Autonomous Mission Operations Roadmap

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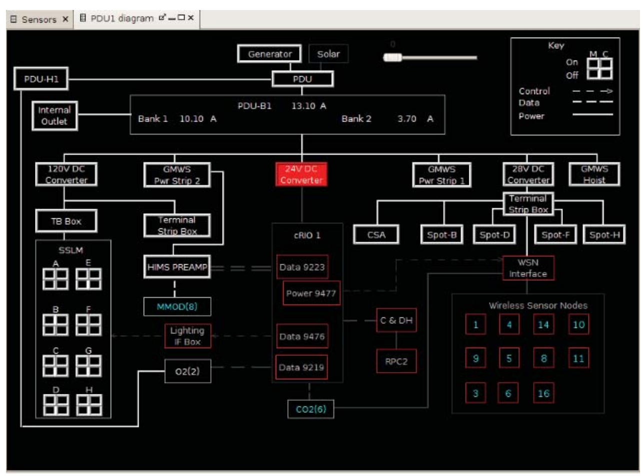
Executive Summary

- *Autonomous Mission Operations* is the capability of flight controllers and crews to manage a crewed mission with minimal reliance on Earth-based Mission Control.
  - Autonomy is accomplished by automating vehicle functions, and by transitioning responsibilities from Mission Control to crew.
- This capability is *enabling* for missions to NEAs and Mars.
- Near-term capability demonstrations onboard ISS and using ground-based analogs are funded. Gaps have been identified; filling them requires further funding.

Defining Autonomous Mission Operations

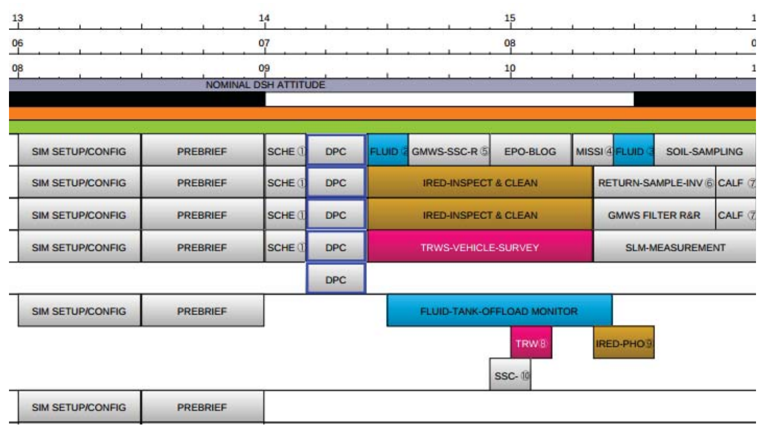
Mission Operations Capabilities

- **Monitoring Displays:** displays are groups of commands and telemetry / data used by flight controllers and crew to monitor and command a subset of spacecraft systems in conjunction with a specific activity.
- **Manage Faults:** Failures are the unacceptable performance of an intended function. Failures are caused by faults.
  - Fault management includes detection, isolation and recovery from faults.
  - Managing faults is often done using pre-defined fault management procedures.



Mission Operations Capabilities

- The **Plan** (or Timeline) is the list of all activities occurring during the mission including those performed by the crew, occurring on the spacecraft (e.g. maneuvers, docking/ undocking), or impact the mission (e.g. communications coverage changes).
  - Activities last from 5 minutes to tens of minutes.
  - Activities refer to procedures or procedure steps.
- **Perform Procedures:** procedures are step-by-step instructions to perform a specific task.
  - Crew and flight controllers perform procedures during the mission.
  - Procedure steps take seconds to minutes.



Mission Operations Performance Parameters

Telemetry is shown on **Displays.**

Failures are shown on **Displays.**

Commands are issued from **Displays.**

Commands are organized into **Procedures.**

Failures trigger **Procedures.**

Procedures are organized into **Plans.**

Operational Guidelines constrain **Plans.**

Operational Guidelines constrain **Procedures.**

Failures disrupt **Plans.**

Capability Discriminators

- Low time delay
  - <10 seconds 1-way light-time
  - Based on 2012 AMO experiment; flight controllers dispensed with 10 second test case because it was deemed identical to ISS operations
  - Covers LEO and Lunar DRMs
- NEA without EVA
  - < 8 minutes 1-way light-time
  - DRMs assume NEA operations correspond to 1 Astronomical Unit (AU) distance from Earth, which incurs 8 minute 1-way delay
- NEA with EVA
  - EVA increases complexity of missions compared to non-EVA
- Mars without EVA
  - <22 minutes 1-way light-time
- Mars with EVA

Gap Fillers

Analysis

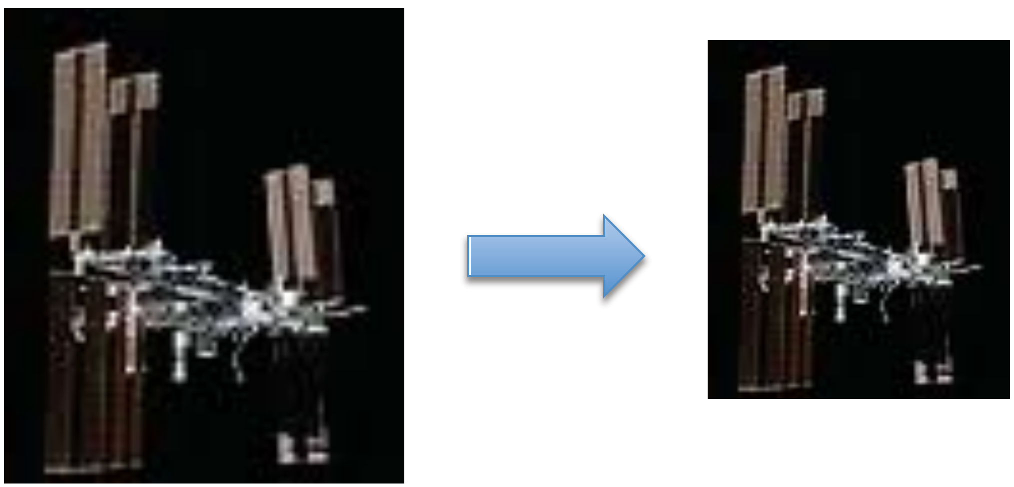
International Space Station

Command (distinct types)	70,000
Telemetry (distinct types)	177,000
Procedures (distinct)	4,000
Operational Guidelines / Constraints	1,000 (Flight rules and crew planning constraints)
Failure messages (distinct types)	18,000 (estimated from emergency books)
Displays (ground)	1,500
Displays (onboard)	3,000
Plan size (activities / day)	200 (estimated from crew, power and attitude plans)

These parameter values are for USOS only.

Approach to Capability Growth Assessment

- Capability thresholds for each class of DRMs were derived by scaling ISS capability.
- Scaling was derived from:
  - Crew size reduction (4 for Exploration, 6 for ISS)
  - Increased autonomy for NEA and Mars DRMs
  - Reduced capability required if EVA not part of DRMs



Scaling relative to ISS for Autonomous Ground Operations

Time Delay/ Capability	Low <10 sec	NEA w/o EVA < 8 min	NEA w EVA < 8 min	Mars w/o EVA < 22 min	Mars w EVA < 22 min
Desired	ISS	ISS	ISS	ISS	ISS
Threshold	2/3 ISS	1/2 ISS	2/3 ISS	2/3 ISS	ISS
State of the Art	ISS	1/2 ISS	1/2 ISS	1/2 ISS	1/2 ISS

Scaling relative to ISS for Autonomous Crew Operations

- NEA and Mars DRMs assume increased autonomy.
  - Crew cognizance of Operations Constraints and Guidelines *increases* due to time delay.
  - More vehicle automation *reduces* required crew cognizance of Commands and Telemetry.
  - This manifests as reductions in effort to Monitor Displays and Perform Procedures.

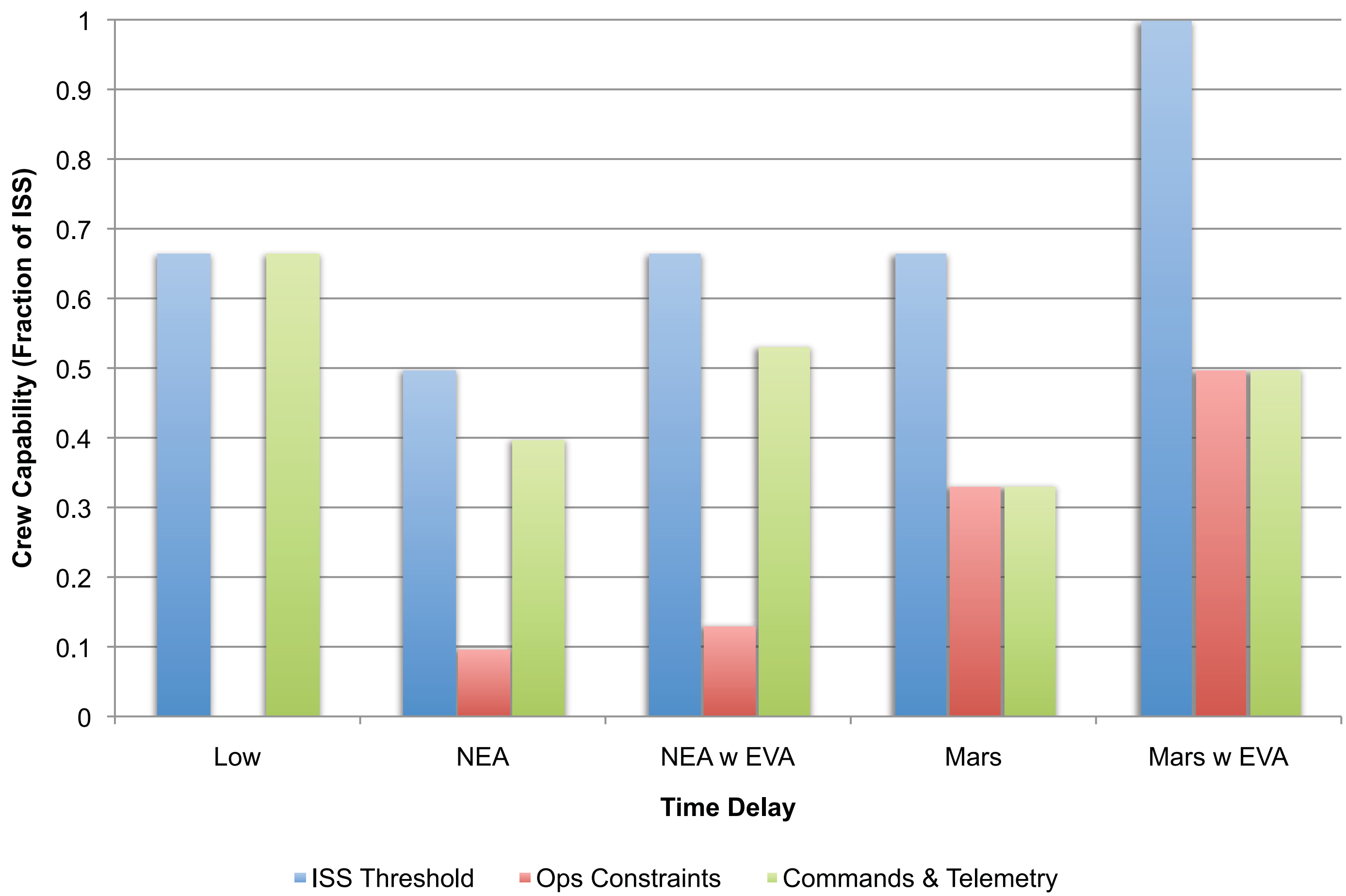
Scaling relative to ISS for Autonomous Crew Operations

Time Delay/ Capability	**Low** <10 sec	**NEA w/o EVA** < 8 min	**NEA w EVA** < 8 min	**Mars w/o EVA** < 22 min	**Mars w EVA** < 22 min
Desired	ISS	ISS	ISS	ISS	ISS
Threshold	2/3 ISS	1/2 ISS	2/3 ISS	2/3 ISS	ISS
State of the Art	ISS	1/2 ISS	1/2 ISS	1/2 ISS	½ ISS

Scaling relative to ISS for Autonomous Crew Operations

Time Delay/ Capability	Low <10 sec	NEA w/o EVA < 8 min	NEA w EVA < 8 min	Mars w/o EVA < 22 min	Mars w EVA < 22 min
Desired	ISS	ISS	ISS	ISS	ISS
Threshold	2/3 ISS	1/2 ISS	2/3 ISS	2/3 ISS	ISS
State of the Art	ISS	1/2 ISS	1/2 ISS	1/2 ISS	½ ISS
% ops guidelines	0	20%	20%	50%	50%
% commands, telemetry,	100%	80%	80%	50%	50%

Scaling relative to ISS for Autonomous Crew Operations



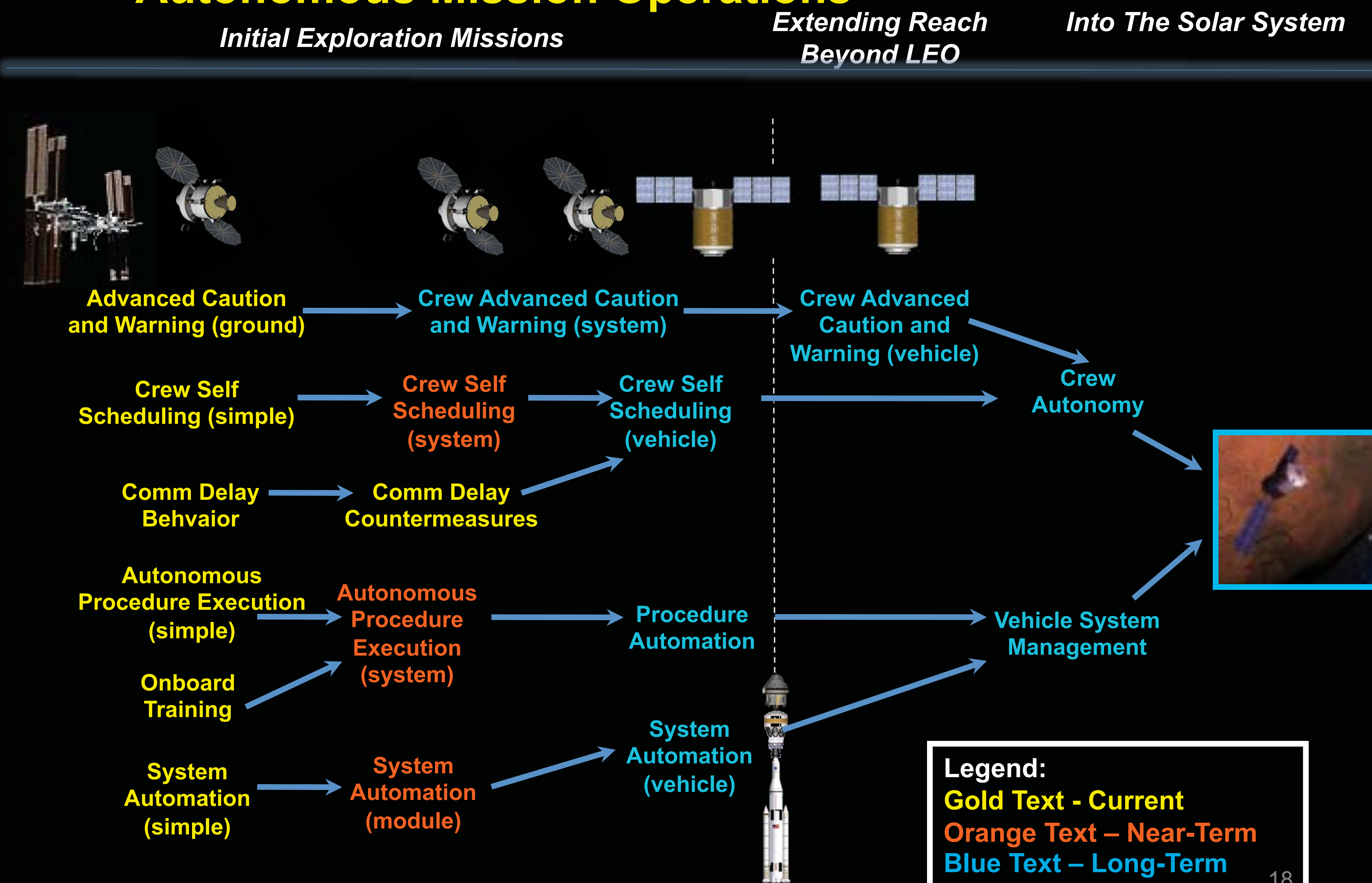
Gap Fillers

Activity

Activities on Capability Roadmap

- Extending autonomy capability requires:
  - Transitioning responsibility from ground to crew (e.g. autonomous procedure execution)
  - Automating functions done by people (e.g. procedure automation)
  - Expanding autonomy from simple to complex tasks (e.g. from single procedures to managing entire system)
  - Scaling autonomy from smaller to larger systems (e.g. one power bus to four)
  - Expanding autonomy to more types of systems (e.g. power, ECLSS and Thermal)

Capability Progression / Dependency
– Autonomous Mission Operations



Activity (Current: ISS)

- Comm Delay Characterization
  - Observe impact of time delay on team interaction
- Autonomous Procedures
  - Revise existing procedures for ISS crew execution without ground assistance
- ISS Texting
  - Develop texting protocols; demonstrate texting to and from ISS
- Crew Self Scheduling
  - Compare multiple crew self-scheduling technologies

Activity (Near-Term: ISS)

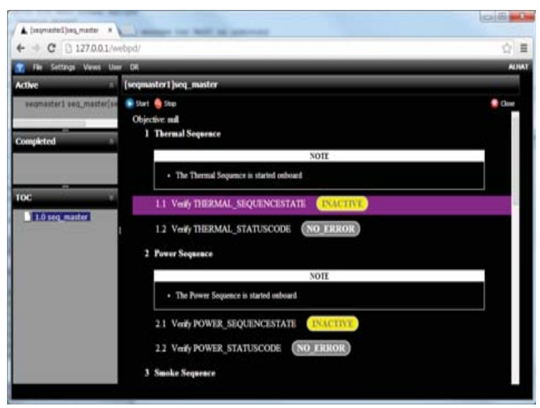
- AMO TOCA-SSC
  - Demonstrate crew autonomous management of TOCA and monitoring of SSCs
- AMO-EXPRESS
  - Demonstrate ground initiated powerup and configuration of EXPRESS rack
  - Set stage for crew initiated experiment using novel operations technology

Activity (Long-Term: ISS)

- Autonomous Systems and Operations (ASO)
  - Demonstrate crew autonomous management of complex ISS system (TBD)
- Autonomous Logistics Management (ALM)
  - Demonstrate crew use of static and mobile RFID readers onboard ISS to track logistics
- Autonomous Remote System Management (ARSM)
  - Demonstrate crew ability to teleoperate systems without ground assistance

Activity (Long-Term: ISS)

- Autonomous Extra Vehicular Activity (EVA)
  - Demonstrate tools to assist ISS crew in autonomously conducting EVA (in order to demonstrate capability to do so at high time delay)
- Autonomous Flight Dynamics (AFD)
  - Demonstrate tools to assist crew in performing vehicle maneuvers at high time delay

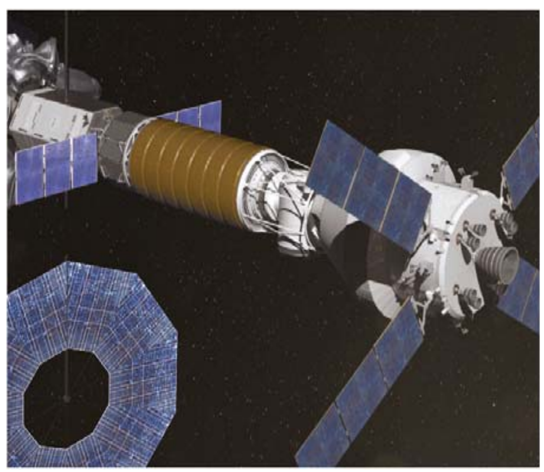


Activity (Current: Ground)

- EFT-1 Advanced Caution and Warning (ACAWS)
  - Demonstrate advanced caution and warning tools during EFT-1
- EM-1 ACAWS
  - Demonstrate advanced caution and warning tools during EM-1

Activity (Long Term: Ground)

- VSM (Power)
  - Demonstrate autonomous power systems management of an Earth-Moon L2 vehicle
- VSM (Life Support)
  - Demonstrate autonomous life support management of an Earth-Moon L2 vehicle



Gap Filler Activities and Capabilities

Autonomous Crew Operations

Parameters Activities	Telemetry	Commands	Displays	Procedures	Plan Steps	Operational Constraints	Faults
AMO TOCA-SSC (Monitor Displays, Perform Procedures, Manage Faults)	<100		<10	<100		<100	<100
AMO EXPRESS (Perform Procedures, Manage Faults)	<100	<100		<10		<10	
Auto Procedures (Perform Procedures, Manage Faults)	<1000	<100		<10			<1000
Crew Self Scheduling (Execute Timeline)					TBD	TBD	

Autonomous Ground Operations

Parameters Activities	Telemetry	Commands	Displays	Procedures	Plan Steps	Operational Constraints	Faults
EFT-1 ACAWS (Manage Faults)	<1000	<10	<10				<10000

Gap Fillers

Costs

Main Costs to Fill the Gaps

- Autonomous Crew Operations
  - Technology development duration
  - Technology development costs
  - Testing onboard ISS
- Autonomous Ground Operations
  - Testing with ISS

Main Costs to Fill the Gaps

- The pacing items for demonstrating autonomy technology in the presence of time delays of less than 8 minutes are:
  - ISS on-orbit time
  - Availability of a sophisticated human spaceflight simulation on the ground
  - Availability of trained flight controllers and crew to perform experiments.

Inter-SMT Relationships

- Direct relationships
  - EVA demonstrations
  - Human Systems demonstrations
  - Robotic Systems
- Indirect relationships
  - Activities that eliminate tasks (e.g. reduced maintenance of ECLSS hardware)
  - Activities that eliminate operational constraints (e.g. cameras that can operate in low light)
  - Activities that produce automated systems (e.g. automate power distribution)

STMD and I-SMT

- STMD Discussions have commenced
  - TA04,7,11
- Several ISS / International Exploration Working Group (Team 6) concepts have international participation
  - Crew Self Scheduling
  - Autonomous Procedures
  - Advanced Autonomy Software
- One International-SMT proposal suggestion
  - Autonomous Inspection (CSA proposal, joint with Robotics)

In-Space Inspection

A few thoughts

Autonomous In-Space Inspection

- Manage Timeline
  - Can activity be performed when planned?
  - Can Crew decide when to start activity without assistance from ground?
- Perform Procedures
  - Can Crew perform procedures without assistance?

Autonomous In-Space Inspection

- Monitor Displays
  - Can combination of In-Space Inspection system and Crew perform preliminary analysis of images without assistance from ground?
  - Can downlink management be automated without Crew intervention?
- Manage Faults
  - What faults can system help Crew address without assistance from ground?
  - Can faults in In-Space Inspection system be addressed by Crew without ground?

Future Plans

- Former ISS Expert Working Group (Team 6) and AMO SMT will join forces
  - Engagement with international partners will be extended to ESA, Russia
- Interaction with STMD Roadmaps will continue
- Commence engagement with HAT and Evolvable Mars
- Publish this roadmap!

Team

- J. Frank (ARC TI) (Lead)
- M. Lowry (ARC TI)
- D. Alfano (ARC TI)
- M. Schwabacher (ARC TI)
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- W. Spetch (JSC OM)
- A. Haddock (MSFC EO)
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- L. Morin (JSC CB)
- A. Stroupe (JPL 317)

BACKUP

Definitions of Parameters

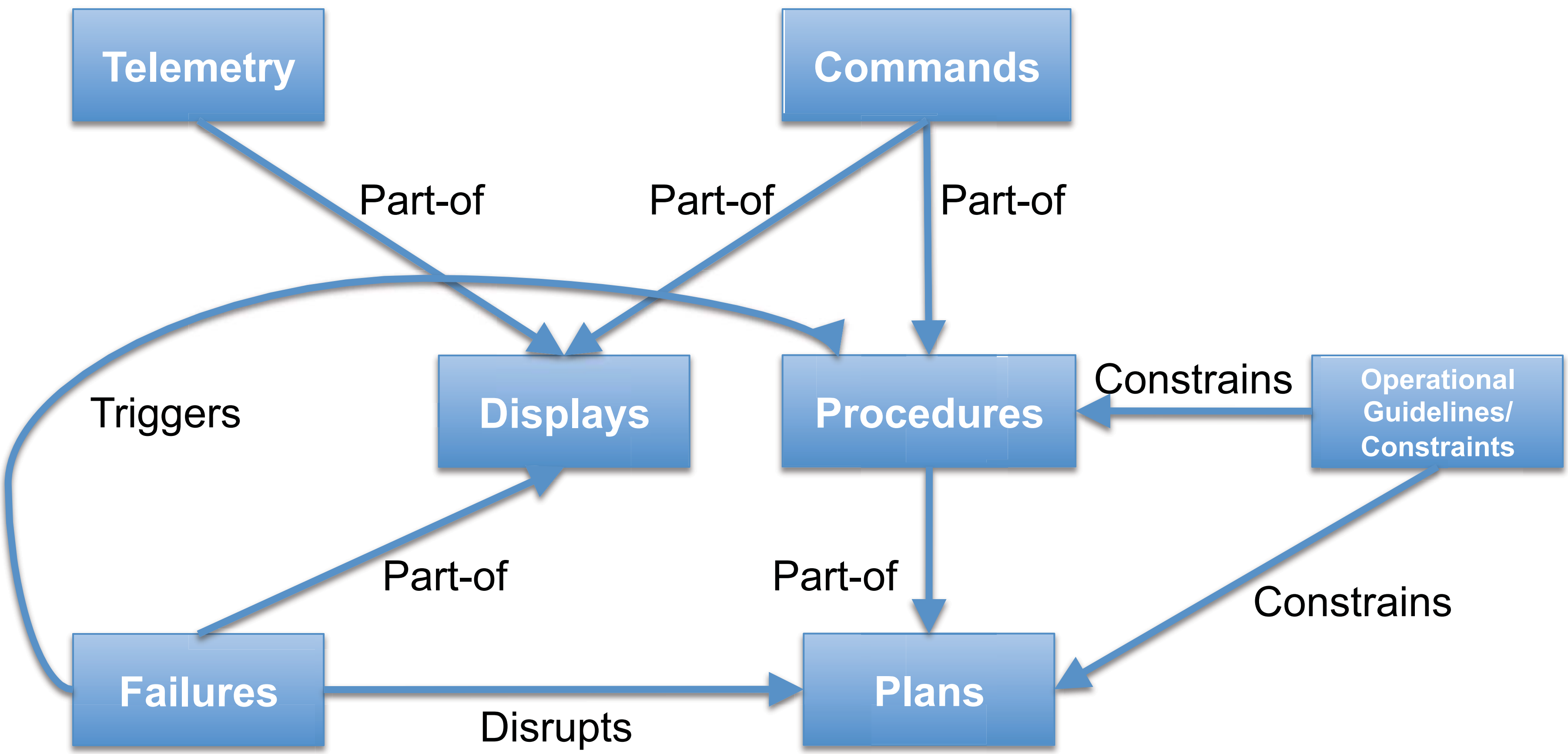
- **Commands** – directive to spacecraft or spacecraft subsystem
- **Telemetry** – single data item produced by spacecraft
  - Strictly speaking telemetry is what gets sent to ground
- **Display** – group of commands and telemetry used by flight controller in single tool or part of tool to run mission
- **Procedures** – step by step instructions to perform task
- **Plan** (Timeline) – distinct types of planning are required to create an operations plan (e.g. power, attitude, crew plan, etc.)
- **Operational Constraints and Guidelines**: – Generally includes any constraint, e.g. Crew Scheduling Constraints and Ground Rules and Constraints. Plans and procedures must respect / satisfy these constraints.
- **Failures** – loss of function of (part of) a system element

Capabilities and Parameters

Parameters Capabilities	Telemetry	Commands	Displays	Procedures	Plan Steps	Operational Constraints	Faults
Monitor Displays	✓	✓	✓			✓	
Perform Procedures	✓	✓	✓	✓		✓	
Execute Timeline					✓	✓	
Manage Faults	✓	✓	✓			✓	✓

These capabilities must be advanced both onboard (Autonomous Crew Operations) and ground (Autonomous Ground Operations). Transitioning authority, re-scoping ground control roles, increasing onboard automation and increasing ground automation are all needed to grow autonomous operations capability.

(Simple) Relationships between Parameters



What params and capabilities are missing?

- Knowledge
  - Console handbooks, systems briefs, crib sheets, on-board training, and other forms of knowledge
  - Access to this information will be key to future human spaceflight missions
- Analysis (Models and Simulations)
  - Flight dynamics (attitude and trajectory), consumables estimation, power and thermal models, communications interference
  - Migration of this functionality onboard will be likely to enable future human exploration missions

What params and capabilities are missing?

- Better explanation of how automation reduces required capability
  - Crew: better model for how reduction in telemetry and commands reduces effort to monitor displays, run procedures
  - Crew: automation should reduce effort in managing faults, means we need reduction in faults too
  - Ground: automation / autonomy should reduce effort for ground functions too

Definitions of Parameters

- Commands – directive to spacecraft or spacecraft subsystem
- Telemetry – single data item produced by spacecraft
  - Strictly speaking telemetry is what gets sent to ground; may need better terminology to distinguish data produced by spacecraft vs telemetry received by ground
  - Computations transform telemetry into other quantities for use in MCC. So there are really 3 ‘classes’ of data item: onboard, telemetry, comps.
- Display – group of commands and telemetry used by flight controller in single tool or part of tool to run mission
- Procedures – step by step instructions to perform task
  - JSC parlance: ‘Procedures’ are written to be executed by crew
  - JSC parlance: ‘Task-based displays’ used by flight controllers to run procedures.
  - Procedures could be automated or run by hand
- Timeline (Plan) – distinct types of planning are required to create an operations plan (e.g. power, attitude, crew plan, etc.)
- Operational Constraints and Guidelines: – Generally includes any constraint, e.g. Crew Scheduling Constraints and Ground Rules and Constraints. Plans and procedures must respect / satisfy these constraints.
  - Flight Rules - real time operations guidelines and situation response guidance
  - Groundrules and Constraints - Constraints and boundaries used in plan development and replanning
  - For launch vehicles there are also Launch Commit Criteria (LCCs).
- Failures – loss of function of (part of) a system element

(Simple) Relationships Between Parameters

- Telemetry is grouped into displays.
- Commands and telemetry are referenced in Procedures.
- Procedure steps are grouped into single Timeline (Plan) steps.
- Timelines and Procedures must satisfy Operational Guidelines and Constraints.
- Failures disrupt Timelines and Procedures.
- Failures are managed using displays and procedures.