An Open Avionics and Software Architecture to Support Future NASA Exploration Missions

IEEE MetroCon 2017
October 26, 2017

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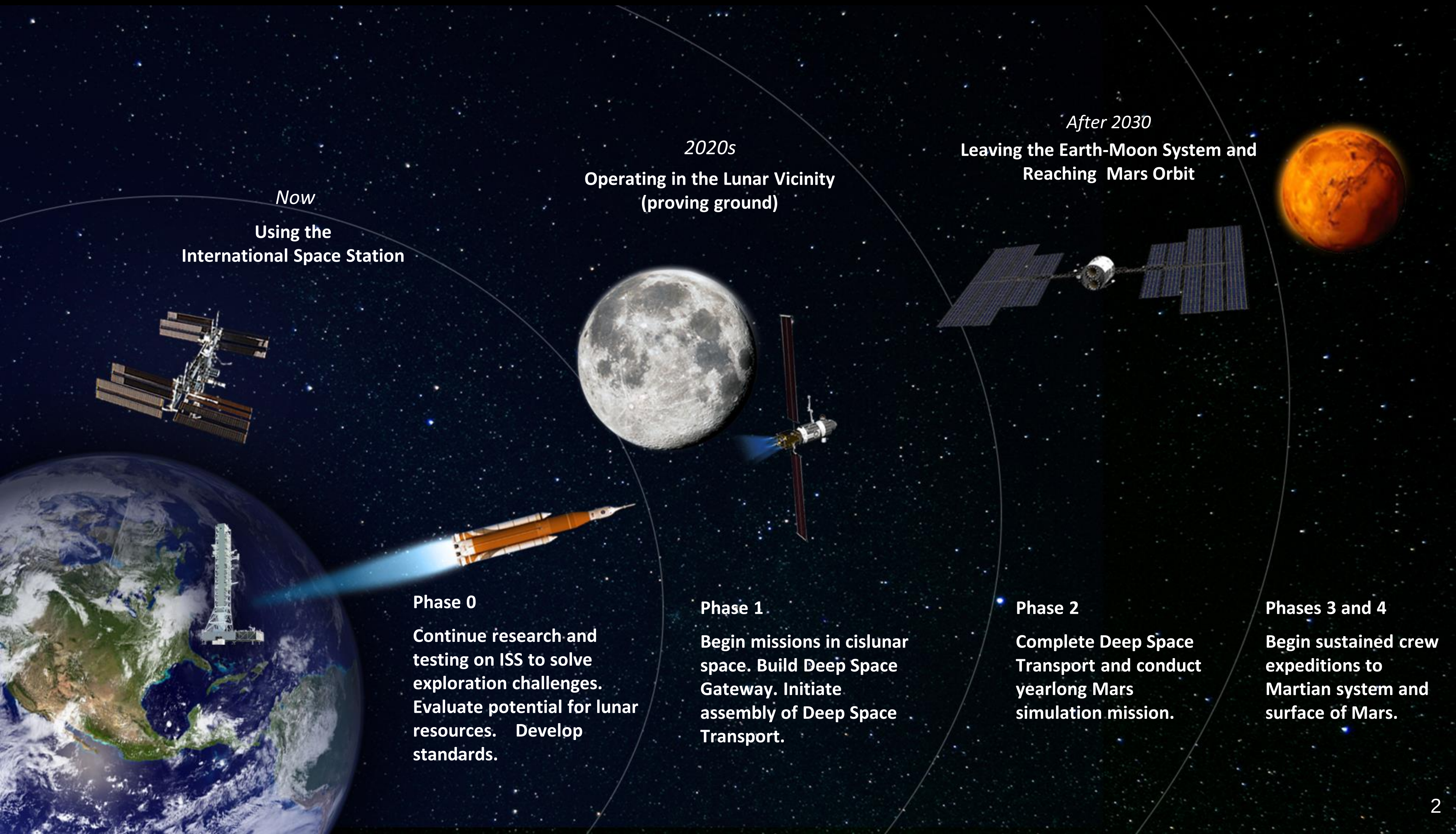
NASA's Exploration Roadmap

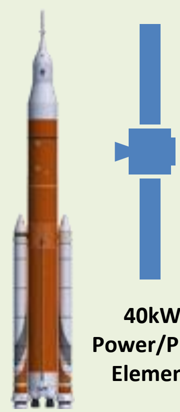
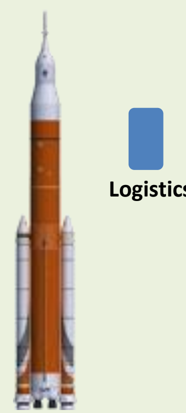
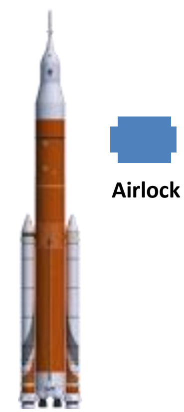
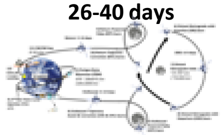
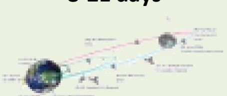
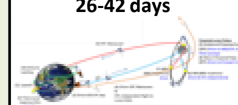
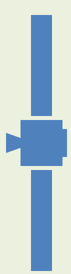
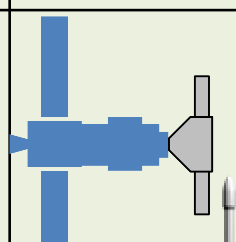
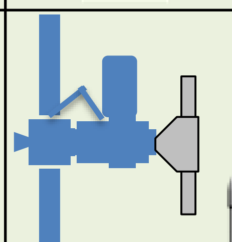
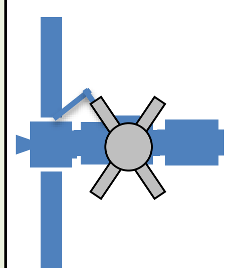
EXPANDING HUMAN PRESENCE IN PARTNERSHIP

CREATING ECONOMIC OPPORTUNITIES, ADVANCING TECHNOLOGIES, AND ENABLING DISCOVERY



Phase 1 Plan

Establishing deep-space leadership and preparing for Deep Space Transport development

		Deep Space Gateway Buildup			
EM-1	**Europa Clipper**	**EM-2**	**EM-3**	**EM-4**	**EM-5**
2018 - 2025					**2026**
SLS Block 1 Crew: 0 	SLS Block 1B Cargo  Europa Clipper (subject to approval)	SLS Block 1B Crew: 4 CMP Capability: 8-9T  40kW Power/Prop Element	SLS Block 1B Crew: 4 CMP Capability: 10mT  Habitation	SLS Block 1B Crew: 4 CMP Capability: 10mT  Logistics	SLS Block 1B Crew: 4 CPL Capability: 10mT  Airlock
Distant Retrograde Orbit (DRO) 26-40 days 	Jupiter Direct 	Multi-TLI Lunar Free Return 8-21 days 	Near Rectilinear Halo Orbit (NRHO) 16-26 days 	NRHO, w/ ability to translate to/from other cislunar orbits 26-42 days 	NRHO, w/ ability to translate to/from other cislunar orbits 26-42 days 
Gateway (blue) Configuration (Orion in grey)			 Cislunar Support Flight	 Cislunar Support Flight	

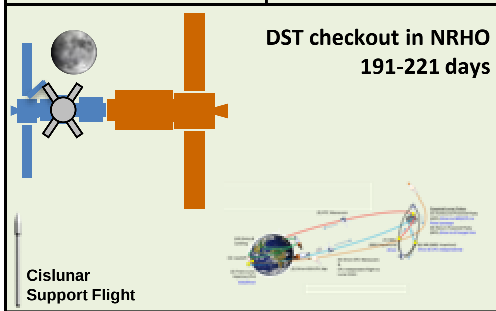
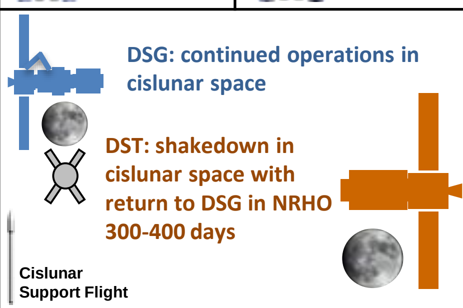
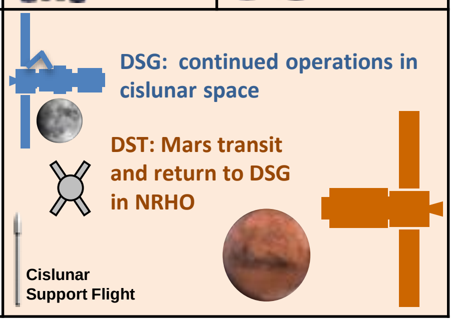
These essential Gateway elements can support multiple U.S. and international partner objectives in Phase 1 and beyond

Known Parameters:
- Gateway to architecture supports Phase 2 and beyond activities
- International and U.S. commercial development of elements and systems
- Gateway will translate uncrewed between cislunar orbits
- Ability to support science objectives in cislunar space

Open Opportunities:
- Order of logistics flights and logistics providers
- Use of logistics modules for available volume
- Ability to support lunar surface missions

(PLANNING REFERENCE) Phase 2 and Phase 3

Looking ahead to the shakedown cruise and the first crewed missions to Mars

Transport Delivery		Transport Shakedown		Mars Transit	
EM-6	EM-7	EM-8	EM-9	EM-10	EM-11
2027		2028 / 2029		2030+	
SLS Block 1B Cargo P/L Capability: 41t TLI	SLS Block 1B Crew: 4 CMP Capability: 10t	SLS Block 1B Cargo P/L Capability: 41t TLI	SLS Block 2 Crew: 4 CMP Capability: 13+t	SLS Block 2 Cargo P/L Capability: 45t TLI	SLS Block 2 Crew: 4 CMP Capability: 13+t
Deep Space Transport	Logistics	DST Logistics & Refueling	Logistics	DST Logistics & Refueling	Logistics
DST checkout in NRHO 191-221 days  Cislunar Support Flight		DSG: continued operations in cislunar space DST: shakedown in cislunar space with return to DSG in NRHO 300-400 days  Cislunar Support Flight		DSG: continued operations in cislunar space DST: Mars transit and return to DSG in NRHO  Cislunar Support Flight	

Reusable Deep Space Transport supports repeated crewed missions to the Mars vicinity

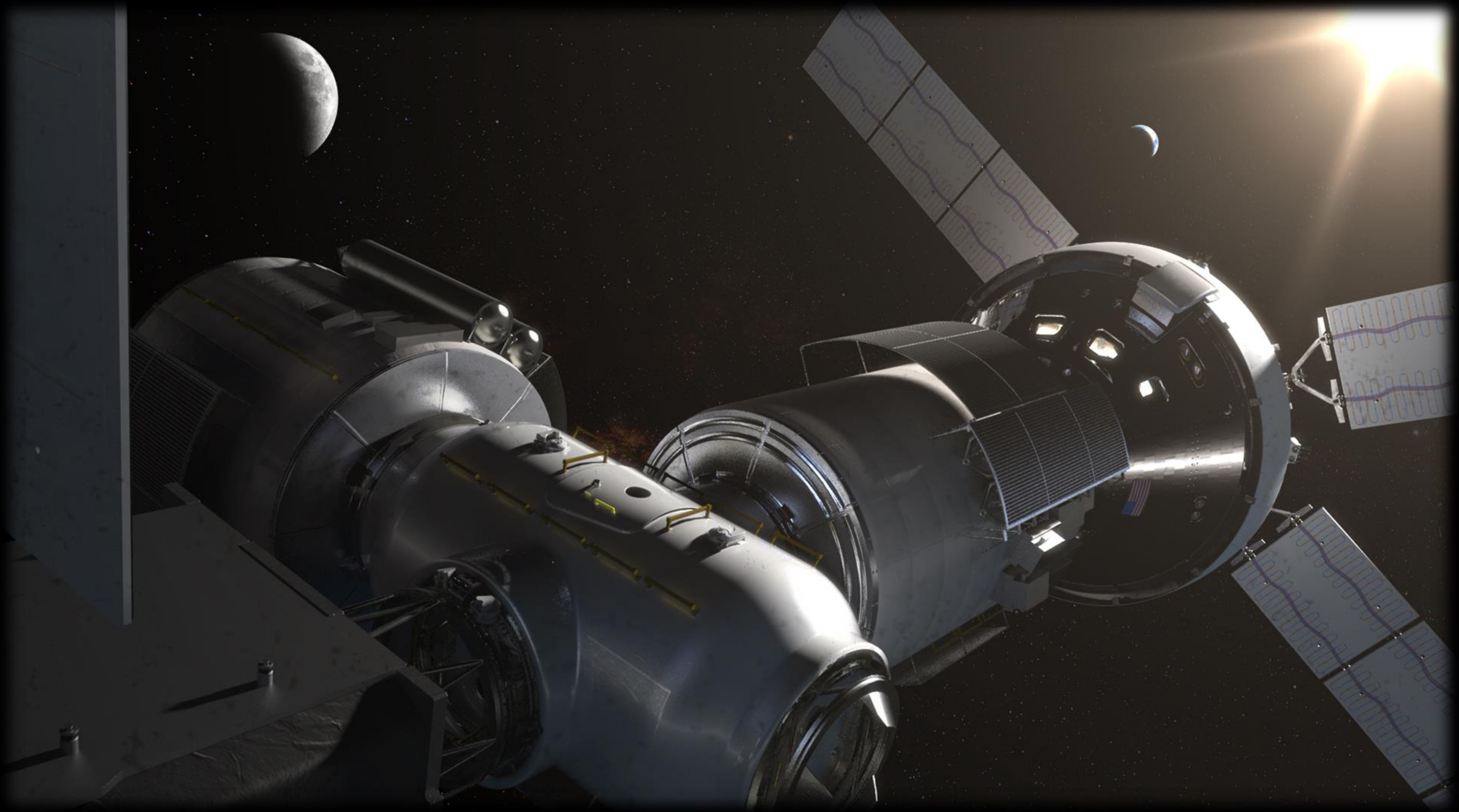
Known Parameters:

- DST launch on one SLS cargo flight
- DST shakedown cruise by 2029
- DST supported by a mix of logistics flights for both shakedown and transit
- Ability to support science objectives in cislunar space

Open Opportunities:

- Order of logistics flights and logistics providers
- Shakedown cruise vehicle configuration and destination/s
- Ability to support lunar surface missions

Deep Space Gateway Conceptual Drawing



Advanced Exploration Systems (AES) Division

- **NASA's Advanced Exploration Systems (AES) division is pioneering innovative approaches and public-private partnerships to rapidly develop prototype systems, advance key capabilities, and validate operational concepts for future human missions beyond Earth orbit**

- **AES activities are related to crew mobility, habitation, vehicle systems, robotic precursors, and foundational systems for deep space**

- **AES infuses new technologies developed by the Space Technology Mission Directorate and partners with the Science Mission Directorate to address Strategic Knowledge Gaps for multiple destinations**

- **AES is leading NASA's Deep-Space Gateway & Transport (DSG&T) Efforts**

AES Avionics & Software (A&S) Project

- **AES Avionics & Software (A&S) Project Goal:**
  - Define and exercise an avionics architecture that is open-source, highly reliable with fault tolerance, and utilizes standard capabilities and interfaces, which are scalable and customizable to support future exploration missions

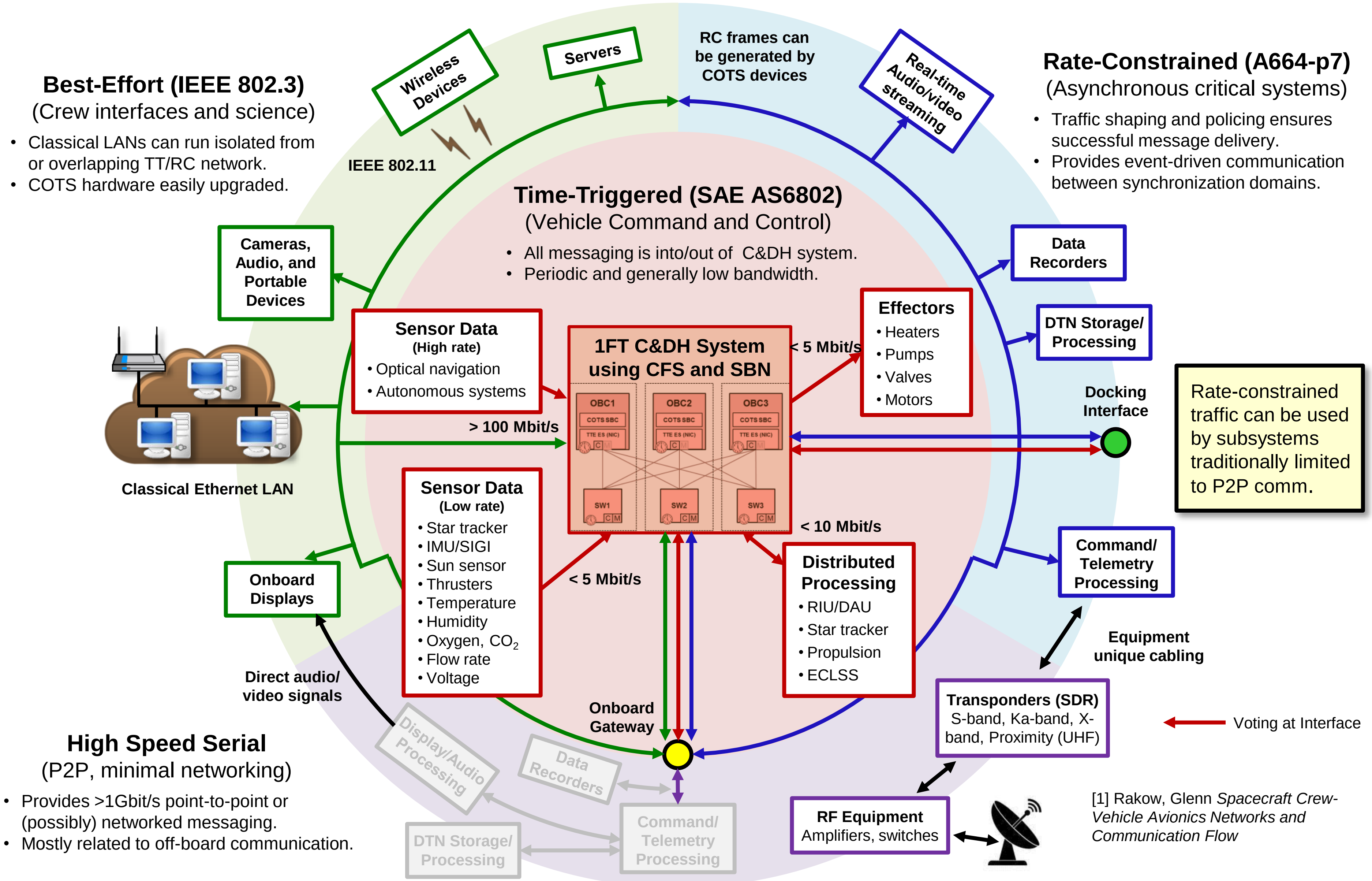
- **A&S Drivers:**
  - **Technology Transparency**
    - The underlying hardware should not have any impact on an application either during development or execution
    - Code reuse and portability
  - **Reliability and Maintenance**
    - Operate in the presence of failures so that Maintenance Free Operating Periods (MFOPS) can be achieved
    - Provide autonomous operations
    - Minimal number of unique spares
  - **Incremental Update & Certification - Designed for Growth and Change**
    - Applications can be inserted/altered with minimum impact on other systems and on the supporting safety case
    - Flexible scheduling to meet the deadlines of all the applications for each viable configuration and when system is upgraded

AES Avionics & Software (A&S) Project

- **A&S Focus Areas and Objectives:**
  - **Command & Data Handling (C&DH)** - Define a reliable, high-performance & modular C&DH architecture and build HW catalog
  - **Software** - Provide a reusable software architecture and tools suitable for human-rated missions
  - **Human Interfaces** - Identify, integrate & test human interface technologies that are scalable, sustainable, and evolvable to support future exploration
  - **Communication and Wireless Systems** - Enable interoperable, wireless & networked communication for inter/intra-vehicle systems
  - **Systems Engineering and Integration (SE&I)** - Model, build & test flexible and robust integrated vehicle systems

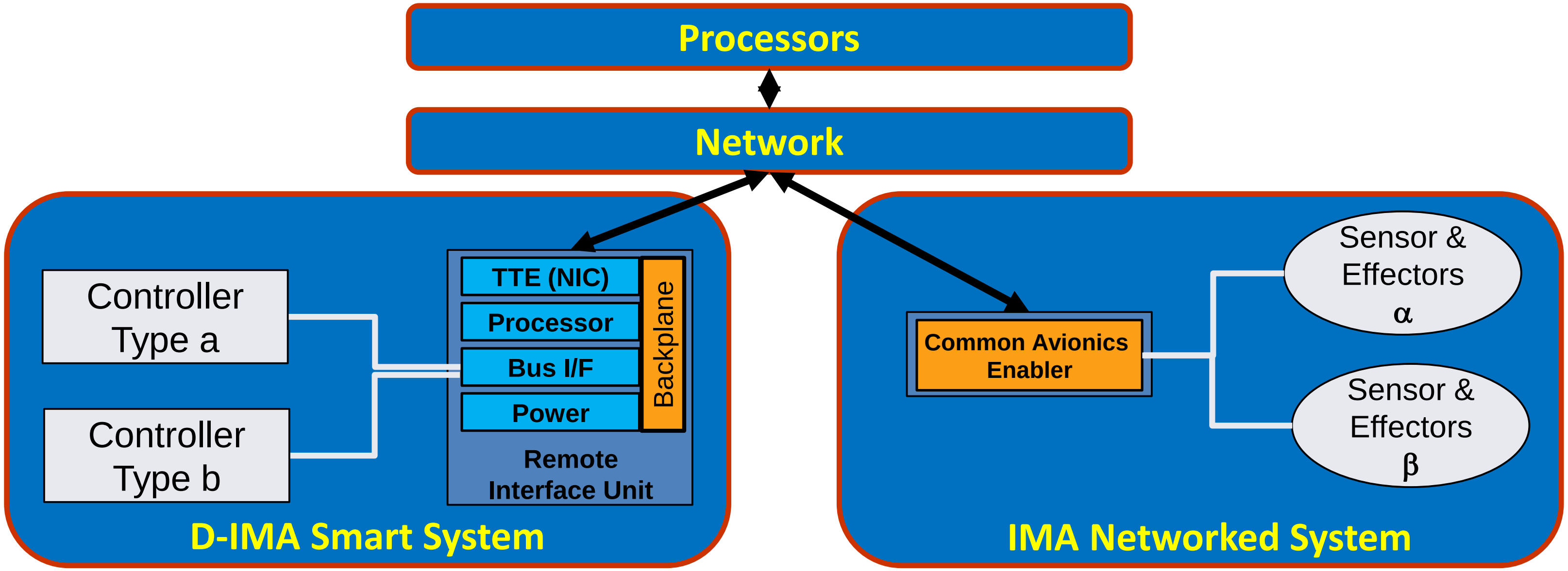
- **A&S Benefits:**
  - Results in an open architecture that allows use of hardware from multiple vendors
  - Enables use of evolving (near-launch) technology
  - Ability to upgrade capabilities and infuse new technologies with cost effective validation

Avionics & Software Architecture



Blueprint of the Architecture: Distributed Integrated Modular Avionics (D-IMA)

	Description	Rationale
Distributed	• Resources (both hardware and software) are physically distributed	• Reduce harness mass • Provide for local control of local functions • Lowers flight computer load
Integrated	• Multiple functions of different criticalities running on separate, high integrity, partitions	• Re-locatable functions not limited to a single line replaceable unit (LRU) boundary
Modular	• Standard interfaces/Virtual Backplane • Avionics boxes built up of hub card(s), power supply(s) and subsystem slices • Software constructed of re-locatable modules	• Provides for composability • Allows for hardware reuse • Allows for software reuse
Avionics	• Board level building blocks used to assemble boxes into systems	• Allows for multiple vendor hardware components

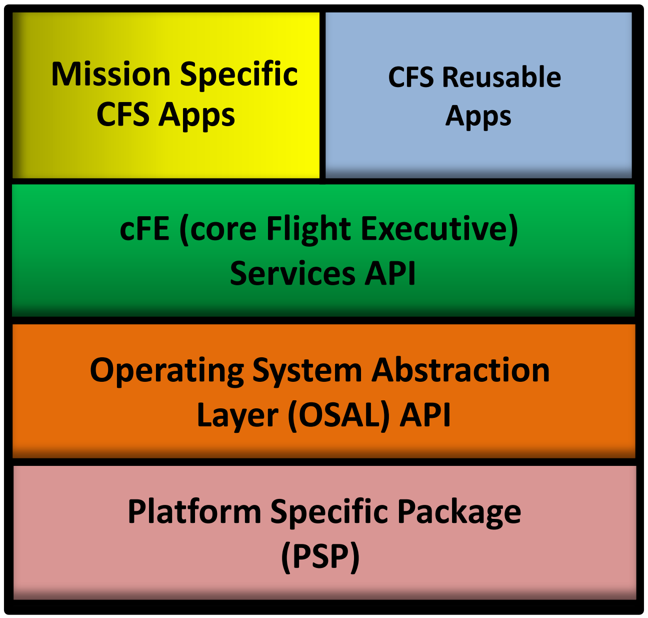


Brain of the Architecture: NASA's Core Flight Software (CFS)

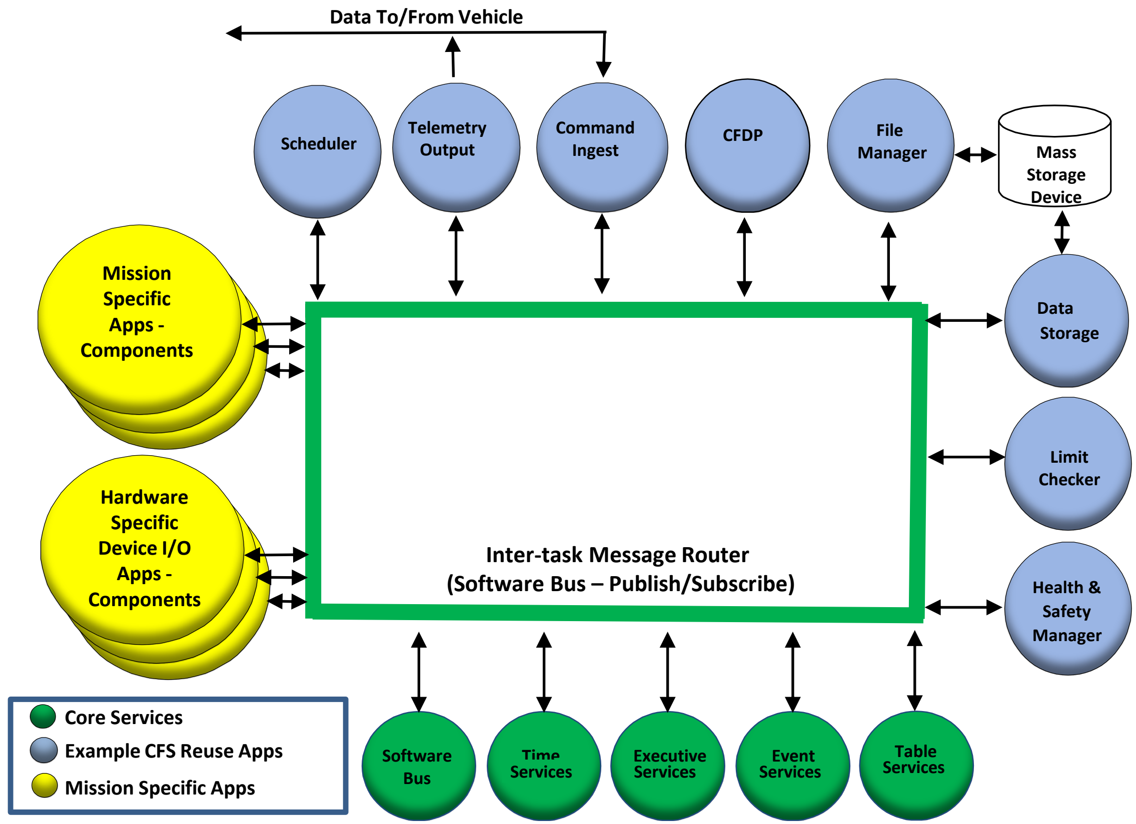
- **Core Flight Software (CFS) is a NASA-developed asset for spacecraft flight software reuse that is available as open-source:**
  - http://sourceforge.net/projects/coreflightexec/
- **Productized real-time flight software developed over several years by Goddard Space Flight Center to serve as reusable software framework basis for spacecraft missions, test missions, real-time systems**
- **AES has since advanced the product line, including achieving human-rating, as a reusable software solution for future exploration missions**
- **CFS provides a published service layer (cFE) and an Operating System Abstraction Layer (OSAL) for common services to run on multiple platforms and with several operating systems**
  - Pub/Sub message bus, time services, events, tables, file, task execution
  - http://sourceforge.net/projects/osal/
- **CFS provides common reusable spacecraft functions as open-source or government-purpose applications**
  - Scheduler, commanding, telemetry, communication, data recording, limits, system health, sequences

CFS Architecture

Core Flight Software Framework- Architectural Layers



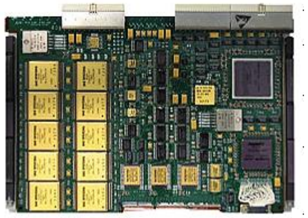
Notional CFS Application Software Architecture



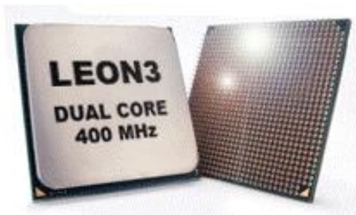
- **CFS also provides a mechanism to link distributed CFS instances called Software Bus Network (SBN), including an SBN library (SBN-lib) for non-CFS applications that need access to software bus data**

Some CFS Supported Platforms: Non-Exhaustive

- **CFS has been ported to work on many processors…**

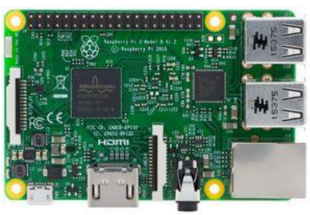


BAE RAD750



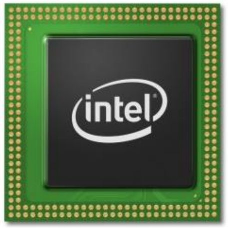
LEON3

Space Micro Proton 400K



Raspberry Pi

AITECH SP0-100



Intel x86

Maxwell SCS750

- **…and with many operating systems, both real- and non-real-time**

VxWorks

Linux™

RTEMS™

Raspbian

Green Hills® SOFTWARE

XENOMAI

PikeOS®

Backbone of the Architecture: Time-Triggered Ethernet

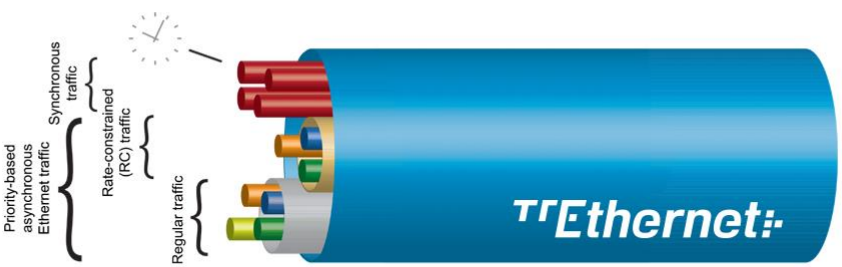
- **Time-Triggered Ethernet (TTE) is compatible with, can coexist with on the same physical media, and expands classical Ethernet with services to meet time-critical or deterministic conditions, supporting three message types:**

- **Time-triggered (SAE AS6802): Sent over the network at predefined times and take precedence over all other message types**
  - Occurrence, delay and precision of messages are predefined and guaranteed

- **Rate-constrained (ARINC 664 p7): Used for applications with less stringent determinism and real-time requirements**
  - Bandwidth is predefined and guaranteed for each application and delays/jitter have defined limits

- **Best-effort (IEEE 802.3): Follow classical Ethernet policy**
  - Use the remaining network bandwidth and have lower priority than TT or RC messages

- **TTE Standards exist or are in-work and NASA supports development of an open TTE Standard**
  - SAE AS6802 – Time-Triggered Ethernet
  - European Cooperation for Space Standardization (ECSS) ECSS-E-ST-50-16 – Time-Triggered Ethernet
  - Consultative Committee for Space Data Systems (CCSDS) Sub-Network Services WG

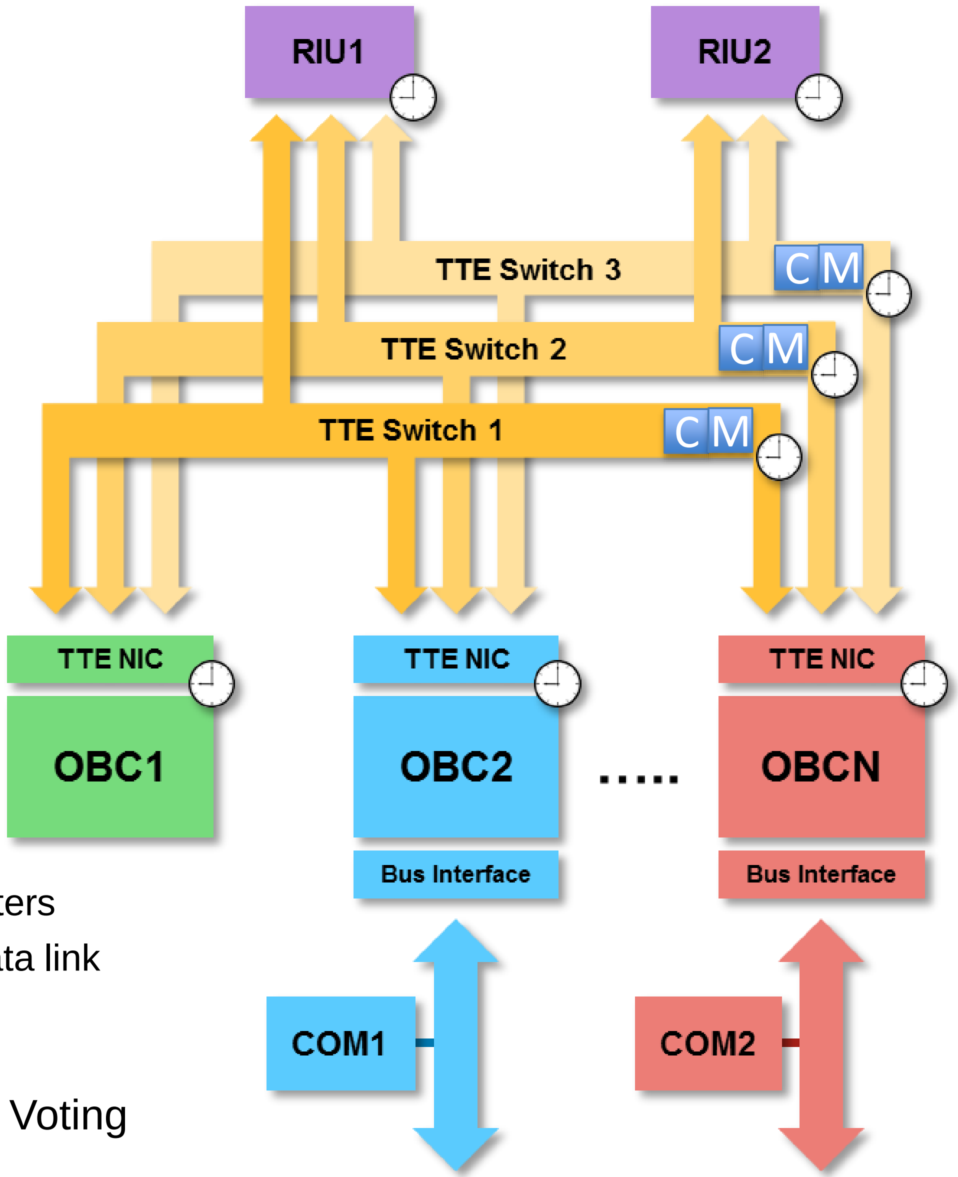


Sikorsky S-97 RAIDER

NASA's Orion Spacecraft

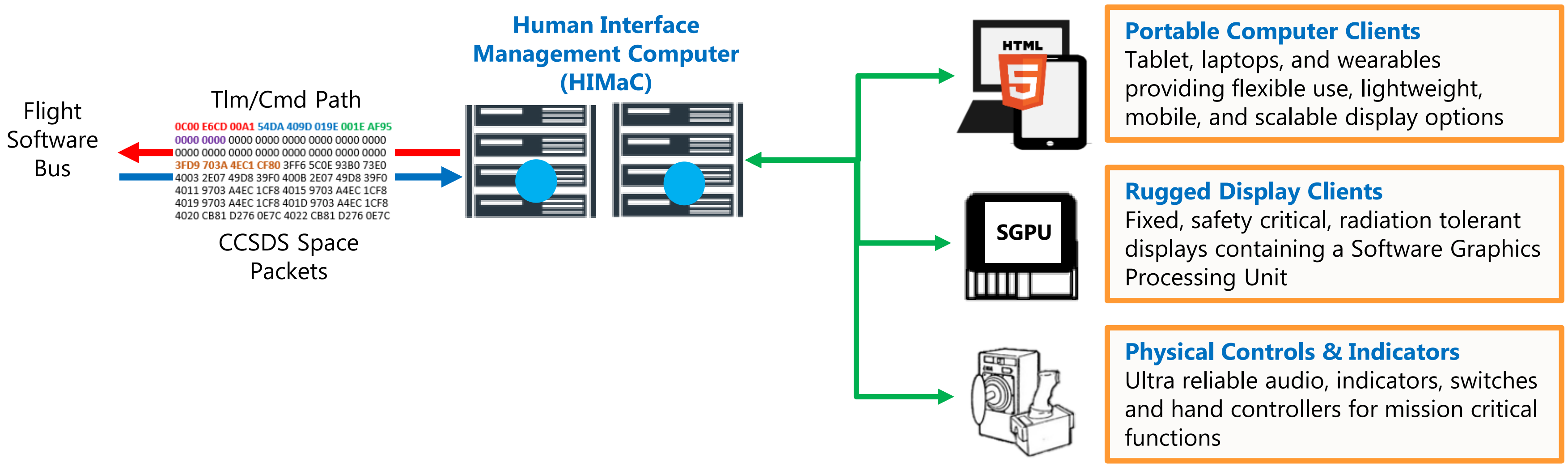
Reliability and Robustness: Triplex Voting Architecture

- **Developed a 1-Byzantine Fault tolerant voting architecture using TTE and CFS using current COTS technologies**
  - Three Onboard Computers (OBC)
  - Three High-Integrity (command/monitor) TTE Switches
  - Remote Interface Units (RIU)
- **Architecture is scalable through additional network planes, high-integrity devices, etc.**
- **Approach uses TTE for data distribution and sync and built CFS apps to do so**
- **Benefits of the voting architecture:**
  - Enables the use of COTS single board computers
  - Eliminates need for separate cross-channel data link
  - Eliminates need for separate timing hardware
- **Paper:** "A Proposed Byzantine Fault-Tolerant Voting Architecture using Time-Triggered Ethernet"



The Crew Element: Human Interface Architecture

- **Developed a human interface architecture to reduce barriers between the crew and the vehicle**
- **Core component is the Human Interface Management Computer (HIMaC) that acts as a Display Server, Telemetry/Command Exchange Server and Audio/Video Server**
  - HIMaC is tied to flight software bus network and supports different traffic classes
- **Architecture consists of open interface standards to provide flexible and reconfigurable peripherals**
  - Displays, Controls, Wearables, Audio, Video, Virtual/Augmented Reality
- **Provides a robust approach to data security**
- **Designed to be scalable, sustainable, and evolvable enabling support for system build up, upgrades and extensions**



Can You Hear Me Now?: Wireless and Communication Architecture

- **The communication links that the architecture is designed to support include:**
  - DSG ↔ Earth
  - DSG ↔ Lunar Surface
  - DSG ↔ Visiting Vehicle
  - DSG ↔ Proximity/Wireless Communications (i.e. Extra-Vehicular Activity (EVA))
- **Architecture supports several standard wireless standards and technologies for internal spacecraft and proximity communications**
  - IEEE 802.11 Family
  - 5G Technology (LTE)
  - Wireless Sensor Networks
  - Radio Frequency Identification (RFID) for both logistics and sensing
- **Candidate standards and technologies have been identified, are still being evaluated, and have not been finalized**
  - Optical communication is also being looked at for DSG
- **Will leverage the Interagency Operations Advisory Group (IOAG) Service Catalog and Consultative Committee for Space Data Systems (CCSDS) Standards**
- **Internetworking capabilities are a requirement, and must operate in the presence of time delays and outages**
  - Delay/Disruption Tolerant Networking (DTN) is the solution

Consultative Committee CCSDS for Space Data Systems

IOAG Interagency Operations Advisory Group

IEEE

ISA

5G

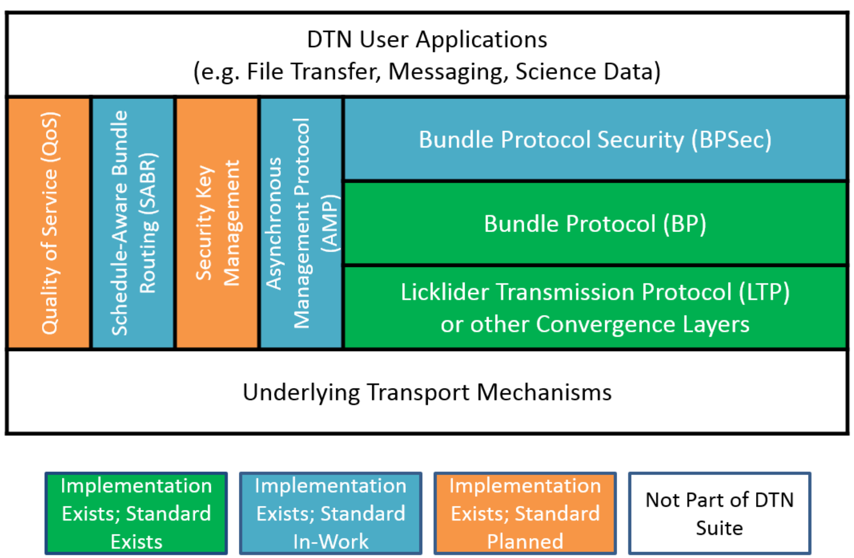
Connecting to the Solar System Internet (SSI): Delay/Disruption Tolerant Networking (DTN)

- **Delay/Disruption Tolerant Networking (DTN) is an AES developed protocol suite that extends the terrestrial Internet capabilities into highly stressed data communication environments where the conventional Internet does not work**
  – These environments are typically subject to frequent disruptions, unidirectional/asymmetric links, long delays and high error rates

- **DTN is being standardized by the Consultative Committee for Space Data Systems (CCSDS) and the Internet Engineering Task Force (IETF) DTN Working Groups**

- **NASA's Interplanetary Overlay Network (ION) DTN implementation is open-source software:**
  – https://sourceforge.net/projects/ion-dtn/files/

- **Some of the benefits of DTN include improved operations and situational awareness, interoperability and reuse, space link efficiency, utilization and robustness, security and quality-of-service**



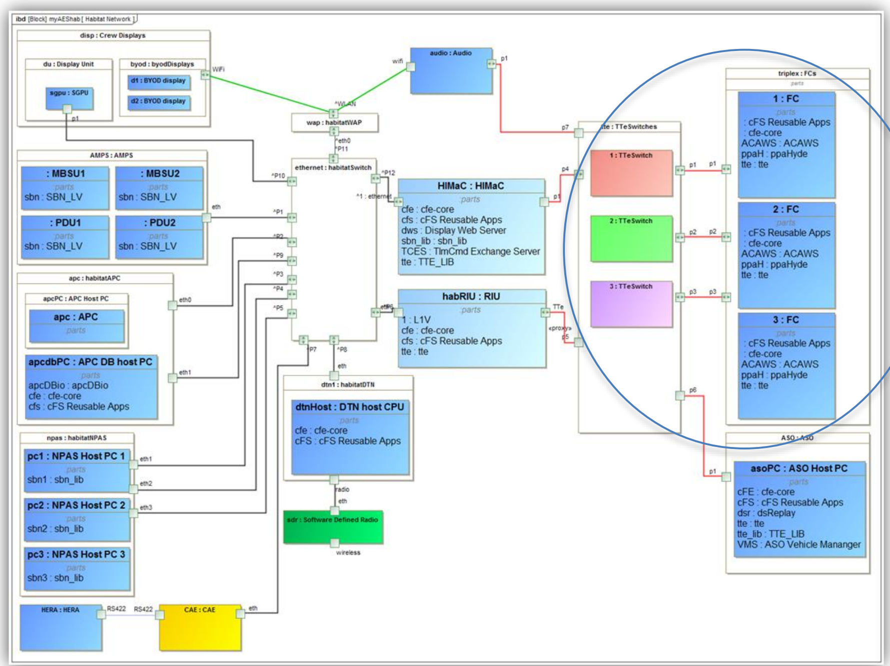
Putting it All Together: Systems Engineering and Integration (SE&I)

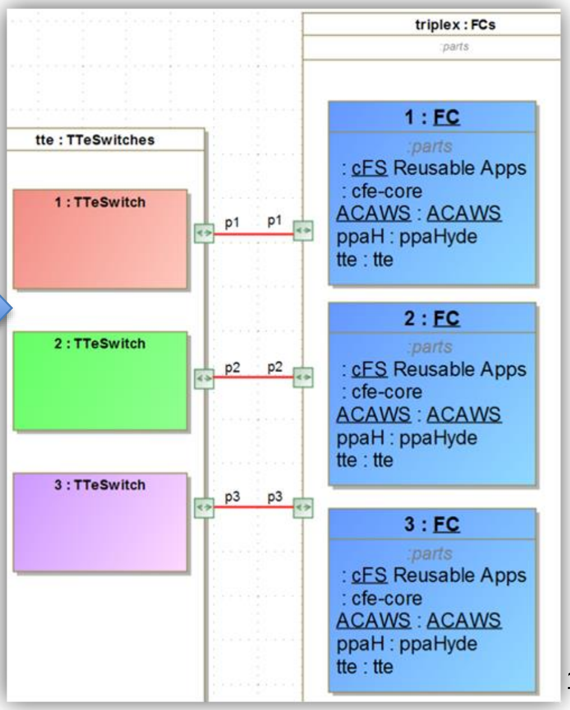
- **Determined the necessary avionics functions for architecture, allocated the functions to abstract systems and implemented the systems to perform the functions**

- **Modeled the avionics and software architecture using Model-Based Systems Engineering (MBSE) tools using the Systems Modelling Language (SysML) throughout life-cycle**

- **Led the migration of other spacecraft subsystems to run CFS applications on path-to-flight processors and connect to the architecture**
  - Power, Environmental Control and Life Support System (ECLSS), Vehicle Autonomy applications, etc.

- **Conceptualized mission scenarios to exercise/stress the architecture through both simulation and testing**





An Enabling Architecture: Supporting Future Autonomous Systems

- **As human exploration moves farther out into space, the need for autonomous systems significantly increases**
  - Many functions of the current Mission Control Center (MCC) will need to move onto the spacecraft
- **AES, STMD and others within NASA are researching various autonomy applications that could be used as part of the Deep-Space Gateway and Transport efforts**
- **NASA is also closely tracking commercial developments that could support autonomous systems**
  - AI and Cognitive Computing, Deep-Learning Algorithms, Model-based Condition Monitoring, Industrial and Home Automation, IoT, etc.
- **The developed avionics and software architecture will serve as a platform to exercise autonomy applications and concepts**
  - Exercise onboard autonomous Integrated Vehicle Health Management (IVHM) applications
  - Explore distributed and centralized autonomy concepts
  - Build crew and ground operator familiarity and comfort with autonomy applications
  - Provide reliable command/control capabilities for spacecraft subsystems
  - Provide additional processing/storage for less-capable systems
  - Monitor subsystems and serve as an operations advisor
- **Open architecture will also serve as a technology development platform to help establish partnerships and collaborations to further enhance architecture**
  - Support Academia, International Partner or commercial technologies

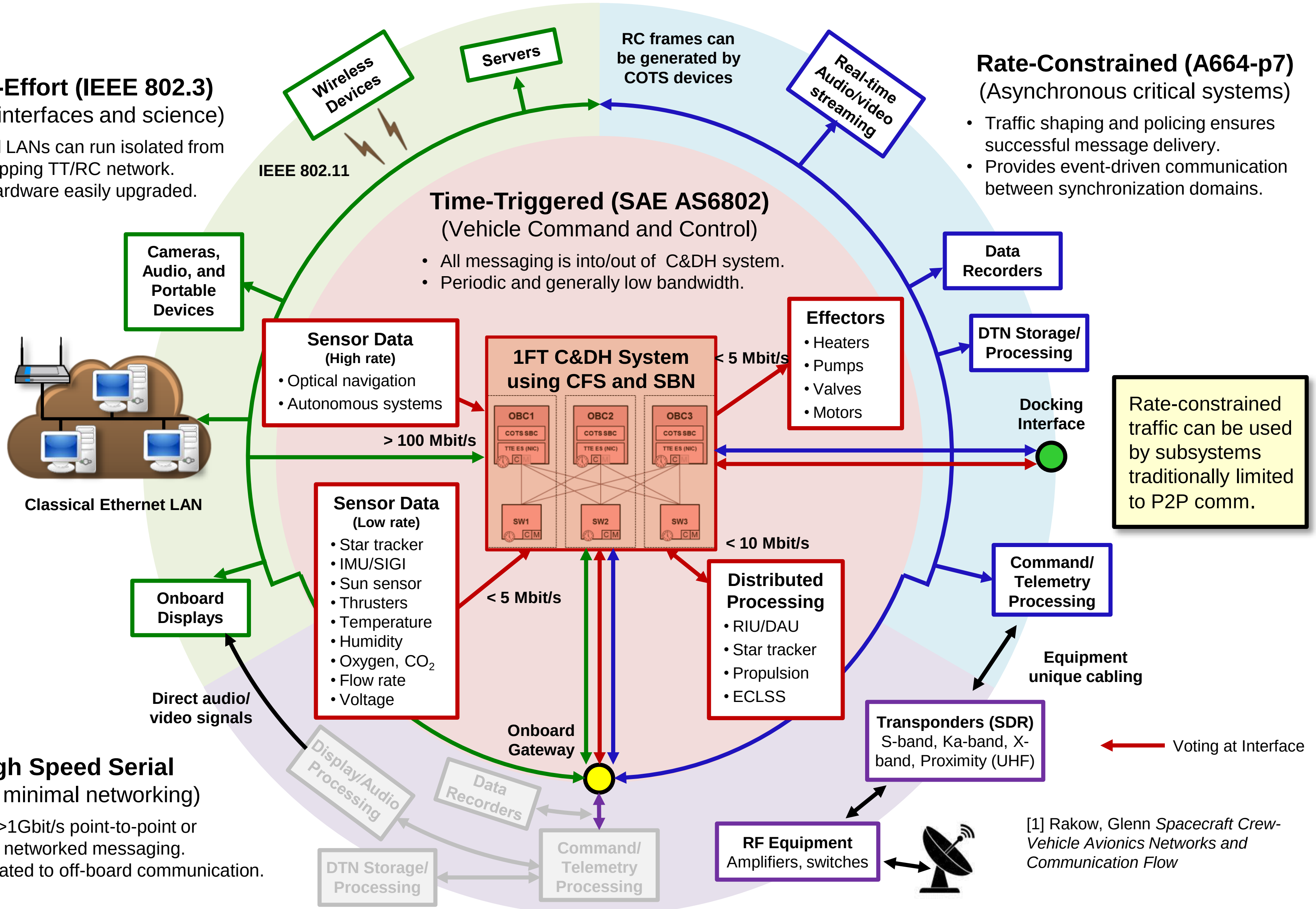
Avionics & Software Architecture

Best-Effort (IEEE 802.3)
(Crew interfaces and science)

- Classical LANs can run isolated from or overlapping TT/RC network.
- COTS hardware easily upgraded.

Rate-Constrained (A664-p7)
(Asynchronous critical systems)

- Traffic shaping and policing ensures successful message delivery.
- Provides event-driven communication between synchronization domains.



High Speed Serial
(P2P, minimal networking)

- Provides >1Gbit/s point-to-point or (possibly) networked messaging.
- Mostly related to off-board communication.

[1] Rakow, Glenn *Spacecraft Crew-Vehicle Avionics Networks and Communication Flow*

Key Takeaways

- **The AES A&S project has developed an Avionics & Software architecture that is:**
  - Open-source, with standard capabilities and interfaces
  - Highly reliable with 1-Byzantine fault tolerance
  - Scalable and customizable to support future exploration missions such as the Deep Space Gateway and Transport
  - Built on a foundation of NASA's Core Flight Software (CFS) and Time-Triggered Ethernet (TTE)
  - Realizable with currently available COTS technology and supports multi-vendor hardware
  - Fully modeled in SysML, implemented and tested in relevant environments
  - Designed to support various autonomy technologies that will be needed for deep-space human exploration