NASA Research and Technology Studies (RATS) 2012: Evaluation of Human and Robotic Systems for Exploration of Near-Earth Asteroids

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INTRODUCTION

The NASA Research and Technology Studies (RATS) 2012 test focused on optimizing utilization of a four-person crew, deep space habitat (DSH), multi-mission space exploration vehicle (MMSEV), extravehicular activity (EVA) jetpacks, and Mission Control Center operating with 50-seconds each-way communication latency during exploration within an immersive virtual-reality simulation of the near-Earth asteroid (NEA) Itokawa.

The RATS 2012 test was a direct continuation of the Desert-RATS 2011 field trials conducted in the Arizona desert [1] and the NASA Extreme Environment Mission Operations (NEEMO) 15 and 16 missions [2, 3], with results informing NASA's ongoing human exploration architecture development by providing recommendations for the crew size, exploration systems and capabilities, and operations concepts required to safely and effectively conduct human and robotic exploration of a NEA. The purpose of RATS 2012 was to provide quantitative and qualitative data to answer the following specific questions:

1. How will EVA be used during exploration of a NEA and how does that affect design of the EVA system and the MMSEV?
2. Does the MMSEV need to be capable of anchoring to a NEA? How does anchoring affect crew workload and propellant requirements?
3. Does MMSEV need to be a 2-person or 3-person vehicle for NEA operations?
4. How does NEA size, spin rate, and exploration ops concept affect design of MMSEV guidance, navigation and control and propellant requirements?
5. Are the Generation 2A MMSEV prototype cabin human factors acceptable?

METHODS

Test subjects operated the MMSEV and interacted with the simulation environment from inside the Generation 2A MMSEV prototype while viewing the simulation on video walls through the MMSEV windows. Head-mounted virtual reality (VR) displays, instrumented gloves, and an EVA jetpack control module were used during simulated free-flying EVAs while a gravity offloading system was used during simulated anchored EVAs for evaluation of EVA translation and geologic sampling tasks. (Fig. 1).

Simulation telemetry and consensus subjective ratings were used to assess, evaluate and compare exploration traverses incorporating different combinations of extravehicular and intravehicular crewmembers; anchored versus free-flying operations; EVA jetpacks versus astronaut positioning system (APS) attached to the MMSEV; and NEA size and spin rates. Human factors of the MMSEV prototype were evaluated by two separate two-person crews, each inhabiting the MMSEV for 3 days and 2 nights.

Fig. 1. (Clockwise from top left) MMSEV-EVA NEA simulation; VR Lab; Active response gravity offload system (ARGOS); simulation viewed from inside Gen 2A MMSEV.

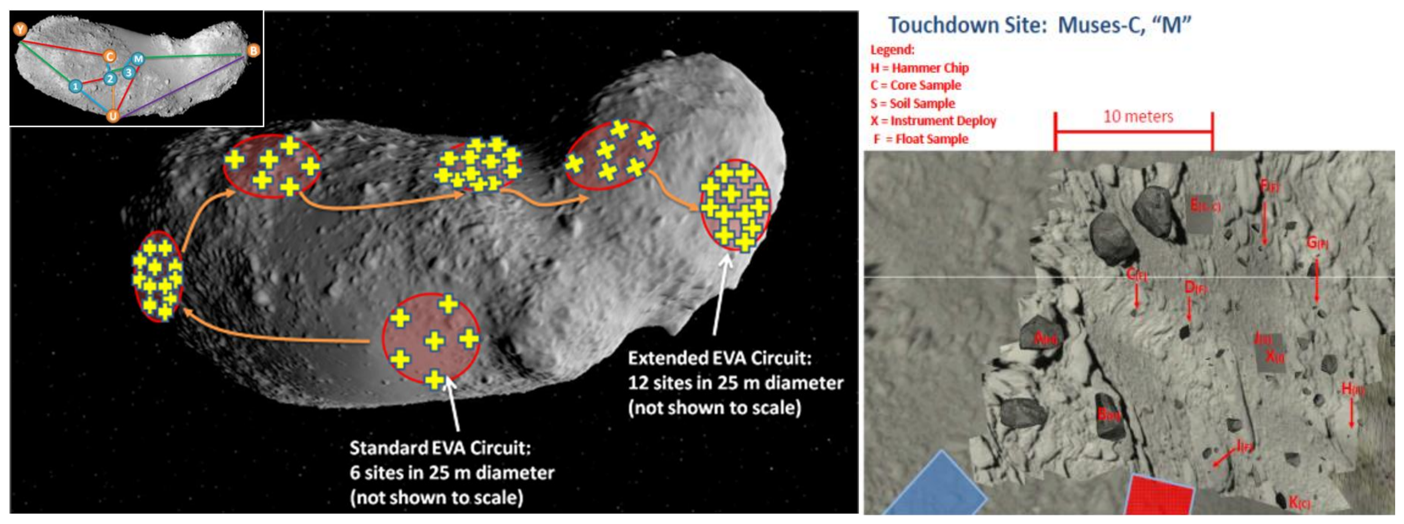

Fig. 2. Traverse plan approach (left) and detailed science tasks (right).

Traverses consisted of translations in the vicinity of the NEA combined with focused inspection and a prescribed sequence of exploration EVA tasks performed at each of several predefined locations. The same series of tasks was previously used during NEEMO 15 and NEEMO 16 tests to collect data from eight crewmembers in simulated weightlessness [2, 3]. Example traverse plan documents are shown in Fig. 2.

www.nasa.gov/exploration/analogs/desertrats/

The communications architecture (Fig. 3) was based on previous testing [1-3]. Crewmembers communicated with each other exclusively on the Big Loop, which was always being transmitted to the Mission Control Center (MCC). Flight controllers and scientists MCC would receive audio and video on the Big Loop but would not transmit on it; instead, they would transmit voice and text primarily on the Small Loop to the DSH IV crewmember(s) who would then respond to MCC and/or synthesize and pass on relevant information to the MMSEV and EVA crewmembers at an appropriate time.

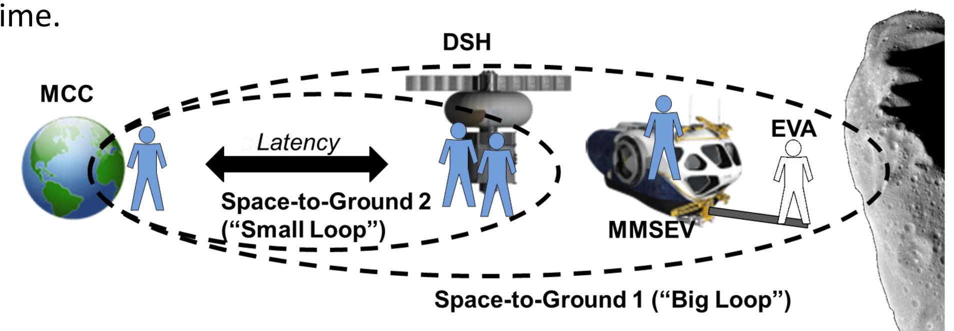

Fig. 3. Communications architecture (Condition 6A FF shown).

The same metrics used during DRATS11 and NEEMO 15 and 16 missions [2-3] (Figs. 4-7) were used to assess each test condition and associated capabilities. The test conditions are illustrated in the results section (Fig. 8) and represent variations on operating modes (Conditions 6 and 7) rated as acceptable by Science and Crewmember teams during DRATS11. In Anchored modes the MMSEV is attached to the NEA.

Scale Rating	Criteria
1	Simulation quality (e.g. hardware, software, procedures, comm., environment) presented either zero problems or only minor ones that had no impact to the validity of test data.
2	Some simulation limitations or anomalies encountered, but minimal impact to the validity of test data.
3	Simulation limitations or anomalies made test data marginally adequate to provide meaningful evaluation of test objectives (please describe).
4	Significant simulation limitations or anomalies precluded meaningful evaluation of major test objectives (please describe).
5	Major simulation limitations or anomalies precluded meaningful evaluation of all test objectives (please describe).

Fig 4. Simulation Quality rating scale. Conditions rated 4 or 5 are not used in hypothesis testing. All RATS12 conditions were rated 3 or better.

Totally Acceptable		Acceptable		Borderline		Unacceptable		Totally Unacceptable		No Rating
No improvements necessary		Minor improvements desired		Improvements warranted		Improvements required		Major improvements required		Unable to assess capability
1	2	3	4	5	6	7	8	9	10	NR

Fig 5. Acceptability rating scale.

Minimal Workload		Low Workload		Moderate Workload		Significant Workload		Extreme Workload		No Rating
Minimal operator effort required to maintain workload - All operations completed with maximum possible performance		Low operator effort required to maintain workload - All operations completed with maximum possible performance		Moderate operator effort required to maintain workload - Performance of some operations may decrease marginally due to workload		Significant operator effort required to maintain workload - Performance of some tasks is decreased due to workload		Extreme operator effort required to maintain workload - Unable to satisfactorily complete all tasks due to workload		Unable to assess workload
1	2	3	4	5	6	7	8	9	10	NR

Fig 6. Operator Workload rating scale.

Essential / Enabling		Significantly Enhancing		Moderately Enhancing		Marginally Enhancing		Little or No Enhancement		No Rating
Impossible or highly inadvisable to perform mission without capability		Capabilities are likely to significantly enhance one or more aspects of the mission		Capabilities likely to moderately enhance one or more aspects of the mission or significantly enhance the mission on rare occasions.		Capabilities are only marginally useful or useful only on very rare occasions		Capabilities are not useful under any reasonably foreseeable circumstances.		Unable to assess capability
1	2	3	4	5	6	7	8	9	10	NR

Fig 7. Capability Assessment (CA) rating scale.

RESULTS

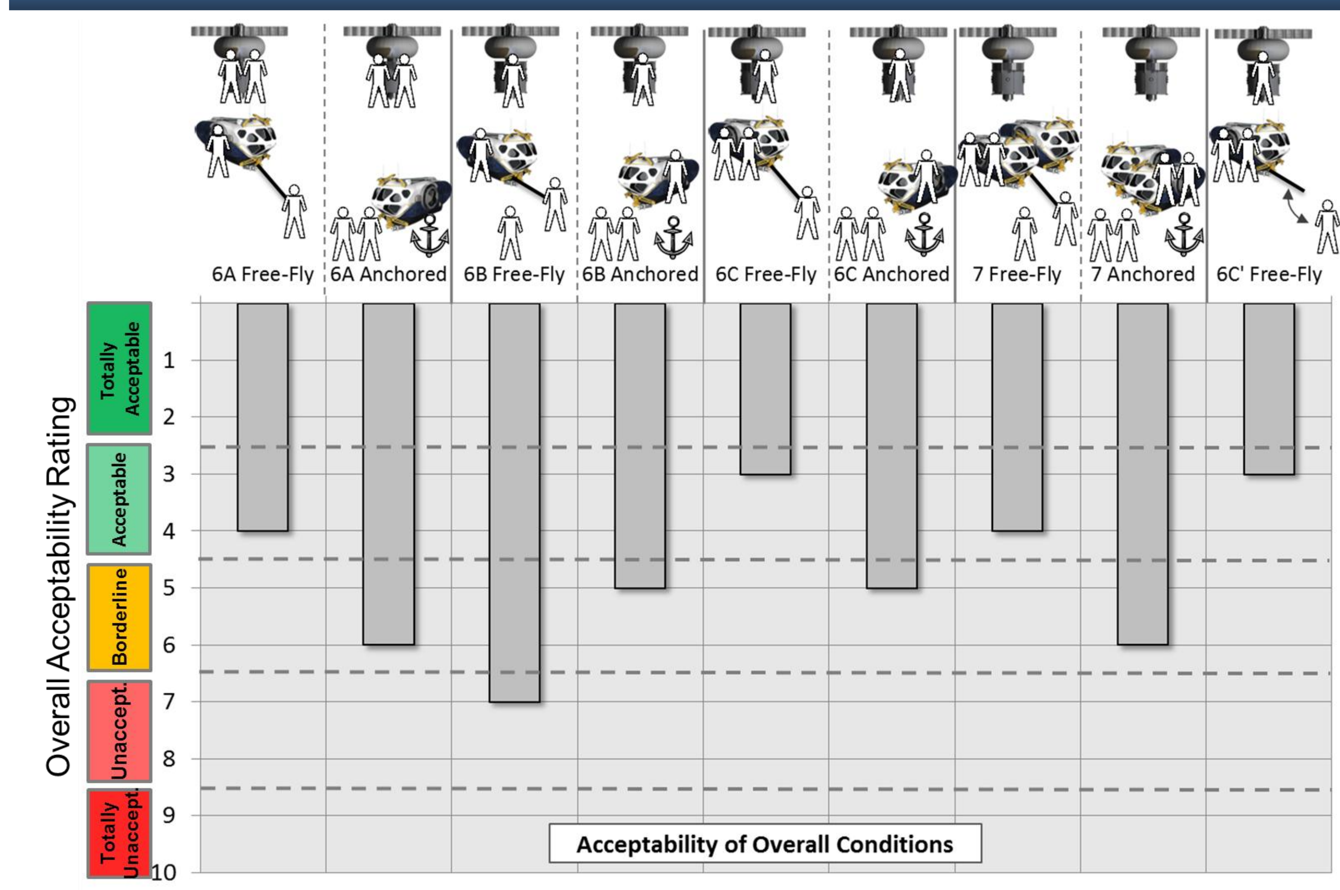

Fig 8. Acceptability ratings. Ratings are consensus of all five test subjects.

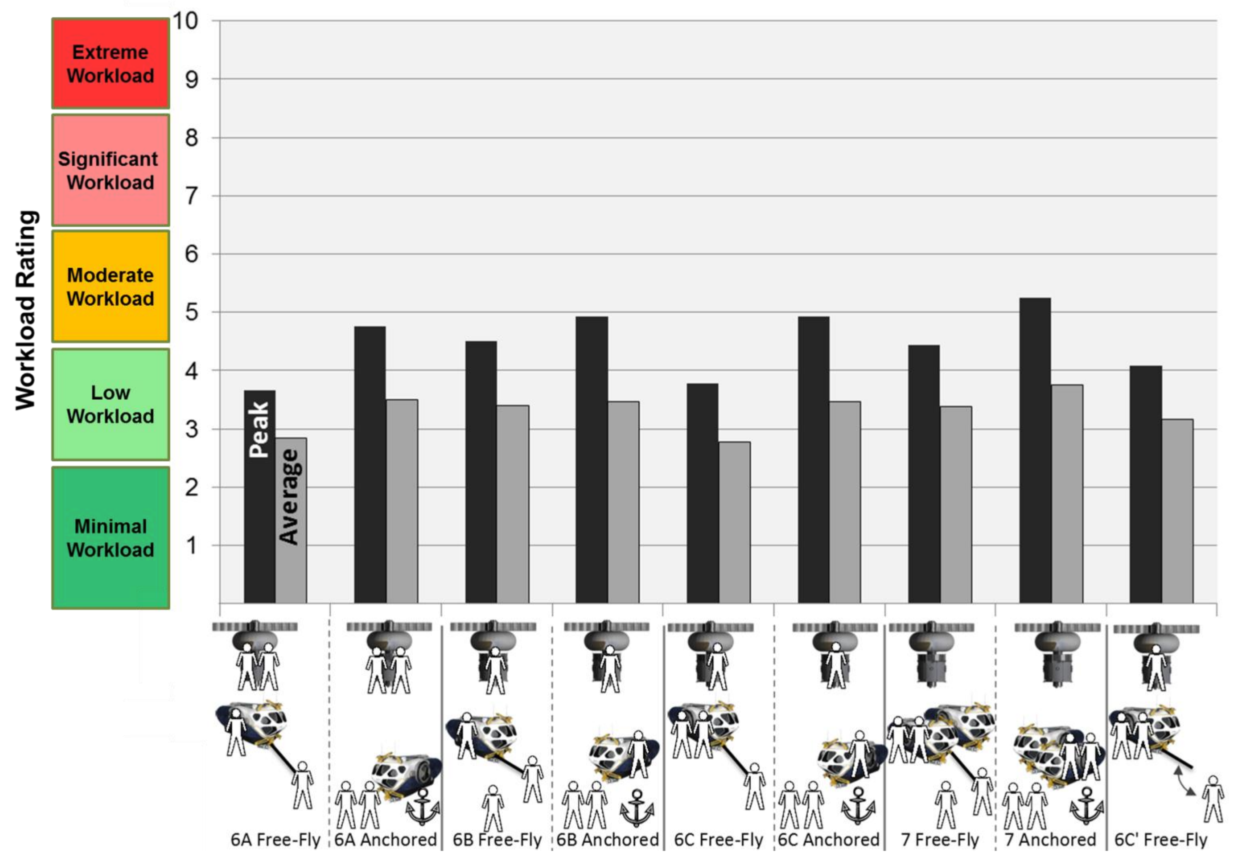

Fig 9. Peak and Average Operator Workload ratings. Values are means of five test subjects.

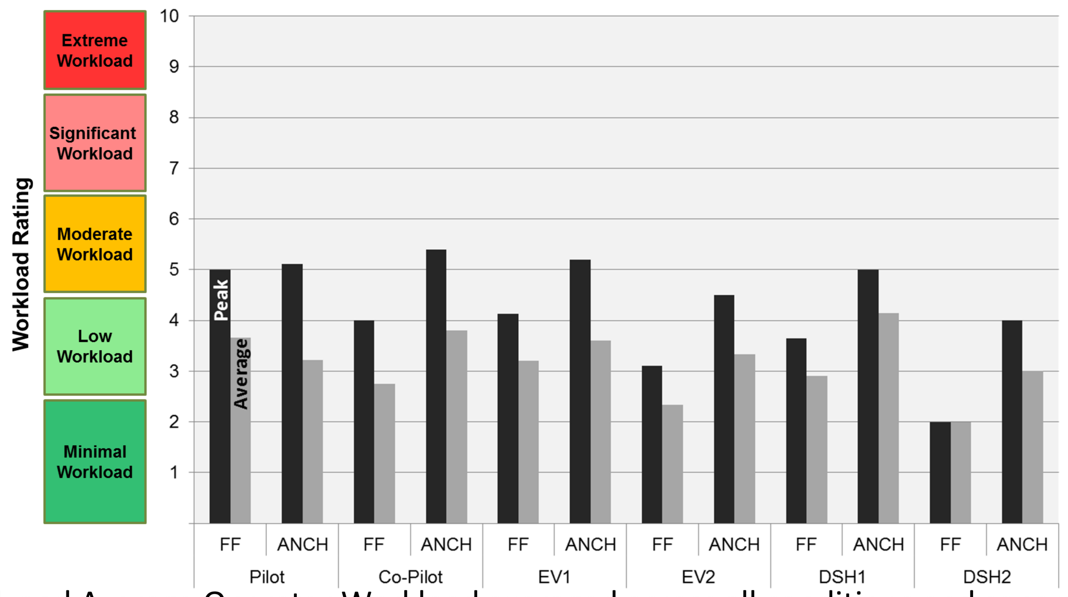

Fig 10. Peak and Average Operator Workload averaged across all conditions and separated by crewmember roles. Peak and Average workload is higher during Anchored than Free-Flying for all roles except pilot.

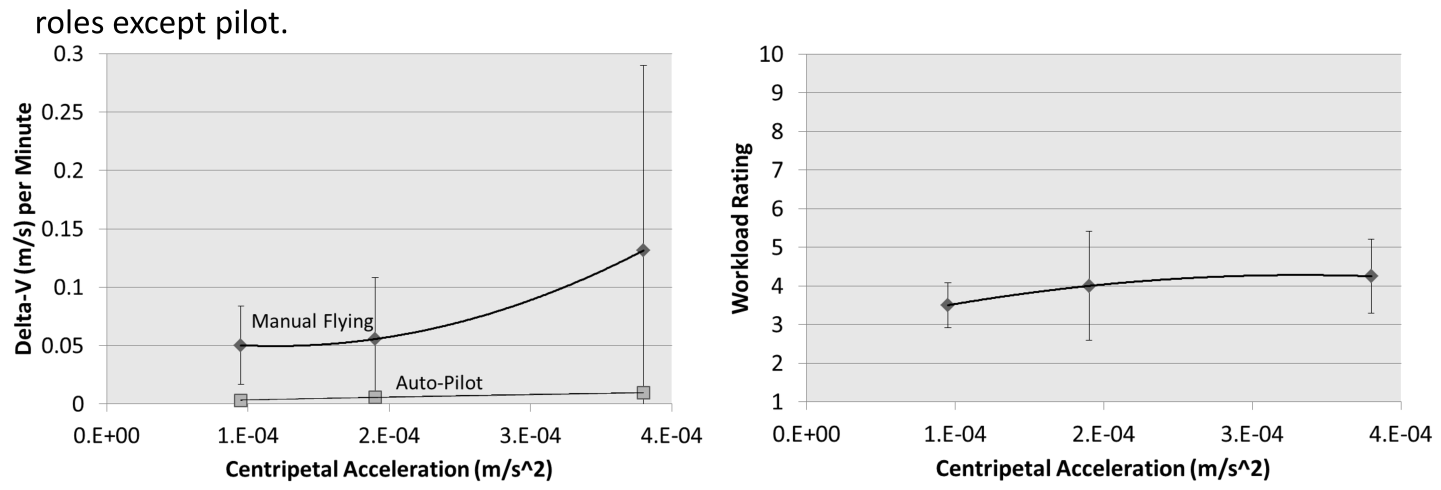

Fig. 11. Delta-V (left) and pilot workload (right) variation with centripetal acceleration. Values for crewmember data are means ± standard deviation (n = 5). Delta-V for automated station-keeping is also shown.

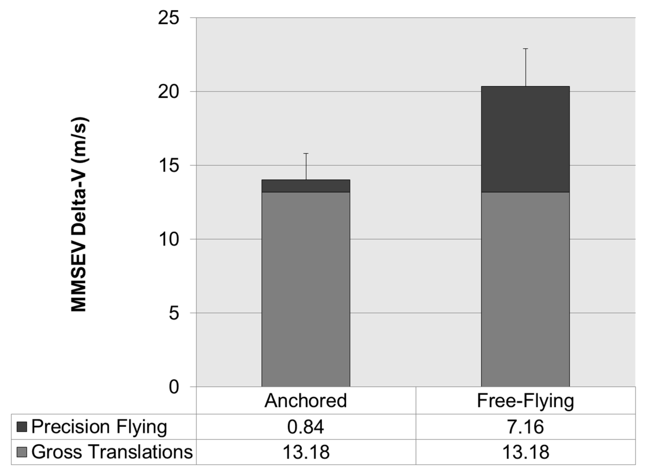

Fig. 12. Delta-V comparison of FF versus ANCH modes. Mean values calculated across all conditions. Standard deviations are for total values. Assumes anchoring equivalent to 10-min precision station-keeping task at three sites per traverse. Seven samples collected at each site.

Table 1. CA ratings for capabilities tested during RATS 12. Ratings are consensus of five crewmembers. Anchored EVA ratings do not include potential benefits of reduced surface pluming by MMSEV.

General Capabilities	**Capability Assessment Rating**	
MMSEV	2	*Essential / Enabling*
MMSEV Astronaut Positioning System - APS	3	*Significantly Enhancing*
EVA Jetpack	4	*Significantly Enhancing*
Anchored EVA	6	*Moderately Enhancing*
MMSEV Capabilities		
Asteroid-Relative Attitude & Position Hold	2	*Essential / Enabling*
Pan-Tilt-Zoom Mast Camera	2	*Essential / Enabling*
Separate Translational & Rotational Hand Controls	3	*Significantly Enhancing*
Laser Pointer / Designator	3	*Significantly Enhancing*
Pointable Range Finder	2	*Essential / Enabling*
External Views / Virtual Model of MMSEV	2	*Essential / Enabling*
"Cherry Picker" controls on APS	4	*Significantly Enhancing*
Portable Cockpit Controls	5	*Moderately Enhancing*
EVA Jetpack Capabilities		
Asteroid-Relative Attitude & Position Hold	3	*Significantly Enhancing*
Separate Translational & Rotational Hand Controls	3	*Significantly Enhancing*
Laser Pointer / Designator	4	*Significantly Enhancing*
Pointable Range Finder	4	*Significantly Enhancing*
Improved Displays (rates, navigation, consumables)	2	*Essential / Enabling*

CONCLUSIONS

1. The recommended distribution of crewmembers for NEA DRMs is two in the DSH, one in the MMSEV, and one EVA (Condition 6A FF).
   a) Crewmembers rated this condition as "Acceptable" and experienced lower workload and greater situational awareness versus other conditions.
   b) Unlike Condition 6C, Condition 6A does not require a 3-person MMSEV.
   c) Alternating between APS and jetpack (versus APS only) did not improve acceptability but may reduce propellant usage.
2. Free-flying modes were preferred versus anchoring the MMSEV to the NEA because of decreased overhead and increased situational awareness, although propellant savings of 31% were estimated with anchoring. Ratings did not differ when twice as many tasks were performed at each traverse station.
3. Free-Flying MMSEV with two EVA crew was rated "Unacceptable" (Cond 6B) unless both IV crew were in the MMSEV (Condition 7)
   a) Condition 7 requires two MMSEVs either docked together or with one unoccupied autonomously station-keeping at a safe distance.
   b) Overall Acceptability ratings (Figure 14) of all three conditions with a single EV crewmember were within the acceptable range (≤ 4) whereas five of the six conditions with two EV crewmembers were rated "Borderline" or "Unacceptable".
4. MMSEV Delta-V usage during station-keeping $\propto \omega^2 \times r$, where ω = NEA angular velocity and r = distance from spin axis. NEA-relative attitude and position hold function rated as "Essential / Enabling", which would reduce crew workload and Delta-V usage.
5. Human NEA exploration operations are significantly enhanced or even enabled by an MMSEV. Consensus ratings of RATS12 crew, DRATS11 crew, and the DRATS11 Science team conclude that it is "impossible or highly inadvisable to perform [NEA] mission without [MMSEV] capability".
6. Generation 2A MMSEV human factors are acceptable overall; however, multiple areas for improvement were identified and are being incorporated into the Generation 2B vehicle.

REFERENCES

[1] Abercromby, A. F. J. et al. *Desert RATS 2011: Human and Robotic Exploration of Near-Earth Asteroids*, Acta Astronautica, *Accepted*.
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[3] Chappell, S. P. et al, *NEEMO 16: Evaluation of Techniques and Equipment for Human Exploration of Near-Earth Asteroids*, 44th Lunar and Planetary Science Conference, March 18-22, 2013, The Woodlands, Texas.

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