NASA'S Identified Risk of Adverse Outcomes Due to Inadequate Human-Systems Integration Architecture

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Overall Problem

NASA needs to be able to solve real-time threats to exploration vehicles, that currently are addressed by having 85+ ground-based experts immediately available, with 4 autonomous crewmembers.

The NASA Human System Risk Board (HSRB)

Identifies

Tracks

Ranks

Describes

Human system risks for human spaceflight

- ❖ Tracks the evolution of the top ~30 human system risks identified to be associated with human spaceflight
- ❖ Characterize the risk by likelihood and consequence
- ❖ Uses Directed Acyclic Graphs (DAGs) to
  - describe intermediate causal relationships between risk contributing factors and countermeasures that link hazards to outcomes
  - identify common factors and countermeasures across risks
  - communicate how astronaut exposure to spaceflight hazards leads to mission-level health and performance outcomes

Challenges for Human Spaceflight Beyond Low-Earth Orbit

NASA's Human Research Program has organized hazards astronauts will encounter on a continual basis into five classifications:

HAZARD ONE
Radiation

HAZARD TWO
Isolation & Confinement

HAZARD THREE
Distance from Earth

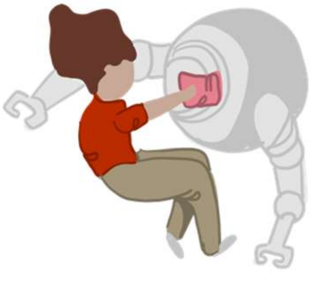
HAZARD FOUR
Altered Gravity

HAZARD FIVE
Hostile Closed Environments

HSIA

[human-systems integration architecture] | noun

a construct to describe the **communication, coordination, and cooperation** between humans and cyber-physical systems that must occur in order to accomplish an operation or mission, including managing critical events.



Human Spaceflight Operations in Low-Earth Orbit

❖ **ISS Mission ops rely on:**
- Real-time communication
- Frequent resupply
- Evacuation opportunity

Experts on the ground constantly manages the state of the vehicle

- **85+** specialists available
- **~660** years combined on-console experience
- **22** <u>unique</u> console disciplines

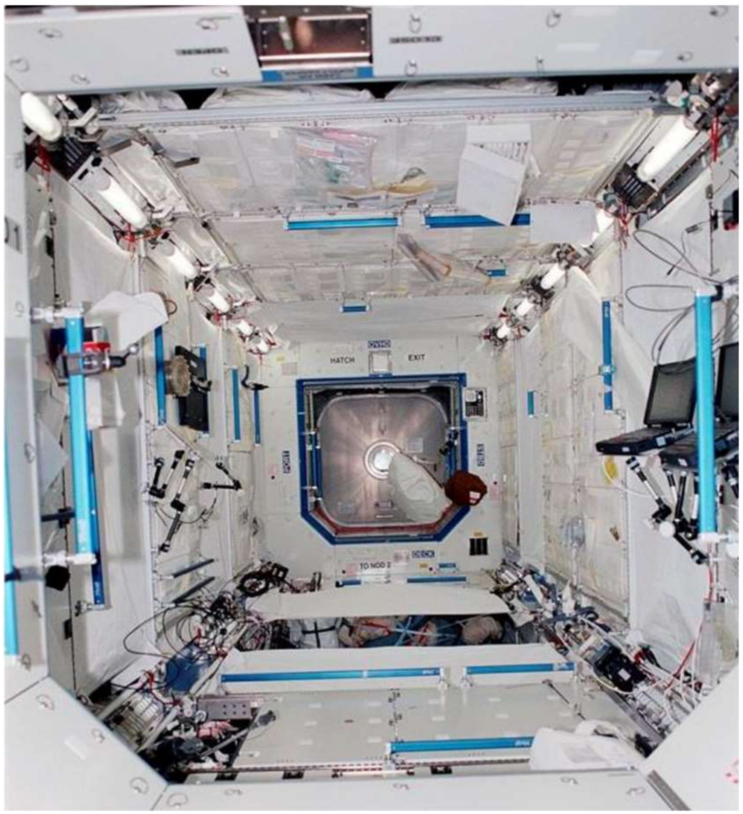
The ISS relies on frequent resupply of spare parts and other resources from visiting vehicles to maintain the vehicle

An example Orbital Replacement Unit (ORU)

Mission Control provides crew with real-time direction and oversight for complex task execution

Anomaly Response Procedures

Designed For This



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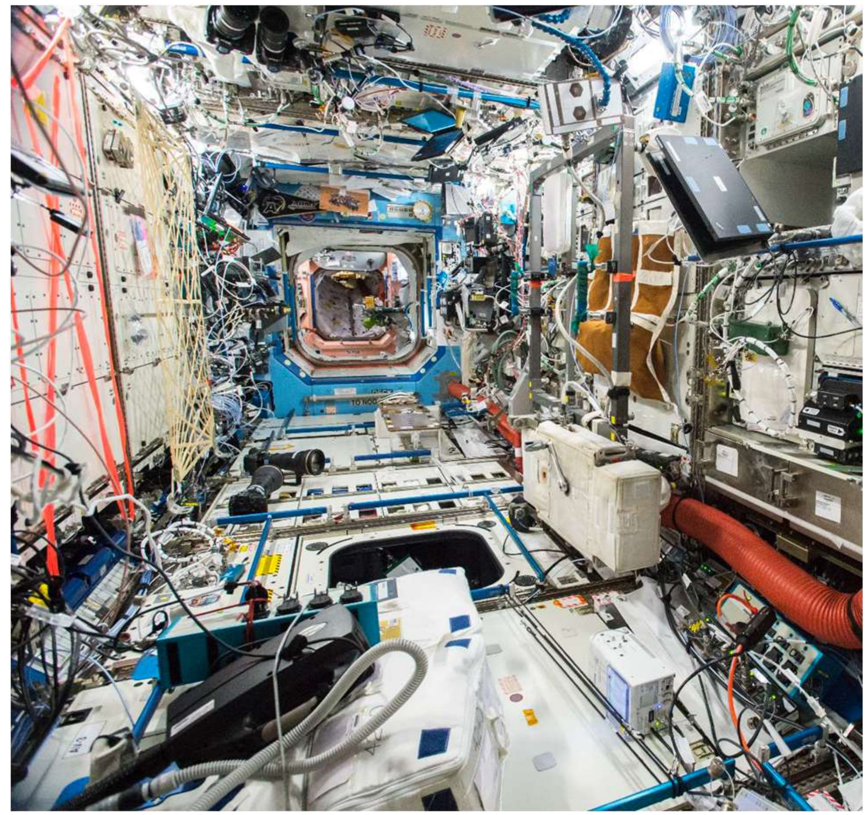


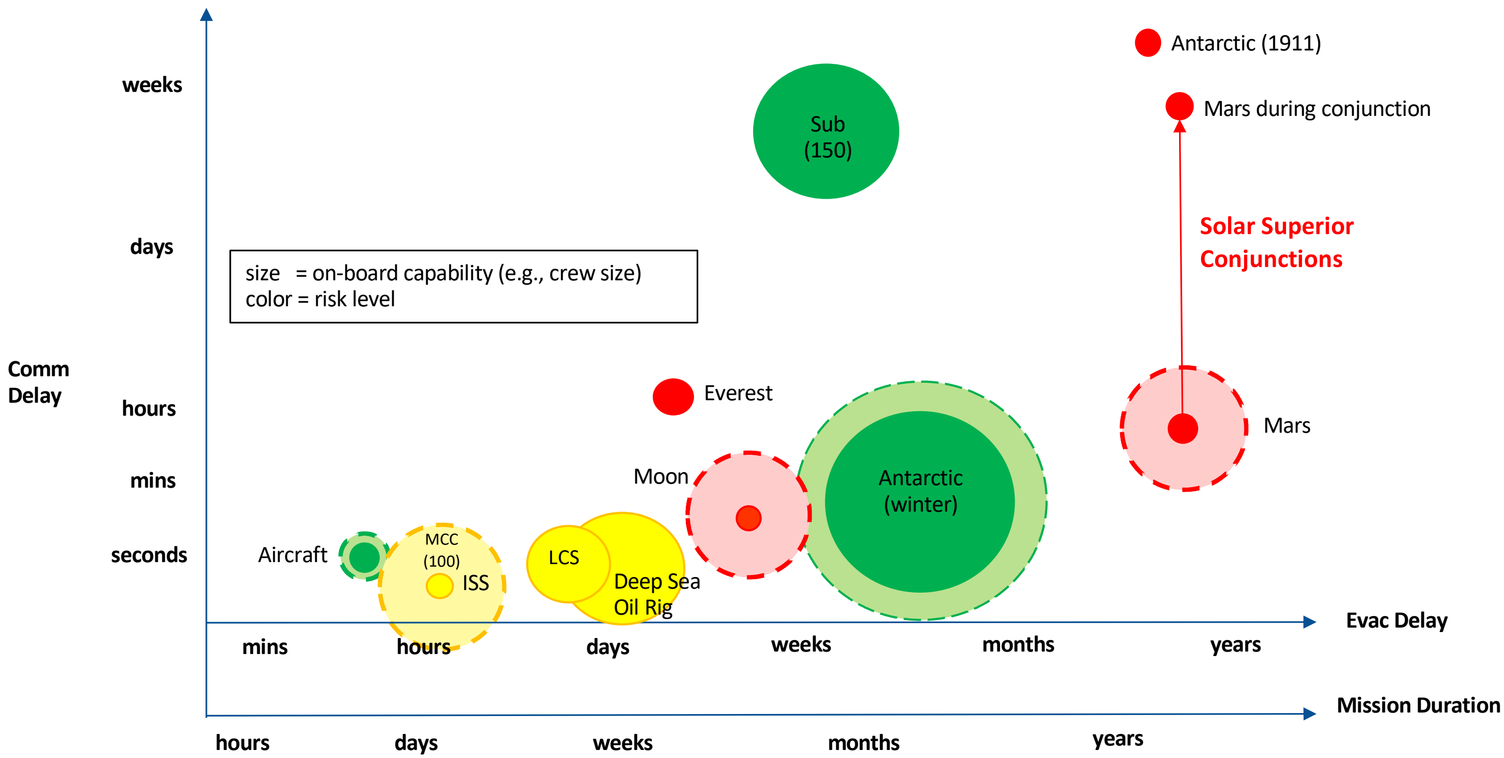
Inadequate solutions

Lack of comprehensive evidence results in limited perspectives that often focus in a singular area and lead to four erroneous assumptions about possible solutions:

1. Engineering can design more reliable/robust systems so that anomalies do not occur
2. Artificial Intelligence will address anomalies
3. MCC can continue to address anomalies, even with delayed comm
4. Training can be amplified to prepare crew to address anomalies

Earth-independent operations are not viable without advances in all four of these areas.

State of Knowledge: What do analogues tell us?



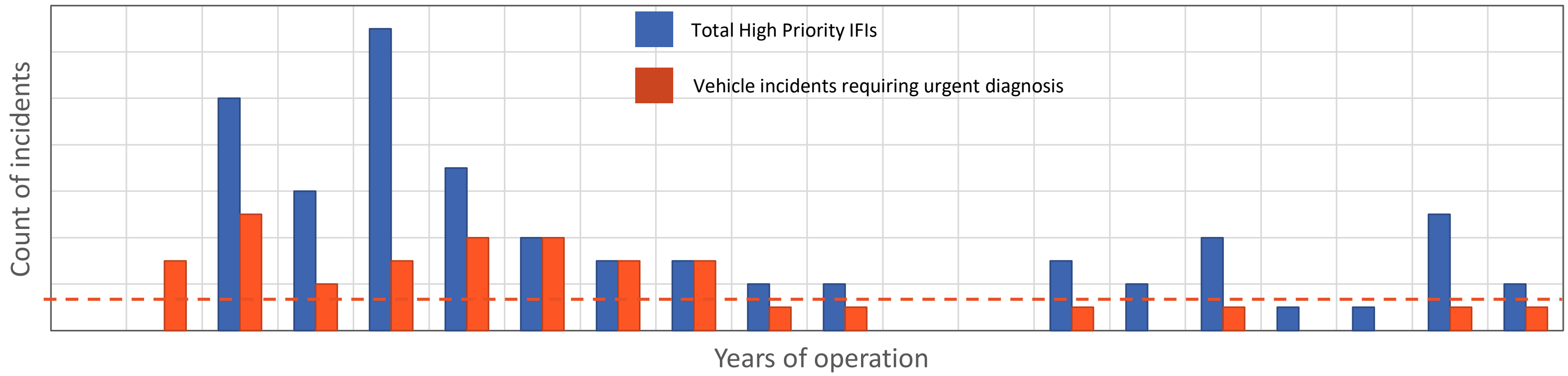
Anomaly response requires human intervention; independent capability needs to exist locally, tailored to size and capacity of team

Characterizing the HSIA Risk

Anomaly Rates for Human Spaceflight

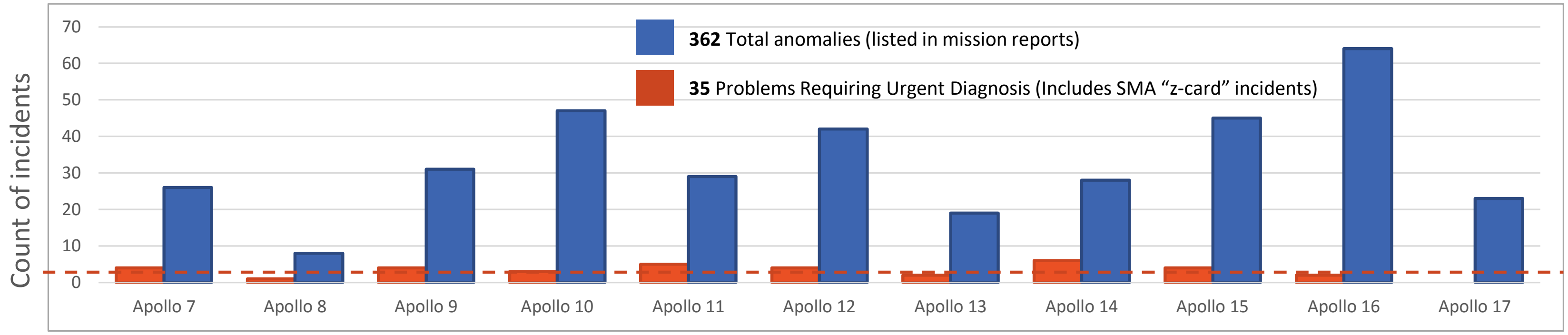
ISS

Avg: 1.7/year
Vehicle incidents requiring urgent diagnosis



Apollo

Avg: 3/mission
Vehicle incidents requiring urgent diagnosis



Human Spaceflight Beyond Low-Earth Orbit

- **Challenges beyond LEO:**
  - Limited communication
  - Limited resupply
  - Limited evacuation opportunities

Increasing Earth-independence and crew autonomy

Need to adequately respond to unanticipated critical malfunctions

The HSIA Risk

The Risk of Adverse Outcome Due to Inadequate Human Systems Integration Architecture

Given increasing need for crew independence and greater operational complexity in future exploration missions, there is a possibility of adverse outcomes associated with deficiencies in Human-Systems Integration, specifically that crew are unable to **adequately respond to unanticipated critical malfunctions** and/or perform safety critical procedures.

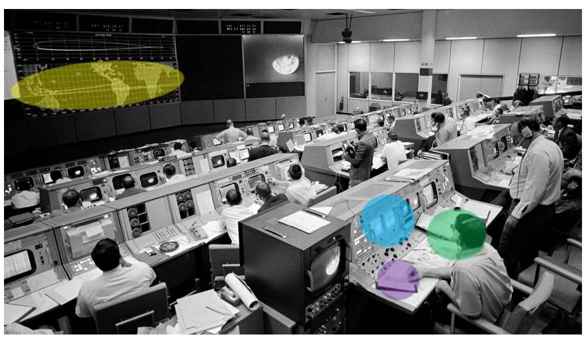
DRM Categories	Mission Type and Duration	LxC Ops	Risk Disposition	LxC LTH
Low Earth Orbit (LEO)	Short (<30 days)	5x2	Accepted	
	Long (30 d-1 yr)	5x2	Accepted	
Lunar Orbital	Short (<30 days)	5x2	Requires Mitigation /Standard Refinement	
	Long (30 d-1 yr)	5x2	Requires Mitigation /Standard Refinement	
Lunar Orbital + Surface	Short (<30 days)	5x3	Requires Mitigation	
	Long (30 d-1 yr)	5x3	Requires Mitigation	
Mars*	Preparatory (<1 year)	5x4	Requires Mitigation	
	Planetary (730-1224 days)	5x5	Requires Mitigation	

Red Risk (high) for Lunar surface and Mars missions due to the probability of Loss of Crew and Loss of Mission consequences

A Paradigm Shift in HSIA is Needed

- NASA's mission operations paradigm is one of near-complete real-time dependence on experts on the ground to control and manage the combined state of the mission, vehicle, and crew.
- NASA's HSIA has evolved, but not fundamentally changed.

Apollo, 1961 - 1973



ISS, 2000 - present

Shared information displays

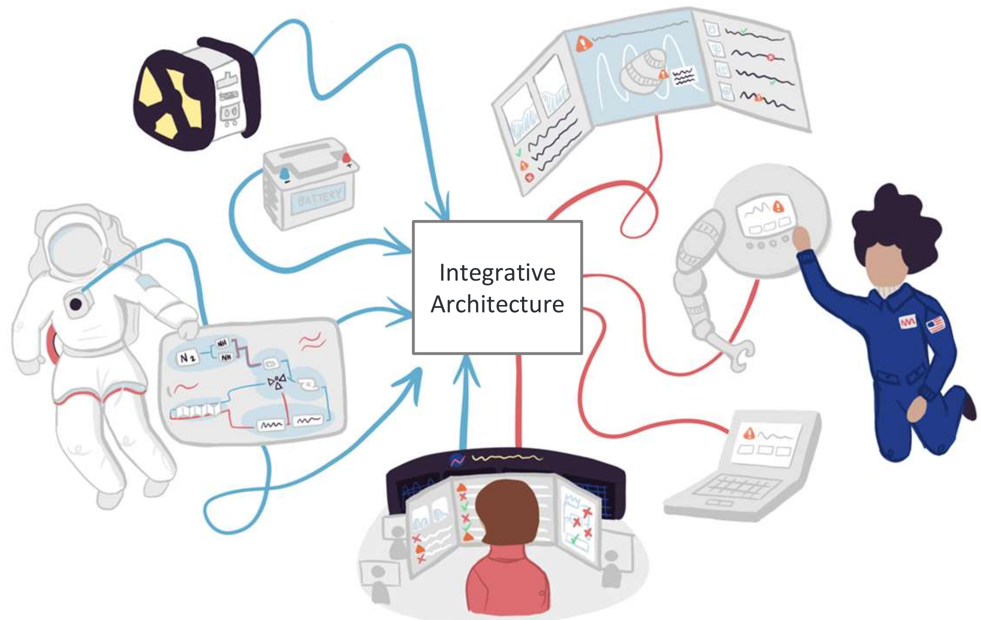
Personal information displays

Audio

Paper

A Paradigm Shift in HSIA is Needed

- System architecture perspective needed to achieve overall human-systems resilience



Distance from Earth → Anomalous Events → Detect Events → Diagnose Events → Intervention Decision → Task Performance → Outcome

Reimagining Mission Systems, Tools, and Roles for Beyond LEO

1. How do we train an independent crew to use all the technologies shown without real-time assistance?
2. How do we display the information consistently across the system to crew so they can make the correct decision at the right time?
3. What decision support can be used across the system?
4. How can HF principles be better reflected in requirements to allow maintainability in spaceflight?

Reimagining Mission Systems, Tools, and Roles for Beyond LEO

- Onboard data systems that support monitoring, analysis, and trend identification for vehicle systems via sensors
- Diagnostic tools such as data visualization and decision aids
- AR/VR and other supportive technologies to help crew characterize and assess impacts of problems in complex, interconnected systems
- In-space manufacturing technologies
- Standards and requirements for advanced maintainability, reliability, and diagnosability must be established early

Research and technology capabilities to focus on

Timeline points indicate when the capability should be available

Simulation capabilities for determining requirements and validating concepts for Earth-independent crew anomaly resolution and complex operation execution.

Data integration, data architecture, and data visualization to support crew in vehicle diagnostic processes.

Artificial intelligence (AI) to aid the crew in data monitoring, analysis, and trend identification for vehicle systems.

Asynchronous communication support to mitigate effects of delays and intermittency.

Advanced **sensors** and sensor fusion to support crew diagnosis and repair of vehicle systems.

Advanced **maintainability standards** and sparing approaches (e.g., additive manufacturing) that support crew in both routine operations and conditions requiring critical repairs.

Virtual/augmented reality for crew execution support.

PRE-PHASE A: **Concept Studies**

PHASE A: **Concept Development**

PHASE B: **Preliminary Design**

PHASE C: **Final Design and Build**

PHASE D: **System Assembly, Integration, Test**

PHASE E: **Deployment, Operations, Sustainment**

▲ *LETS (Lunar Exploration Transportation Services)* for HLS

▲ *Gateway*

▲ *ORION*

Backup slides

Human Spaceflight Operations in Low-Earth Orbit

- **ISS Mission ops rely on**
  - Real-time communication
  - Mission Control commanding vehicle from the ground
  - Generous onboard supply of spares, equipment, consumables
  - Frequent resupply
  - Large orbital replacement units (sent back to Earth for maintenance)
  - Evacuation opportunity

- Up to ~30 min
- Lost items

Up to ~90 min

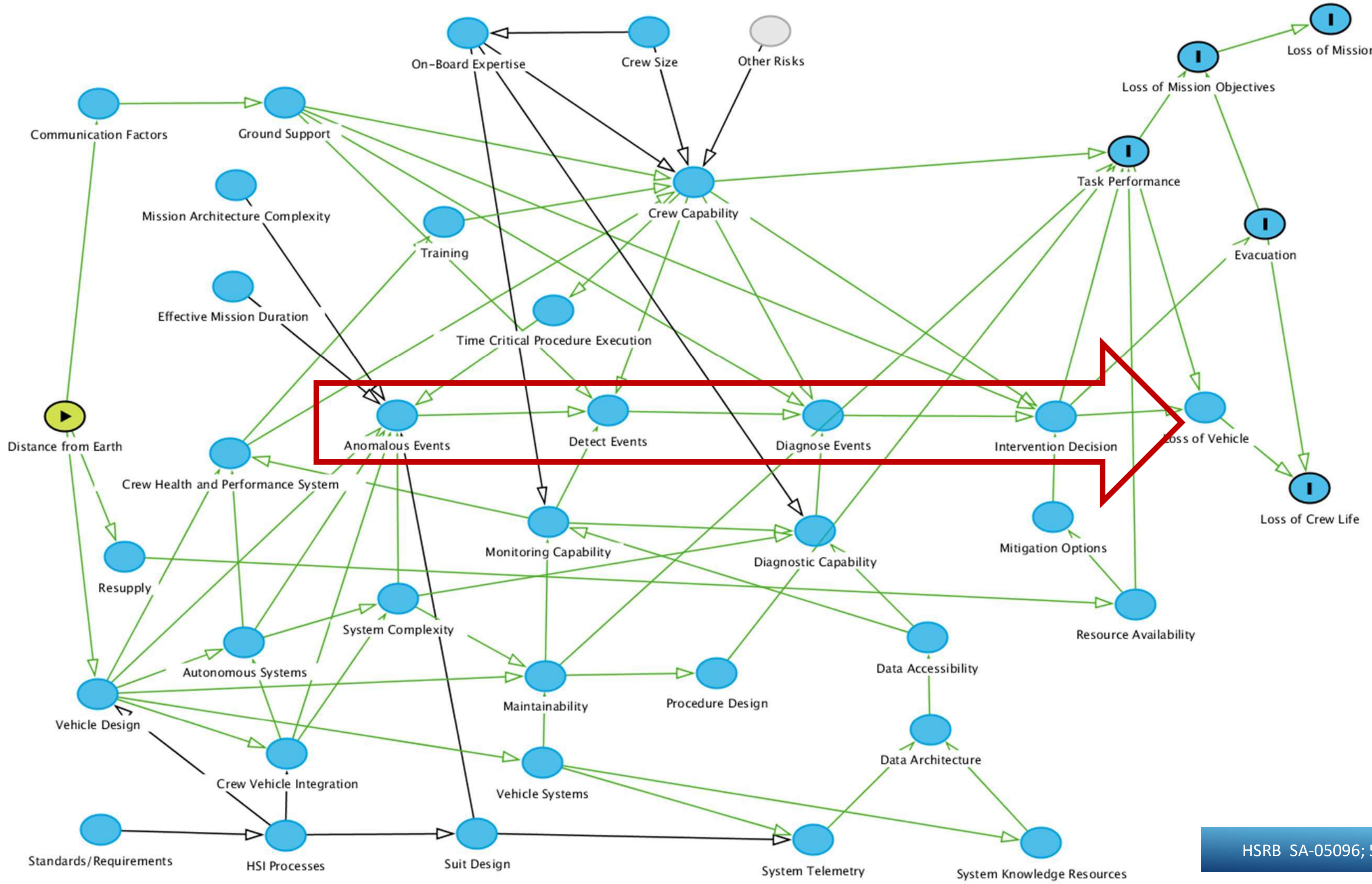
Challenge

- Access can be very time consuming
- Some areas are very difficult for crew to access

Potential Solution

- Inspect stowage and hardware before accessing

HSIA Risk DAG: Full



From 85+ to 4 people available to respond

MCC + MER

- 85 system experts
- 660 years combined specific systems experience
- ~2 years to operator cert
- Additional years to specialist cert
- In-depth understanding of a single system
- Training builds academic engineering background
- Constantly using skills and studying flight rules

Astronauts

- 4 crew members
- 91 years combined relevant work experience**
- 2 years ASCAN training
- ~2 years flight-assigned training
- *I&S, C&T, EPS, ETCS, ECLSS, ITCS, Emergency, MCS, OOM, Struc & Mech, Crew Systems, VV, Orb Mech, CMO, Med Ops, EVA, ROBO, Ops LAN, Photo/TV
- Time gap between training and flight; degradation of knowledge may be significant

**Calculated based on all active astronauts who are eligible to be assigned a flight as of January 2021

> ***"4 people with 25 years experience each on 4 console positions cannot replace 10 people with 10 years of experience on 10 console positions even though both groups have 100 years total experience. It's not just the experience, it's the experience in unique console positions."***
>
> -D. Dempsey, Training Expert

Human Research Program HSIA Gaps

	GAP ID	KEYWORD	GAP TITLE
Risk Characterization / Formulation	HSIA-101	**Metrics**	Establish HSIA performance measures and **metrics** needed to characterize and mitigate risk for future exploration missions beginning with lunar surface operations.
	HSIA-201	**Scenarios**	Characterize safety-critical mission **scenarios** (e.g., unanticipated anomalies of unknown origin requiring urgent response) to enable assessment of human-systems needs in research and simulation studies of future exploration missions beginning with lunar surface operations.
	HSIA-301	**Simulation**	Characterize needs for research, **simulation**, and analog capabilities to assess outcome measures and metrics for gap 201-801, to characterize and mitigate risk for future exploration missions beginning with lunar surface operations
Countermeasures / needs	HSIA-401	**Habitat**	Characterize *human-systems needs* for **vehicle/habitat** to enable increasingly Earth-independent performance of critical functions (e.g., telemetry monitoring/analysis, anomaly response, complex procedure execution, etc.) during future exploration missions beginning with lunar surface operations.
	HSIA-501	**HCI**	Characterize *human-systems needs* **for computer interfaces** to enable increasingly Earth-independent performance of critical functions (e.g., telemetry monitoring/analysis, anomaly response, complex procedure execution, etc.) during future exploration missions beginning with lunar surface operations.
	HSIA-601	**Tasks**	Characterize *human-systems needs* for enabling more Earth-independent execution of dynamic and adaptive mission **procedures** and **processes** during future exploration missions beginning with lunar surface operations.
	HSIA-701	**Training**	Characterize **training** needs for crew, both pre and in-mission, for increasingly Earth-independent operations to enable critical on-board functions currently performed by ground controllers (e.g., problem-solving, planning, procedure execution direction and oversight, etc.)
	HSIA-801	**Automation & Autonomy**	Characterize *integrated human-systems needs* with respect to **intelligent systems, automation, and robotic capabilities** to enable monitoring, diagnosing and repair of critical vehicle systems during future exploration missions beginning with lunar surface operations.
Validate / integrate	HSIA-901	**Integration**	Characterize **integrative architecture** for human-system needs, with countermeasures to validate capability requirements for future exploration missions beginning with lunar surface operations.

State of Knowledge: Problems during crewed space flight

HRP Funded

Apollo Mission Reports Analysis:

Anomalies per Mission* (Rounded Average):

33

Anomalies per Mission Day (Rounded Average):

3

Incidents Requiring Urgent Diagnosis per Mission (Rounded Average):

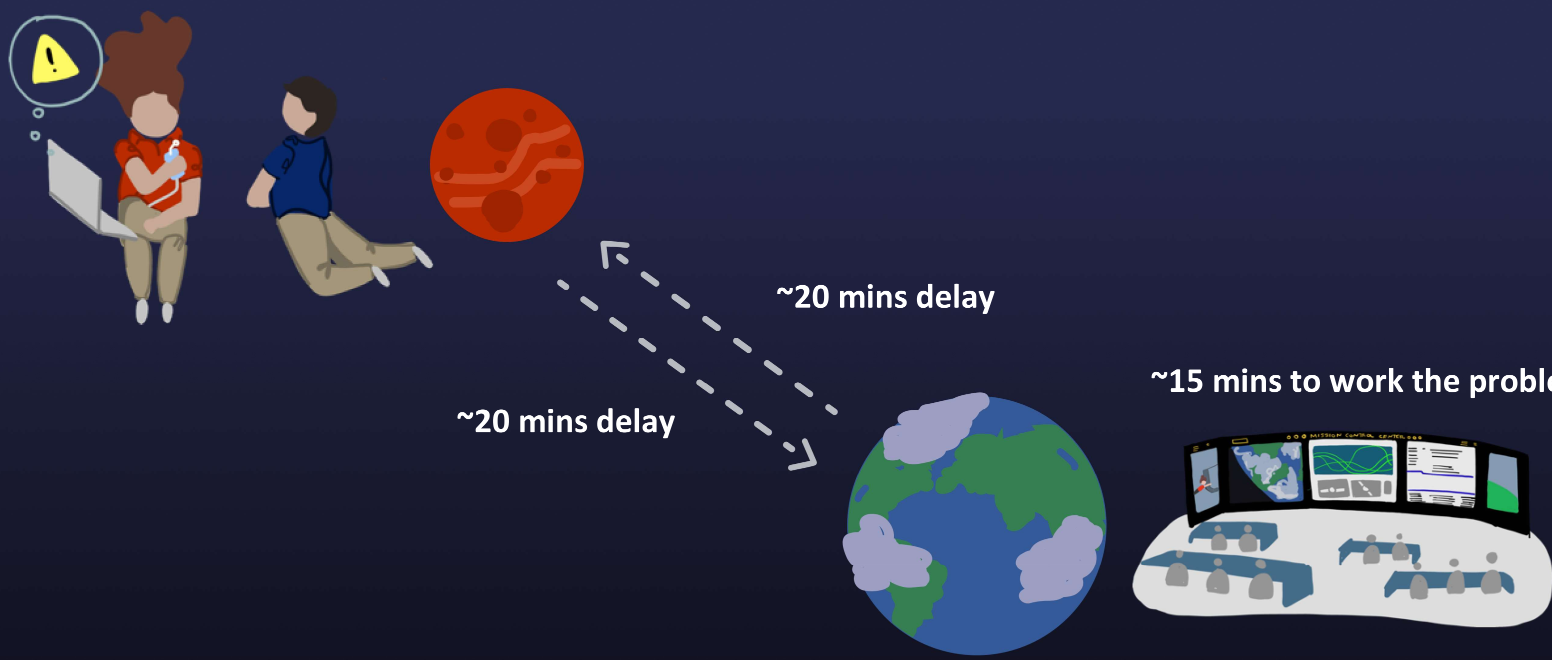
3

Anomaly count pulled from Apollo Mission Reports

362 Total Anomalies

- Problems Requiring Urgent Diagnosis (Assessed by SME)
- Significant Incidents (Assessed by JSC Safety & Mission Assurance in Human Spaceflight Z-Card)
- All other anomalies listed in mission report

Increased complexity of mission systems and interaction leads to increased likelihood of adverse events



Advice from ground will be up to 1 hour outdated

Mars Transit Projection of anomaly response with supportive technologies

Example Technologies to Aid Anomaly Response

First few days of anomaly response: