Development and Execution of Autonomous Procedures Onboard the International Space Station to Support the Next Phase of Human Space Exploration

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Now that major assembly of the International Space Station (ISS) is complete, NASA's focus has turned to using this high fidelity in-space research testbed to not only advance fundamental science research, but also demonstrate and mature technologies and develop operational concepts that will enable future human exploration missions beyond low Earth orbit. The ISS as a Testbed for Analog Research (ISTAR) project was established to reduce risks for manned missions to exploration destinations by utilizing ISS as a high fidelity micro-g laboratory to demonstrate technologies, operations concepts, and techniques associated with crew autonomous operations.

One of these focus areas is the development and execution of ISS Testbed for Analog Research (ISTAR) autonomous flight crew procedures intended to increase crew autonomy that will be required for long duration human exploration missions. Due to increasing communications delays and reduced logistics resupply, autonomous procedures are expected to help reduce crew reliance on the ground flight control team, increase crew performance, and enable the crew to become more subject-matter experts on both the exploration space vehicle systems and the scientific investigation operations that will be conducted on a long duration human space exploration mission. These tests make use of previous or ongoing projects tested in ground analogs such as Research and Technology Studies (RATS) and NASA Extreme Environment Mission Operations (NEEMO).

Since the latter half of 2012, selected non-critical ISS systems crew procedures have been used to develop techniques for building ISTAR autonomous procedures, and ISS flight crews have successfully executed them without flight controller involvement. Although the main focus has been preparing for exploration, the ISS has been a beneficiary of this synergistic effort and is considering modifying additional standard ISS procedures that may increase crew efficiency, reduce operational costs, and raise the amount of crew time available for scientific research.

The next phase of autonomous procedure development is expected to include payload science and human research investigations. Additionally, ISS International Partners have expressed interest in participating in this effort. The recently approved one-year crew expedition starting in 2015, consisting of one Russian and one U.S. Operating Segment

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(USOS) crewmember, will be used not only for long duration human research investigations but also for the testing of exploration operations concepts, including crew autonomy.

I. ISTAR Exploration Risk Reduction Process

NASA's human exploration strategy calls for the use of ISS to mitigate beyond low earth orbit (BLEO) exploration risk. ISTAR supports exploration risk reduction by:

- Conducting exploration capability and risk gap analyses to identify opportunities for ISS exploration testing.
- Developing exploration relevant test objectives utilizing ISS.
- Documenting, tracking, and communicating completion of exploration objectives.
- Accurately showing how ISS is being used to mitigate exploration risks.
- Providing exploration risk buy-down progress feedback to exploration community.
- Participating in increasing awareness of the contributions of ISS for exploration in support of education and outreach.

Exploration risks must be reduced in a systematic fashion, using a risk reduction process. There are five phases to this process: Exploration Design Reference Missions (DRMs) and Concept of Operations (ConOps) data sources, analysis and assessment, product development, ISS integration and execution, and post-mission evaluation.

DRMs and architectures define the risks traveling to and from, and living at each exploration destination. NASA's Human Spaceflight Architecture Team (HAT) has generated (**Error! Reference source not found.**) a list of risks[i] to the successful accomplishment of crewed exploration missions and a list of mission architecture questions that must be answered before completing design for such missions. Similarly, NASA's Human Research Program (HRP) has a list[ii] of human health and performance risks and an assessment of the criticality of these risks (Figure 2). ISTAR uses these HAT- and HRP-generated risks and architectural questions for influencing its mission formulation, development strategy, and mission-evaluation criteria. Arrows point to the risk and question most relevant to crew autonomous procedures.

ID	Exploration Mission RISK
M-EDL	EDL of large Mars payloads
E-EDL	Earth re-entry at high velocities
LV	Launch vehicle failures
Lndr	Lander propulsion systems failure
CSM	Long duration low/zero boiloff cryo-storage and management
CFT	In-space cryogenic fluid transfer
ISP	In-space propulsion failures
A-ISP	Reliability verification of advanced in-space propulsion
Env	Environmental risks: radiation, MMOD, dust, electromagnetic
Dock	Docking/assembly failures
Sys	Systems failures: ECLSS, power, avionics, thermal
EVA	EVA system/suit failure
Comm	Operations under time delayed communication
Aut	Autonomous crew/vehicle operation
Health	Crew health: behavioral, health care/remote medical, micro-gravity
SW	Software failure
Hum	Human error
ISRU	ISRU equipment failure: propellant, consumables

ID	Exploration Mission Architectural Questions
Q1	What is the safest way to approach a small/non-cooperative/ non-stable object? (i.e. NEA, satellite)
Q2	What is the safest and quickest way to anchor to a NEA?
Q3	What Earth Orbit activities are needed to reduce risk for deep space missions?
Q4	What are the impact of the planetary protection requirements on operations and elements?
Q5	What are the functional/volumetric requirements for habitation and IVA activities in zero and low – g?
Q6	What is the difference in operational efficiency between crew size? (3 and 4 crew for NEA, 4 and 6 crew for Mars)
Q7	What is the most efficient way to communicate under a long >30 sec time delay? Does this change as the time increases?
Q8	What improvements of logistics and packaging can be realized?
Q9	What is the most effectives trade between level of repair and on-orbit manufacturing?
Q10	How do you best reuse/repurpose disposable materials?
Q11	What is the most effective means of surface transportation? (NEA, Moon/Mars short distance, Moon/Mars long distance)
Q12	Given current robotic capabilities, what level of human/ robotic interaction provides the highest level of operational efficiency? (EVA at destination, In-space EVA, IVA, Teleoperations)
Q13	What level of IVA/EVA activities at a destination provides the most benefit?

Figure 1: Human Spaceflight Architecture Team's (HAT) Exploration Mission Risks and Architectural Questions

HRP Risks & Criticality

Human Research Program (HRP) Elements:

- HHC: Human Health Countermeasures
- SHFH: Space Human Factors & Habitation
- ExMC: Exploration Medical Capability
- BHP: Behavioral Health & Performance
- SR: Space Radiation

HRP Elem	Risk Title (Short Title) U: Unacceptable Risk, A: Acceptable Risk, C: Controlled Risk, I: Insufficient Data	Criticality		
		Lunar	NEA	Mars
HHC	Risk of Orthostatic Intolerance During Re-Exposure to Gravity (Short Title: OI)	C	A	A
HHC	Risk of Early Onset Osteoporosis Due to Spaceflight (Short Title: Osteo)	C	A	A
HHC	Risk Factor of Inadequate Nutrition (Short Title: Nutrition)	C	A	U
HHC	Risk of Compromised EVA Performance and Crew Health Due to Inadequate EVA Suit Systems (Short Title: EVA) - *Pending Human System Risk Board (HSRB) Risk Management Analysis Tool (RMAT) Approval*	A	A	A
HHC	Risk of Impaired Performance Due to Reduced Muscle Mass, Strength and Endurance (Short Title: Muscle)	A	A	U
HHC	Risk of Renal Stone Formation (Short Title: Renal)	C	C	C
HHC	Risk of Bone Fracture (Short Title: Fracture)	C	C	C
HHC	Risk of Intervertebral Disc Damage (Short Title: IVD)	C	I	I
HHC	Risk of Cardiac Rhythm Problems (Short Title: Arrhythmia) - *Pending HSRB RMAT Approval*	C	I	I
HHC	Risk of Reduced Physical Performance Capabilities Due to Reduced Aerobic Capacity (Short Title: Aerobic)	A	A	U
HHC	Risk of Crew Adverse Health Event Due to Altered Immune Response (Short Title: Immune)	C	C	I
HHC	Risk of Impaired Control of Spacecraft, Associated Systems and Immediate Vehicle Egress due to Vestibular / Sensorimotor Alterations Associated with Space Flight (Short Title: Sensorimotor)	C	A	A
HHC	Risk of Therapeutic Failure Due to Ineffectiveness of Medication (Short Title: Pharm) - *Pending HSRB RMAT Approval*	C	C	I
HHC	Risk of Microgravity-Induced Visual Impairment/Intracranial Pressure (Short Title: VIIP) - *Pending HSRB RMAT Approval*	I	I	I
HHC	Risk of Injury from Dynamic Loads (Short Title: Occupant Protection)	U	U	I
SHFH	Risk of Performance Decrement and Crew Illness Due to an Inadequate Food System (Short Title: Food)	C	C	U
SHFH	Risk of Inadequate Human-Computer Interaction (Short Title: HCI) - *Pending HSRB RMAT Approval*	C	C	A
SHFH	Risk of Performance Errors Due to Training Deficiencies (Short Title: Train) - *Pending HSRB RMAT Approval*	C	C	A
SHFH	Risk of Inadequate Design of Human and Automation/Robotic Integration (Short Title: HARI) - *Pending HSRB RMAT Approv*	C	C	A
SHFH	Risk of Poor Critical Task Design (Short Title: Task) - *Pending HSRB RMAT Approval*	C	C	A
SHFH	Risk of Adverse Health Effects of Exposure to Dust and Volatiles During Exploration of Celestial Bodies (Short Title: Dust) – *Pending HSRB RMAT Approval*	A	I	I
SHFH	Risk of an Incompatible Vehicle/Habitat Design (Short Title: Hab) - *Pending HSRB RMAT Approval*	C	C	A
SHFH	Risk of Adverse Health Effects Due to Alterations in Host-Microorganism Interactions (Short Title: Microhost)	A	I	I
ExMC	Inability to Adequately Recognize or Treat an Ill or Injured Crew Member (Short Title: ExMC)	A	A	U
BHP	Risk of Adverse Behavioral Conditions and Psychiatric Disorders (Short Title: Bmed) - Reference RMATs for Risk of Adverse Behavioral Conditions, and Risk of Psychiatric Disorders	C	A	U
BHP	Risk of Performance Errors Due to Fatigue Resulting from Sleep Loss, Circadian Desynchronization, Extended Wakefulness, and Work Overload (Short Title: Sleep)	C	C	C
BHP	Risk of Performance Decrements due to Inadequate Cooperation, Coordination, Communication, and Psychosocial Adaptation within a Team (Short Title: Team)	C	A	A
SR	Risk of Radiation Carcinogenesis (Short Title: Cancer)	A	U	U
SR	Risk of Acute Radiation Syndromes Due to Solar Particle Events (Short Title: ARS)	A	A	A
SR	Risk of Acute or Late Central Nervous System Effects from Radiation Exposure (Short Title: CNS)	A	I	I
SR	Risk of Degenerative Tissue or other Health Effects from Radiation Exposure (Short Title: Degen)	A	I	I

Figure 2: NASA's Human Research Program (HRP) Risks and Criticality

Analysis and assessment tools determine the key risks using HAT and HRP findings and gap analyses. These key risks are used to select objectives using exploration risk-based criteria. The ISTAR Integrated Product Team (IPT) (Figure 3) coordinates and integrates these risk assessments.

The ISTAR IPT has proposed operations concepts and techniques for ISS simulations that mitigate exploration risks. Candidate operations concepts and techniques that are submitted to and approved by the ISS increment research planning process are implemented and tested using standard ISS processes. Results are tracked, reported, and communicated internally at NASA via presentations and reports, and to the public via papers such as this.

II. Exploration Research on ISS

In addition to supporting exploration risk mitigation and capability development, ISTAR studies have been beneficial to the ISS by demonstrating the value if its use as a high fidelity testbed for exploration research by:

- Providing iterative evaluation of exploration risk reduction using ISS
- Analyzing results of exploration operations techniques and providing lessons learned
- Providing options for future exploration testing on ISS using exploration DRMs and risk-based criteria
- Providing vetted high-value exploration risk mitigating operations techniques and simulations
- Working with the NASA and international exploration community to effectively burn down exploration risk
- Actively collaborating with organizations across NASA that are developing operations investigations

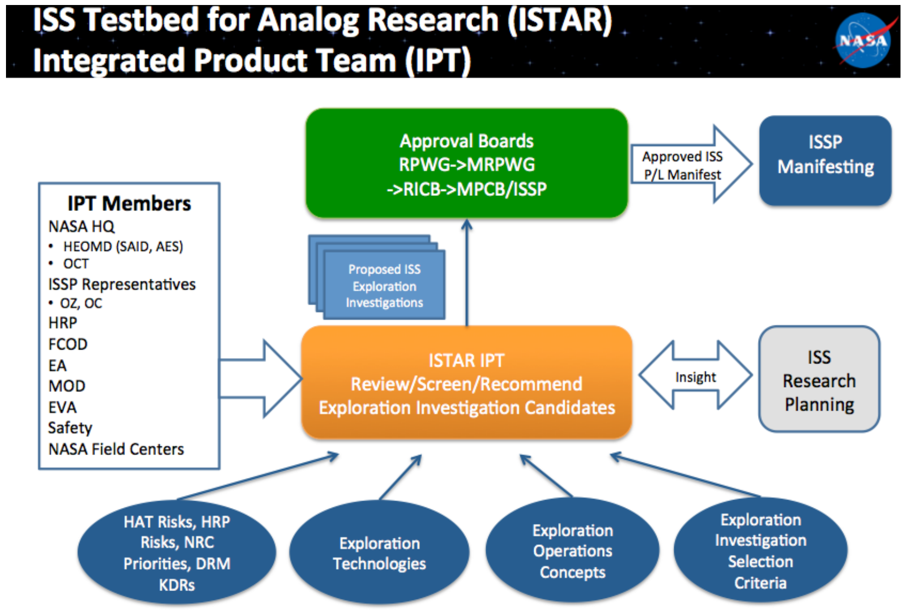


Figure 3: ISTAR IPT

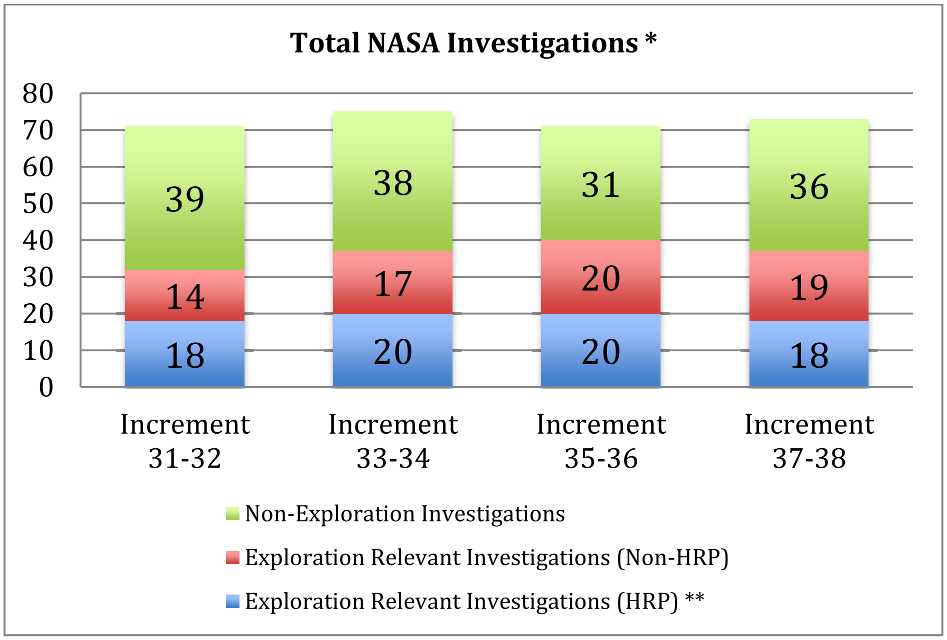
ISTAR has provided ISS integration products (e.g. investigation summaries, requirements for flight rules, procedures) and developed protocols for exploration investigations. Additionally, ISTAR has also developed an ISS one-year exploration simulation plan.

ISTAR has showcased exploration studies on ISS by explaining the "why," not just the "how" of exploration testing on ISS. Awareness of the contributions of ISS for exploration has been increased by providing scorecards of ISSP investigations traced to exploration risks and capability gaps and by proposing new exploration relevant operations techniques utilizing ISS. For example, ISTAR's Jet Propulsion Laboratory (JPL) team members performed an analysis of NASA payloads that have flown recently or are planned to fly that help mitigate exploration risks. The study analyzed how many ISS Increment 31-38 payloads addressed HAT and HRP mission risks and how many addressed HRP risk areas. Figure 4 summarizes the results of the study.

III. ISTAR History

In October 2010, ISTAR[iii] was established within the Human Exploration Development Support (HEDS) Office, which provides expertise and knowledge in BLEO mission design, analysis, planning, and integration. The focus of ISTAR is to reduce risks for manned missions to exploration destinations by utilizing ISS as a high fidelity micro-g laboratory to demonstrate technologies, operations concepts, and techniques. This was planned by exercising crew activities during simulations of exploration missions. In addition, ISTAR has planned for long duration Mars Transit and Landing Transition simulations. By utilizing technology and operational tools and concepts developed and tested during previous ISTAR and Earth-based Analogs, strategic planning of increasingly complex ISS-based exploration mission simulations could be accomplished.

ISTAR is part of the exploration planning process. ISTAR fully engages the NASA exploration community by working with HAT, NASA's pre-eminent exploration formulation group, to identify exploration capability needs and buy-down exploration risk for DRMs. ISTAR collaborates with NASA's Strategic Analysis Integration Division (SAID), Advanced Explorations Systems (AES), HRP, and the Office of the Chief Technologist (OCT) on ISS testing of exploration capabilities and capability development efforts. ISTAR provides synergistic operations concepts and techniques and has established a solid working relationship with MSFC's Payload Operations Integration Center (POIC) to integrate the exploration community's ISS testing plans and possible use of new technologies and payloads.



* From Increment *Rollup Ascent/Descent Spreadsheet* published by ISS Program's *Research Integration Office (OZ).*
** Sum represents payloads addressing HRP exploration risks and those addressing HAT "Crew Health" risks.

Figure 4: Exploration Mission Risks Addressed by ISS Payloads

ISTAR defines objectives, requirements, and simulation operations timelines, and obtains buy-in from the exploration community (HAT, HRP, etc.). The ISTAR team develops mission integration timelines, plans, and protocols, and provides recommendations for exploration investigation candidates to the ISSP for implementation; this includes estimating the required staffing and funding resources for planning, design, execution, and post-simulation analysis. ISTAR supports procedure execution, documents lessons-learned and feedback, and applies these results to future missions. Team members track results of investigation objectives met and explorations risks retired, and report to the exploration community and ISSP.

ISTAR has worked to mitigate exploration risks by submitting exploration related investigation candidates to the ISS Technology Demonstration Office for Increments 31 – 38. The team is working with the Johnson Space Center's (JSC)' Mission Operations Directorate (MOD), NASA/Headquarters' Advanced Exploration Systems (AES) Division, the HRP, and AES' Autonomous Mission Operations (AMO) Project to test various communication delay techniques and communication delay countermeasures. ISTAR has performed a JSC/JPL/Ames Research Center (ARC) collaborative effort to augment existing human and robotic activity scheduling systems to enable intelligent autonomous crew activity scheduling.

ISTAR team members at JPL have developed an ISS exploration testing "scorecard" to identify ISS payloads that mitigate exploration risks. Their assessment of exploration related technology demonstrations and operations testing conducted during ISS Increments 31 – 38 have been traced back to exploration gaps/risks (e.g. HAT, HRP) to help identify areas that still need to be addressed.

ISTAR has performed several standalone studies for exploration planning. A preliminary crew isolation location assessment was conducted using the current and future ISS configurations. Team members have analyzed historical human spaceflight and ISS timelines and started building Mars mission timelines. ISTAR has coordinated technical interchanges with AES Projects to develop ISS Mars simulation objectives traceable to exploration gaps/risks and to determine participation by AES projects in the simulation. ISTAR is working with ISSP to support the HEOMD Integrated Human Spaceflight Plan to utilize the ISS for exploration testing.

ISTAR has focused much of its recent work in the area of operations techniques and simulations. By necessity, initial ISTAR missions have focused on discrete exploration forward activities. A primary focus has been on crew autonomous procedures.

IV. ISTAR Crew Autonomous Procedures

Since the latter half of 2012, selected non-critical ISS systems crew procedures have been used to develop techniques for building ISTAR autonomous procedures, and ISS flight crews have successfully executed them without flight controller involvement. While the main focus has been preparing for exploration, the ISS has been a beneficiary of this synergistic effort. The ISS program is considering modification of additional standard ISS procedures that may improve ISS crew efficiency, reduce operational costs, and increase the amount of crew time available for scientific research.

Why do we need to perform tests using crew autonomous procedures? Communications delays will force the exploration crews and their vehicles to be more autonomous. Crewmembers will not have the ground to rely on for instant assistance, advice, and troubleshooting help while performing systems operations procedures. The objective is to prepare the flight and ground crews for more autonomous flight operations (including autonomous crew procedure execution). Procedure authors will gain experience in developing autonomous procedures and get a better understanding of the information the crew needs to autonomously execute procedures. This information will also help them develop crew training methods. This will give the crew experience in executing procedures without relying on the ground and may also provide insight into how communication delay might affect not only procedures but also the design, building, and operation of hardware and software for future spacecraft and systems.

The goal of the ISTAR crew autonomous procedures study is to evaluate autonomous procedures as a countermeasure to the communication delays expected on missions that involve travel over long distances. Procedure authors have already developed many tools and techniques for writing procedures for autonomy for the study.

The ISTAR versions of existing ISS procedures give the crew more ownership of the hardware. This can be a concern to the hardware owners. Procedure modifications must be reviewed thoroughly with the hardware owners and NASA safety personnel. The crew must be able to interact with the ground personnel if needed, even though this impacts the autonomy aspect of the study.

A. Autonomous Procedure Selection

To date, fourteen ISS system activities have been performed using ISTAR autonomous procedures. These procedures were selected based upon their opportunities to test various aspects of autonomy, such as commanding, off-nominal condition response, analysis of results to determine subsequent actions, and use of just-in-time training. The crew and flight controllers have completed questionnaires indicating which changes they found to be beneficial for autonomy.

B. Flight Control Team Role in Autonomous Procedures

The flight control team’s role in an autonomous procedure is with procedure development and preparation of the crew for the upcoming procedure. The flight controller responsible for the task provides the crew with “big picture” information on why the procedure is being performed as an ISTAR procedure, and explains the goal of the procedure so that if the crew encounters a problem, they will know the reasoning behind the procedure and be able to resolve the issue appropriately.

During the procedure, the flight control team monitors the data displays and video, following along with the crew. The flight controllers do not interact with the crew unless the flight controller is concerned about crew safety or hardware health, the crew calls down with a question, or the crew has a serious problem that requires aborting the test.

If a crewmember that performs an autonomous procedure reaches an impasse, falls far behind the timeline, or is concerned about damaging flight hardware, he or she may abort the test and call MCC using ordinary space-to-ground voice. The crewmember and the Mission Control Center (MCC) can then make a plan to complete the task. If a life- or hardware-threatening emergency arises on ISS during an autonomous procedure, the crew and MCC will abort the test and respond to the emergency as they have been trained.

C. Crew and Flight Control Team Surveys

The crew and flight controllers have completed questionnaires indicating which changes they found to be beneficial for autonomy. The surveys ask the crew and flight controllers to provide acceptability ratings of both the original procedure and the autonomous procedure for comparison, and they also include a rating that will help determine to what extent outside influences affected the test. The surveys invite respondents to provide any additional data to support their responses. Additional questions for the crew include start and stop times of the procedure and whether another crewmember assisted in the procedure. Additional questions for the flight controllers include the amount of time spent modifying the procedure to make it autonomous. Since flight controller responses are voluntary not all flight controllers have responded to the surveys.

D. Autonomous Procedures Performed to Date

Fourteen ISTAR autonomous procedures have been performed as of June 2013. These include the Treadmill 2 (T2) Monthly, Quarterly, and 6-Month Maintenance activities, Inter-Module Ventilation (IMV) flow measurement using the Velocicalc device, Extravehicular Mobility Unit (EMU) Loop Scrub, and Ultrasonic Background Noise Test (UBNT) sensor placement. Seven crewmembers have performed at least one ISTAR procedure; one, Kevin Ford, has performed six.

E. Preliminary Results

ISTAR autonomous procedure testing is in its infancy, and the results are preliminary at this time. With very few data points, it is premature to determine whether to accept or reject the ISTAR hypotheses that increased autonomy for crew procedures will be beneficial for mitigation of exploration mission communication delays. In addition, varying numbers of respondents participated in each survey, so the data is not complete. The results presented here should be viewed with this in mind.

Acceptability Results

Figure 5: ISTAR Acceptability Results graphically illustrates the results of the acceptability portion of the questionnaire from the tests that have been performed to date. On a scale of 1 to 6, with 6 being the highest score, autonomous procedures executed on the ISS are rated. Then the original, non-autonomous procedure is also rated using the same scale. The blue bars represent the acceptability of each original, non-autonomous procedure. That bar is compared to the red bar from the autonomous procedure to determine which procedure, autonomous or original, the crew and ground controllers found more acceptable. The green bars indicate the degree to which outside influences influenced each test. Note: In this chart, higher values for acceptability and lower values for outside interference are better.

Each crewmember who performed an activity responded to his survey. However, not all ground controllers responded to each survey. In some cases, several flight controllers responded, while in other cases none did. In addition, several respondents did not rate the acceptability of the original procedure since they were not familiar with it. As a result, the findings shown above are not conclusive and additional autonomous procedure executions and modifications must be made to accurately gauge the comparison and acceptability of original vs. autonomous procedures. Below is a brief narrative on each procedure.

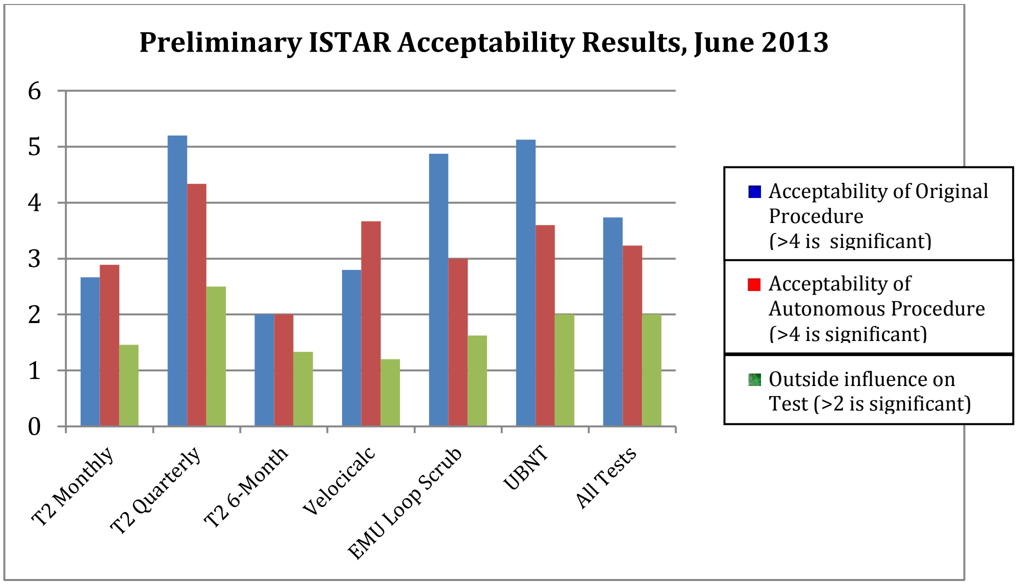


Figure 5: ISTAR Acceptability Results (Preliminary)

Treadmill 2 (T2) Monthly Maintenance

The ISTAR T2 Monthly Maintenance procedure was performed four times. This procedure moves engineering data from the ground to the crew to allow the crewmembers to continue troubleshooting and recognize next step operations. Also, the procedure incorporates video to help qualify acceptable play "wiggle" in snubbers. The primary lesson learned from executing this procedure is that the procedures need more descriptive information to explain what steps the crew is accomplishing.

No anomalies occurred during the ISTAR T2 Monthly Maintenance procedure. As anticipated, the autonomous procedure was found to be more acceptable for crew use than the original procedure.

T2 Quarterly Maintenance

The ISTAR T2 Quarterly Maintenance procedure was performed twice. This procedure moves engineering data from the ground to the crew to allow the crewmembers to continue troubleshooting and recognize next step operations. It also includes descriptive information to explain what various steps are accomplishing.

During the ISTAR T2 Quarterly Maintenance procedure execution, the crew had to perform some of the ISTAR contingency steps due to problems with the T2 hardware. The crew could autonomously perform the contingency steps without ground communication and so the T2 device was available much quicker than usual. This allowed the crew to perform the exercise activity that was scheduled immediately after the T2 maintenance activity. Without the ISTAR procedure, this exercise activity would have needed to be rescheduled or deleted. However, the autonomous procedure was found to be less acceptable for crew use than the original procedure, most likely because the crew was confused with the subjective wording regarding the amount of "wiggle" that was acceptable for adjusting one piece of hardware.

T2 6-Month Maintenance

The ISTAR T2 Quarterly Maintenance procedure was performed once. This procedure moves engineering data from the ground to the crew to allow the crewmembers to continue troubleshooting and recognize next step operations. It also includes descriptive information to explain what various steps are accomplishing.

No anomalies occurred during the ISTAR T2 6-Month Maintenance procedure. The autonomous procedure and the original procedure were found to be equally acceptable for crew use.

Velocicalc Ops – Inter-Module Ventilation (IMV) flow measurement

The ISTAR Velocicalc Operations procedure was used on two occasions to perform the IMV flow measurement activity. The autonomous nature of the procedure allowed the crewmember more flexibility in executing the task during a very busy day (Soyuz docking) that might have caused the task to be deferred if implemented in a more traditional non-autonomous manner. Initially, the only modification to this procedure has been for the crew to perform initial safing commanding. For the long term engineering data from the ground to the crew to help the crewmembers analyze readings and determine whether ducts need cleaning.

No anomalies occurred during the Velocicalc procedure. The autonomous nature of the procedure allowed the crewmember more flexibility in executing the task during a very busy day (Soyuz docking) that might have caused the task to be deferred if implemented in a more traditional non-autonomous manner. The autonomous procedure was found to be more acceptable for crew use than the original procedure, as expected.

Figure 6: ESA Astronaut Andre Kuipers holds the Velocicalc meter while performing an ISTAR procedure (source: NASA)

Extravehicular Mobility Unit (EMU) Cooling Loop Maintenance

The ISTAR EMU Cooling Loop Maintenance procedure was performed once. Modifications to the procedure include crew complex commanding of critical systems (previously performed by ground controllers), crew data evaluation, crew critical thinking, and the addition of operations constraints within the procedure. Procedure developers also included more descriptive information to explain overall intent and constraints.

During execution of the loop iodination portion of the activity, the crewmember encountered water loop temperature issues requiring him to step into subordinate troubleshooting steps. The autonomous procedure was found to be less acceptable for crew use than the original procedure because there was a subordinate (nested "if") procedure that led the crew to a procedure that had not been modified for autonomy. This caused confusion, as the crew was unsure how to perform the procedure autonomously.

Ultrasonic Background Noise Test (UBNT) Sensor Placement

The ISTAR "crib sheet" used as a supplement to the UBNT procedure was available for the crew to use if needed. It was used four times, including twice on two separate days. This "crib sheet" contains supplementary execution references that aid in troubleshooting various problems, similar to the "crib sheet" used in EVAs. In addition, UBNT used just-in-time training.

No anomalies occurred during the UBNT Sensor Placement procedure. The autonomous procedure was found to be less acceptable for crew use than the original procedure because there were significant problems with the rack rotation prior to one of the UBNT sensor placements. However, it should be noted that the rack rotation was not part of the ISTAR sensor placement autonomous procedure.

Respondents said in their survey responses that it was difficult to separate the rack rotation task from the UBNT sensor placement activity.

Figure 7: Astronaut Tom Marshburn performs the ISTAR EMU Loop Scrub procedure (source: NASA)

Figure 7: CSA Astronaut Chris Hadfield installs UBNT Sensors using ISTAR procedures (source: NASA)

Execution Time Results

Figure 8: ISTAR Procedure Execution Time, shown in Figure 9 below, illustrates the difference between execution time in the original procedures and in the ISTAR autonomous procedures. These results are preliminary since there are very few data points. The limited data available indicate that the first time a crewmember performs any activity, the execution time will be longer than it will be on subsequent executions. This would explain the minor differences in the T2 and Velocicalc procedures. The ISTAR EMU Loop Scrub took far longer than the original procedure primarily because of the additional activities that the crew needed to perform in order to make the procedure autonomous. The T2 6-Month time is not included because the crew did not record start and stop times for the activity.

Lessons Learned

That crew can perform procedures autonomously without ground interaction is not a new lesson, but one that has been proven throughout manned spaceflight. The question for exploration is how much autonomy is appropriate for a crew? Consideration must be given to the additional time it might take to execute a procedure autonomously. For example, the crew experienced an anomaly during the T2 Quarterly procedure executed in December 2012 and had to perform a 30-minute contingency step. While that step took nearly 30 minutes to execute, if the procedure had not had this autonomy already implemented, the interaction with the ground to determine that this step was needed, and then to uplink the necessary actions, would have made the activity even longer. On the other hand, the modifications to the EMU Loop Scrub procedure performed in January 2013 to make it autonomous will extend the time needed – even if there are no contingencies – by over an hour, due to the additional crew tasks that the ground nominally performs. However, for exploration the benefit of increased crew autonomy may outweigh the time increase and it is expected that autonomous procedure execution time will decrease as the crew gains more experience with it.

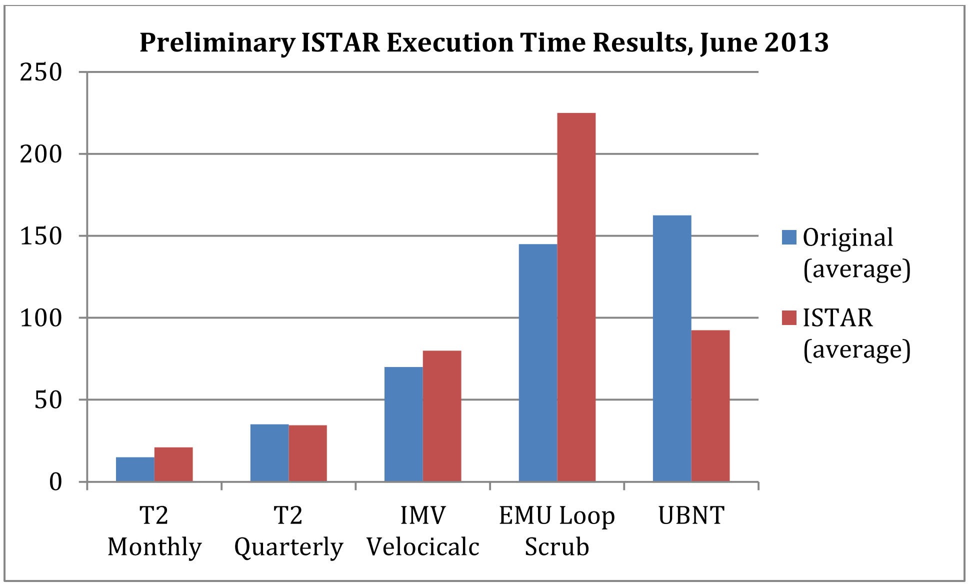


Figure 8: ISTAR Procedure Execution Time (Preliminary)

Automation available on ISS could be used to perform repetitive tasks. For example, the IMV Flow Measurement/Velocicalc procedure is very tedious and requires large amounts of data entry. This would be well suited for Robonaut, once it has the required capabilities.

Just-in-Time-Training (JITT) could be very useful for autonomous procedures. JITT reduces pre-flight crew training, which is a limited resource. Often, the crew does not perform an activity until two years after they were trained, so they have forgotten much of what they had learned. JITT would use videos and other tools to provide the crewmember refresher training, or it could provide all of the training required for an activity.

There are times when a crew activity is deferred or cancelled, and there are "gaps" in a crewmember's day. It would be beneficial to have autonomous procedures available that the crew could execute if the opportunity arises.

Writing an Autonomous Procedure

ISTAR purposefully did not give rules for writing crew autonomous procedures. The goal was to inspire procedure authors to think of creative methods to implement autonomy, and this has been successful.

The ISTAR tests have helped procedure developers determine the information needed by the flight crew to autonomously execute procedures that have normally either been performed by the ground or by coordinating with ground controllers. Flight crews have also provided a greater understanding of what is involved in making procedures more autonomous. Some of the lessons learned are described below.

Perhaps the most important lesson learned in writing autonomous procedures is that the crew must have all of the information they need to perform the procedure. "Big picture" words must explain the procedure goals; without this information, the crewmember cannot resolve anomalies that might occur. Similarly, many steps will need rationale, such as whether the crewmember may continue with the procedure if certain failures occur. Examples include contingency steps, safety concerns, and critical commanding.

A picture may be worth 1000 words, but a short video clip can mean the difference between success and failure. Subjective wording causes confusion, but a video that shows how much "wiggle" is acceptable, for example, can show that which cannot be described adequately in words.

Troubleshooting steps, safing steps, and pause/stop points should be included in the procedure. "Crib sheet" tables and "star blocks" within procedures list contingency actions for specific anticipated failure causes. Safing steps place the hardware into a safe configuration in case the procedure must be halted abruptly, and pause/stop points allow the crewmember to pause or stop indefinitely the procedure execution.

The crew needs to know what constraints they will be working under. Examples include the amount of time that hardware can be unpowered, wait-time constraints, and expected time needed for troubleshooting steps.

The crew needs to know what information to provide to the ground. If there is a need to troubleshoot beyond the detail written in the procedure, the hardware experts on the ground will need to have the appropriate data, pictures, or video. If the crew knows this ahead of time, they can collect this data as they proceed through the procedure, when it is appropriate and convenient, and can relay the information to the ground in an efficient manner.

Stowage has been an issue throughout manned spaceflight. With so many pieces of equipment in a small amount of space, and most of them hidden behind several other pieces of hardware, it is often difficult for the crew to find the parts they are looking for. Sometimes, ground personnel know of alternate locations for the equipment, and they should provide the crew with this information.

Some procedures require large amounts of data to be input. This can be a tedious task for a crewmember. Procedure writers can help the crew by splitting up large tables into smaller pieces that are more easily dealt with.

How deep within the failure tree should the troubleshooting go? There is a tradeoff among time savings by having the procedures available, the time spent developing the steps, and the comfort level of the hardware engineer with the troubleshooting steps.

Writing a procedure to make it autonomous can save the crew time in many cases. However, it must be noted that there is a time cost to make these updates on the ground. Crew time is far more expensive than an engineers' time on the ground, so there is benefit to writing many procedures to be autonomous; however, time must be budgeted to allow for adding the autonomy modifications discussed above.

Implementation Process

Once a procedure is written, the flight control team updates several elements of the crew's documentation to implement the procedure. The procedure is reviewed through the standard ISS procedure review process, and is uplinked to the crew's International Procedure Viewer (IPV). Words are added to the crew's Daily Summary to provide the "big picture" of the activity. The crew activity block, including Execute Notes and Ops Notes, which provide procedure references and details, is added to the crew timeline. The activity block for the questionnaire, which includes the questionnaire itself and the original, non-ISTAR procedure (for reference when filling out the questionnaire) is also added to the crew timeline. A flight note is submitted to provide information on the flight controller survey location and process.

When scheduling an ISTAR procedure, time is added to the crew activity blocks for the crew survey (15 minutes, to include time to both set up the computer for the survey and fill in the survey itself). Time is added to the procedure the first time a crewmember executes it, as per standard ISS scheduling. For ISTAR procedures, it is beneficial to schedule the procedure before unscheduled crew time, if possible, since contingency steps add time to the procedure if they are executed, and this minimizes the impact to the crew day.

The flight controllers who participate in the procedure and author it or having responsibility for its execution (Flight Director, CAPCOM, and systems operator(s)), fill in the survey electronically using the system developed by NASA JSC/Human Health and Performances Directorate personnel.

Open Work

While the lessons learned from crew autonomous procedure testing have been significant, many questions remain unanswered. What is the most effective way to handle referenced procedures and data needed in subordinate (nested "if") procedures? In which cases are contingency steps best placed in embedded star blocks, and which are better in "crib sheets"? What is the best way to effectively convey task execution constraints, so that this reference information is not lost or forgotten? Autonomous procedures will continue to be tested on ISS to help answer these questions.

V. Future ISTAR Testing

ISTAR will continue its work on autonomous procedures. In addition, ISTAR is collaborating with several other organizations on additional tests.

A. Autonomous Procedure Testing

More crew autonomous procedures are planned for ISS including additional executions of those previously performed and newly updated procedures. Additionally, International Partners and payload developers plan to perform some of their procedures autonomously. In most cases, after the ISTAR procedure has been performed and the survey filled out three times, the procedure should remain onboard ISS as the prime procedure. If the ISTAR autonomous procedure takes longer than the original procedure, or if there are specific concerns with using it as the prime procedure, the original, non-ISTAR procedure should to be used once the ISTAR procedure testing period is complete. Autonomous procedure testing is planned to continue through at least Increment 40.

B. Instant Messaging (IM) Texting

The goal of the IM Texting study is to evaluate IM texting as a countermeasure to communication delay. The ISTAR team will evaluate operations and protocols for use as a supplement to voice communications. MOD personnel have developed texting protocols based on lessons learned from analog studies such as RATS and NEEMO.

For the ISTAR study, an IM client will be uplinked to the crew's Space Station Computer (SSC) and/or iPad. Texting will be scheduled for one crewmember during moderate ground/crew interaction in times of low criticality, during the ISS Orbit 2 shift (starting ~8 am Houston time). Communications will not be delayed during this test. The tests will increase in scale and complexity to evaluate use of texting with multiple control centers and the effect on control teams' situational awareness.

The IM texting capability should be implemented during Increment 36 and will continue through Increment 38.

C. Communications Delay Testing

The ISTAR team has collaborated with HRP to develop a Behavioral Health & Performance (Voice) communication delay study. The HRP will study the effects of communications delay on the ISS crew and ground controllers. This communication delay study is planned for Increments 39 and 40. The subjects are the crew, Flight Directors, and CAPCOMs. For the test, the delay will be 50 seconds 1-way; the delay will be implemented only during a task – not the entire day. Only voice will be delayed.

Instant messaging will not be used during communication delay testing because it requires the use of the ISS KU band communication link, which has long periods of signal loss.

The communication delay will be implemented by using special MCC ground equipment to delay a space-to-ground voice loop. Several challenges are being worked, such as how best to reconfigure (disconnect the communication delay box) in case of ISS needs the loop, and how to simulate acquisition of signal (AOS)/loss of signal (LOS) clocks. For example, if the simulated round-trip delay is 20 minutes, operators would begin talking 10 minutes before the real AOS and stop talking 10 minutes before the real LOS. This will be the first analog to implement communication coverage LOS.

D. Crew Self-Scheduling

Exploration missions may require the crew ability to autonomously plan and re-plan. The ISTAR tests will evaluate which types of data, tools, and capabilities are necessary for the crew to effectively and efficiently perform these functions. A series of exercises will be performed, increasing in complexity, data needs, and tool functions:

- Basic scheduling (pre- and post-sleep, meals, exercise)
- De-conflicting resources (exercises, conferences)
- Scheduling a sequence of events
- Scheduling a sequence of events with complex resource requirements and constraints

The results of this testing will be used for the next phase, when the crew will be provided tools to enable more extensive self-planning and re-planning. The crew will make use of the previous operations techniques developed to plan and execute one or more complete days of ISS operations; eventually, the entire crew may schedule and execute a week of operations. The crew and ground will also evaluate the tools and materials needed to sustain planning and scheduling by crews as well as the appropriate complexity of tasks to be planned and/or scheduled. Crew self-scheduling activities are planned for Increment 36 through Increment 40.

E. Autonomous Crew Systems Management

The ISTAR team has also collaborated with the Autonomous Mission Operations (AMO) group at Ames Research Center to evaluate tools, procedures, and reference materials provided to enable the crew to manage an onboard operational system. The Total Organic Compound Analyzer (TOCA) will be used for this test. Additionally, the crew may monitor the performance of their SSCs. Larger and more complex ISS systems will be added to this list when appropriate.

The concept of this AMO test is to turn over as much operations/management of a system as possible to the crew without increasing preflight training; software aids will be provided onboard for training. Areas included in the test are failure recognition, procedure recommendation, analysis and "Go for Operations" capability, constraint compliance, scheduling, and system expertise.

This test will not change the nominal ground analysis processes, but will be performed in addition to them.

Autonomous crew scheduling activities are planned for Increment 39 and 40.

F. Other ISS Exploration Testing

Headquarters NASA and the Russian Federal Space Agency (Roscosmos) have recently approved a one-year crew expedition starting in 2015. The primary purpose of this one-year expedition is to perform long-duration multilateral human research investigations, but it will also test exploration operations concepts, including crew autonomy. The results from this NASA and Roscosmos scientific study will be used to help send explorers to new destinations. The ISTAR team is helping to define operations-technique objectives for this mission.

The ISTAR team has also worked with the NASA Headquarters Human Exploration and Operations Mission Directorate (HEOMD) to include ISS exploration risk mitigation testing and NEA/Mars simulations as part of an executable framework for spaceflight through 2021 and a strategy for BLEO missions post-2021. ISTAR is a member of the product team responsible for developing plans to support ISS testing and simulations.

Acronym List

AES	Advanced Exploration Systems Division (NASA HQ/HEOMD)
AMO	Autonomous Mission Operations
AOS	Acquisition of Signal
ARC	Ames Research Center (NASA)
ARGOS	Active Response Gravity Offload System
BLEO	Beyond Low Earth Orbit
DRM	Design Reference Mission
EA	JSC Engineering Directorate
EMU	Extravehicular Mobility Unit
EVA	Extravehicular Activity
FCOD	JSC Flight Crew Operations Directorate
HAT	Human Spaceflight Architecture Team
HEDS	Human Exploration Development Support
HEOMD	Human Exploration and Operations Mission Directorate (NASA HQ)
HQ	Headquarters
HRP	Human Research Program (NASA JSC)
IDRD	Increment Definition and Requirements Document
IM	Instant Messaging
IMV	Inter-Module Ventilation
IPT	Integrated Product Team
ISS	International Space Station
ISSP	International Space Station Program
ISTAR	ISS Testbed for Analog Research
JITT	Just In Time Training
JPL	Jet Propulsion Laboratory (NASA)
JSC	Johnson Space Center (NASA)
KDR	Key Driving Requirement
LOS	Loss of Signal
MCC	Mission Control Center
MOD	JSC Mission Operations Directorate
MPCB	ISSP Multilateral Payloads Control Board
MRPWG	ISSP Multilateral Research Planning Working Group
MSFC	Marshall Space Flight Center (NASA)
NEA	Near-Earth Asteroid
NEEMO	NASA Extreme Environment Mission Operations
NRC	National Research Council
OC	ISSP Mission Integration and Operations Office
OCT	Office of the Chief Technologist (NASA HQ)
OZ	ISSP Research Integration Office
P/L	Payload
PCB	Payloads Control Board
POIC	MSFC’s Payload Operations Integration Center
RATS	Research and Technology Studies

RPWG	ISSP Research Planning Working Group
SAID	Strategic Analysis and Integration Division (NASA HQ)
SSC	Space Station Computer
T2	Treadmill 2
TIM	Technical Interchange Meeting
TOCA	Total Organic Compound Analyzer
UBNT	Ultrasonic Background Noise Test
USOS	United States Operating Segment

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