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

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NASA’s Exploration Roadmap

EXPANDING HUMAN PRESENCE IN PARTNERSHIP
CREATING ECONOMIC OPPORTUNITIES, ADVANCING TECHNOLOGIES, AND ENABLING DISCOVERY

Now
Using the International Space Station

2020s
Operating in the Lunar Vicinity (proving ground)

Phase 0
Continue research and testing on ISS to solve exploration challenges. Evaluate potential for lunar resources. Develop standards.

Phase 1

Phase 2
Complete Deep Space Transport and conduct yearlong Mars simulation mission.

Phase 3 and 4
Begin sustained crew expeditions to Martian system and surface of Mars.

After 2030
Leaving the Earth-Moon System and Reaching Mars Orbit
Phase 1 Plan
Establishing deep-space leadership and preparing for Deep Space Transport development

<table>
<thead>
<tr>
<th>EM-1</th>
<th>Europa Clipper</th>
<th>EM-2</th>
<th>EM-3</th>
<th>EM-4</th>
<th>EM-5</th>
</tr>
</thead>
<tbody>
<tr>
<td>2018 - 2025</td>
<td>2026</td>
<td></td>
<td></td>
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<tr>
<td>SLS Block 1 Crew: 0</td>
<td>SLS Block 1B Cargo Crew: 4 CMP Capability: 8-9T</td>
<td>SLS Block 1B Crew: 4 CMP Capability: 10mT</td>
<td>SLS Block 1B Crew: 4 CMP Capability: 10mT</td>
<td>SLS Block 1B Crew: 4 CPL Capability: 10mT</td>
<td></td>
</tr>
<tr>
<td>Distant Retrograde Orbit (DRO) 26-40 days</td>
<td>Jupiter Direct</td>
<td>Multi-TLI Lunar Free Return 8-21 days</td>
<td>Near Rectilinear Halo Orbit (NRHO) 16-26 days</td>
<td>NRHO, w/ ability to translate to/from other cislunar orbits 26-42 days</td>
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</tr>
</tbody>
</table>

Gateway (blue) Configuration (Orion in grey)

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

These essential Gateway elements can support multiple U.S. and international partner objectives in Phase 1 and beyond.
**Phase 2 and Phase 3**

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

<table>
<thead>
<tr>
<th>Transport Delivery</th>
<th>Transport Shakedown</th>
<th>Mars Transit</th>
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</thead>
<tbody>
<tr>
<td>EM-6</td>
<td>EM-8</td>
<td>EM-10</td>
</tr>
<tr>
<td>SLS Block 1B Cargo P/L Capability: 41t TLI</td>
<td>SLS Block 1B Cargo P/L Capability: 41t TLI</td>
<td>SLS Block 2 Cargo P/L Capability: 45t TLI</td>
</tr>
<tr>
<td>Logistics</td>
<td>DST Logistics &amp; Refueling</td>
<td>DST Logistics &amp; Refueling</td>
</tr>
<tr>
<td>DST checkout in NRHO 191-221 days</td>
<td>DST: shakedown in cislunar space with return to DSG in NRHO 300-400 days</td>
<td>DST: Mars transit and return to DSG in NRHO</td>
</tr>
<tr>
<td>SLS Block 1B Crew: 4</td>
<td>SLS Block 2 Crew: 4</td>
<td>SLS Block 2 Crew: 4</td>
</tr>
<tr>
<td>CMP Capability: 10t</td>
<td>CMP Capability: 13+t</td>
<td>CMP Capability: 13+t</td>
</tr>
</tbody>
</table>

**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

Reusable Deep Space Transport supports repeated crewed missions to the Mars vicinity
Deep Space Gateway Conceptual Drawing
• 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

**Best-Effort (IEEE 802.3)**
(Crew interfaces and science)
- Classical LANs can run isolated from or overlapping TT/RC network.
- COTS hardware easily upgraded.

**Time-Triggered (SAE AS6802)**
(Vehicle Command and Control)
- All messaging is into/out of C&DH system.
- Periodic and generally low bandwidth.

**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.

**Sensor Data**
- (High rate)
  - Optical navigation
  - Autonomous systems

**Sensor Data**
- (Low rate)
  - Star tracker
  - IMU/SIGI
  - Sun sensor
  - Thrusters
  - Temperature
  - Humidity
  - Oxygen, CO₂
  - Flow rate
  - Voltage

**Effectors**
- Heaters
- Pumps
- Valves
- Motors

**Distributed Processing**
- RIU/DAU
- Star tracker
- Propulsion
- ECLSS

**Onboard Gateway**

**Onboard Displays**

**Classical Ethernet LAN**

**Wireless Devices**

**Servers**

**Real-time Audio/video streaming**

**IEEE 802.11**

**RC frames can be generated by COTS devices**

**IEEE 802.3**

**Data Recorders**

**Command/Telemetry Processing**

**DTN Storage/Processing**

**RF Equipment Amplifiers, switches**

**Transponders (SDR)**
- S-band, Ka-band, X-band, Proximity (UHF)

**Docking Interface**

**Equipment unique cabling**

**Voting at Interface**

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

<table>
<thead>
<tr>
<th>Description</th>
<th>Rationale</th>
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</table>
| **Distributed** | • Resources (both hardware and software) are physically distributed | • Reduce harness mass  
| | • Reduce harness mass | • Provide for local control of local functions  
| | • Reduce harness mass | • 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  
| | • Provides for composability | • Allows for hardware reuse  
| | • Provides for composability | • Allows for software reuse  
| **Avionics** | • Board level building blocks used to assemble boxes into systems | • Allows for multiple vendor hardware components |

### Diagram:

- **Processors**
- **Network**
  - **D-IMA Smart System**
  - **Controller Type a**
  - **Controller Type b**
  - **TTE (NIC)**
  - **Processor**
  - **Bus I/F**
  - **Power**
  - **Remote Interface Unit**

- **IMA Networked System**
  - **Common Avionics Enabler**
  - **Sensor & Effectors α**
  - **Sensor & Effectors β**
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/](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

- CFS provides common reusable spacecraft functions as open-source or government-purpose applications
  - Scheduler, commanding, telemetry, communication, data recording, limits, system health, sequences
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
  - AITECH SP0-100
  - Space Micro Proton 400K
  - Intel x86
  - Maxwell SCS750
  - Raspberry Pi

- ...and with many operating systems, both real- and non-real-time
  - VxWorks
  - Linux
  - RTEMS
  - Raspbian
  - Green Hills Software
  - XENOMATE
  - 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

![Ethernet Diagram]
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

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

<table>
<thead>
<tr>
<th>Portable Computer Clients</th>
<th>Rugged Display Clients</th>
<th>Physical Controls &amp; Indicators</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tablet, laptops, and wearables providing flexible use, lightweight, mobile, and scalable display options</td>
<td>Fixed, safety critical, radiation tolerant displays containing a Software Graphics Processing Unit</td>
<td>Ultra reliable audio, indicators, switches and hand controllers for mission critical functions</td>
</tr>
</tbody>
</table>
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
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

• 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
Best-Effort (IEEE 802.3) (Crew interfaces and science)
- Classical LANs can run isolated from or overlapping TT/RC network.
- COTS hardware easily upgraded.

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High Speed Serial (P2P, minimal networking)
- Provides >1Gbit/s point-to-point or (possibly) networked messaging.
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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