

# Effects of Communication Delay on Human Spaceflight Missions

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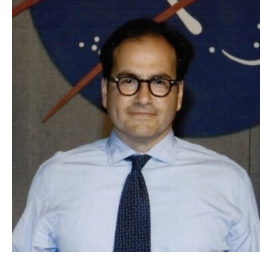
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# Human-Systems Integration Architecture (HSIA)

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



Apollo, 1961 - 1973



ISS, 2000 - present



Moon to Mars



# Current Mission Paradigm

COMM

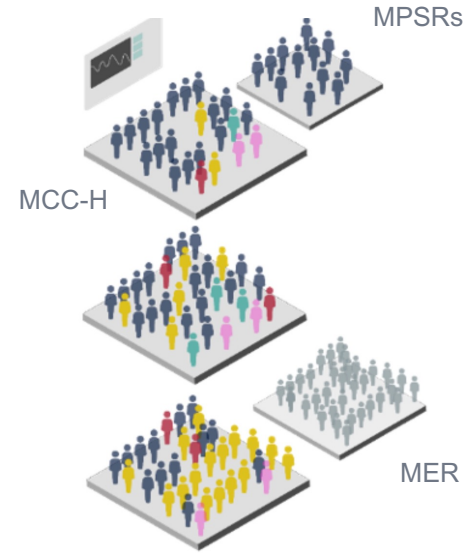
Near-complete **real-time dependence** on experts on the ground to control and manage the combined state of the mission, vehicle, and crew.

SUPPLY

Frequent resupply of spare parts and other resources from visiting vehicles to maintain the vehicle

EVAC

Evacuation back to Earth is possible within hours



Mission Control Expertise:  
85+ specialists available  
with ~660 years combined  
on-console experience



# Current Mission Paradigm

COMM

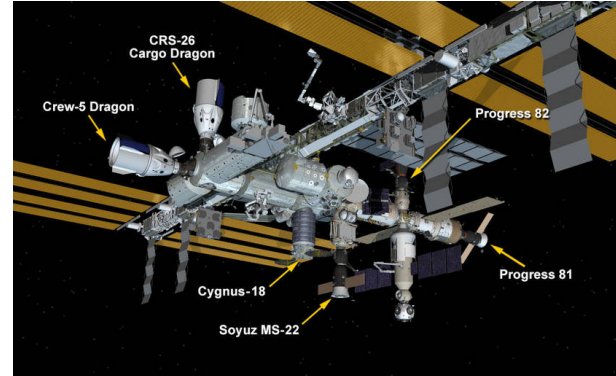
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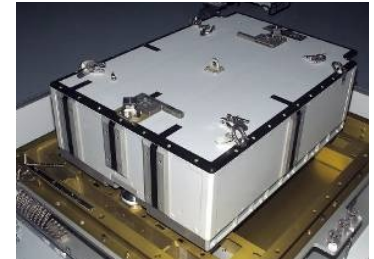
Frequent resupply of spare parts and other resources from visiting vehicles to maintain the vehicle

EVAC

Evacuation back to Earth is possible within hours



The International Space Station and select visiting vehicles



An example Orbital Replacement Unit (ORU)



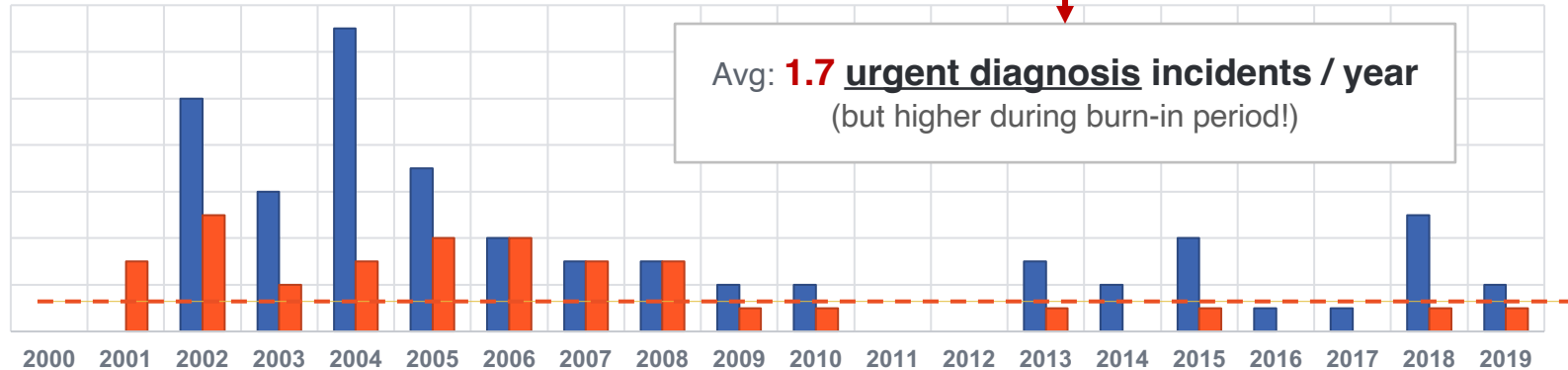
# Anomaly Response on the ISS

Time-Critical Anomalies on the ISS, 2001 - 2019

68 Total High Priority IFIs

**33** Vehicle incidents  
requiring urgent diagnosis:

**Unanticipated  
Urgent  
Unknown Origin**



# Human-Systems Integration Architecture (HSIA)

Our HSIA has evolved but not fundamentally changed.



Apollo, 1961 - 1973



ISS, 2000 - present



Moon to Mars



# Current Mission Paradigm

Safety-critical operations are managed from the ground:

Direct control

Oversight and guidance

Decision making

Problem solving



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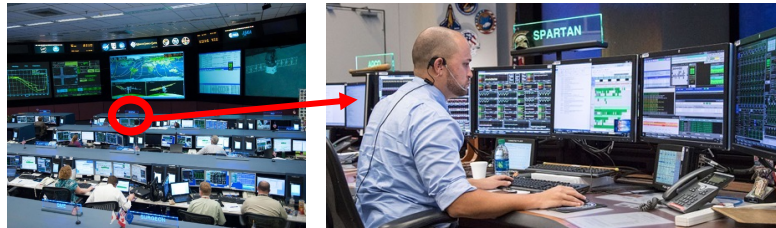
Direct control

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Problem solving

- MCC-H maintains near-full command of the vehicle from the ground
- MCC-H constantly manages the state of the vehicle



Amount of data evaluated by a single flight controller



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



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- MCC-H uses distributed decision-making to defer to the right systems expert at the right time
- Flight directors rapidly assess risk and make decisions



# Current Mission Paradigm

Safety-critical operations are managed from the ground:

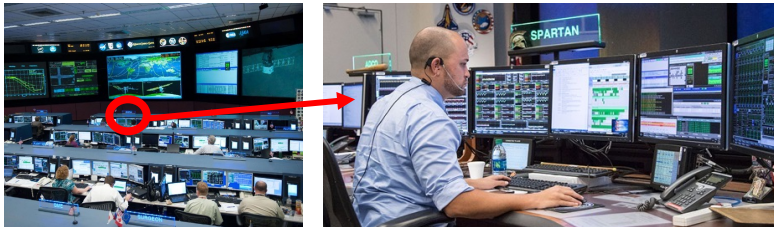
Direct control

Oversight and guidance

Decision making

Problem solving

- Flight controllers constantly monitor systems, detect anomalies, assess times-to-effect, and determine workarounds
- MCC-H and MER Engineers leverage historical data and deep systems expertise to troubleshoot, diagnose anomalies



Amount of data evaluated by a single flight controller



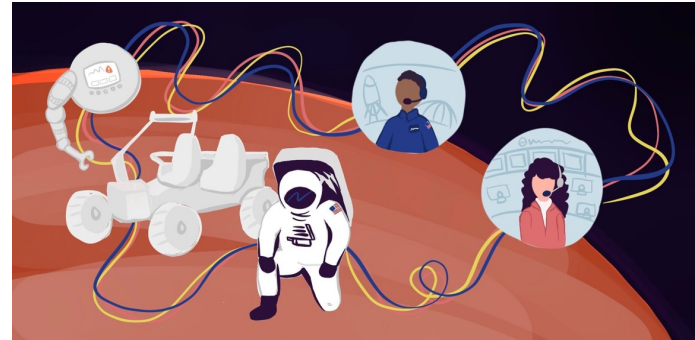
# Missions Beyond LEO: A Paradigm Shift

**COMM:** Bandwidth-constrained and delayed communication with ground

**SUPPLY:** Limited resupply

**EVAC:** Limited evacuation opportunity

**OPS:** Increased complexity of operations



# Apollo



3 second round-trip delay

Short duration, no resupply

Nearside landing site

# Artemis



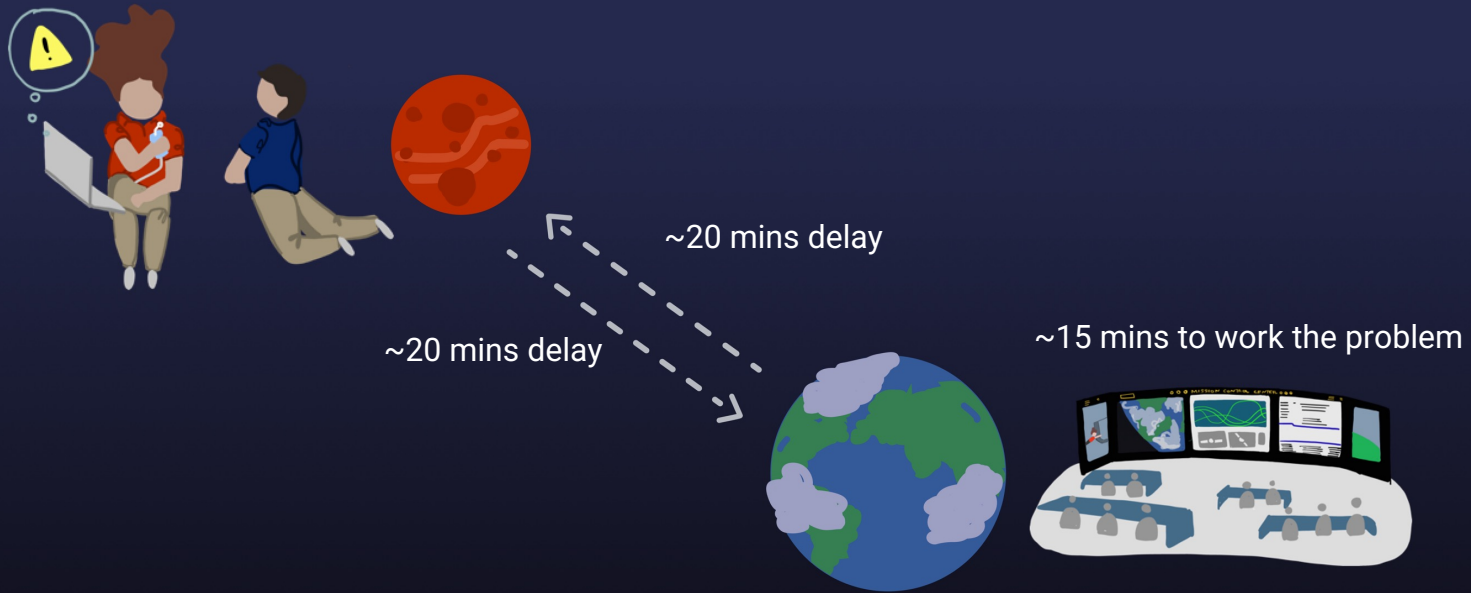
5 – 14 second round-trip delay

Sustainable lunar basecamp

Lunar south pole landing site with  
harsh illumination conditions



# Mars Mission



Advice from ground will be up to 1 hour outdated


# Comm Delay Studies

Round-trip Delay (seconds)	0-4	10	100	600	1200	2400
<b>Analog</b>	NEEMO 7 & 9, AMO		DRATS 2011 & 2012, AMO, DSH, NEEMO 16, ISS, ISTAR	AMO, NEEMO 16, ECLSS Computer Sim	DRATS 2012, NEEMO 16	NEEMO 13 & 14, DRATS 2012
<b>Year</b>	2004, 2006, 2012		2011, 2012, 2016, Incr 35/36	2012, 2014	2012	2007, 2010, 2012
<b>Normal Ops</b>	✓		✓	✓		✓
<b>EVA</b>			✓	✓	✓	✓
<b>Medical/ Emergency</b>	✓		✓	✓	✓	✓
<b>Maintenance</b>	✓		✓	✓		
<b>Contingency</b>	✓		✓	✓		
<b>Troubleshooting</b>	✓		✓	✓		

Rader et al., 2013; Kintz et al., 2016; Fischer & Mosier, 2014



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					<b>MARS</b>	

Rader et al., 2013; Kintz et al., 2016; Fischer & Mosier, 2014



# Comm Delay Studies: Limitations

- Definitions of operational regime (e.g., “contingency”)
- Levels of situational or task acuity/complexity
- Controls
- Measures of simulation fidelity
- Measures of outcomes (e.g., ”degraded capabilities”)
- Repeatability
- Small sample sizes



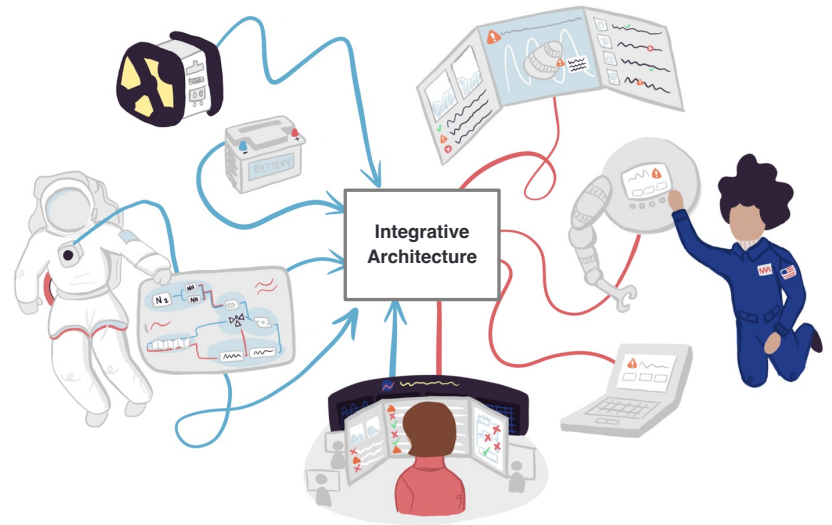
The reported impacts of communication delays in low fidelity environments may be underestimated, particularly for tasks involving highly complex, dangerous, and/or off-nominal situations.

– Kintz et al., 2016



# Missions Beyond LEO Require a New HSIA

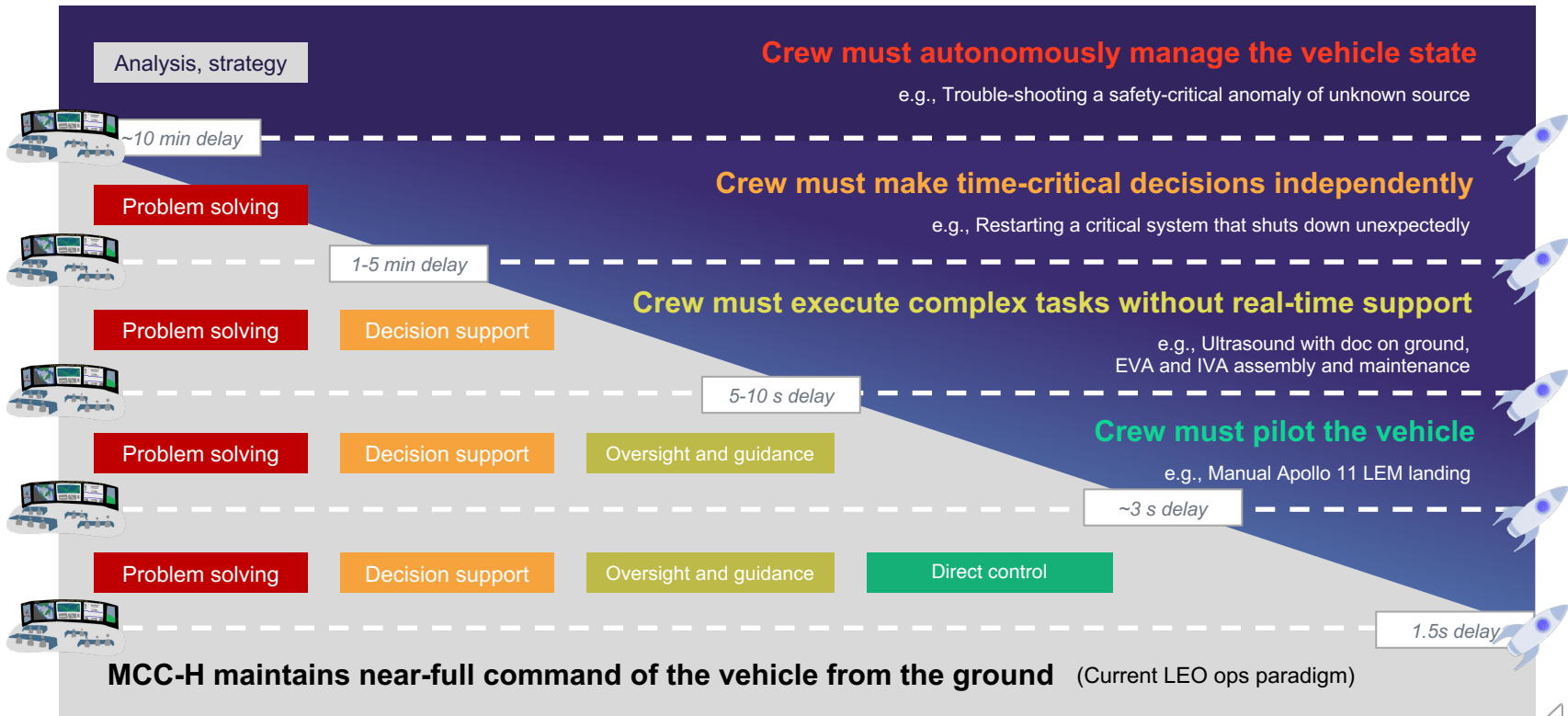
Development and validation of a new HSIA requires conducting **simulations** with **realistic tasks** and **expected comm delays**.



# Ground-to-onboard shift of safety-critical operations with increasing comm delay

ROLE OF GROUND TEAM

ROLE OF FLIGHT CREW



Ground will always have more expertise and personnel; anything that can be worked at a pace that allows interaction with the ground will utilize those resources



# Lunar Anomaly Analysis

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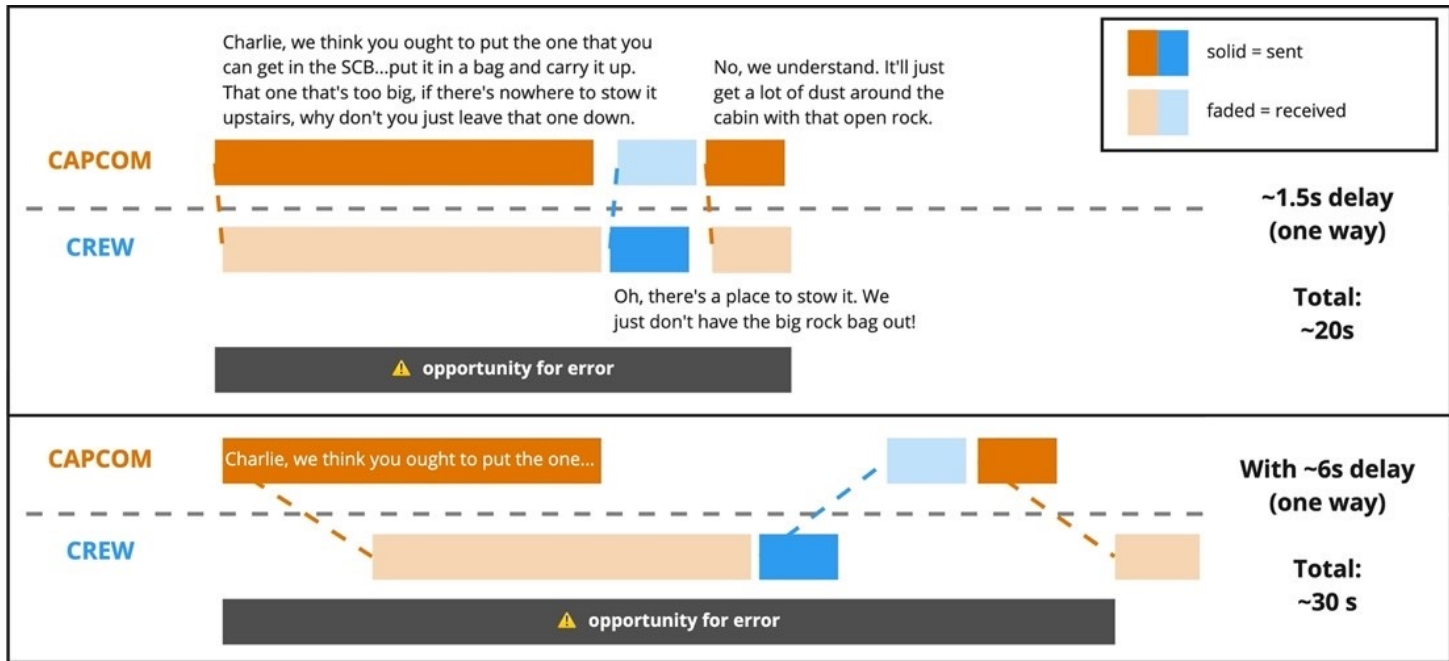


# Comm delay example

Apollo 16 EVA with simulated 12-second round-trip delay



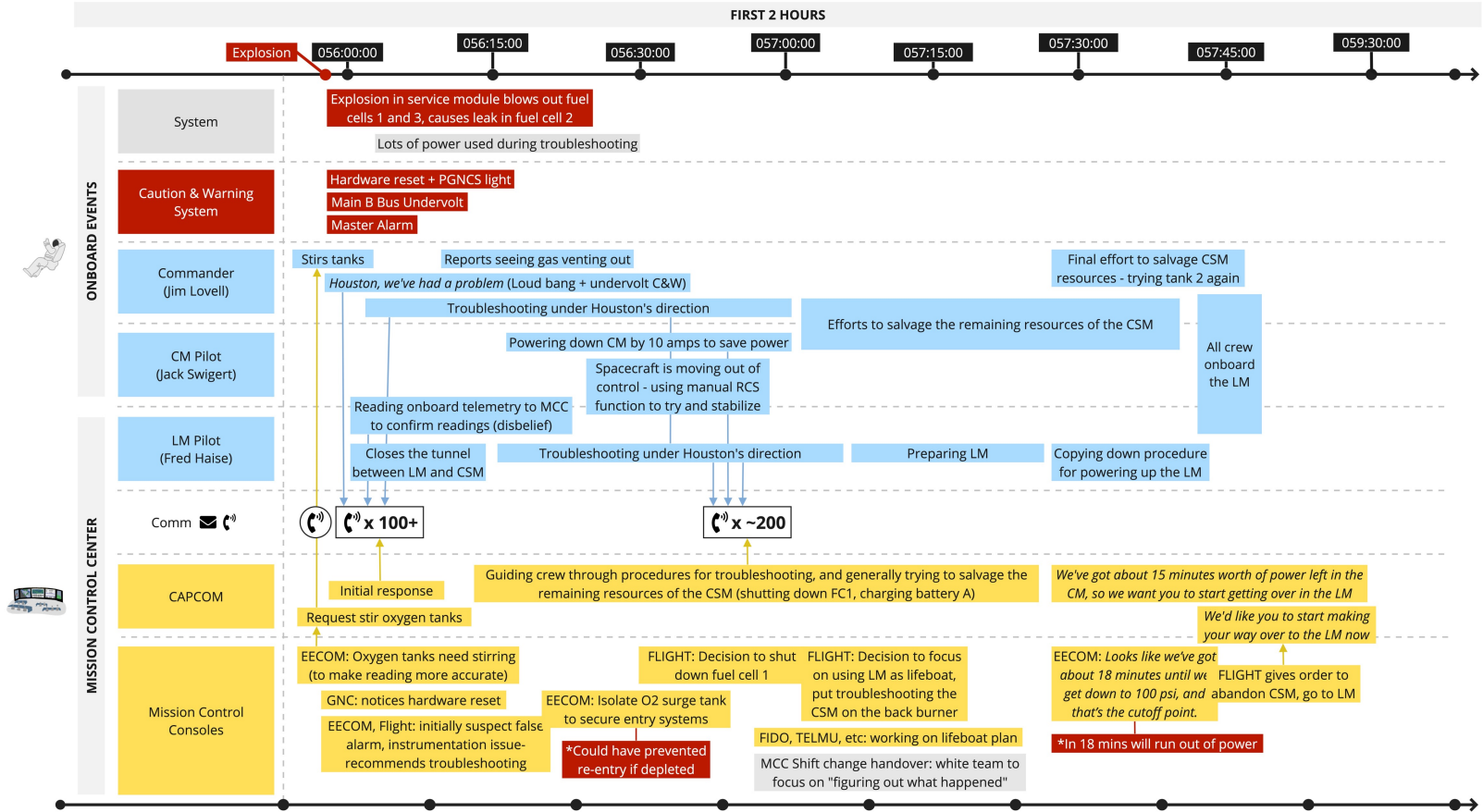
# Apollo 16 EVA Space-to-Ground Dialog



Expected lunar comm delay limits the ground's ability to oversee crew task execution, increasing the opportunity for crew error.



# Apollo 13: First Two Hours



# Apollo 13: First Two Hours

## COMPLEX TASK EXECUTION

**CapCom:** It's just four lines. Go to Activation 1, do step 3. Go to Activation 11, omit step 1. Do Activation 12, and then go to Activation 13 and do step 1. Do you copy?

**Crew 2:** Okay. Is that Activation 1? Do step 3. Is that correct?

**CapCom:** That's affirmative, Jim.

**Crew 2:** Activation 11, omit step 1, do the rest. Is that correct?

**CapCom:** That's affirmative.

**Crew 2:** Do Activation 12 and Activation 13, step 1.

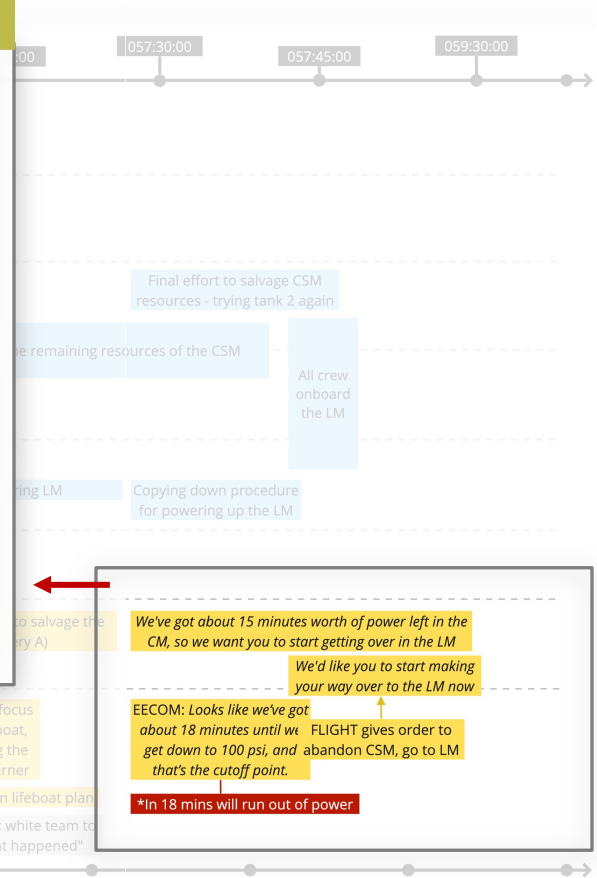
**CapCom:** That's all correct.

**Crew 3:** Okay, Jack. Pressure in tank 1 is approaching 100 psi. What's going to be the symptoms of this fuel cell starting to drop off?

**CapCom:** Stand by, Jack. We'll get the word on that.

**Crew 3:** Okay.

**CapCom:** And, Jim, when you get to the end of that procedure, we'd also like to have you put the Demand Regs to Cabin.

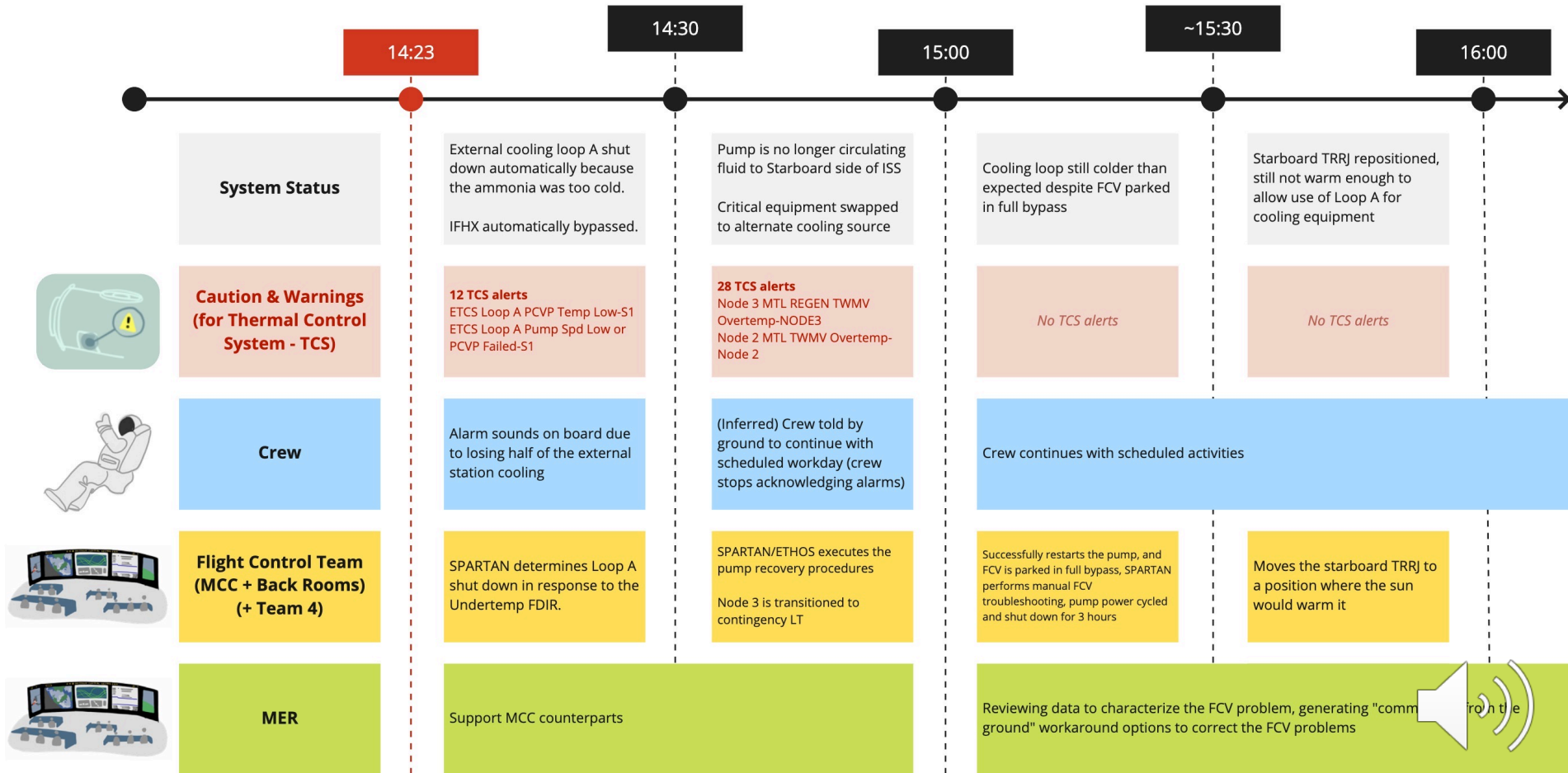


# Mars Anomaly Analysis

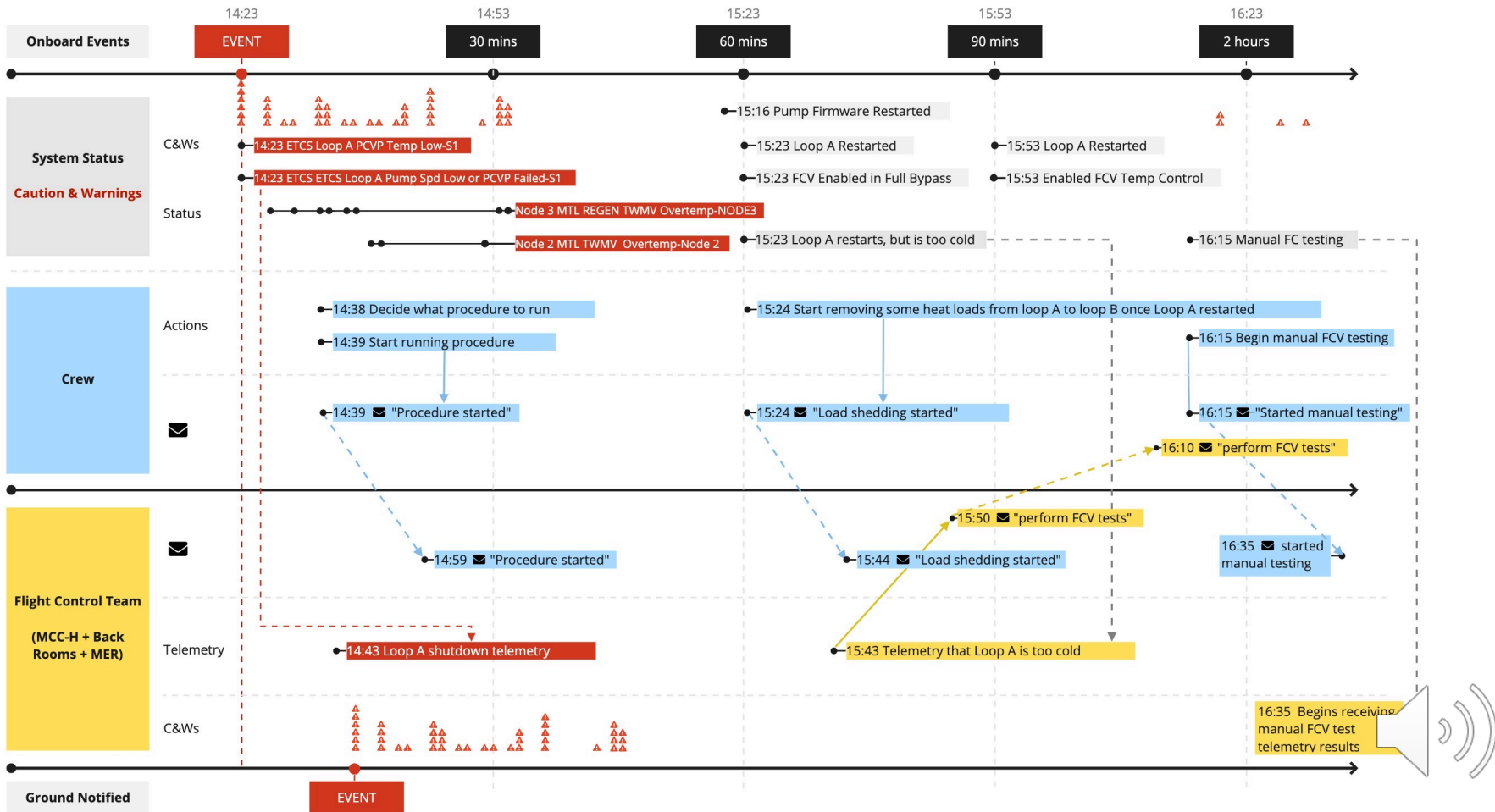
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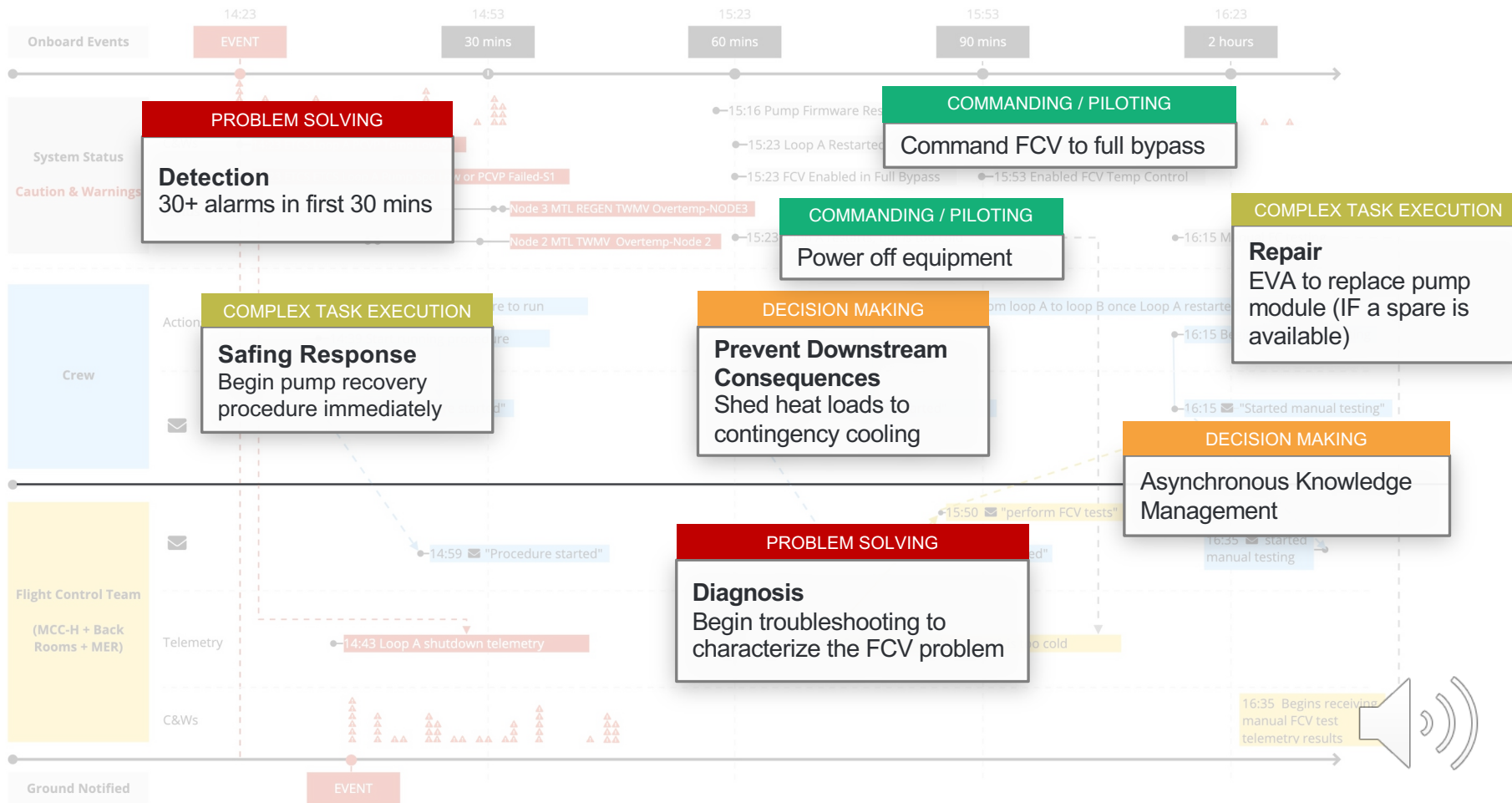
# ISS Cooling Loop A Anomaly: Actual Events



# Mars Transit Projection of the ISS Cooling Loop A Anomaly



# Mars Transit Projection of crew anomaly response



# Application to Future Simulations



# Critical Scenario Characteristics: Lunar

- **Time pressured** due to safety-criticality or need to complete additional tasks
- **Complex**, requiring some support from ground to be completed correctly
- Delayed **oversight** from ground is available
- **Data availability** at site of task (e.g., telemetry indicating successful step completion) and on the ground (delayed)
- **Multiple parallel elements** (e.g., an alarm sounds during procedure execution)
- **Local situation awareness** (i.e., crew has immediate information that the ground does not have)



Problem solving

Decision support

Oversight and guidance

Direct control

# Critical Scenario Characteristics: Mars

- **Causal relationships** are not immediately understood
- **No perfect information** is available during initial stages
- **Intervention options are limited** (e.g., limited resources, redundancy, sparing), requiring creative thinking to generate workarounds
- **Short-time-to effects** and **competing priorities** that require simultaneous efforts



# Needed Technologies

- **Artificial intelligence** to aid the crew in data monitoring, analysis & trend identification
- Advanced **maintainability** and sparing approaches (e.g., additive manufacturing) that support crew in both routine operations and conditions requiring critical repairs.
- Advanced **sensors** and **sensor fusion** to support crew diagnosis and repair of vehicle systems
- **Data integration, data architecture,** and **data visualization** to support crew in vehicle diagnostic processes
- **Asynchronous communication support** to mitigate effects of delays and intermittency.
- **Virtual/augmented reality** for crew execution support.



# Thank you

