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Detrimental Effects of Micro/Zero G

- 1. Bone fracture
- 2. Optic nerve damage/visual changes
- Kidney stone formation
- 4. Balance/neuro-vestibular impairment
- 5. Muscle atrophy and skeletal
- 6. Alteration of cardiovascular system functions
- Decreased production of red blood cells
- Weakening of the immune system
- 9. Fluid redistribution
- 10. Loss of body mass, nasal congestion, sleep disturbance and excess flatulence



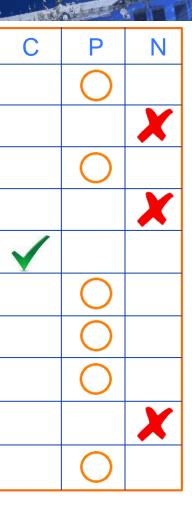
✓ C = Complete Mitigation with Diet & Exercise



P = Partial Mitigation with Diet & Exercise



N = Negligible Mitigation with Diet and Exercise



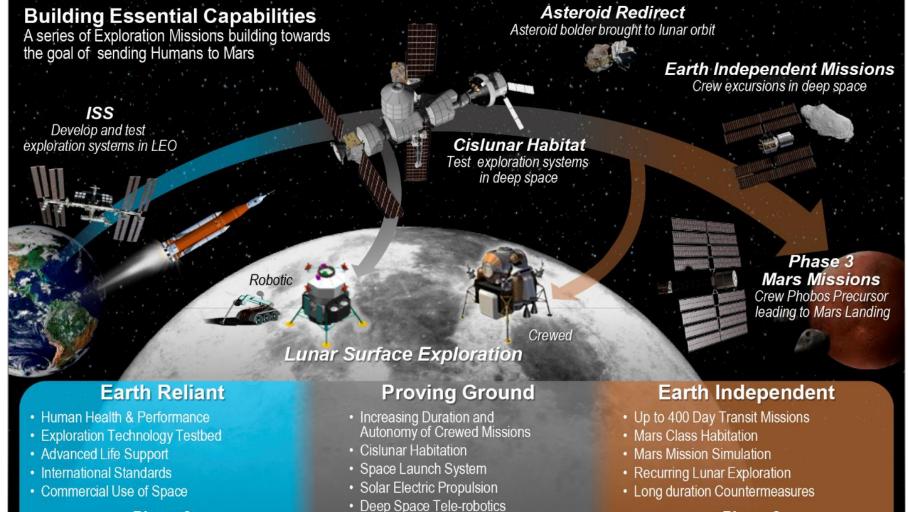
NASA Exploration Phases

Phase 0



Phase 2

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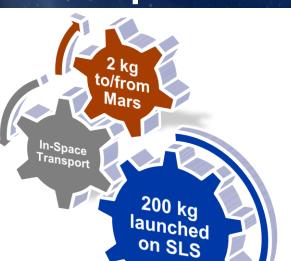


Currently No Artificial Gravity as Part of Plan

Phase 1

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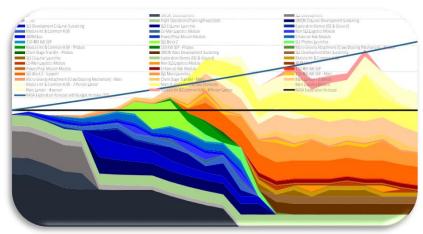
Four Fundamental Challenges of Mars Exploration



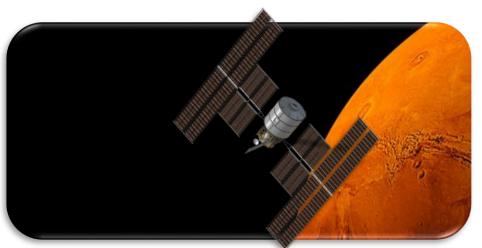
Physics



Health and Human Performance



Affordability



Earth Independence

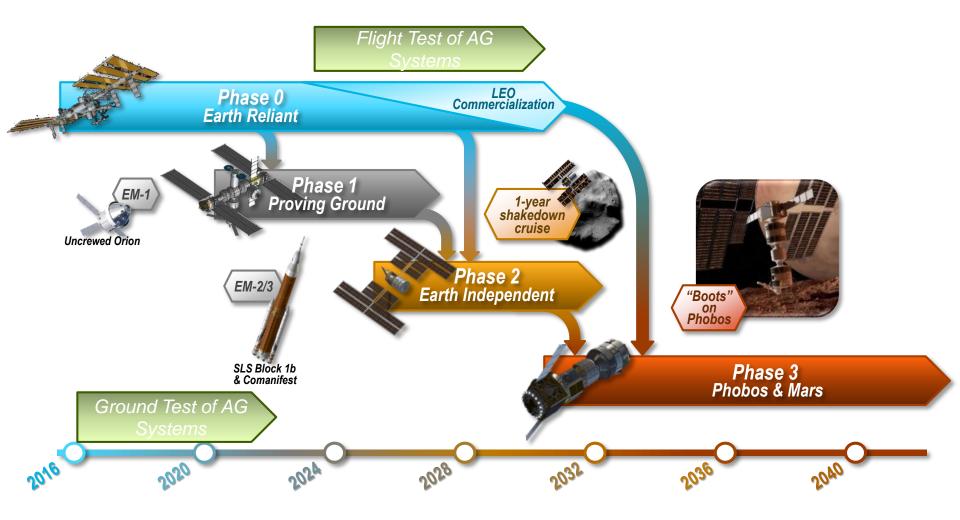
Motivation and Approach

 Artificial gravity (AG) could provide a comprehensive countermeasure for astronaut physiological deconditioning during long-duration space exploration missions

- Long-radius AG systems historically too complex, costly, lacked technological feasibility
- Shorter-radius design potentially more technologically feasible and reduces cost but introduces limitations including:
 - 1. Vestibular cross-coupled (CC) illusion (i.e., Coriolis Illusion)

 * thought to be the biggest limitation of the three
 - 2. Coriolis forces
 - 3. Gravity gradient
- Investigations at University of Colorado Boulder (CU) aim to "train" subjects to adapt to the CC illusion at higher spin rates thus allowing for a shorter-radius centrifuge design
- Boeing spacecraft and habitat design and architecture leverage benefits of short radius to develop potentially feasible configurations

Phases for AG Development



Defense, Space & Security Space Exploration

- Subjects spun on custom-build "Human Eccentric Rotator Device" (HERD) at CU
- Subjects seated upright in the dark, HERD spins around Earth-vertical axis
- First training session began spinning subjects at 1 RPM, subsequent days started at the spin rate at which no illusion was felt (i.e., beginning threshold) on the previous day
- At each spin rate, subjects complete 40° roll head tilts over ~ 1 second then report whether or not they felt the CC illusion immediately after the head tilt
- When the illusion was not felt, the spin rate was increased by 1 RPM; otherwise, spin rate was maintained
- This continued for 25-minute sessions performed daily for 10 subsequent days
- Measured the CC illusion "threshold" (the spin rate at which no illusion was felt) at the BEGINNING and ENDING of each session

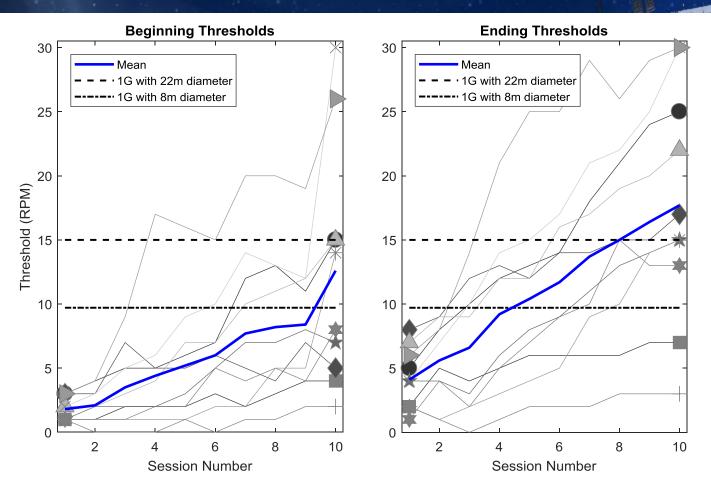




Three Experiments

- Defense, Space & Security
 Space Exploration
- Personalized adaptation protocol training protocol in which spin rate is individually modulated based on subject response to head tilts at each spin rate
- 2. Non-personalized adaptation protocol each subject completes the same training protocol, which is based on median values of the personalized protocol for the first 9 days, then the 10th day is a 'personalized' protocol for direct comparison of thresholds
- 3. Retention study subjects return for three days of testing 30 days after the completion of their original incremental adaptation training to determine how much of the adaptation was preserved

Personalized Protocol



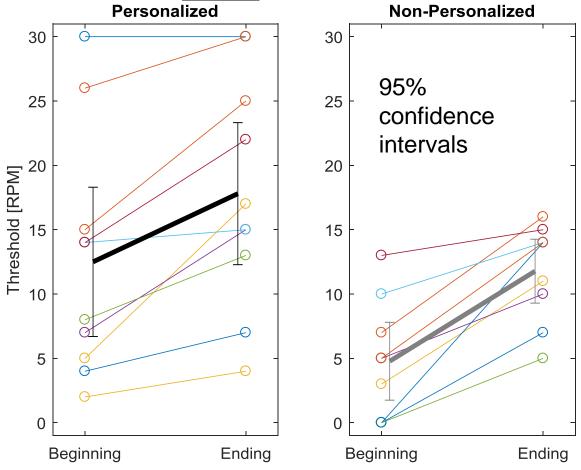
Defense, Space & Security

Over the 10 days/sessions of training, subjects were able to increase their beginning thresholds on day 1 from a mean of 1.75 RPM (range 1-3 RPM) to an ending threshold on day 10 of a mean of 17.8 RPM (range 4-30 RPM). This corresponds to a centrifuge of < 8m diameter (<4m radius)

Non-Personalized Protocol

CC illusion thresholds on **Day 10** of personalized vs. non-personalized training

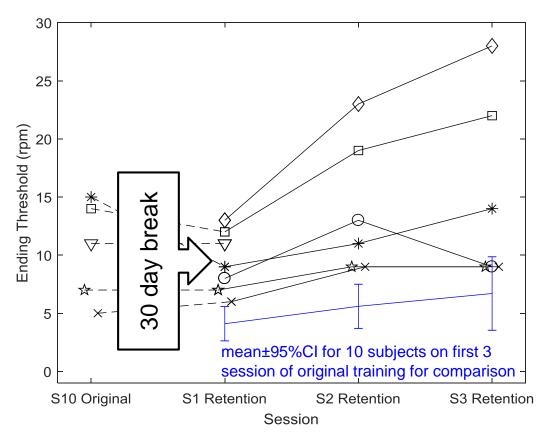
Defense, Space & Security



Subjects who completed the non-personalized protocol were still able to adapt to higher spin rates, though to a lesser extent than the personalized group.

Retention Study





After 30 day break, subjects were able to retain much (if not all) of their original 10 days of adaptation training (little decrease in threshold from S10 Original to S1 Retention)

On average they were able to adapt even more quickly than they did during the original 10-day study (change in black lines from S1 Retention to S3 Retention are more steep than blue line)

Phase 0

Commercial LEO Transportation to ISS

 Test and validate human performance in AG systems – benefits and limitations

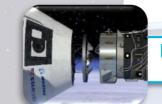
Defense, Space & Security



 Continuous human presence on ISS evaluates long-duration inspace human health risks and mitigations

Three Years in Space?

 Technology demonstrations validates exploration capabilities in a microgravity/vacuum environment



International Docking System Standard (IDSS)

Year in Space

Advanced ECLS Technologies

Advanced Solar Arrays



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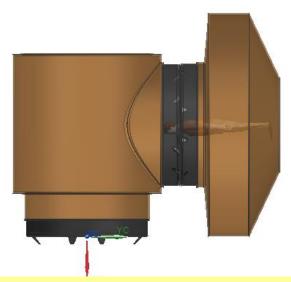
2050

2058

2030

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Demo in Low Earth Orbit



Small radius concept: 3.2m AG floor radius.

Constrained by

- Avoiding interference to station
- Use of CBM



Grey volume is Dragon Trunk

5.0m 4.0m 3.2m In this arrangement, limited for 50th Percentile Male to stand up

Radius	RPM for	RPM for
	0.5 g's	1.0g's
3.2m	13	17
4m	11	15
5m	10	13

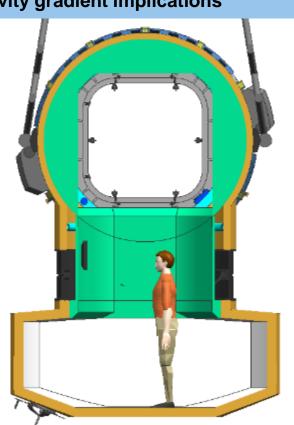
3.2m 2-Element System Details

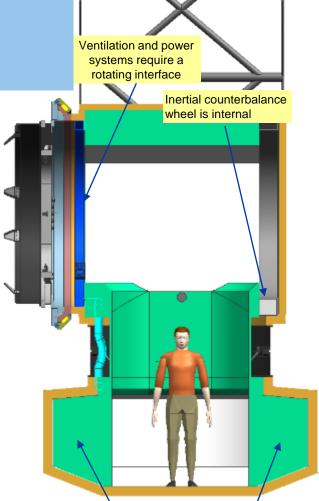
Crew Operations and Science Questions:
Primary type of exercise?
of crew to use?
Time to spin up, slow down?
Duration at spin?

Communications, record keeping?

Sensors?

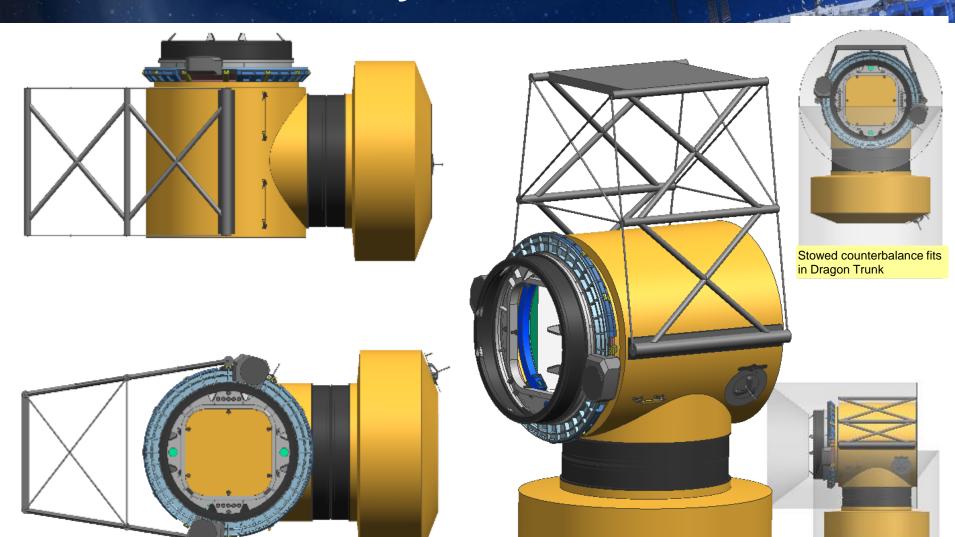
Gravity gradient implications





Equipment stowage on the side volumes

3.2m 2-Element System Details

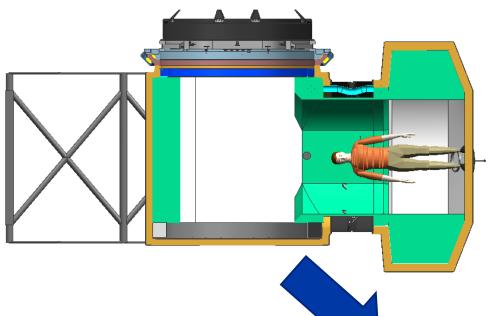


TFR-TRI WORK Camera TFR-TRI

Defense, Space & Security

Deployed system includes counterbalance and rotation mechanism.

LEO Demo Extensible to Full Scale Implementation



LEO Demo

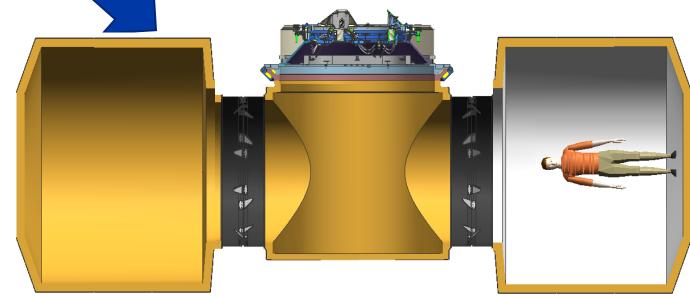
Defense, Space & Security

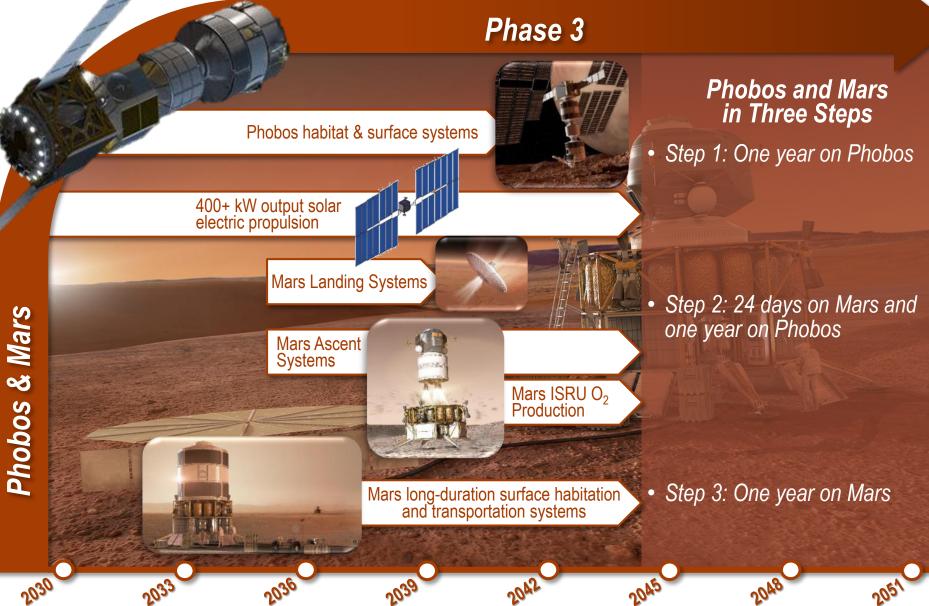
3.7 M Hab Module
3.2 M Radius of Rotation

Mars DST

4.2 M Dual Hab Module 5 M Radius of Rotation

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Deep Space Transport with AG



Defense, Space & Security

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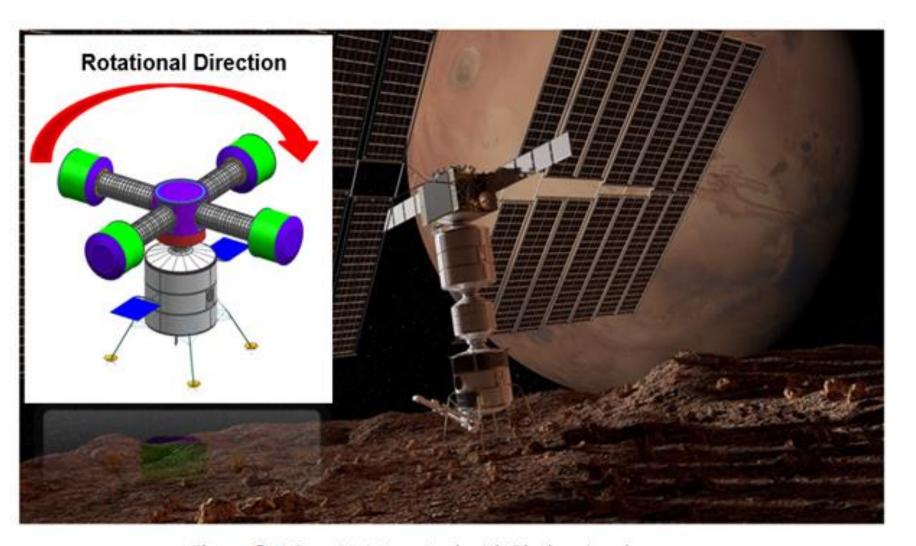


Figure 8. AG units integrated with Phobos Lander

Summary

- Defense, Space & Security
 Space Exploration
- AG is currently in the Global Exploration Roadmap
 - Not integrated in to Industry and NASA's Cis-lunar exploration architecture.
- AG offers the potential to address key Human Health and Performance needs for long-duration deep-space exploration.
- There are potentially feasible configurations that can fit in to the current exploration planning
 - Boeing has developed a number of enabling technologies to make this happen, including 9 AG patent pending concepts.
 - Working closely with University of Colorado to support physiological needs and testing
 - Currently performing ground-based studies to further inform our AG centrifuge system designs.
- Human space centrifuge in LEO, near the ISS, would allow for:
 - Fundamental scientific and validation experiments,
 - Demonstrate necessary technologies