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Use of International Space Station to Simulate Interplanetary Transit: Human Health and Performance Applicability of Current Increment Durations and Extended Durations

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Contents

Acronyms

ATV	Automated Transfer Vehicle
D-RATS	Desert Research and Technology Studies
HTV	H-II Transfer Vehicle
ISS	International Space Station
NEA	Near-Earth Asteroid
NEEMO	NASA Extreme Environment Mission Operations
SME	Subject Matter Expert

1.0 INTRODUCTION

Preparation for future crewed missions to Mars will require utilization of space analogs for research (such as for feasibility and verification of monitoring technologies or countermeasures) and for training of flight crews and ground support personnel. Although several ground-based analogs, such as the Arctic Haughton-Mars Project (http://www.marsonearth.org/), NASA Extreme Environment Mission Operations (NEEMO) (http://www.nasa.gov/mission_pages/NEEMO/), and NASA Desert Research and Technology Studies (D-RATS) (http://www.nasa.gov/exploration/analogs/desert_rats.html) mimic various aspects of space exploration missions, the influence of Earth's ever-present surface gravity cannot be ignored. Until recently, lunar missions were expected to be a stepping-stone for Mars expeditions,[1] but recent programmatic de-emphasis of lunar missions has encouraged consideration of piloted missions to Near-Earth Asteroids (NEAs) instead. It has been suggested that in-space simulations of Mars (and now NEA) missions be conducted on the International Space Station (ISS). Some possibilities for, and space life sciences implications of, such an effort are described in this paper.

A brainstorming session involving space life sciences subject matter experts (SMEs) associated with the NASA Human Research Program, the Johnson Space Center Space Life Sciences Directorate, and the Ames Research Center Exploration Technology Directorate was convened on September 25, 2009, to respond to two questions:

1. How can the ISS be used to mimic Mars missions?
2. How can crew increment duration be increased to 9 to 12 months from the existing 6 months?

The positions and recommendations of the SMEs are specifically indicated in this white paper. The response to question 1 is addressed first, in the next section. The response to question 2 is addressed in the section titled "Increasing Increment Duration." Additional recommendations are derived from a variety of other sources relevant to ISS, Mars, and NEA considerations.

1.1 Using the International Space Station to Mimic a Mars (or Near-Earth Asteroid) Mission

The ISS provides a space flight environment needed to enhance and validate technologies and countermeasures for long-duration missions to Mars. Many of them will be relevant to NEA missions, which will themselves serve as precursors to, and simulations of, Mars missions.

The SMEs observed that there are two categories of activities to be considered:

1. those that require the use of the ISS (or a comparable orbiting facility), typically because of the need for prolonged weightlessness, either as a stimulus or as a confounding factor; a high-risk environment that could not ethically be provided in ground-based simulations; and other fundamental environmental factors that cannot be produced on Earth; and,
2. those that do not require ISS use in the strictest sense but can exploit its use to maximize their scientific return more efficiently and productively, due to higher fidelity, than in ground-based simulations.

The first category includes studies of human physiological adjustments to the weightless environment of ballistic flight, which can be mimicked on Earth only poorly. Simulations such as bed rest and hypokinesia promote cardiovascular and musculoskeletal atrophy that is qualitatively similar to atrophy seen in weightlessness, but they provide only a redirected gravitational stimulus to the sensorimotor system. Any sensorimotor influence on other systems[2] is modified in ways different from those that occur in space flight. This category also includes weightless mobility and restraint, and interactions with tools and other hardware. These can be simulated during water immersion; but again, the influence of gravity is not eliminated, only redirected. In addition, the issue of increased viscosity must also be taken into consideration when using water immersion techniques. Weightlessness can be provided by parabolic aircraft flight, but it lasts approximately 20 seconds and is interspersed between bouts of hypergravity, so its usefulness in determining the effects of prolonged, uninterrupted weightlessness is limited.

The first category also includes countermeasures against the deleterious effects of weightlessness, especially those that require validation in a real-world space flight environment. Among the countermeasures, intermittent artificial gravity produced by the use of a short-radius (e.g., 2 m [~6.5 ft]) centrifuge could be tested on the ISS as a multisystem (i.e., bone, muscle, cardiovascular, and sensorimotor) countermeasure to combat the deleterious physiological effects of weightlessness. Demonstration of its potential benefits to the health and fitness of astronauts and thus to mission success would require considerable effort and expense to implement it aboard the ISS as currently configured. However, if this is not done aboard the ISS, there are no clear alternative flight venues in which to evaluate this potentially paradigm-changing capability.

To protect the crew from an unacceptable level of deconditioning, any new systems for exercise must be at least as effective as the latest systems on the ISS and must deliver their benefits in a more resource-efficient and reliable manner. In addition, there would need to be monitoring capability and secondary protection (like pharmaceuticals) that can be added if necessary. This work would be validated on the ISS.

The second category includes a much more varied list. Use of the ISS for these activities will provide necessary information without the expense of establishing lower-fidelity simulation facilities or scenarios duplicating the non-weightlessness aspects of space flight aboard the ISS (e.g., confinement, isolation, separation, workload, and astronaut-like individuals assembled as functioning teams).

Activities that can exploit the use of the ISS include:

- Acquisition of operational and medical experience in high-autonomy situations in which environmental constraints and conditions require that the individual crewmembers exercise their own decision making to complete tasks and mission objectives with little or no direction from Mission Control. One key aspect of an actual Mars mission will be the communication delay between the Mars-bound astronauts and the Earth-based support personnel. In an ISS analog mission, gradually increasing the one-way communication delay from zero at the start of the increment to about 7 minutes at the time of the simulated Mars arrival after 6 months will require crewmembers to function with increasing autonomy and will enhance the sense of crew and individual isolation due to the perceived remoteness. Figure 1 illustrates the variation in distance and communications delay between Earth and Mars.

- For behavioral health risks, further work to determine optimal crew selection, composition, and training criteria, and to ensure that effective crew support techniques are on board for monitoring and intervention of issues. The connections between physiological and neurobehavioral changes require further investigation.

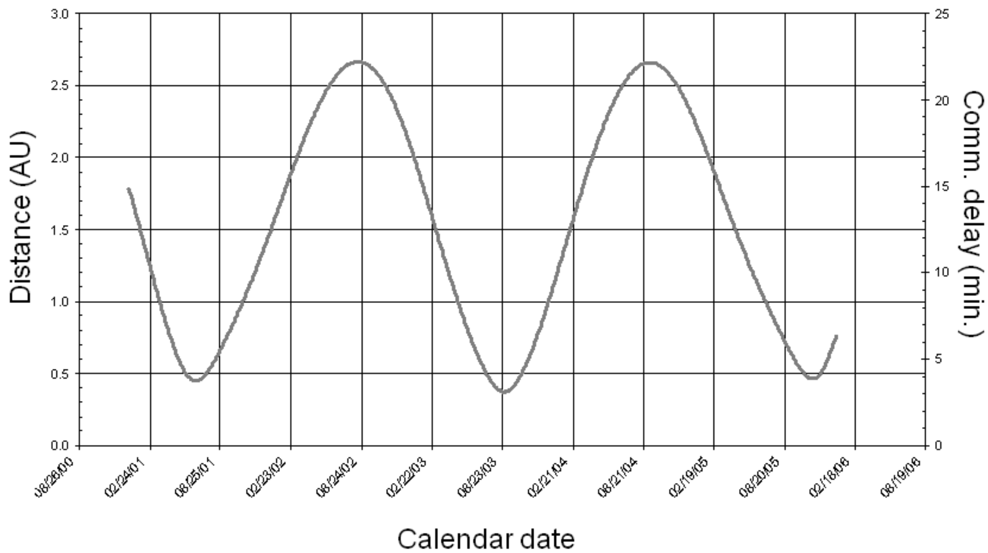

Figure 1. Variation in Distance and Communications Delay between Earth and Mars (2001-2005). In an actual Mars mission, the one-way communication delay will continue to increase to about 22 minutes at the midpoint of the 18-month Mars surface stay, with a 2-week communication blackout at opposition, then decrease to about 7 minutes at departure for Earth, reaching zero again at Earth arrival. NEA missions are expected to have much more variability, but a 2025 mission to one well-studied target, 1999 AO10, would have a one-way communications delay increasing gradually to 30 seconds at NEA arrival after 110 days, then decreasing back to zero for the remainder of the 155-day round-trip mission.

- Tests of lighting and other behavioral health countermeasures for circadian-rhythm disturbances and fatigue. The ISS orbits the Earth 16 times a day, with 16 sunsets and sunrises each day; therefore, crews living on the ISS rely on artificial lighting as an external cue for their circadian rhythms. A transit to Mars will also require that crews rely on artificial day-night cycles, as the vehicle will be continuously exposed to direct sunlight for months at a time.

- Evaluations *in situ* of analysis techniques for medical specimens and samples from biological experiments. It will not be useful to the crew involved in an ongoing mission to postpone analysis of such specimens and samples from a Mars mission until return to Earth. *In situ* analysis techniques taking advantage of the microgravity environment can be thoroughly evaluated during simulated Mars missions on the ISS to understand their areas of greatest usefulness.

- Evaluations of acceptability of outdated food in controlled circumstances. Experience with long-duration missions has shown that both nutrition and well-being depend on an adequate food system. Today, the shelf life of foods and the packaging efficiency of the food system are inadequate and inefficient for 1000-day exploration-class missions. Food prepared with current methods will reach their expiration dates before the end of a 900-day Mars mission. Evaluating food during an ISS simulation can be accomplished by delivering appropriately aged food in routine deliveries by resupply vehicles such as Progress from the Russian Federal Space Agency, Automated Transfer Vehicle (ATV) from the European Space Agency, H-II Transfer Vehicle (HTV) from the Japan Aerospace Exploration Agency, and commercial orbital transportation services.

- Tests of robust, highly reliable life support systems in a microgravity environment required for Mars missions.

- Tests of expanded data management systems designed for use on a Mars mission during a simulation.

- Studies and refinement of concepts for stowage and inventory control, which will be challenging during a lengthy Mars mission.

- Reliance on human research hardware only as maintained on orbit, not refurbished on Earth, for a higher fidelity simulation.

- Finally, demonstration of appropriate onboard training facilities and protocols that will be required for maintaining astronauts' technical skills for lengthy periods or will provide just-in-time training without the aid of current Earth-based support infrastructure. In particular, extensive simulation capabilities will ideally be provided so planetary landings and other operational procedures can be practiced during the transit phase.

Again, none of the foregoing suggested activities requires the ISS for implementation. However, their incorporation into the ISS missions, whether or not a Mars expedition is being simulated, will enhance the applicability of those missions to Mars-forward planning.

The degree of fidelity of ISS-based activities to activities in a genuine interplanetary mission varies significantly, and selected mission elements are listed in Table 1.

Table 1. Low- and High-Fidelity Mission Elements to be Investigated during Transit Simulations on ISS

Low-Fidelity Mission Elements	**High-Fidelity Mission Elements**
Circadian Shift and Desynchronization	Autonomy
Confinement	Communications Delay
Isolation	Crew
Operational Mode	Ground Support
Proximity to Earth (visual)	Task Design
Radiation	Weightlessness
Risk	Workload (type and quantity)

1.2 Increasing Increment Duration

Current 6-month ISS mission operations and human biomedical research are already relevant to Mars transit because the duration of every increment mimics portions of future Mars missions.

Studying issues related to weightlessness drives most of the activities requiring the use of the ISS, and the combination of long-duration confinement, realistic workload, separation from familiar surroundings and support mechanisms, and, of course, the unique characteristics of the astronauts themselves greatly magnify its applicability to Mars mission simulations. The current ISS increment duration is 6 months, which is also the nominal Earth-Mars transit duration for baselined conjunction-class missions[3] using anticipated propulsion capabilities.[4] Thus, the physiological, behavioral, and operational experiences of astronauts on current ISS missions are at least qualitatively comparable to those of Mars-bound crewmembers.

The most applicable duration greater than 6 months is the 9- to 12-month interval, which corresponds to the worst-case Earth-Mars transit duration. The longest applicable duration is 22 months, which approximates an intentional Mars flyby, an aborted Mars orbit insertion and subsequent return to Earth, or a Mars-orbit mission, perhaps to explore the Martian moons, without landing on Mars. This duration would involve continuous weightlessness for a period about 8 months longer than any individual has ever experienced in the history of human space flight.

Of all the ISS-based scenarios, the one that seems to make the best use of available resources and existing operational expertise with minimal impact on other "non-Mars" applications is mimicking the Mars outbound transit, whether nominal or worst-case. The outbound transit has the advantages of a recent departure from Earth and the increasing acclimation to space flight as the mission progresses, as would be the case for an actual Mars-bound mission. Those advantages are absent from other possible mission phases, such as inbound to Earth.

An increase in mission duration can provide opportunities for enhanced and focused research; however, several problematic issues must be considered as well. The SMEs agreed that increasing the ISS crew increment duration to 9 or even 12 months from the current 6 months would pose little additional risk to crewmembers; however, after the workshop, evidence surfaced to suggest that recently identified ocular changes, usually associated with increased intracranial pressure in clinical patients on Earth, were becoming more frequent among crewmembers after as little as one month in space. Therefore, some additional medical monitoring capabilities seem to be required beyond those currently used for ISS operations. It is also advisable that an increase in mission duration occur gradually over several increments due to psychological concerns.

From both physiological and psychological perspectives, the primary benefit of an extended mission is the ability to document the adapted state of some human systems in weightlessness. In addition, such missions may uncover unsuspected gaps ("unknown unknowns") that would not have been found in missions of shorter duration. An increase in mission duration for each astronaut subject means obtaining data on fewer unique astronauts than in the same time span of shorter missions. This would encourage life sciences investigators to prioritize the variables of primary importance and ensure that the results for those variables will have statistical significance, instead of depending on larger numbers of subjects to provide enough statistical power to detect significance of secondary variables. The longer duration might also allow more precise characterization of effects that steadily increase or even accelerate with time. In addition, it would enable researchers to examine team dynamics and individual psychology over an extended duration, both with astronauts in space and support personnel on Earth—an option that does not currently exist in either space flight or high-fidelity analogs.

Several negative aspects are associated with extended missions and should be taken into account before planning begins. An important finding of such extended missions might resolve the question of whether bone loss continues unabated. In addition, the SMEs expect an increased likelihood of vision changes and kidney stones in longer missions and increased dependence on countermeasures to prevent behavioral health problems. Finally, repeat fliers may reach their lifetime radiation limit while participating in longer missions.

1.3 Concerns About Implementation

If the ISS is to be used for high-fidelity Mars mission simulations, several issues concerning the fidelity and utility of the simulations should be considered. Since crew safety is the paramount concern on any space flight mission, emergency medical interventions and system failures will obviously break the simulation. The most important factor in deciding to terminate the simulation will be the severity of the emergency or failure. In addition, as there is great difficulty in isolating “Mars” crewmembers from “regular” ISS crewmembers, it is crucial that International Partners (Russia, Canada, Japan, and the member states of the European Space Agency) be fully involved in the simulations, and not merely observers.

All of the partners in the ISS are already obligated to use the space station’s unique characteristics to answer fundamental questions in the physical sciences, life sciences, and technology development, in fulfillment of national commitments. Those obligations need not be compromised by re-purposing the ISS as a Mars-transit analog. A range of Mars-related simulations could be conducted depending on requirements and resources and could include simply adding a maintenance task to a regular mission to targeting the penultimate ISS increments as dedicated simulation increments about 2 years before decommissioning the station.

Finally, unlike in a real Mars mission, Earth will always be outside the ISS windows. This phenomenon is unavoidable, and should temper the effort dedicated to maximizing the realism of other aspects of the Mars transit simulation.

1.4 Future Enhancement of International Space Station Analog

A future enhancement of the Mars mission simulation experience on the ISS is possible, albeit at significantly greater cost. To increase the fidelity of the Mars analog scenario, one could incorporate a planet-side phase into a full mission simulation. In the most extensive version, this would involve back-to-back ISS tours separated by 6 to 18 months on Earth in a simulated Mars surface environment, perhaps Antarctica, or in some specially designed facility. This configuration would provide the best simulation of an entire Mars mission for a variety of reasons. In particular, we speculate that human factors and some of the behavioral health issues do not asymptote, peak and recede, or increase linearly with mission duration. Rather, they are expected to arise only past the 6-month mark, especially when communication and support from Earth are reduced or lost. Risks associated with an enhanced analog mission include crew safety and health ethical issues, especially concerning nonintervention during a medical event. In addition, a detailed cost-benefit analysis would have to be performed before commitments were made by crewmembers, the ISS Program, and International Partners.

2.0 RECOMMENDATION

The ISS provides components of a high-fidelity, cost-effective simulation of an eventual Mars (and NEA) mission: personnel (both in flight and on the ground) representative of likely Mars mission participants; a vehicle in space, with all of its operational ramifications; exposure to—and threat from—the actual space environment; perceived risk to life and limb that is qualitatively similar to that of an exploration mission, and one that could not ethically be duplicated in ground-based studies; and meaningful work.

Any such simulation is limited by the constant presence of Earth outside the window, aspects of infrastructure (e.g., resupply timing, real-time Mission Control monitoring) that cannot easily be altered, potential confounding influences of ongoing non-Mars experiment activities, and the ability to break simulation when necessary. The benefits of conducting such missions are so great that the limitations can be tolerated; therefore, the SME group recommends using the ISS for Mars simulations.

A logical progression of activities during ISS increments would permit the orderly development of Mars-forward activities with minimal disruption of ongoing non-Mars activities, at least in the near term. In general terms, a four-stage approach is indicated (suggested dates are notional, and assume U.S. commitment to the ISS through 2025):

1. 2010-2012: Current ISS operations and activities in which operational and experimental protocols intended to protect the safety, health, and efficiency of ISS crewmembers are evaluated for their applicability to Mars (and NEA) missions.
2. 2013-2016: ISS increments into which are inserted discrete Mars-forward activities, such as intermittent multiday periods exploring different degrees of bounded autonomy by the ISS crew, including communication delays typical of Mars missions. Sets of assigned tasks will be accomplished with minimal intervention by Mission Control, but with few alterations to onboard procedures and Mission Control monitoring of ISS systems. Minimal impact to non-Mars onboard science operations will be required. Flight rules will specify the threshold at which the simulation is broken in case of emergency or system malfunction.
3. 2017-2020: ISS increments in which crew procedures and Mission Control oversight are modified to provide more realistic experience in in-flight autonomous operations to both crew and ground personnel. More rigorous, longer periods of autonomy are planned. There will be some inevitable impact to non-Mars-related scientific activities.
4. 2021-2025: ISS increments in which transits to Mars (and NEAs) are simulated as rigorously as feasible in low-Earth orbit with the existing infrastructure. Progressively increasing communication delays may be introduced, reaching a maximum of 6 to 8 minutes after 6 months to mimic arrival in Mars proximity. Onboard science operations must be compatible with Mars-like mission parameters.

Given the need for a series of incremental demonstrations of high autonomy and other Mars-related procedures and technologies, preparations for full opposition-class[4] simulated missions must commence soon. Preparations, including crew recruiting, informed consent, and long-term planning for simulations of even the 6-month Mars transit must commence soon to maximize their value and minimize their impact on ongoing use of the ISS for other purposes.

Results from these and other possible simulations can then be used to inform Mars crew selection and composition for missions circa 2030.

3.0 CONCLUSION

The use of the ISS to simulate aspects of Mars missions seems practical. Current ISS operations and human biomedical research are already analogous to Mars missions because every 6-month ISS mission mimics portions of future Mars missions. Longer durations, up to 9 to 12 months, may be possible without significantly increased risk to crewmembers beyond that of 6-month missions. Incrementally increasing Mars-specific focus is achievable, but will require programmatic decisions. Higher-fidelity Mars simulations involving the ISS may foreclose other options for ISS use, requiring International Partner buy-in.

A group of NASA flight surgeons at Johnson Space Center has observed that "… an Expedition-class life science research program would allow the ISS Program to not only further our understanding of deconditioning and countermeasures, but pave our way to Mars."[5] The ISS can and should be a valuable resource to prepare for future human Mars missions, and the highest-possible fidelity simulation of the Earth-to-Mars transit phase is the best fit to ISS capabilities.

4.0 WORKSHOP ATTENDEES

Workshop on International Space Station Crew Increment Extension Beyond 6 Months, For Use as Mars Analog

Center for Advanced Space Studies
Houston, Texas
September 25, 2009

Maneesh Arya
Yael Barr
Regina Buccello-Stout
Michael Chandler
John Charles
Tamara Durham
Stephen Hart
Cindy Haven
Judy Hayes
Albert Holland
Mary Kaiser (by telephone)
Lauren Leveton
Linda Loerch
Ronald Moomaw
Joe Neigut
Michele Perchonok
Bob Pietrzyk
Michael Rapley
Richard Scheuring
Edward Semones
Mark Shavers
Camille Shea
Gwyn Smith
Tom Sullivan
Terrance Taddeo
Mary Van Baalen
Robert Welch (by telephone)
Mark Weyland
Sandra Whitmire
Barbara Woolford

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[5] The Skylab Medical Operations Project (NASA/TM-2009-214790), p. 6.

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13. ABSTRACT *(Maximum 200 words)*

Preparation for future crewed missions to Mars will require utilization of space analogs for research (such as for feasibility and verification of monitoring technologies or countermeasures) and for training of flight crews and ground support personnel. Although several ground-based analogs mimic various aspects of space exploration missions, the influence of Earth's ever-present surface gravity cannot be ignored. Until recently, lunar missions were expected to be a stepping-stone for Mars expeditions, but recent programmatic de-emphasis of lunar missions has encouraged consideration of piloted missions to Near-Earth Asteroids (NEAs) instead. It has been suggested that in-space simulations of Mars (and now NEA) missions be conducted on the International Space Station (ISS). Some possibilities for, and space life sciences implications of, such an effort are described. A brainstorming session involving space life sciences subject matter experts associated with the NASA Human Research Program, the Johnson Space Center Space Life Sciences Directorate, and the Ames Research Center Exploration Technology Directorate was convened on September 25, 2009, to respond to two questions: how can the ISS be used to mimic Mars missions; and how can crew increment duration be increased to 9 to 12 months from the existing 6 months. Positions and recommendations are indicated.

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