What Might Partial Gravity Biology Research Tell Us?

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Since before the space age there has been periodic interest in manned space facilities that spin to provide artificial gravity. This was based first on theoretical concerns, and later on experience with the negative effects of sustained microgravity on humans. Interest usually focuses on space settlements, or on deep-space expeditions lasting months to years. This paper has a different focus: the biological effects of sustained partial gravity on humans and support ecosystems, particularly at Mars and Moon gravity levels. Surprisingly, all 13 bodies in our solar system with surface gravities between 0.09 and 2.5X earth gravity cluster fairly tightly near 3 distinct gravity levels: 5 of 8 planets have 90-110% of earth gravity, Mercury and Mars each have 38% of earth gravity, and the 6 largest moons in our solar system each have 13-18% of earth gravity. We already know the effects of earth gravity; the main goal of partial-gravity biological studies will be to affordably discover the effects of lunar and Mars gravity levels on humans, and also on any ecosystems we use to support ourselves off earth.

1. Introduction

In the last half century, we have learned that humans can tolerate the absence of gravity for over a year and live normally after return to earth. But other findings are less encouraging: bones lose calcium and muscles lose mass and strength. The immune system and other systems are also affected. Diet, exercise, and medical countermeasures reduce but do not eliminate these problems. Other biology experiments also indicate problems. Fertilized mouse eggs do not implant properly. Even single-cell organisms respond to the absence of gravity.

The stated goal of US government human space policy since 2010 is to make human activity beyond earth ultimately "more sustainable and even indefinite." We can reduce problems by spending lots of time in centrifuges, but this complicates facility design, especially on bodies having non-trivial gravity. "Commuting" between free fall and a rotating facility may cause repeated adaptation problems. Sustainable "indefinite" stays also need to include food production. This seems to require not just crops but full crop-centered ecosystems viable at that gravity level.

If we are serious about "more sustainable and even indefinite" human activity beyond earth, we should consider serious biological research on the effects of relevant sustained non-earth gravity. And we should consider the effects not just on people, but also on managed ecosystems. The plot below suggests that it may be useful to focus partial-gravity research mostly on Moon and Mars gravity levels, 0.16 and 0.38 gee, because all known bodies in our solar system with surface gravity from 0.09 to 2.5 gees cluster very close to earth, Mars, or lunar gravity:

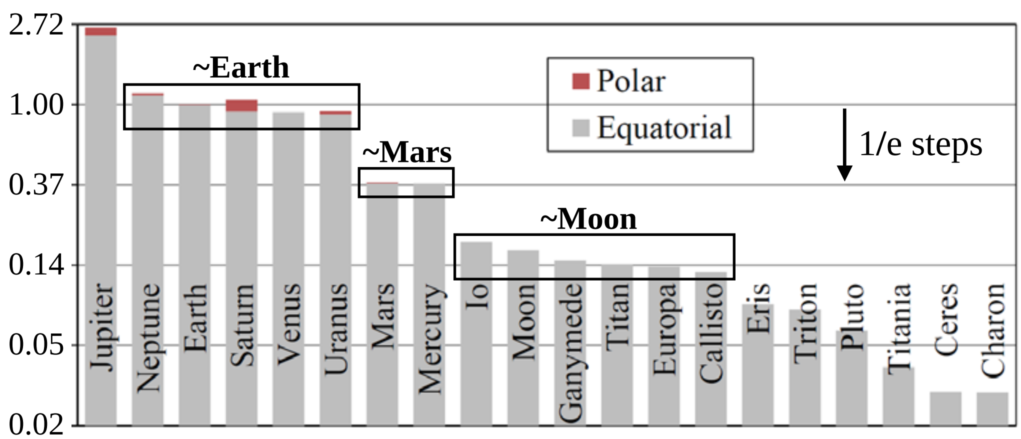

Figure 1. Clustering of surface gravity levels in our solar system (earth = 1.0)

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My main focus in my 33 years in the aerospace industry has been exploring and developing applications for long tethers in space. I am not in any way an expert in human factors, human physiology, biology, or ecology. But I think that making human presence off earth ultimately "more sustainable and even indefinite" requires explicit attention to the effects of non-earth gravity levels, both on people, and on ecosystems people will bring with them for support.

In this solar system, the most relevant gravity levels other than 0 and 1 gee (=earth gravity) are 0.16 and 0.38 gee, because they cover 8 interesting bodies in the solar system. The only other non-earth levels present are 2.7 gees on Jupiter, 0.06-0.09 gees on Eris, Triton, & Pluto, and <0.04 gees on all other known dwarf planets, moons, asteroids, and comets. We have experience with both one gee and microgravity, but our data on 0.16 gee is limited to a dozen Apollo astronauts each spending a few days on the Moon. We have no data on the effects of Mars gravity level on humans. The biological effects of long-term 0.38X earth gravity are directly relevant to the future of earth life on 2 planets, and 0.16X earth gravity is relevant to all 6 of the largest moons in our solar system. Study of those effects seems likely to be needed for viable expansion of earth life onto these bodies. These levels are also usefully spaced as initial partial-gravity test levels, and may suggest intermediate levels to test for free-space human settlements.

The rest of the body of the paper addresses these questions:

2. Questions affecting near-term manned exploration options
3. Effects of sustained Moon and Mars gravity levels on people and lab animals
4. Effects of Moon and Mars gravity levels on important crops and ecosystems
5. Basic biological research
6. Conclusions and recommendations

Three appendices follow the bibliography. Appendix A explains why "rotating room tests" do not tell us what rotation rates may actually be suitable for space facilities providing artificial gravity, and discusses tests in existing ground facilities that may be able to modestly reduce this uncertainty.

Appendix B describes tests of rotation sensitivity and partial gravity that seem feasible on future crew flights to the International Space Station (ISS), during the hours to days the crew spends "phasing" to catch up with ISS.

Appendix C provides more details on the design of a Moon/Mars rotating dumbbell facility that seems suited to answering most of these questions. It is digested from a 2010 IAC paper available at www.artificial-gravity.com.

2. Questions Affecting Near-term Manned Exploration Options

The last several US administrations have had "manned exploration plans," but unlike Apollo, the lion's share of planned spending has consistently been deferred to later administrations, which are free to change those plans. So it seems more relevant to describe all such plans, and similar ones in other countries, as "options" rather than actual plans. It also seems fair to include in "manned exploration" all manned missions to the moon or beyond.

2.1 How much gravity should we use cruising to/from Mars or NEOs?

Trips to the moon involve only a few days of travel, but trips to Mars, most NEOs, or most other interesting destinations well beyond the moon using currently practical propulsion concepts will take many months. We know that people can tolerate free fall for such periods, but we also know that they will be weak when they arrive at the destination, even if they spend hours per day exercising while in transit. This seems like a particularly challenging issue at Mars, due to the combination of substantial gravity, a likely need for fairly heavy EVA suits and backpacks, and a possible need for strenuous contingency activities soon after arrival on Mars.

Hence it appears useful to provide enough gravity for the crew to be ready for strenuous work as soon as they reach the surface of Mars. Mars gravity levels in transit may be sufficient, but if some of the negative effects seen in free fall persist even at Martian gravity, higher levels may be justified. If so, it is possible that substantially higher gravity (perhaps even earth levels) might be useful during most of the cruise. This might drop to Mars levels a week or more before the crew descends to the surface, so the crew can acquire experience with these levels. But based on the apparent ease of Apollo crew accommodation to even lower lunar gravity, this may not be necessary.

On the way back to earth, gravity in transit might use earth levels, or ramp up to earth gradually or in steps. The infeasibility of protecting the crew from high-Z cosmic ray doses in transit also allows an opportunity to test for any possible synergistic effects of radiation and partial gravity. This may help refine planning for later missions.

Appendix B in this paper describes a rotating-tether test on Gemini XI, and more ambitious tests that might be done on future crewed missions to the ISS, using a spent booster stage as counterweight. The same approach might be used on any multi-month manned cruise, if the mission involves a staging event after departure. Deceleration into Mars orbit can be done without discarding a tethered counterweight, by spinning normal to the orbit insertion thrust. Then the "flat spin" becomes conical during the orbit insertion maneuver.

The total mass penalty for this should be dominated by the mass of a suitably damage-tolerant tether, plus the propellant needed to spin up, adjust the spin plane to keep solar arrays aimed at the sun during cruise, and added propellant to decelerate the counterweight mass into Mars orbit. If there is another staging event after departure for earth, that stage can be used as counterweight on the way back. Using spent stages as counterweights lets all critical equipment stay at the crewed end, so any tether failure affects only the gravity level, not crew survival.

It is possible that a good mission design can limit the mass penalties for even full earth gravity (at least on the return leg) to low enough values that we can reasonably baseline that. If not, then we need to study what levels are sufficient to keep the crew capable enough for the mission, including contingency activities after arrival.

2.2 What spin rates and vehicle architectures may be suitable during such multi-month cruises?

As discussed in Appendix A, we do not really know what spin rates are suitable, because it is hard to do relevant tests on the ground. But rotating tether tests that can be done on the way to ISS, as described in Appendix B, should be able to resolve questions about long-term sensitivity to rotation effects and how that varies with gravity level.

2.3 Can crews easily adapt to free-fall EVAs on NEOs, if they live in a nearby spinning facility?

People generally take several days to adapt from earth gravity to free fall, after launch from earth. We have not been able to test people "commuting" daily between gravity and free-fall. This is relevant to crews using a spinning facility to visit and explore a NEO or other low-gravity object. Appendix C describes designs for a manned rotating dumbbell facility in low earth orbit. Most versions of this allow easy "shirtsleeve" crew transfer between substantial gravity levels (up to earth level), and a free-fall module at the center of mass. Hence such a facility could evaluate the realism of plans involving repeated commuting between free fall and a spinning exploration vehicle.

2.4 What countermeasures may still be needed if we use much less than full earth gravity?

Even if we use full earth gravity both ways in transit, extended visits to low-gravity objects like Mars, the Moon, or NEOs may require countermeasures. Free-fall countermeasures should also be useful in partial gravity, but they do have side effects, so it seems prudent to test for both effectiveness and side-effects in partial gravity. This seems likely to require long-duration testing in a large dumbbell facility like that described in Appendix C.

3. Effects of Sustained Moon and Mars Gravity Levels on People and Lab Animals

Before mankind spends serious money preparing for long-term bases, settlements, or colonies on the Moon or Mars, it is prudent to learn whether people living on the Moon or Mars experience continuing negative health trends as they do in microgravity. If these problems persist even at significant partial gravity levels, then it is also important to develop and test effective countermeasures, since countermeasure effects could have drastic effects on exploration plans. Such tests can be done in low earth orbit, as described in Appendices B and C.

3.1 What spin rates and facility size are needed?

As with question 2.2, spin tests on multiple crew missions to ISS may be enough to identify artificial-gravity spin rates acceptable for years rather than just months. If not, then a dumbbell facility as in Appendix C seems needed.

3.2 Are lunar or Mars gravity levels high enough for good health during *indefinite* human stays?

Answering this requires sustained testing, in a facility large enough to allow normal "indoor lifestyle" activities including walking. This seems to require a large rotating dumbbell facility, along the lines described in Appendix C.

3.3 If special exercises, diets, and/or medicines are *still* needed, what combinations work best?

Known countermeasure combinations do not stop the negative health trends that humans experience in free fall. To learn whether countermeasure combinations work well enough in partial gravity, much testing and refinement seem necessary at both Moon and Mars gravity levels. As Figure 1 shows, these levels are also relevant to 6 other interesting solar system bodies, not just the Moon and Mars.

3.4 Can animals and people safely return to earth after years at Moon or Mars gravity levels?

Astronauts returning after 6-12 months in microgravity are greatly weakened by the experience, and many of the negative trends do not seem to approach a limiting value on these timescales. So we don't know the effects of multi-year human exposure to microgravity. The effects of sustained substantial partial gravity are likely to be less serious, but we don't know whether the trends will self-limit or continue indefinitely at a lower rate, or whether other factors may enter in, particularly when the experience also includes countermeasure treatments and radiation exposure.

The loss of an ability to return to earth, or substantial problems after such a return, seems likely to be a real issue in any meaningful debates and decisions regarding long-term settlements or colonies. A lack of ability to return does not preclude settlements or colonies, but it seems likely to affect the attitudes of most funders and participants (even if the funders are the participants).

3.5 Does the full reproductive cycle work successfully in animals and eventually humans?

Most parts of the reproduction cycle seem to work in microgravity tests on mice, but apparently fertilized eggs do not implant properly. The small centrifuge on the ISS is limited to tests on microorganisms. A large centrifuge capable of testing mice at various gravity levels was designed and built for ISS, but not launched. Testing of mouse egg fertilization and implantation might be done during crew flights to ISS. The full reproductive cycle might be tested on a dedicated DragonLab mission, but a larger dumbbell facility will be needed to test the effects of partial gravity on larger animals. There are serious ethical issues associated with human tests (see Woodmansee's book in the bibliography), but such tests seem likely to be done anyway, either by intent or inadvertently.

3.6 Can rats, monkeys, and eventually people raised in partial gravity adapt to full earth gravity?

This is the multi-generational analog of question 3.4. This question can be addressed using the rotating dumbbell designs of Appendix C. Ethical issues like those associated with question 3.5 occur here as well.

4. Effects of Moon and Mars Gravity Levels on Important Crops and Ecosystems

The terms base, settlement, and colony have different connotations of permanence and self-sufficiency. Both bases and settlements may permanently rely on a supplier "back home" to provide necessary supplies. But colonists in a viable colony will want to expand that colony, and they will probably have to support expansion mostly using local resources and processing.

The introduction to the US National Space Policy of June 2010 says that the goal of US government human space policy is to make human activities beyond earth ultimately "more sustainable and even indefinite." This is a very long term focus, and clearly one that can easily be changed by the next administration.

If we do get serious about making human activity beyond earth both more sustainable and indefinite, this implies a push to gradually close the loop in life support. The ISS recycles air and water, but nothing else. ISS depends on earth for propellant, equipment, supplies, and food. Recent tests of additive manufacturing on ISS suggest that some replacement equipment and supplies might be provided by recycling, at least for equipment and supplies specifically designed to ease both recycling and remanufacture. Facilities located on the Moon, Mars, or other bodies may be able to use local materials for many things, again, mostly after we can design equipment and supplies for this.

The most serious challenge for closing the life support loop seems likely to be food. And as soon as we combine "more sustainable" and "indefinite" we need to consider food production. The questions below are by a non-expert. The questions and my thoughts about them may be naïve, but naïve questions can be useful if they stimulate better thinking about subjects that are both important and timely.

4.1 What current or novel crop types may be most useful for food production in partial gravity?

It seems likely that most serious candidates for food production will involve major crops on earth: they have significant edible mass fractions; they use growing area efficiently; people know how to prepare the edible fraction and recycle the rest; and we already know a lot about those crops and their needs and sensitivities. There may be a few counter-examples, but most serious candidates for early food-production off earth seem likely to be found in the top hundred current food crops, and perhaps even the top dozen. And as will be discussed with questions 4.4 and 4.5, whatever we can learn from growing these crops in partial gravity may have substantial economic benefit back here on earth. If that crop is more important now, any such benefit will be larger.

4.2 What soil-based, hydroponic, or aeroponic cultivation techniques are most appropriate?

In space facilities, the "scarce resources" to optimize for include mass, volume, light (perhaps filtered sunlight), crew time and attention, and specialized equipment and skills. There is a great deal of expertise available, but the experts are unlikely to either be astronauts, or to attend space-related conferences or read papers like this. So a key issue is finding ways to connect with those experts.

One option is "aggie schools." I was surprised to realize that 2 universities heavily involved in smallsats (Utah State) and cubesats (Cal Poly San Luis Obispo) both had large agricultural departments. I mentioned this to Jordi Puig-Suari of Cal Poly. He thought it might be because such schools usually also have good mechanical engineering departments and their personnel look for other uses for their expertise. I suggest that readers from such schools talk about this paper and issues it raises with agricultural colleagues, and enlist their help if they are interested.

4.3 What microbes, worms, pollinators, and other support species do we need besides the crops?

Even if crops can be grown in sterile or isolated environments, that seems unlikely to be the best environment for them. Many crops depend on insects for pollination, and nearly all may benefit from many of the micro-organisms found in soil. It is probably not an exaggeration to say that growing crops both on and off earth involves intentional or at least inadvertent creation of suitable ecosystems, including both other species and non-living resources. In a space colony, "The worms are dying and we don't know why!" may be a less immediate but more serious problem than "We have an air leak!"

4.4 What valuable new insights will partial-gravity tests give us about currently important crops?

When you look at something familiar in a new way, you usually learn something new. Plant-growth tests that we do in partial gravity are likely to tell us things we didn't expect to learn about even the best-studied crops. They may also answer some questions whose economic value is already known. For example, a key part of processing wood into paper is removing and responsibly disposing of lignin, which trees need structurally. Growing plants in partial gravity will probably reduce lignin concentrations. A better understanding of what factors affect lignin levels and how we might change them even on earth may have huge value to the US paper industry.

4.5 What novel insights into important crops may challenge key aspects of current theories?

More valuable than new insights about important crops may be insights that challenge parts of the conventional wisdom about those crops. Often we are handicapped less by what we don't know, than by what we are convinced we do know (but wrongly). I know of no way to guess what insights may be corrected, but it seems likely that there will be some corrections. A related issue is disputed questions about currently valuable crops. Some disputes may be resolved by crop growth tests in partial gravity. Others may be resolved by partial-gravity test results raising questions that can be answered by new ground-based tests.

The 2010 US National Space Policy, after stating that the goal is more sustainable and even indefinite human activities beyond earth, also says that "in fulfilling this task, we will not only extend humanity's reach in space—we will strengthen America's leadership here on earth." Anything we learn about important crops, as a direct or indirect result of doing partial-gravity tests (or even doing some novel ground-based control tests) is likely to provide substantial return on earth. Even countries with no space program may wish to participate in partial-gravity crop growth tests, if such tests start to show benefits for crops important to other countries.

5. Basic Biological Research

Besides research on people and lab animals, and crops and their ecosystems, a partial-gravity research facility focused on biological issues can also address more basic biology questions. The 2 questions below result from discussions years ago with Lynn Harper of NASA Ames. To learn more about them, I suggest readers contact her.

5.1 What changes in gene expression and metabolism occur at Mars, Moon, and lower gravity levels?

NASA apparently used to routinely reject proposed microgravity experiments on single-cell micro-organisms, based on an expectation that the presence or absence of gravity would not have a significant effect at that scale. But in the late 1990s, an experimenter did a test that showed that "turning gravity off" had very observable effects even on single-cell micro-organisms. This led to other experiments that showed that microgravity turned far more genes on or off than occurred with changes like temperature, chemical concentrations, light, or pH.

Astrium has developed a small centrifuge for ISS. It is available for commercial use through NanoRacks. It is primarily intended to provide 1-gee control tests on ISS, but should also be able to provide partial gravity for gene expression and other micro-organism studies.

5.2 Do partial gravity experiments allow advances in basic biology?

The theme here is the same as for question 4.4, that when you look at familiar things in a new way, you usually learn something new. But here the focus is not limited to crops and the ecosystems supporting them, but includes all types of living things, and all biological questions regarding them which may be affected by gravity level.

Since life first evolved on earth, the chemistry, temperature, and nearly everything else has changed. Life has adapted to those changes, and life has also developed general tools for adaptation. But all life on earth has remained at one gee. Even when a cell is floating in water, parts of it are denser than others. This may be how cells feel the presence of gravity. We have been learning about the effects of "turning gravity off" for over 50 years. Many of the insights had to wait until the development of suitable genomics research tools in the last few decades. We are now poised to learn about the effects of gravity levels between 0 and 1 gee. It is feasible to do "hypergravity" biological research on the ground, and a new ground-based ESA centrifuge will be exploring such questions. Extending the test opportunities to partial gravity may tell us a range of new things. This seems likely to include (as suggested to me by Neal Pellis), gravity threshold values for various differences that have been found between 0 and 1 gee responses.

6. Conclusions and Recommendations

The goal of this paper is to encourage consideration of biological research in partial gravity, with particular focus on Moon and Mars gravity. As Figure 1 shows, those levels are relevant to 8 interesting bodies in this solar system, not just 2. No other gravity levels between 0.1 and 1 gee appear as relevant to this solar system as those 2 levels are.

Research on the effects of these gravity levels can be done far more cheaply in a spinning facility in low earth orbit, than "in-situ" on the Moon or Mars, and with much lower radiation exposure. A spinning LEO facility also allows far better analyses, since it can do frequent targeted tether deorbit of samples for analysis on the ground.

There are additional reasons to study those 2 levels. As Figure 1 shows, the "gravity steps" from Earth to Mars, and Mars to the Moon, are each roughly a factor of 1/e, where "e" is the basis of natural logarithms. Neal Pellis has suggested to me that steps of about this size are natural to consider when looking for gravity-dependent effects and thresholds. Also, "tumbling dumbbell" facilities like those shown in Appendix C can also include an inboard station at the next 1/e step, 0.06 gee. That level may be popular if it is near the lowest level that allows intuitive activities like sitting comfortably in a chair, eating normally, or rolling over in bed without continuing the roll onto the floor.

A facility that can provide research space at 3 different levels that are each ~1/e steps apart can also explore other levels. For example, during facility assembly, after the structure is complete but before most equipment has been delivered, the facility will be lighter and hence can handle higher acceleration loads. It might provide earth, Mars, and Moon gravity levels, at 60% higher rotation rates than planned after full outfitting. And if that spin is slowed about 22% (which allows further outfitting), the facility can provide 0.62, 0.27, and 0.10 gee. Those 3 levels are logarithmic half-steps between earth and Mars, Mars and the Moon, and the Moon and 0.06 gee. They are probably the most useful test levels to complement what can be learned at Mars, Moon, and 0.06 gee levels.

My main recommendation is that readers seriously consider the value of answering the questions discussed above, and decide whether that value is high enough to justify at least the first steps in the directions suggested by Appendices A and B: ground and flight tests of rotation sensitivity and partial-gravity effects.

Gravity is an analog parameter. Study of its biological implications has focused on it as a digital parameter, either on or off. We can do better. I encourage those interested in doing so to contact me, at tether@cox.net.

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Appendix A: Why Don't We Know What Spin Rates Are Usable?

Early in the space age, tests were done on the accommodation of six young men to conditions in a rotating room over two days. After that the rotation stopped and they remained in the room for added tests on the third day. The room was round, windowless, and 15 foot in diameter, and smoothly rotated about a vertical axis, at rates from 1.71 to 10 rpm. The results were reported by Graybiel, Clark, and Zarriello in 1960 in the Archives of Neurology, 3, 55-73. Some subjects reported mild general malaise, nausea, or headaches even at 1.71 rpm, and one vomited at 2.21 rpm. The frequency and severity of reported negative reactions increased at 3.82 and 5.44 rpm. But one subject had minimal negative reactions even at 10 rpm. In addition, a control subject who was deaf and also lacked normal vestibular function had little response to rotation.

Since then, NASA analysts have developed various criteria for constraining the spin rate and size of artificial-gravity facility designs, based on data from these and related tests and other factors, including head-to-foot gravity differences and changes in weight caused by walking with or against the rotation.

John Charles of NASA JSC suggested to me that the rotating room tests may not be relevant for estimating maximum allowable spin-rates of orbiting artificial-gravity facilities, since the rotation axis is parallel to gravity, rather than normal to it as in an artificial-gravity facility. A footnote in the above paper by Graybiel et al. also notes this issue. At first this seemed like a subtle difference, but I gradually realized that the difference has important implications.

Two distinct effects need discussion: rotation itself, and Coriolis accelerations. Room rotation rates of order 1 rpm may be detectable even when people are still, but people seem to tolerate that. They can even adapt to reversals in rotation direction, but time may be required for accommodation. But in artificial gravity facilities, the direction of felt rotation depends on which way you are facing at the time. Turning around reverses the felt rotation immediately. Turning around even has an azimuth-specific effect: one turn causes a shift in sensed rotation one way, and the next causes an opposite shift in sensed rotation. This is a key difference between ground-based rotating-room tests and orbiting artificial-gravity facilities.

Now consider Coriolis accelerations. To a person sitting or standing anywhere in a room rotating about a vertical axis, purely vertical motion causes no Coriolis effects. Horizontal motion can cause substantial Coriolis acceleration. In a room rotating clockwise (when you look down), the acceleration is to the left of the motion. It is equal to twice the room rotation rate times the horizontal velocity. If you walk at 1 m/s in a room rotating clockwise at 1 rpm (=0.1047 rad/sec), you must lean 1.2^{o} to the right, or 1.2^{o} to the left if you step backward. This may be annoying initially, but it is consistent, so people can adapt to it. As long as the spin direction and rate remain the same, the side acceleration is independent of location and orientation in the room. Every time you walk at a given speed, or reach your arm out at a given speed, you feel the same perturbation, in the same direction in your body coordinates. Most people may adapt to this fairly well over time.

Contrast this with an artificial-gravity facility. Both vertical and horizontal motions cause perturbations. And in body coordinates, the effects of both motions vary with azimuth. Vertical (radial) motion causes a horizontal force aligned with the direction of rotation. Most vertical motion is stroke limited (eg., standing up), so the total impulse is limited and may be tolerable. For example, when you stand up, you may raise your CM by ~0.4m. In a facility with 1 rpm rotation, that is like standing up from a wheeled chair moving at 42 mm/sec (1.6"/sec) in a fixed direction, independent of which way the chair is facing. That is probably tolerable, especially since you usually make transient balance adjustments anyway while you are standing up.

But now consider horizontal motion with or against the direction of rotation. If you walk only 2.5% as fast as the facility moves at your radius, you get 5% heavier, since weight scales with V^2/r. But if you turn around, walking makes you 5% lighter. If you walk at right angles to the rotation, there is no effect. Such changes are relevant because ordinary elevators typically have ~0.05 gee acceleration. People often stumble a bit if they are taking a step when an elevator starts or stops. (A better test than intentionally walking at such times may be to slave the vertical motion of a motion-base simulator to horizontal motions of a single occupant.) Such tests may show that people can detect weight changes as little as $\pm$1% when walking.

Another key issue is that the threshold for conscious detection and that for negative effects like general malaise or nausea may be different—and it is not clear which may be higher. The threshold for negative effects may be well above the threshold for conscious detection. But queasiness and other negative effects may possibly be problems even when you are not consciously aware of the rotation artifacts. Because of this uncertainty, it may make sense to consider the implications of a possible threshold for non-trivial negative effects that ranges from ±1 to ±3% weight change at a modest walking speed of 1 m/s. This corresponds to facility rotation rates of 0.47 to 1.41 rpm, and overall lengths of 240-2200 meters for a Moon/Mars dumbbell facility.

An important related question is what happens to the thresholds of detection and negative effects in lower gravity. Coriolis accelerations scale with rotation rate but are independent of radius, so walking in a facility rotating at 0.47 to 1.41 rpm will cause weight changes equal to ±1 to ±3% of ***earth*** gravity, whether you are at earth, Mars, lunar, or a lower gravity level. The detection threshold for changes in sensory input often nearly scales with input level, but at low levels, this may not hold as accurately. If thresholds do drop with gravity level, then allowable facility rotation rate will be limited more by effects at the lunar node than the Mars node. If thresholds for negative effects scale with the square root of gravity level, then the allowable rotation rate in lunar gravity may be only 40% of a 0.47 to 1.41 rpm range that may be relevant at earth gravity, and could be as low as 0.19 rpm (requiring a 14 km facility length!). Such rates are far below what others have assumed acceptable. Good choices really require more relevant test data.

For very long slowly-rotating facilities there is one more effect to consider: periodic gravity variations between the horizontal and vertical, due to gravity-gradient effects and also induced variations in rotation rates. This effect scales linearly with length. This does not require occupant motion, so people may be more sensitive to it than to comparable variations caused by walking, for the same reason that people seem more prone to motion sickness when they are passengers than when they are driving. Moon/Mars dumbbells near ISS altitude have a total range of gravity variation of 1% per 6.75 km dumbbell length, with maximum weight at the vertical and minimum at the horizontal. On the other hand, this is a smooth and slow sinusoid, with a period of 1 minute for a 2 km dumbbell rotating at 0.5 rpm. For a ~500m 1 rpm facility, the period is 30 seconds, but the total range of variation is only 0.07%.

Based on the above discussion, the most detectable artifact in a slowly-rotating facility, and the best candidate for an upper limit to rotation rates, may be direction-dependent weight changes when people walk with or against the direction of rotation. A key feature of the facility design may be long thin aircraft-like cabin layouts, with narrow "aisles" aligned with the spin axis. Ted Hall recommended this in a 1993 paper. It does require reaction wheels or masses on long booms to keep the cabin axis aligned with the spin axis. But it seems worth doing, because then most walking will be nearly parallel to the axis of rotation, and walking-induced weight changes will be low. Steps across the aisle will be at much lower speed since there is so little room to start and stop. A useful supporting design feature might be a decorative floor covering with an intuitive directional pattern like arrows showing rotation direction, to help people anticipate rotation effects. This would be especially useful in hallways between adjacent cabins. This small detail may be important, because if a good layout and floor covering allow use of even 10-20% higher facility spin rates without problems, they could allow 17-31% shorter facility lengths.

It also seems important to keep rotation artifacts too low to trigger negative effects in ***most*** people spending time at a facility, without limiting personnel selection significantly. We may want the lowest rotation rate (and longest length) compatible with a convenient and affordable facility design. This may involve limiting rotation rates to <1.0 rpm. This requires facility lengths >500 m. Appendix C shows designs fitting a very wide range of facility lengths.

Ground tests to reduce the uncertainty in allowable spin rates

We can mimic some but not all of the effects of turning around in a partial-gravity facility by rotating a room or even a reclining seat at ~0.5-2 rpm, and then smoothly reversing the rotation direction. This still does stimulate the wrong perceptual axis. But if such tests are easy, they may help quantify direct sensitivity to changes in rotation.

It also appears feasible to explore the effects of weight changes caused by walking, using the Vertical Motion Simulator at NASA Ames. The VMS allows 18m vertical motion, and 12 and 2m horizontal strokes. The VMS has 4 interchangeable cabs, including one with a 1.8 x 3.7m floor. This is large enough to get up some speed walking in different directions. What is needed is to outfit the large cab with suitable interior layouts, add an occupant motion sensor, write code to move the cab in response to occupant motion, and do all needed safety reviews to make sure that the tests can be done safely. The VMS even allows simulation of Coriolis impulses caused by standing up and sitting down. The VMS can also simulate the periodic long-facility gravity variations for facilities up to 2 km long, without needing occupant sensors or feedback control.

Such tests will not eliminate uncertainty but just reduce it. But this can be useful if it bounds the facility design space, or if it identifies questions for study in crewed flight tests like those described next, in Appendix B.

Appendix B: Rotating-Tether Flight Tests Using Crewed Vehicles

A precursor: the rotating-tether flight test on Gemini XI

The Gemini spacecraft program actually began after Apollo, to answer time-critical questions that Mercury could not answer. Gemini answered most of those questions well before its last flight. This provided an opportunity to add additional tests that could be readied quickly. These tests included rotating tether operations on Gemini XI, and passive stabilization by weak gravity gradient effects on Gemini XII. The time to develop the Gemini XI test was <1 year.

The plan for Gemini XI already included rendezvous and docking with a separately launched Agena stage, as on missions VIII and X. What was new was a 30 meter tether stowed in the Agena's docking collar. The seatbelt-like tether was secured for launch by weak "rip-stitching" designed to break under modest tension. During an EVA, the crew attached the free end of the tether to a releasable docking bar on Gemini. Later they undocked from the Agena and fired the Gemini's thrusters to slowly drift away and pull out the tether. They had difficulty keeping the tether taut until they fired the Gemini thrusters to slowly spin up the system, first to 40^{o}/minute, and then 55^{o}/minute. This provided only 0.2-0.4 milligee acceleration, but that was enough to stabilize the dynamics. The test was uneventful enough that the crew took a break to eat during the test. After 3 hours they released the tether and moved away. The Gemini XI mission movie is available on YouTube, and describes this test starting at 10:40 into the movie. Narrator comments in the movie suggest a focus more on passive station-keeping than on sensible levels of artificial gravity.

It seems to take much longer than a year to plan crewed flight tests today, but it need not take much longer to develop an analogous test that provides far higher artificial gravity levels. A strong seatbelt-like strap can be stitched into place as on Gemini. The test can actually be simpler than on Gemini, if it uses the booster's upper stage as the counterweight. Then neither docking nor EVA are needed, since the stage is attached to the crew vehicle before launch, and the tether can be as well (but it must be quickly released if a launch escape is necessary). This appendix discusses 4 key aspects of such experiments: goals, mission scenarios, payload mass penalties, and safety issues.

Possible goals

Current human spaceflight vehicles do not have large enough cabins to support tests involving walking around. So useful tests may be limited to better characterizing other constraints on allowable spin-rate, and how they vary with gravity level. If such tests prove easy enough to do, more ambitious goals may be possible. For example, low levels of partial gravity such as 0.06 or 0.16 gee may ease crew adaptation to microgravity. If so, spinning-tether operations might become a standard part of crew launches to ISS or other facilities. If such operations are continued for days, it may be feasible to directly detect physiological differences in crew response to partial vs micro-gravity. John Charles has told me that data from the several days that Apollo astronauts spent in lunar gravity did not provide an unambiguous signal compared to data from their colleagues who remained in free fall, in the command module. And any such signal might have been due more to their spacewalks on the surface than to the lunar gravity itself. With today's biochemical and other monitoring capabilities, especially once crews arrive at ISS, it may be feasible to get useful signals from partial gravity experiments lasting only a few days, over a range of partial gravity levels.

Such tests should also be able to narrow down many details of more ambitious follow-on tests involving crew rendezvous with a separately-launched module large enough to live in and walk around in for weeks. These tests can also provide opportunities to test many aspects of guidance for trapeze captures (see Appendix C), without requiring capture hardware or even very close approaches.

Possible mission scenario

Crew vehicle thrusters usually have lower Isp than the booster upper stage, but discarding the stage mass usually more than makes up for this. So the crew vehicle can be more efficient at orbit raising than the booster, as long as it has room for enough propellant to complete its mission.

Usually the crew vehicle separates from the spent booster stage right after MECO, coasts to apogee, and uses its maneuvering thrusters to raise perigee. It then stays in a low "phasing orbit" to catch up with the ISS, often several days later. Phasing is needed because launch must occur when the earth's rotation moves the launch site through the ISS orbit plane, whether or not the ISS is nearby at the time. The lower the vehicle orbit is compared to that of ISS, the faster it will catch up to ISS. Using a "depressed launch trajectory" can also reduce peak reentry gee-loads during a worst-case abort of a crew launch. It also increases payload, if there is no heavy fairing to discard on the way to orbit. The best MECO condition may be near the perigee of a parking orbit as low as 120 x 200 km.

The scenario described below provides lunar gravity at 1 rpm rotation. It assumes a crewed Dragon 2 launched by a Falcon 9, during phasing on the way to ISS. Similar scenarios might be used by the CST-100, Soyuz, Shenzhou, or any other crew vehicle delivered to low orbit by a booster stage that can then be used as a counterweight.

I assume that a crewed Dragon has enough propellant to start in a 120 x 200 km MECO orbit, climb to and berth with ISS, and later accurately deorbit itself. I also assume that MECO is near perigee, and that after MECO, Dragon weighs 2X as much as Falcon after Falcon vents residual propellant. Providing lunar gravity level with 1 rpm spin requires Dragon's crew to be 148 m from the CM. If Falcon weighs half as much as Dragon, it needs to be twice as far away, for a total endmass separation of 444 m (with the tether itself being perhaps 8 m shorter).

Dragon can coast until 25 minutes past perigee, to climb to 170 km before it separates from Falcon. This reduces aero heating and AO erosion of the tether. Then Dragon pitches up 60^o, separates from Falcon, and thrusts directly away from Falcon at 1 m/s. The thrusters used must be located and oriented so they do not damage the tether by impingement heating. Seven minutes later, Dragon reaches 187 km altitude, the full tether length is deployed, and Dragon is nearly straight above Falcon and moving at the same inertial velocity. Stronger rip-stitching in the last ~10% of the tether can slow deployment passively, to reduce any tendency to rebound.

The tension rise near the end of tether deployment also cues Dragon to start thrusting, to start a prograde spin. This uses thrusters at right angles to the tether, so impingement heating need not be an issue. Thrust might continue until Dragon is ~30^o forward of Falcon in an LVLH frame. If the thrusters used for this provide 1200 newtons thrust and Dragon weighs 9000 kg, the thrust lasts 65 seconds and provides an 8.7 m/s tangential deltaV to Dragon relative to Falcon. This gives a prograde inertial rotation rate of 67^o/minute (63^o/minute in an LVLH frame). This is similar to the 55^o/minute maximum spin rate on Gemini XI, but it provides far higher gravity since the tether is 15X longer.

Five minutes after the first spin-up impulse ends, Dragon has rotated 300^o in the LVLH frame, and is again within 30^o of straight above Falcon. Hence it can again efficiently boost the center-of-mass orbit while spinning up the system. This time it will be within 30^o of local vertical above Falcon for less time since it is already moving forward. It might thrust during ~1/6 of each LVLH rotation thereafter. It is useful to split the spin-up impulses into at least two episodes, one or more orbits apart. One might provide 60% of the spin-up deltaV during the first orbit, during ~90^o of orbit centered on apogee. This plus the initial 1 m/s separation deltaV will raise the orbit of the tether system center of mass from 120 x 200 km to 210 km circular. The inertial spin rate is then 0.6 rpm. This is a useful spin rate to test, and it provides 0.06 gee of felt gravity inside Dragon. If this aids the crew's later accommodation to free-fall, it might be done routinely during some of the orbit phasing period on most later crew missions to ISS. Note that space shuttle crews experienced ~0.06 gee during OMS engine firings, but only for minutes, not hours or days.

Completing the spin-up during a later orbit increases the inertial rotation rate to 1 rpm, raises the felt gravity level to lunar gravity inside Dragon, and can boost the assembly's center of mass into a 230 km circular orbit. The crew can do any desired tests at this rotation and gravity level, for as long as desired during phasing toward ISS.

Dragon can end the test by releasing the tether whenever it is directly above Falcon. Then it always has all the orbital momentum added during spin-up. With the assumed 2:1 masses, release boosts Dragon from a 230 x 230 km orbit into a 230 x 281 km orbit, and drops Falcon and its attached tether into a very short-lived 125 x 230 km orbit. Any changes in mass ratio, spin deltaV, orbit altitude or eccentricity, or phasing at release will affect the final Falcon perigee altitude. Surprisingly, some cases with mass ratios >2:1 can even target deorbit of the spent stage. This is possible because tether operations can change the booster's orbit shape, raising apogee and dropping perigee.

Possible payload mass penalties (tether, propellant, test supplies, etc.)

The easiest direct mass penalty to calculate is the tether itself. If Dragon weighs ~2X as much as Falcon after Falcon vents residual propellants, then the total required tether length is ~3X the desired Dragon radius of rotation. The tether needs a coating to protect against atomic oxygen, which can cause serious erosion of a polyethylene tether in days of exposure near ~230 km orbit altitude. The required tether strength is simply the Dragon mass during the experiment, times the maximum planned centrifugal acceleration, times a suitable tether safety factor. In a test providing lunar gravity levels to the crew inside a 9000 kg Dragon, a 436m Spectra tether with a safety factor >5 may weigh only 20 kg. Stowage interfaces and structural attachments and release mechanisms will add to this.

With the above assumptions and spin-up by Dragon (unfortunately, the heavier end of the tethered pair), the propellant mass needed to spin up may be ~8X the tether mass. But if thrusting occurs only when Dragon is rotating forward, ***and*** the tether is later released at the same spin phase, then nearly all of the spin-up impulse also ends up boosting Dragon towards ISS altitude. If the spin is in the orbit plane, and thrusting is done during 1/6 of each spin, when Dragon is thrusting within 30^o of the best direction, then Dragon's boost cosine losses are only 4.5%. Then the deltaV penalty is only 2.1 m/s of the 46.5 m/s spin-up deltaV, plus 0.5 m/s of the initial 1 m/deltaV that was pitched up 60^o. The propellant mass penalty may be only ~9 kg, less than half as large as a ~20 kg tether mass penalty.

If a longer tether is used to provide the same gravity level, the tether mass scales with length, but spin-up deltaV scales with Sqrt(Length). And if faster spin is used, for Mars rather than lunar gravity, tether tension and required mass scale with the desired gravity level, while the spin-up deltaV scales only with Sqrt(Gravity). Hence the main penalty in more ambitious tests seems likely to remain the tether itself, not the propellant mass penalty.

One must also consider reboost propellant due to the large area and low altitude. The average CdA of a ~0.05 x 436m twisted flat tether spinning in the orbit plane will be ~20 m^2. The CdA of the full assembly may be ~100 m^2. About 8 kg/day of propellant may be needed to stay at 230 km altitude, vs 2 kg/day for Dragon by itself at 230 km.

There is another category of mass penalty: supplies required to make partial-gravity tests useful. Food, water, and other crew-support supplies should not change as long as the partial-gravity test is completed in the time needed for orbit phasing on a specific mission. But if these tests appear useful enough, there may be interest in extending this period, so added supplies will be needed. In addition, each test may trigger interest in later tests, many of which may require dedicated test supplies, or crew exercise or monitoring equipment beyond what is normally carried. Advocates of each such test will have to justify the direct and indirect mass penalties their experiments impose.

Safety issues

A tape-like tether seems more likely to survive micrometeoroid or orbital debris impact than a round tether, and a ~230 km phasing altitude greatly reduces local debris populations. But any tether size or shape can be severed, and other unrelated failure modes can also trigger unplanned tether release. Such events can be made very unlikely but not entirely precluded. So one basic concept is to ensure that worst-case tether severances are at least survivable.

If a tether is severed or released under design load, it will recoil at ~50 m/s toward its attach point. System spin will make the "pileup point" accelerate away from the attach point, but some tether will hit Dragon and may foul on it, and the remaining length may wrap around it. This may require aborting a planned mission to ISS. High-strength oriented polyethylene fibers like Spectra and its European analog Dyneema have the highest usable strength/weight of any commercial fiber. They also have a low melting point (147C), so a flat tether should melt early in reentry, even if exposed only to afterbody reentry heating. So it should be feasible for Dragon to reenter wrapped in a fouled tether, without the tether being able to prevent parachute deployment at the end of reentry. This is critical, so it can be tested on an earlier Dragon mission by mounting short lengths of candidate tethers externally, in suitable places.

A tether failure when Falcon is on top and moving forward can also sling Falcon and the attached length tether into a higher orbit. A 1 rpm spin with 444 m CM separation and 2:1 mass ratio can boost Falcon up to 107 km above that. If the test is done in 230 km orbit, Falcon could reach 337 km. As long as ISS is safely above 337 km altitude, or some other altitude for other specific test cases, there need be no risk of Falcon or its tether reaching ISS. This plus faster phasing, lower debris populations, and a possibility of passively targeting deorbit of the spent-stage counterweight in some cases are the main benefits of doing spinning-tether tests at the lowest practical altitude.

If tests that use longer tethers or faster spins can reach ISS, additional measures are needed to protect ISS. One measure may be to add a weak springy insert to the tether so it folds up on itself when nearly slack. This can reduce the effective dimensions of the Falcon+tether as a collision target. The combination of tether recoil and rotation will energetically wrap the tether around each endmass, allowing dissipation of the recoil energy. Another measure is to use a spin plane angled to the orbit plane, so a released Falcon is likely to oscillate through the ISS orbit plane (depending on when in the orbit the severance occurs), rather than necessarily remaining in the orbit plane. If there is enough orbit phase separation to provide enough lead time, and we have accurate orbit data from a GPS receiver on Falcon, ISS might also do a ~1 m/s contingency reboost to shift the timing of phase coincidence so Falcon is then above, below, or to one side of ISS. Choosing a launch date that requires a larger launch phasing angle when the launch site passes through the ISS orbit plane can provide additional lead time for such measures. But again, such measures are needed only for missions in which the highest thrown-stage apogee cannot be kept safely below ISS.

There will clearly be additional safety issues and other complications to this test concept, but the ones discussed above seem likely to be the most serious ones directly tied to the use of a tether. And they can probably be avoided by using a low-melting-point tether and keeping the worst-case stage apogee well below ISS altitude.

Appendix C: Facility Design Options for a Range of Spin Rates and Lengths

If ground-based rotating room tests have uncertain relevance, as suggested in Appendix A, then allowable facility rotation rates and required facility lengths are uncertain. And if one wants to cut Coriolis effects by half, one must cut the rotation rate of an artificial gravity facility by half. This requires a 4X longer facility. Because of the wide range of uncertainty, this appendix, digested from my 2010 IAC paper, presents 4 different structural design options suited to rotation rates ranging from 0.25 to 2 rpm. This corresponds to overall facility lengths from 120 m to 8 km.

The radial structure of a rotating "Moon/Mars" dumbbell will serve multiple functions. If it is short enough, the radial structure can join pressurized modules end to end. This lets crew facilities and experiments be positioned anywhere desired along the length. But if the dumbbell is much longer than 100m, the row of modules could get too heavy. A reinforced inflatable tube or "airbeam" (as used to support the roofs of some field hospitals) can be far lighter than a string of modules. It can roll up to stow for launch, and can allow easy "shirtsleeve" crew and cargo transfer between nodes. But beyond ~1 km length, even a ~1.6m diameter inflated tube or tunnel will get too heavy. Redundant cabling may be necessary for at least the longest link. Then transfer between some nodes may require an external elevator. Table C-1 suggests approximate maximum lengths for these different radial structure options:

Table C-1. Radial structure options vs dumbbell length, with key features and limitations

MinRPM	MaxLen,m	Radial structure	Key features	Length-limiting factors
~2.0	~120	Radial modules	Test any level up to Mars	Mass of radial modules
~0.7	~1000	Airbeam tunnels	Easy transfer by elevator	Impact risk; tunnel area
~0.55	~1600	Tunnels + cables	Easy transfers exc. to Mars node	Post-cut perigee; "
~0.25	~8000	Cables	Slow spin; transfers by capsule	Cable mass; "

Table C-2 below shows many important implications of different facility lengths quantitatively. Some values of special concern are flagged in yellow. As is shown later in table C-3, a 1600m length for "tunnel + cable" structures is about the longest that allows "trapeze captures" safely outboard of the Mars node. Only one tunnel + cable case is shown because shorter designs seem likely to not be competitive with all-tunnel designs. Similarly, it may not make sense to use an "all-cable" design unless it is much longer than tunnel + cable designs. So the shortest all-cable case shown is 4 km. The convenience of transfer through pressurized tunnels leads me to show 3 lengths for this design.

Table C-2. Key implications of various dumbbell lengths

Radial structure type:		Modules	Pressurized tunnels			Tun+cab	Cables	
Rpm, inertial	***Scaling***	**2.00**	**1.50**	**1.00**	**0.80**	**0.55**	**0.35**	**0.25**
Dumbbell length L, meters	rpm^{-2}	**121**	**216**	**486**	**760**	**1600**	**4000**	**8000**
V_{Mars} (affects Δweight), m/s	rpm^{-1}	17.7	23.7	35.5	44.4	64.3	101.7	143.8
ΔEarth weight, walk 1 m/s	rpm	±4.3%	±3.2%	±2.1%	±1.7%	±1.2%	±0.75%	±0.53%
Cyclic Δweight(vert-hor)	rpm^{-2}	0.02%	0.03%	0.07%	0.10%	0.24%	0.6%	1.2%
Mars node perigee, km_{345}	$\Delta = rpm^{-1}$	284	263	222	191	125	1	-135
Mars node orbit life, hrs	$\sim 1/\rho_{Per}$	881	626	285	168	6	<1	<1
Moon node orbit life, hrs	"	1464	1291	992	790	467	141	9
Post-cut reboost $prop_{Isp=280}$	rpm^{-1}	0.4%	0.5%	0.8%	1.0%	1.4%	2.2%	3.2%
Radial mass $frac_{15,1\%/km}$	rpm^{-2}	~30%	3.1%	7.1%	11.4%	8.3%	4.0%	8.0%
Radial struct drag CdA, m^2	Σ(LW)	660	492	1140	1783	1355	860	1720

The estimates of radial structural mass fraction in Table C-2 assume rigid radial modules similar to modules at each node but with less equipment, or 1.6m diameter inflatable tunnels with a mass of 15% of the other facility mass per km, and/or atomic-oxygen-tolerant cables with 1% of the other facility mass per km. Perhaps the most important conclusion from this table is that ***all*** length options have potential problems of some kind. For example, if the spin rate is low enough that walking-induced weight changes are <2%, then the Mars node tangential velocity is high enough that radial structure failure can sling that node into a short-lived orbit or even a reentry trajectory.

But a short-lived orbit after structural failure may not be the main issue. If this facility flies in train with the ISS and perhaps other manned facilities, a more critical issue after a badly-timed structural failure is preventing collision with those facilities. Independent of facility length and cut likelihood, it seems essential to have a reliable "smart reboost" capability at each node, to promptly restore each part of the facility to near its original orbit. Prompt return is also needed if one plans to later re-connect the separated pieces, because if the pieces "lap" each other, then their orbits will have different nodes. This greatly increases the total deltaV required to bring the pieces back together.

The propellant mass fraction needed to return the pieces to the original orbit after a cut is listed in Table C-2. The calculations conservatively assume a 70/30 Moon/Mars mass ratio, no inboard node or radial structure mass, and a reboost Isp=280 sec. The propellant is a small fraction of facility mass, so the main issue seems likely to be not the mass so much as ensuring a reliably appropriate and timely response to failure. Note that the thrust can also provide a settling force that delays and eases the transition to free fall (or near that) until the facility is re-assembled.

Table C-3 below explores the effect of facility length on the lengths of "trapeze tethers" deployed outward from the Mars and Moon nodes. Such tethers allow capture of visiting vehicles from low-perigee orbits. Trapeze capture is challenging but worthwhile: it lets each launch deliver 7-10% more total mass than if one uses a normal orbit-matching approach and free-fall berthing at the facility CM node. It also allows capture at the first apogee on days with suitable launch phasing, and lets the visiting vehicle be passivated after capture, during tether retrieval. When a visiting vehicle leaves, it can be deployed to a greater distance and slung into targeted passive deorbit trajectories. This also provides free facility reboost, by recovering more momentum than was loaned to the vehicle after capture.

Table C-3. Trapeze lengths and other key parameters for tethered capture and deorbit

Radial structure:	**Modules**	**Inflatable tunnels**			**Tun+cab**	**Cables**	
Total dumbbell length L, meters	**121**	**216**	**486**	**760**	**1600**	**4000**	**8000**
$L_{MarsCatch}$, Δalt=200km, ΔV=58.4	194	220	218	165	<0	<0	<0
$L_{MarsCatch}$, Δalt=230km, ΔV=67.3	236	277	304	271	48	<0	<0
$L_{MarsSling}$, Δalt=400km, ΔV=117.6	475	596	784	872	922	0	<0
$L_{MoonCatch}$, Δalt=230km, ΔV=67.3	283	362	494	567	672	627	175
$L_{MoonSling}$, Δalt=400km; ΔV=117.6	522	681	974	1168	1546	2005	2122
Gees after capture, Δalt=230km	1.44	1.08	0.72	0.58	0.40	0.25	0.18
Gees before release; Δalt=400km	2.52	1.88	1.25	1.00	0.69	0.44	0.31
Mars retrieval, Δalt=230km, J/kg	2105	1981	1638	1273	183	-	-
Moon retrieval, Δalt=230km, J/kg	2358	2207	2148	2063	1847	1277	296
Minutes to retrieve $_{5kW/ton;\ Mars,\ Moon}$	7, 8	7, 7	5, 7	4, 7	1, 6	- , 4	- , 1

Captures from orbits with 200 km lower perigee are relevant to a facility at 345 km (typical ISS altitude near solar minimum) and a 145 km visiting-vehicle perigee. A 230 km perigee change is relevant to a 30 km higher facility altitude or a ~115 km perigee after MECO. This could be relevant for captures at the first apogee. Dropping perigee 400 km allows well-controlled reentries. Surprisingly, the trapeze lengths required for capture outboard of the Mars node do not vary much with facility length: 194-220m for a 200 km perigee change with the 3 shortest options, and 48-304m for a 230 km change with the 5 shortest options.

Capture and release at the lunar node requires longer tethers, since the Moon node is closer to the CM. For 4-8 km versions, the Mars node rotation speed V_{Mars} exceeds the capture ΔVs listed, so captures from typical MECO trajectories are limited to the Moon or 0.06g (for low-ΔV transfer to/from ISS).

The above calculations assume that captured masses are very small compared to facility mass. Finite-mass effects increase deorbit trapeze lengths, change rotation rates and gravity levels, and affect facility altitude and drift rates relative to co-orbiting facilities. These topics are discussed in more detail in section 4.3 of my 2010 IAC paper.

Finally, if the spinning facility flies in formation with ISS, it can serve as a way-station between the earth and ISS. This reduces round-trip rocket deltaVs to ISS, and lets ISS crew adapt to both ISS and earth gravity in stages.

Figure C-1 on the next page shows in-plane and out-of-plane (IP and OOP) views of 4 length options. They use mostly common components, and the first 3 of the 4 radial structure options listed in Tables C-1 to C3 above.

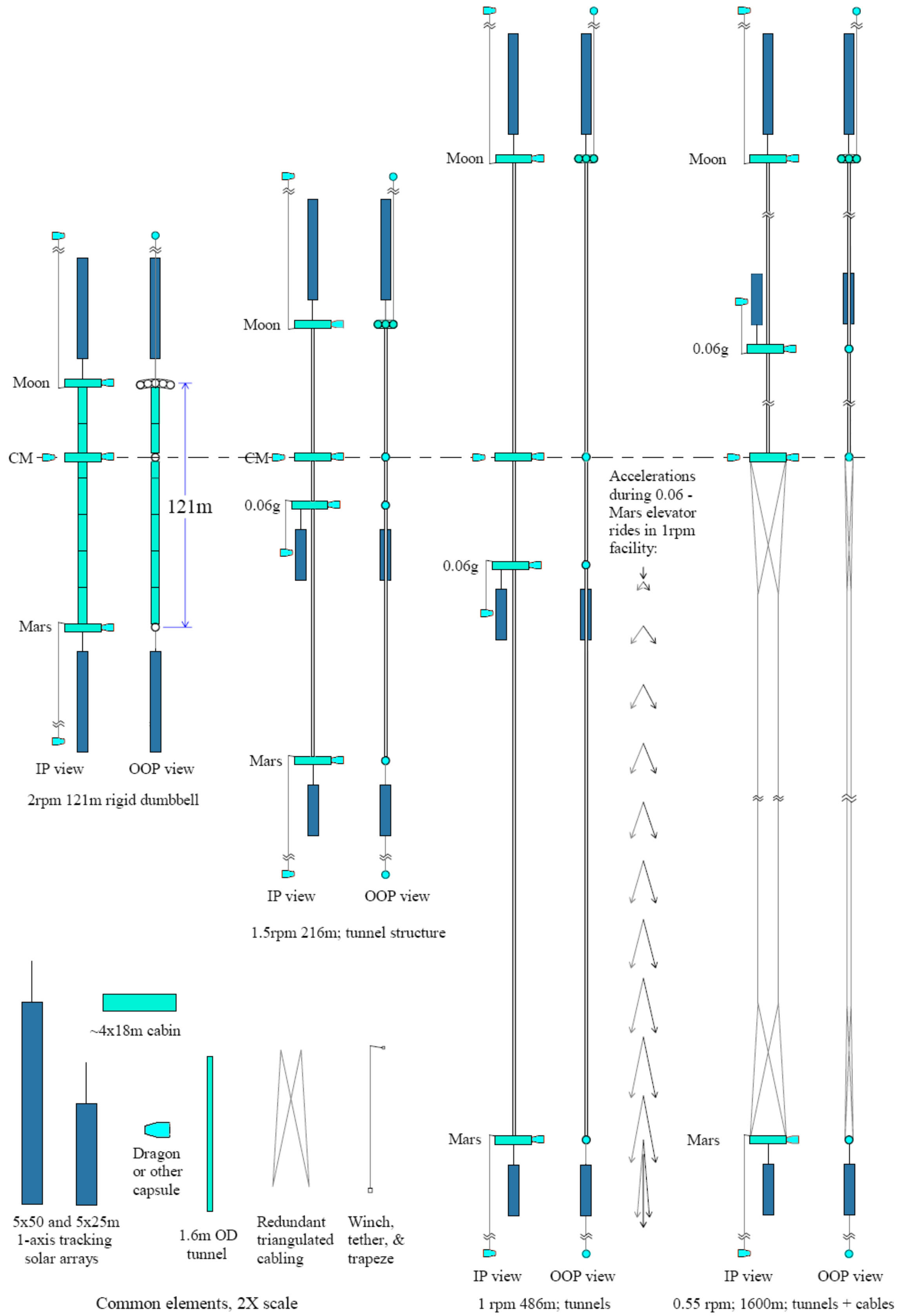

Figure C-1. Different facility structure and length options using mostly common elements

Each option uses multiple copies of a small number of different types of elements, each shown twice as large in the bottom left part of the figure. Each ~4x18m pressurized "cabin" is the size of the passenger cabin of a 737-600. The cabins are sized for launch (partly outfitted) on Falcon 9 or EELVs. The long cabins should pose similar peak aerodynamic bending moments during launch as the shorter but wider 5m fairings used with those launchers.

Figure C-1 also shows the acceleration vectors seen at 10-second intervals during a round-trip elevator ride between the Mars and 0.06 gee nodes in a 1-rpm facility. This assumes 3m/s maximum elevator speed and gentle 0.015 gee accelerations (~30% as large as on typical elevators on earth). Rides to and from the CM may be more disconcerting, because elevator accelerations near the CM will briefly reverse "up" and "down" as felt by riders.

All 4 facility designs in Figure C-1 are to the same scale, except for tunnels, cables, and trapeze tethers shown with truncation symbols. The large number of visiting vehicles indicates potential berthing positions, not how many vehicles might be present at any one time. But as with the ISS, it is prudent to keep enough escape seats for the full crew. It is also prudent to limit the number of people at each node to the number of seats in the capsules berthed there, since some emergencies will disable some inter-node transfer capabilities.

Several version-specific design details are worth noting. The short rigid dumbbell does not need a 0.06 gee node since the radial modules are large enough in diameter to allow crew and other accommodations at any desired radius. On the 0.55 rpm version at the far right, the 0.06 gee node is on the Moon side of the CM, to reduce total tunnel length and weight, while still allowing tunnel access to all nodes other than Mars. This requires additional counterbalance mass at Mars. This design also requires visiting vehicles to maneuver far enough out of the spin plane to avoid the Mars-CM cabling, during any low-ΔV trapeze operations between the 0.06 gee node and the ISS or other co-orbiting facilities. (In the other design options, the 0.06 gee node does not have this problem.)

All 4 design options assume 500m^2 of hanging solar arrays that track only around the hang axis. For the same power when the sun is in the spin plane, this requires 1.57X more total cell area than with 2-axis tracking. But it allows a radical reduction in solar array structure, which should more than pay for the difference in cell costs. And averaged over all sun angles, hanging arrays provide ~1/3 more average power than smaller 2-axis-tracking arrays.

Facility evolution

This asymmetrical dumbbell facility concept lends itself naturally to 5 stages of evolution, as listed below. The key cost-driver at each stage should be the number of cabins built and launched. Each cabin can be re-tasked in later stages, so no cabins need be discarded.

 # cabins & key new operations

0: Tether manned capsules to spent stage, as done on Gemini XI (see Appendix B)
1: Launch 1 cabin; berth capsule; deploy spent stage; spin up (to lunar and then Mars gravity)
3: Launch 2 more cabins; de-spin; assemble; spin up again
6: Launch 3 more cabins + tunnels; de-spin; join to existing 3-cabin lunar node; spin up again
14: Launch 8 more cabins, de-spin; assemble; spin up again.

The first stage might be done with any manned vehicle and its spent booster stage, on the way to ISS. Appendix B goes into more detail on this concept, since it is an affordable first step towards towards the concepts described here, and may resolve questions about acceptable spin rate and hence required facility length and structural design.

The limited volume and time available for capsule-based partial gravity spin tests will limit the scope of testing. But capsule-based tests can refine the objectives and design of a larger and longer-duration single-cabin test. This test tethers a separately-launched cabin to its spent booster stage. A capsule berths with the cabin before spin-up. Spin-up might be done by the spent stage, or started chemically and finished electrodynamically.

The second and third stages of evolution have crew at only one end, and use a spent stage as counterweight at the far end. So no long pressurized tunnel is needed. It is not even necessary to decide on the final facility spin rate and length yet. These stages allow longer-duration and more representative testing of the effects of rotation than feasible in crewed vehicles on their way to or from the ISS or commercial manned facilities. The second and third stages may also be a good time to test trapeze operations. The first test might just deploy and retrieve a manned capsule on a trapeze tether at the end of a mission (without release), to verify winch and tethered berthing operations. Then the capsule can be re-deployed and released to provide a targeted reentry, plus some reboost of the facility.

Figure C-2 below shows possible steps in assembling a 3-cabin lunar node and then a baseline 6-cabin facility. The first stage is shown at top left. It uses a single cabin about the diameter and length of a 737-600 passenger cabin. A crew vehicle berths with the cabin. A tether with multiple well-spaced strands for impact tolerance joins the cabin to its spent stage. This allows long-duration crew tests of various combinations of spin rate and partial gravity level.

The next stage adds 2 more cabins. The first cabin's counterweight and tether can be released into a short-lived orbit rather than de-spinning the assembly. Hatches and hallways are removed so the 3 cabins can be joined. This 3-cabin assembly can use one or both new spent stages as counterweight, with a new tether sized for the 3-cabin loads.

The next expansion requires launch of 3 more cabins plus 3 tunnel segments. This requires selecting the facility design spin rate, which drives the required tunnel lengths. The above 1-cabin and 3-cabin tests can provide the flight data needed for that decision. Each tunnel can be stowed for launch by folding it half and rolling it up, so the two rigid cabin attachment interfaces are on the outside of the roll. After each launch, a manned capsule can dock with the new cabin and use a robotic arm to remove the tunnel from the cabin, attach it to the side of the cabin, and then bring the new cabin to the assembly already in orbit and join the free end of that tunnel to the existing assembly.

Figure C-3 shows facility expansion from 6 to 14 cabins. First, 4 new lunar cabins are joined together in pairs, and the other 4 new cabins are prepared like the outrigger nodes at the top of Figure C-2. Then the facility slows or stops its spin to allow attachment of the new cabins. Completely stopping the spin requires that all loose items be secured and liquids contained. But doing this just once can more than double the usable cabin volume. Most of the required spin changes can be provided by thrusters on a capsule deployed to the maximum length of a trapeze capture/release tether. This can provide a long enough moment arm to cut despin + respin propellant needs to <0.4% of the full facility mass, with a 486m long 1-rpm facility.

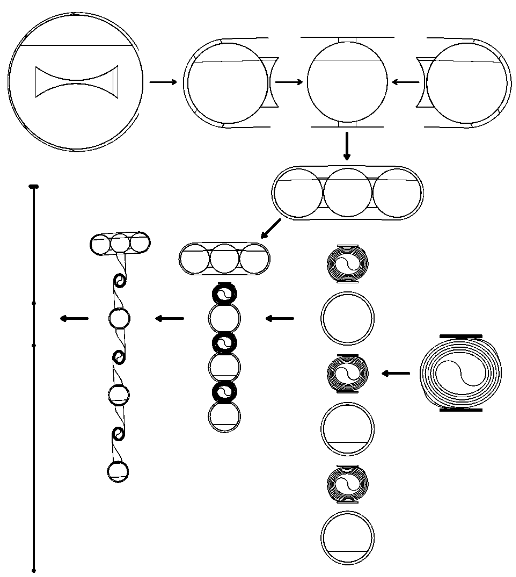

Figure C-2. Assembly of baseline 6-cabin design

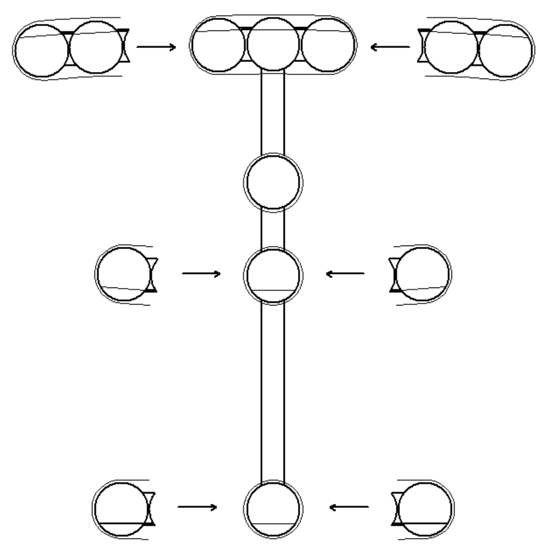

Figure C-3. Expansion from 6 to 14 cabins

After the first (no cabins) stage of evolution, the growth in usable cabin volume is a factor of 2-3 for each stage. Launching and outfitting 8 more cabins for the last stage is obviously a major cost commitment, but it is needed only if demand justifies it. A large step expansion like this seems needed both to keep the facility balanced, and to minimize how often the facility must be despun to connect new cabins. This will disrupt normal gravity-dependent activities and clearly should not be done often. Routine delivery and distribution of new equipment and supplies allows a continuing expansion of capabilities, between occasional major expansions of habitable volume.

For considerably more detail on facility design and operations, including contingency operations, solar array design trades and power profiles, and management of the facility's orbit, CG, and angular momentum, please download my 2010 IAC paper on this facility concept from www.artificial-gravity.com.