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

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

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

<table>
<thead>
<tr>
<th>Time Delay/ Capability</th>
<th>Low &lt;10 sec</th>
<th>NEA w/o EVA &lt; 8 min</th>
<th>NEA w EVA &lt; 8 min</th>
<th>Mars w/o EVA &lt; 22 min</th>
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<tr>
<td>Desired</td>
<td>ISS</td>
<td>ISS</td>
<td>ISS</td>
<td>ISS</td>
<td>ISS</td>
</tr>
<tr>
<td>Threshold</td>
<td>2/3 ISS</td>
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<td>2/3 ISS</td>
<td>2/3 ISS</td>
<td>ISS</td>
</tr>
<tr>
<td>State of the Art</td>
<td>ISS</td>
<td>1/2 ISS</td>
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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

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<td>1/2 ISS</td>
<td>1/2 ISS</td>
<td>½ ISS</td>
</tr>
<tr>
<td>% ops guidelines</td>
<td>0</td>
<td>20%</td>
<td>20%</td>
<td>50%</td>
<td>50%</td>
</tr>
<tr>
<td>% commands, telemetry</td>
<td>100%</td>
<td>80%</td>
<td>80%</td>
<td>50%</td>
<td>50%</td>
</tr>
</tbody>
</table>
Scaling relative to ISS for Autonomous Crew Operations

![Bar chart showing crew capability scaling relative to ISS for various time delays and mission scenarios.](chart.png)
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

Initial Exploration Missions

Extending Reach
Beyond LEO

Into The Solar System

Legend:
Gold Text - Current
Orange Text – Near-Term
Blue Text – Long-Term
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

<table>
<thead>
<tr>
<th>Parameters Activities</th>
<th>Telemetry</th>
<th>Commands</th>
<th>Displays</th>
<th>Procedures</th>
<th>Plan Steps</th>
<th>Operational Constraints</th>
<th>Faults</th>
</tr>
</thead>
<tbody>
<tr>
<td>AMO TOCA-SSC (Monitor Displays, Perform Procedures, Manage Faults)</td>
<td>&lt;100</td>
<td>&lt;10</td>
<td>&lt;100</td>
<td></td>
<td></td>
<td>&lt;100</td>
<td>&lt;100</td>
</tr>
<tr>
<td>AMO EXPRESS (Perform Procedures, Manage Faults)</td>
<td>&lt;100</td>
<td>&lt;100</td>
<td></td>
<td>&lt;10</td>
<td></td>
<td>&lt;10</td>
<td></td>
</tr>
<tr>
<td>Auto Procedures (Perform Procedures, Manage Faults)</td>
<td>&lt;1000</td>
<td>&lt;100</td>
<td></td>
<td>&lt;10</td>
<td></td>
<td></td>
<td>&lt;1000</td>
</tr>
<tr>
<td>Crew Self Scheduling (Execute Timeline)</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td>TBD</td>
<td>TBD</td>
</tr>
</tbody>
</table>

### Autonomous Ground Operations

<table>
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<tr>
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</tr>
</thead>
<tbody>
<tr>
<td>EFT-1 ACAWS (Manage Faults)</td>
<td>&lt;1000</td>
<td>&lt;10</td>
<td>&lt;10</td>
<td></td>
<td></td>
<td></td>
<td>&lt;10000</td>
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</tbody>
</table>
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)
• B. Beuter (ARC TH)
• R. McCann (ARC TH)

• W. Spetch (JSC OM)
• A. Haddock (MSFC EO)
• M Macalyea (MSFC EO)
• D. Korth (JSC DA)
• S. Love (JSC CB)
• 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

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</tr>
</thead>
<tbody>
<tr>
<td>Monitor Displays</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
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<td>Perform Procedures</td>
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<td>✓</td>
<td>✓</td>
<td>✓</td>
<td></td>
<td>✓</td>
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<tr>
<td>Execute Timeline</td>
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<td></td>
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<td></td>
</tr>
<tr>
<td>Manage Faults</td>
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<td>✓</td>
<td>✓</td>
<td></td>
<td>✓</td>
<td>✓</td>
</tr>
</tbody>
</table>

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

- Telemetry
- Commands
- Procedures
- Plans
- Operational Guidelines/Constraints
- Displays
- Triggers
- Failures


Disrupts: Triggers

Constrains: Procedures → Operational Guidelines/Constraints, Plans → Operational Guidelines/Constraints
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.