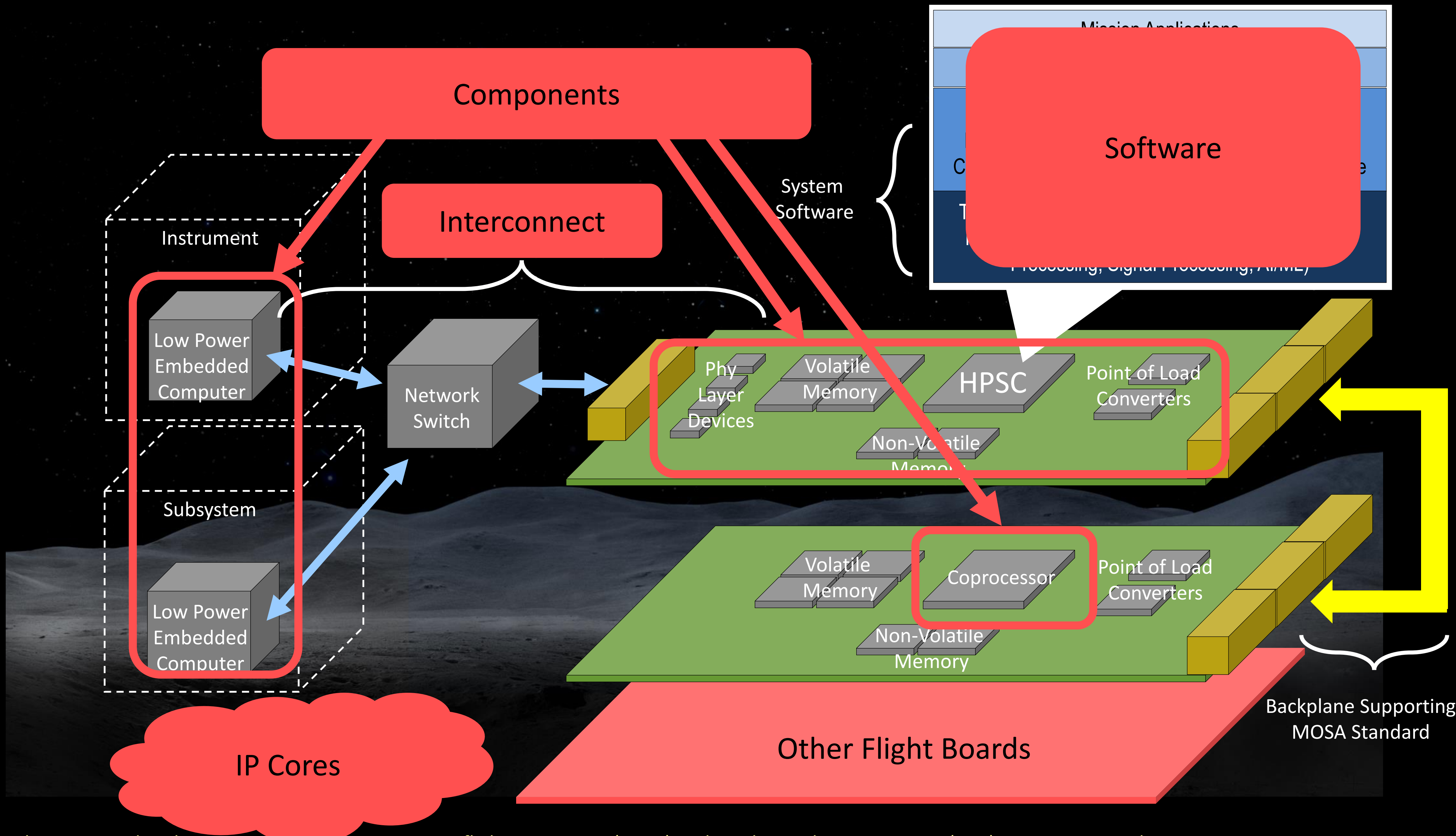
Coprocessor

Point of Load Converters

Non-Volatile Memory

Backplane Supporting MOSA Standard

HPSC Ecosystem - A Deep Dive



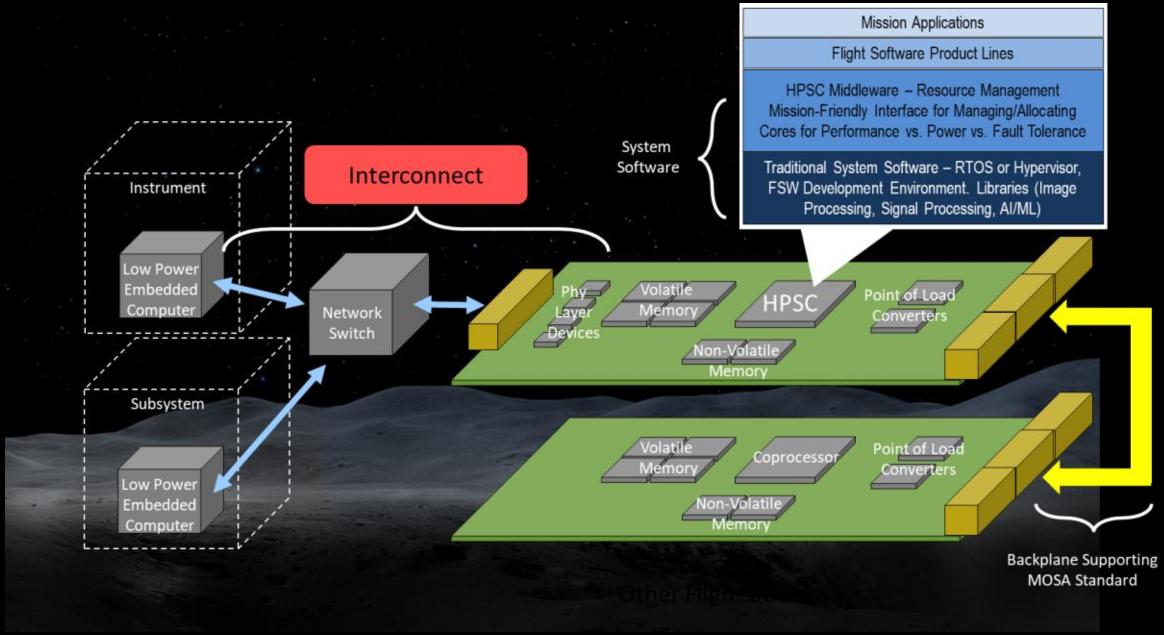
To be presented at the 2024 High Performance Spaceflight Computing (HPSC) Technical Interchange Meeting (TIM), NASA MSFC, February 13 – 14, 2024

HPSC Ecosystem – Interconnect (Chassis to Chassis)

- Industry standard

- Increased bandwidth
  - Multiple video streams for crewed missions
  - Instrument data
    - Hyperspectral imagers
    - Synthetic Aperture Radar (SAR)

- Support for multiple Quality of Service (QoS) levels
  - Best effort traffic
  - Rate constrained traffic
  - Deterministic traffic



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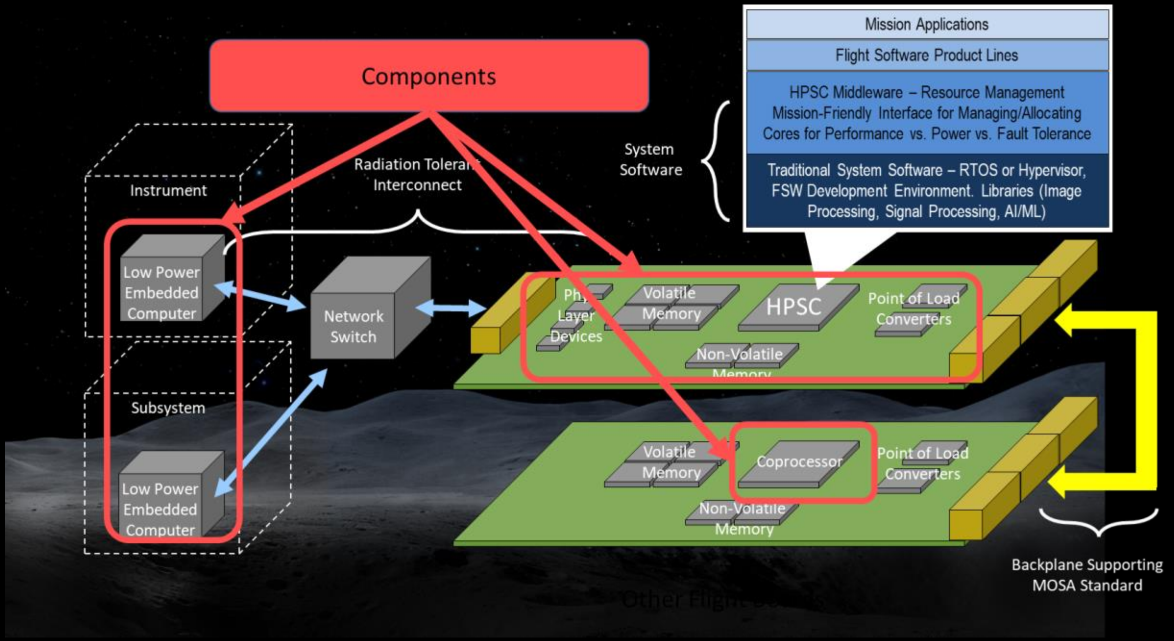
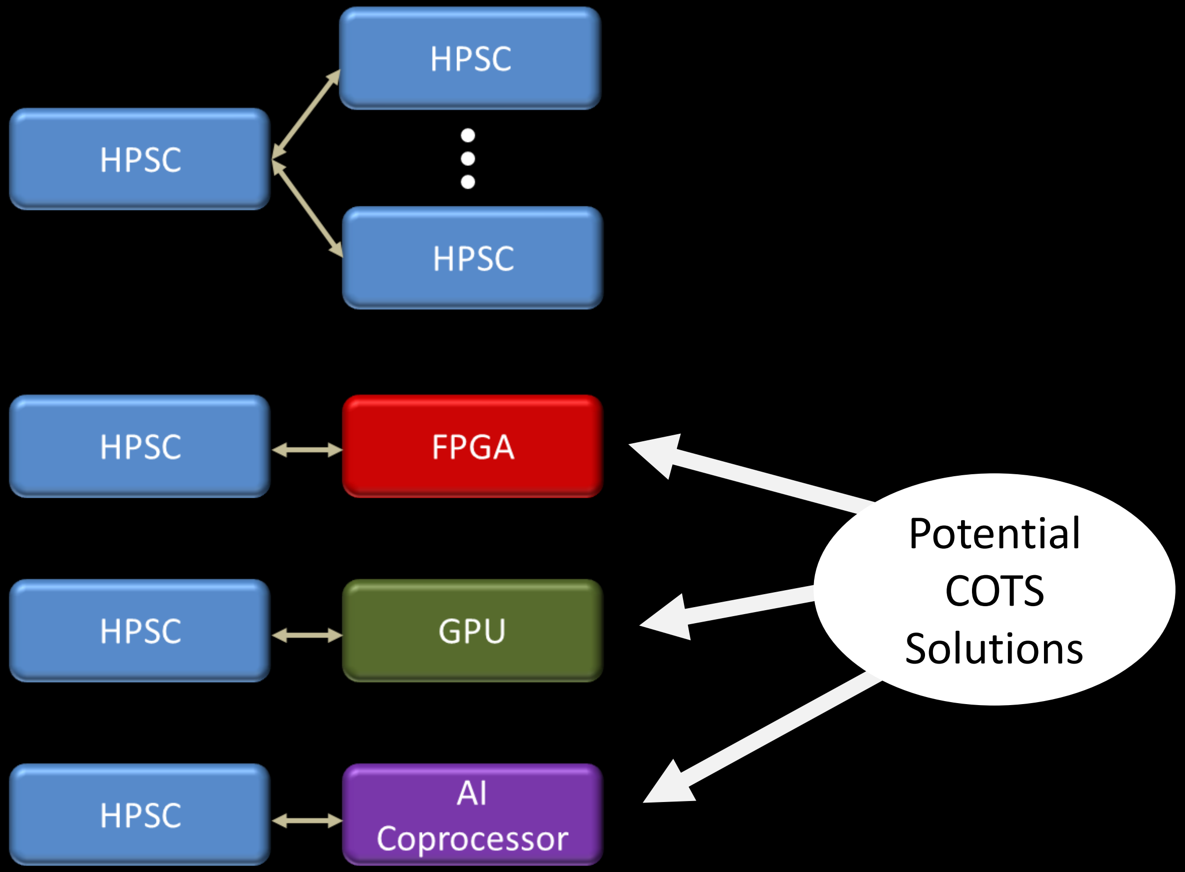
HPSC Ecosystem - Components

- Power Management
  - Intelligent, efficient, rad hard multiple output Point-Of-Load (POL) direct current (DC) to DC power converters to support current and emerging processor and Field Programmable Gate Array (FPGA) devices
- Volatile Memory
  - Advanced spaceflight volatile memory with industry standard DDR3/4 interfaces with Single Event Functional Interrupt (SEFI) radiation tolerance
- Non-Volatile Memory
  - Advanced spaceflight non-volatile memory with Single Event Functional Interrupt (SEFI) radiation tolerance and industry standard interfaces

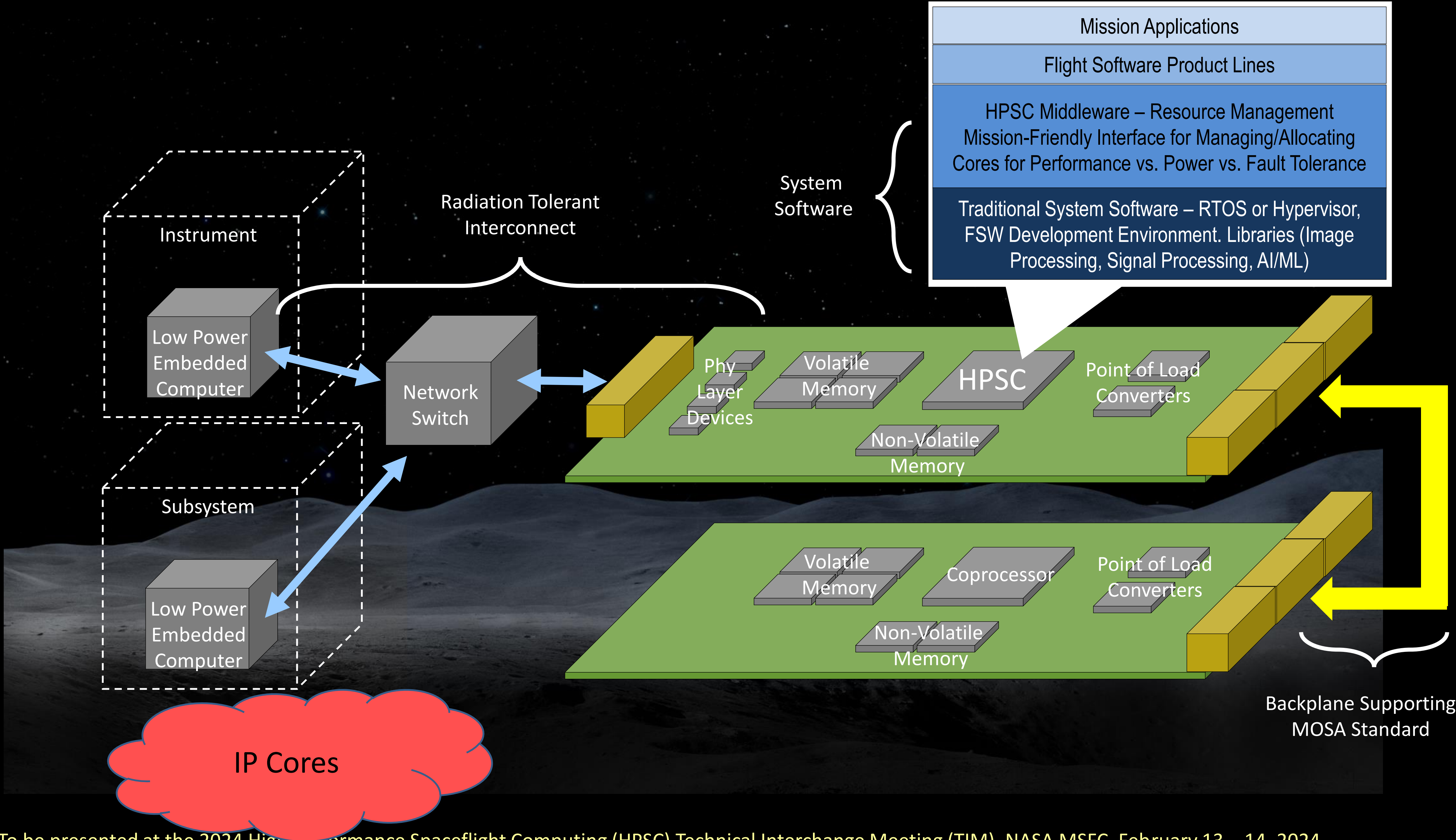


What About COTS Components?

- While much of NASA's emphasis within avionics is on HPSC, there is also a role for COTS processing solutions
- Use of COTS computing technologies must be guided by MEAL principles
- COTS parts from Industry Leading Parts Manufacturer (ILPM) are preferred
- Note that the broader HPSC ecosystem may leverage COTS coprocessors

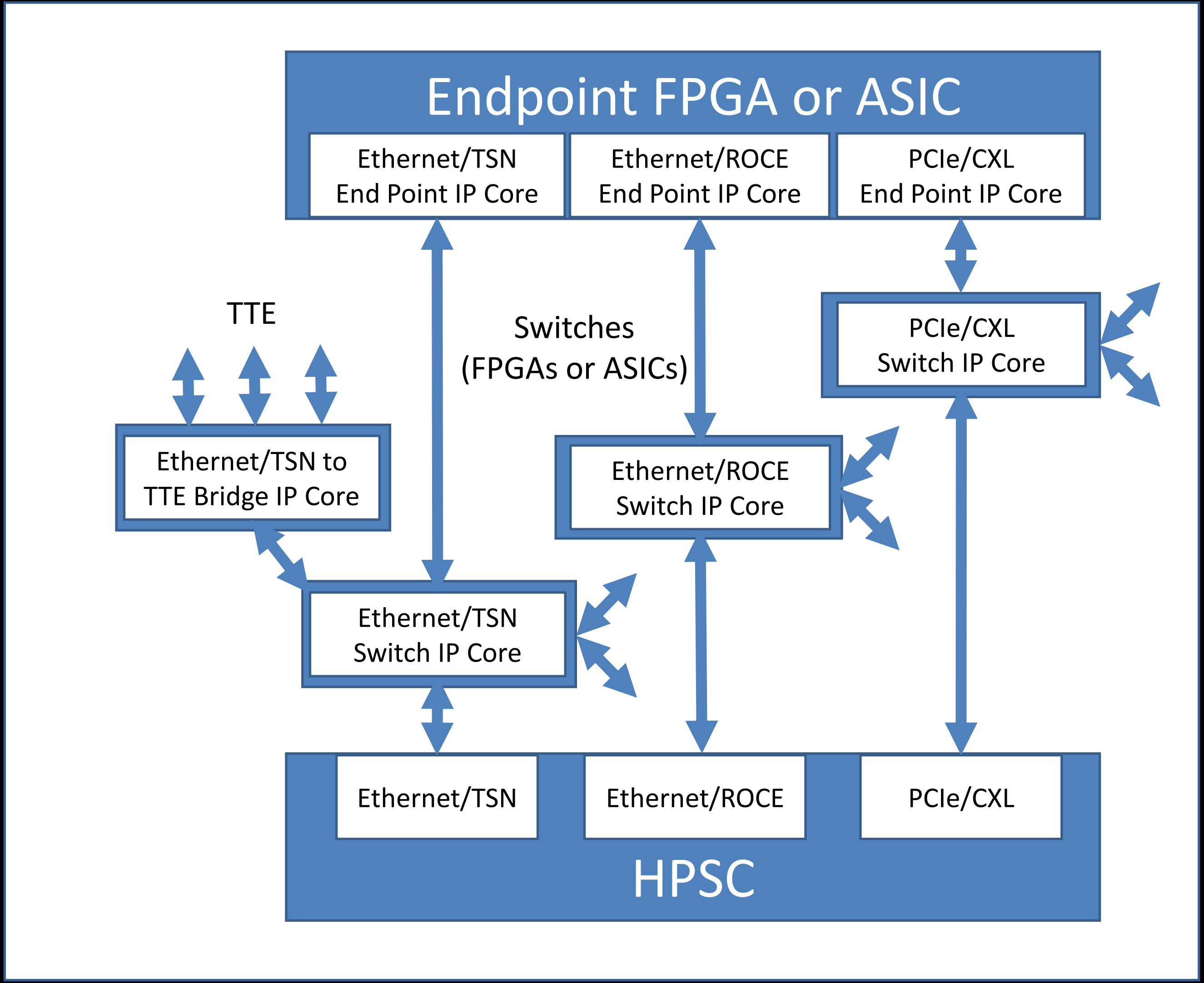


HPSC Ecosystem – IP Cores



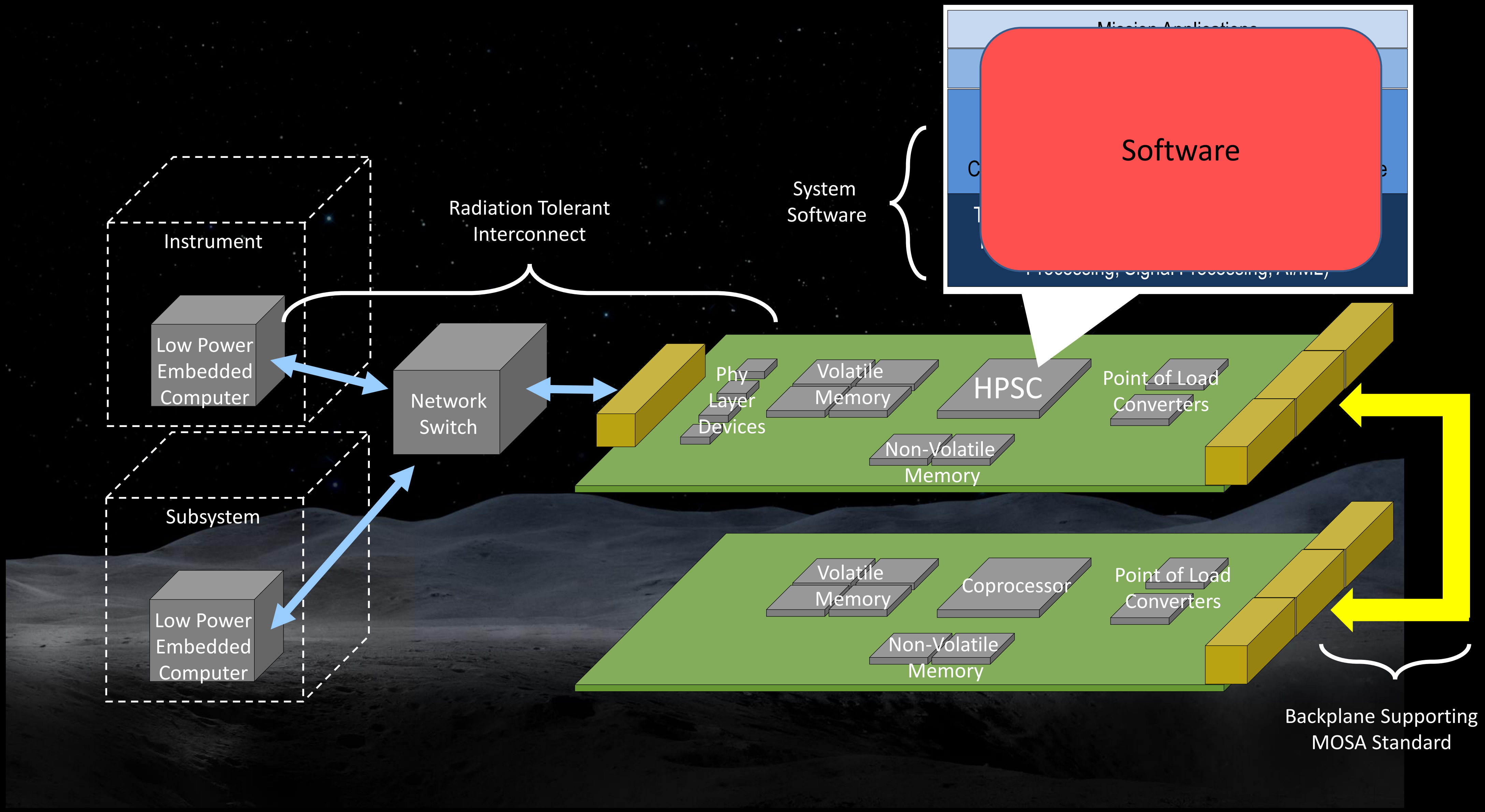
HPSC Ecosystem – IP Cores

- IP Cores are needed to implement complementary interfaces to HPSC as end points within FPGAs or ASICs
  - Ethernet/TSN
  - ROCE
  - PCIe/CXL
- Switch IP cores are also needed for these interfaces
- “Bridging” IP cores are support legacy interconnect standards
  - 1553
  - TTE
  - Others
- These IP Cores are needed across the full range of spaceflight FPGA families
- Additionally, IP cores may be needed to support development of supporting ASICs
  - Coprocessors
  - Switches
  - Low power embedded computers



To be presented at the 2024 High Performance Spaceflight Computing (HPSC) Technical Interchange Meeting (TIM), NASA MSFC, February 13 – 14, 2024

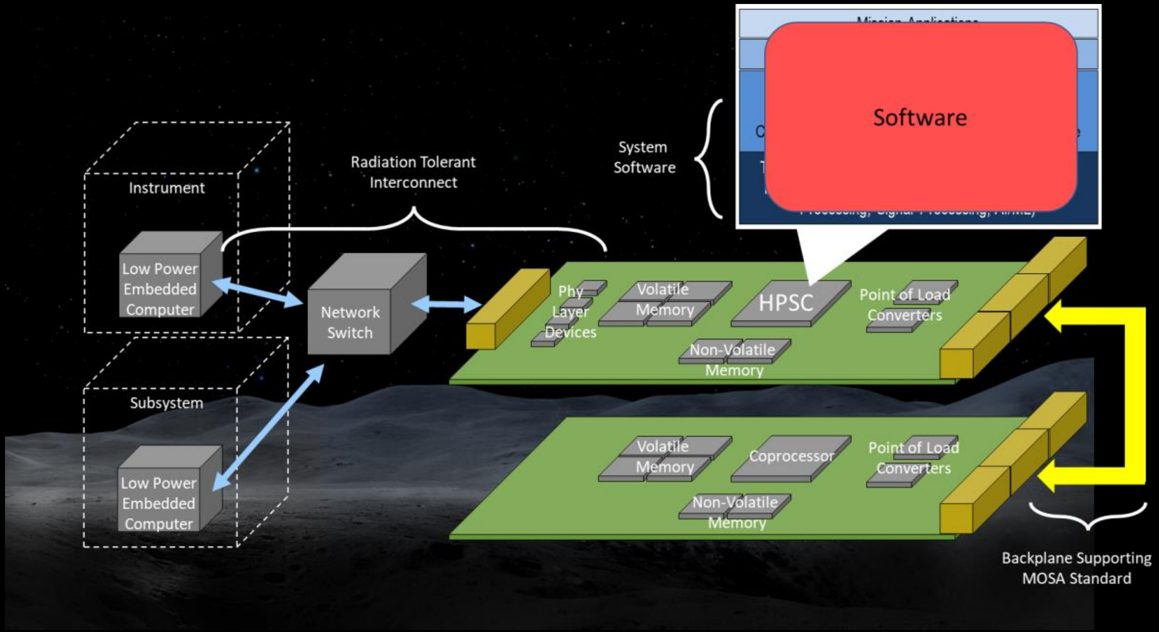
HPSC Ecosystem - Software



HPSC Ecosystem - Software

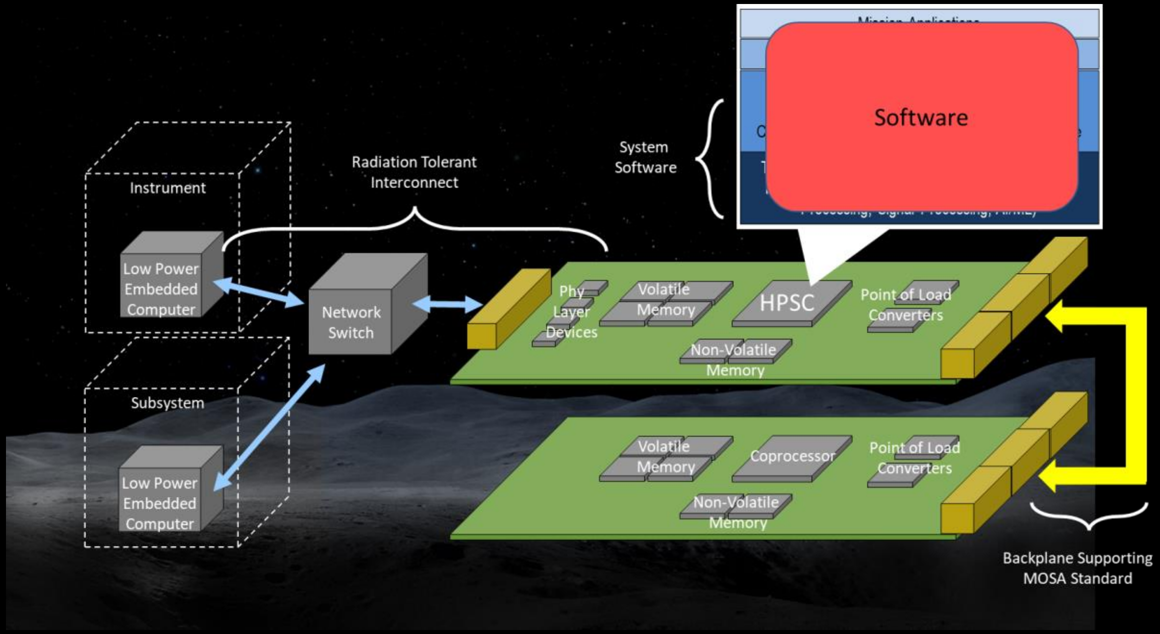
- Flight Software Architectures
  - Assessing adaptations that are needed for cFE/cFS and F’ flight software architectures to fully leverage the features and capabilities of HPSC

- Tools
  - OpenXLA
    - OpenXLA is an open-source machine learning compiler that accepts and optimizes models from a variety of ML frameworks and can target execution on a variety of processing platforms
    - Port to HPSC architecture
  - Vulkan
    - Vulkan is a low-level 3D graphics processing API that can target execution on a variety of processing platforms
    - Port to HPSC

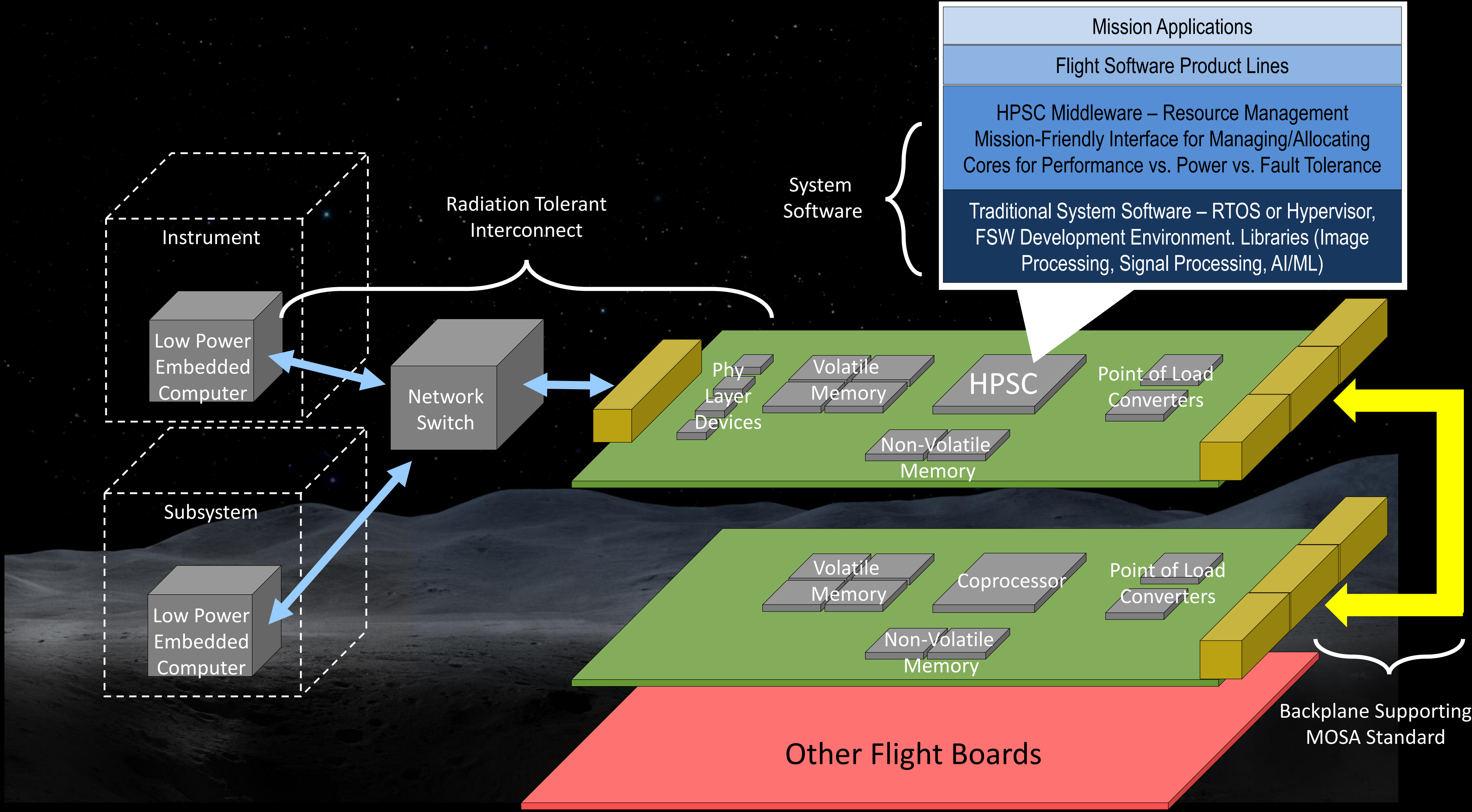


HPSC Ecosystem - Software

- SpaceVPX Support Software
  - Chassis Manager
    - Chassis management software is needed to control SpaceVPX chassis
  - IPMC
    - Intelligent Platform Management Interface (IPMI) Controller software is needed for local control of each SpaceVPX PIC
- Multi-Core Verification & Validation (V&V)
  - V&V tools and methodologies are needed for safety critical applications on multi-core processing platforms
- Cybersecurity methodologies and tools
  - Software tools providing secure boot, cybersecurity policy management, with automated detection and reaction to potential intrusions within avionics systems



HPSC Ecosystem – Boards



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HPSC Ecosystem – Boards

- SpaceVPX is planned as the foundation of the HPSC ecosystem
- Board level products (PICs in SOSA terminology) are needed to establish this ecosystem
- PSCs and PICs must support both single-string and cross strapped redundant configurations
- Standard Products
  - It is expected that most of the SpaceVPX PICs would be available as standard products from industry
  - The Space External I/O PIC and daughtercards that would implement mission specific interfaces may not initially be standard products
- 3U and 6U
  - The need for both 3U and 6U systems is recognized
- Other form factors
  - Some NASA HPSC use cases point to a need for smaller than 3U SpaceVPX

Board Types	Description
Power Supply Card (PSC)	Powers SpaceVPX chassis.
Utility Switch PIC	Provides point-to-point utility plane routing allowing PIC fault isolation.
Single Board Computer (SBC) PIC	Primary processor within chassis. Can optionally serve as system controller and chassis manager.
Co-processor PIC	Processing offload for primary processor. Cannot serve as system controller and chassis manager .
Switch PIC	Expands connectivity for data plane and/or control plane.
External I/O PIC	Provides connectivity outside the SpaceVPX chassis.
Data Storage PIC	Provides network attached storage for bulk memory storage.
SSD PIC	Provides solid state drive with tight coupling to SBC or co-processor.
Radio PIC	Provides uplink and downlink.

Focusing on Data Storage

- Cybersecurity methodologies and tools
  - Software tools providing secure boot, cybersecurity policy management, with automated detection and reaction to potential intrusions within avionics systems

- System analysis and modelling methodologies and tools
  - Avionics systems are becoming orders of magnitude more complex, incorporating autonomy, onboard crew health and performance monitoring, robotic construction and ISRU functionality, and human-robotic interactions
  - As this complexity grows, modelling tools are needed to understand the optimal configuration of avionics components and systems based on mission needs

  - Modelling and simulation tools are also needed for for automated state space delineation and exploration to provide understanding and assurance of correct behavior under both nominal, off-nominal, and unanticipated conditions

Other Ecosystem Needs

- Support federated and distributed computing architectures
  - Low power embedded computing in instruments and subsystems
  - Hierarchical data concentrators to handle large sensor count

- Increased onboard storage
  - Science data, video, science reference data sets, AI/ML models, reference material for crewed operations/maintenance, …

- Cybersecurity methodologies and tools
  - Software tools providing secure boot, cybersecurity policy management, with automated detection and reaction to potential intrusions within avionics systems

- System analysis and modelling methodologies and tools
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Conclusions

- NASA has a diverse set of mission objectives, but general themes exist for future computing needs
  - Support increased autonomy
  - Handling increased sensor bandwidth and sensor count
  - Enable closed loop onboard control systems requiring high bandwidth processing

- Key attributes for future avionics/computing include:
  - Radiation tolerance, Fault tolerance, Scalability, Extensibility, Expandability, Interoperability

- We are engaging industry to develop the avionics/computing ecosystem to meet our future mission needs

- **We welcome your participation!**

Acronym List

AI	Artificial Intelligence	ILPM	Industry Leading Parts Manufacturer	RASSOR	Regolith Advanced Surface Systems Operations Robot
AOA	Angle of Attack	I/O	Intput/Output	RCS	Reaction Control System
API	Application Programming Interface	IP	Intellectual Property	ROCE	Remote Direct Memory Access Over Converged Ethernet
ARMADAS	Automated Reconfigurable Mission Adaptive Digital Assembly Systems	IPMI	Intelligent Platform Management Interface	ROS	Robot Operating System
ASIC	Application Specific Integrated Circuit	IPMC	IPMI Controller	RPOC	Rendezvous, Proximity Operations & Capture
CAL	Cold Atom Laboratory	ISAAC	Integrated System for Autonomous and Adaptive Caretaking	RTOS	Real Time Operating System
cFE/cFS	Core Flight Executive/Core Flight Software	ISRU	In Situ Resource Utilization	SAM	Sample Analysis at Mars
COTS	Commercial Off the Shelf	JPL	Jet Propulsion Laboratory	SAR	Synthetic Aperture Radar
C&DH	Command and Data Handling	kN	kiloNewton	SBC	Single Board Computer
CXL	Compute Express Link	kRad	kiloRad	SEE	Single Event Effect
DDR	Double Data Rate	MEAL	Mission, mission Environment, Application, and Lifetime	SEFI	Single Event Functional Interrupt
DTN	Delay Tolerant Networking	ML	Machine Learning	SEL	Single Event Latchup
ECC	Error Correction Code	MMS	Magnetospheric Multiscale Mission	SET	Single Event Transient
EIMO	Earth Independent Medical Operations	MOSA	Modular Open Systems Architecture	SOC	System-On-a-Chip
ELCSS	Environmental Control and Life Support System	MRad	MegaRadi	SOSA	Sensor Open Systems Architecture
FPGA	Field Programmable Gate Array	NASA	National Aeronautics and Space Administration	SSD	Solid State Drive
FT	Fault Tolerance	OpenXLA	Open Accerated Linear Algebra	STMD	Space Technology Mission Directorate
GB	Gigabyte	OS	Operating System	SW	Software
Gbps	Gigabits Per Second	OWLS	Ocean Worlds Life Surveyor	SWaP-C	Size Weight and Power, and Cost
GCR	Galactic Cosmic Ray	PCIe	Peripheral Component Interconnect Express	TID	Total Ionizing Dose
GPS	Global Positioning System	PDI	Powered Descent Initiation	TNID	Total Non-Ionizing Dose
GPU	Graphics Processing Unit	PIC	Plug-In Card	TSN	Time-Sensitive Networking
IEEE	Institute of Electrical and Electronics Engineers	POL	Point of Load	TTE	Time Triggered Ethernet
HPSC	High Performance Spaceflight Computing	PSC	Power Supply Card	V&V	Verification and Validation
HW	Hardware	QoS	Quality of Service		