Gateway Gravity Testbed (GGT)

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We propose that the Gateway elements be scarred to accommodate possible additional elements that would alow the demonstration and investigation of artificial gravity (AG) at human scale. We show how this could be done using the Gateway elements already envisioned, with minimal additional developments and minimal interference with other Gateway functions. The resulting flight data would be invaluable for understanding both human physiological and system responses to AG, which could be essential information to enable Mars-class missions. AG has never been baselined for exploration mission concepts, mainly due to presumed technical complications, even though Mars-class missions are 2-3x longer than the maximum microgravity duration demonstrated to date. Planning remains at risk until data are in hand. NASA's commitment to build and operate a cis-lunar Gateway provides a timely, and perhaps singular, opportunity to test how humans and vehicle systems respond to variable-g regimes relevant to Mars planning. We show how electric spin-up / spin-down, or alternatively Electric Propulsion (EP) thrusting can be compatible with design and operation of a Gateway configuration that enables AG technology demonstration.

Nomenclature

AG	=	Artificial Gravity
CG	=	Center of Gravity
DSH	=	Deep Space Habitat
ECLSS	=	Environmental Control & Life Support System
EP, SEP	=	Electric Propulsion, Solar Electric Propulsion
EVA	=	Extra-Vehicular Activity
GGT	=	Gateway Gravity Testbed
IOC	=	Initial Operational Capability
ISS	=	International Space Station
LEO	=	Low Earth Orbit
LOP-G	=	Lunar Orbital Platform-Gateway
MTV	=	Mars Transfer Vehicle
PPE, PPB	=	Power & Propulsion Element, Power & Propulsion Bus
PPP	=	Public & Private Partnership
RMS	=	Remote Manipulator System
SLS	=	Space Launch System
TRL	=	Technology Readiness Level

I. Introduction

NASA's choice to move forward with a Lunar Orbital Platform-Gateway (LOP-G) balances the need for a deep space transit habitat development program with established programs, partner needs, political realities, and budget constraints. Existing programs dictate the extension of International Space Station (ISS) knowhow and

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preserve the momentum of Orion and Space Launch System (SLS) development, while political directions and international partner interests lean toward the establishment of a platform that facilitates lunar surface access. Taking these into account, there is also an irrefutable case for setting the stage to address a set of deep space human spaceflight design issues that cannot be solved in any other environment.

AG has hovered at the margins of exploration mission planning for over a half century. Typically it is rather casually invoked as a last-resort fallback, should combinations of other countermeasures prove ineffective in mitigating microgravity degradation of human health or performance for Mars-class missions. Objections to AG system concepts usually center around assumptions about complex configurations, "test as you fly" waivers, and interference with in-flight operations including docking, deployments, and EVA. With minor exceptions (Sherwood 1991; Joosten 2007), the human exploration advanced systems engineering community avoids AG because so far they can: physiological risks have not led to a documented requirement for it.

Mars-class missions are 2-3x longer than the maximum duration demonstrated to date, and often include 3/8-g surface operations at the end of a long microgravity transit. Yet lacking any AG flight data at all, or any demonstration of AG principles in the flight environment, *all microgravity-mode human planetary mission concepts are based on presumptions and hope rather than facts*. This poses a significant "sleeper" risk to NASA's human exploration program.

The Gateway will already demonstrate several key functions required for human planetary exploration, including: extension to a lunar-distance regime of continuous human space flight operations; energetically favorable transportation node supporting diverse activities in the lunar vicinity and on the surface; and extension of NASA's international and commercial partnerships to a cis-lunar outpost. Among diverse Gateway experiments could and should be definitive investigation of: 1) hypothetical g-level thresholds between zero and unity that might preclude, or significantly alleviate, microgravity deconditioning altogether; and 2) lessons for engineering practical, human-occupied AG flight systems in case AG becomes necessary.

NASA's commitment to build and operate a cis-lunar Gateway provides not just a timely, but perhaps singular, opportunity to test how humans and vehicle systems respond to variable-g regimes relevant to Mars planning for the 2030s, and perhaps even lunar surface scenarios for the 2020s. Since proposed LOP-G elements have not been finalized in their design and construction, now is the time to implement minor changes in the structures and interfaces and provide scarring to accommodate loads and resolve forces that would act upon them under centrifugal loading. Strategic scarring and structural reinforcement would be insignificant in cost, yet could be accomplished in such a manner as to address any number of future AG design options.

AG cannot be tested on Earth; ISS cannot be rearchitected for this purpose; no other proposed LEO station (e.g., either the Chinese station or commercial hotels like AXIOM) adopts AG; and no other deep-space vehicles are in pre-formulation. But without AG experiments, a fundamental question about the viability of long-term human occupancy of space will persist. Gateway would be uniquely able to deliver this key information.

Using the Gateway to test Artificial Gravity (AG) in space – for both systems and human crew – would explicitly meet every technology demonstration objective specified by NASA for LOP-G:

- Evolve the Gateway's initial capabilities
- Enable new capabilities for human exploration
- Demonstrate key elements of in-space infrastructure to support future human exploration

AG is one of the most impactful potential demonstrations for human exploration missions. Pragmatically, accommodating AG on the Gateway means architecting for it from the start. However, now is the perfect time to do so. The Gateway pre-formulation phase, even including the current Power & Propulsion Element (PPE) procurement activity, is the right time to onboard AG as a key technology utilization demonstration for the vehicle.

An AG demonstration enables new capabilities for human exploration. The topic recurs continuously in the human-exploration literature – always without resolution – as a potential solution to the potentially intractable problem of long-term microgravity deconditioning. This problem is particularly worrisome en route to conjunction-class surface stays on Mars, but also might constrain surface stays on the Moon, forcing a crew cycling cadence not yet considered a design driver. Because no AG flight data exist, and because Mars-class deconditioning remediation is not assured, it is easy to argue that an AG demonstration may in fact enable human exploration altogether.

An AG technology demonstration would lead directly to development of in-space infrastructure needed to support future human exploration and commercial activities. Results of the demonstration would enable confident writing of requirements for the human system, vehicle systems, and operations plans for all future exploration missions. Commercial activities as currently envisioned (e.g., LEO hotels) do not depend as critically on these data because microgravity would be a key part of the tourist experience, and commercial tours would not last long enough for deconditioning to become a problem. However, in the long term, perhaps contemporary with NASA missions to Mars, commercial LEO tourism facility operators could be expected to seek expertise about AG system design.

Our proposed variable-g approach described in this paper builds directly upon current technology development activities because it proposes AG architectures that use the Gateway elements already being presented, discussed, and even solicited (in the case of the PPE). Avoiding a need for very novel, or numerous, additional development projects is key for incorporating AG into the Gateway with minimal cost and schedule impacts. Up-front architecting now allows AG to be minimally disruptive. We provide a clear path for infusion by showing how these developments could be implemented for AG.

II. Artificial Gravity as a Mission Enabler

AG technology must be demonstrated in space because the correct force-vector geometry can only be obtained in free-fall. Human perceptual responses to AG can only be studied in space for the same reason. Finally, the utility of AG as a microgravity-deconditioning countermeasure can only be studied in space because 1-g simulations of microgravity deconditioning are generally poor. Cis-lunar space per se is not a requirement – any microgravity state with long-term living accommodations would do – but programmatic realities make the Gateway the best platform for variable-g experimentation: the only other extant or contemplated space stations either cannot accommodate AG post facto (e.g., ISS) or do not envision AG demonstration or investigation (e.g., CSS, Aurora, Axiom Space).

Building upon the experience gained on ISS below Van Allen belt altitude, LOP-G has an opportunity to address deep space design and operations issues that must be solved before a human Mars mission, or any mission to other deep space destinations, can be attempted. These topics include deep space radiation effects on crew and equipment (Wilson, et al 2001; Imhof 2001), medical issues (Mader, et al 2011), system health and maintenance for years-long durations (Tai, Alkalai, Chau 1999; Watson, et al 2003), psychological and logistical isolation from Earth (Kanas & Manzey 2008; Broughton 2016; Peldszus, et al 2011), and dealing with microgravity (Cardús 1994; Griffin 1978; Hall 2009) among others. One engineering solution that may have impact on several of the above issues is configuring the LOP-G as an artificial gravity centrifuge.

Countermeasures to the adverse health effects of microgravity on crews have included exercise, nutrition, and pharmaceutical approaches, but studies show such measures are not sufficient to reverse osteoporosis (Schmidt, Goodwin, Pelligra 2016), ophthalmic disorders (Mader, et al 2011), impaired cardiovascular function, and possibly even some brain damage. The most commonly invoked alternative to these countermeasures is artificial gravity, which has been shown to have much promise for maintaining crew health in microgravity (Caiozzo, et al 2008). Unfortunately, all centrifuge research to date has been within Earth's 1g gravity field, and therefore we know virtually nothing about minimums and limits or how artificial gravity could enable a deep space transit mission.

There are many questions that need to be answered regarding the benefits of artificial gravity, such as minimum gravity needed to counteract microgravity effects on crew health, optimal rotation rates and diameters, comfort levels and coriolis effects. Crew comfort would also include adequate volumes, dimensions, and work environments. Do we understand the ergonomics of a lunar or Mars surface habitat architecture? For example, how high should ceilings be? How should stairs be spaced or configured? What are optimal orientations and angles for ladders? In order to answer these questions, we need a reconfigurable orbital facility that can explore the greatest possible range of AG parameters: radius, angular velocity, tangential velocity, and acceleration. To fully explore the parameter space would take years – exposing the crews to different combinations of settings for extended durations to determine efficacy and adaptability.

If artificial gravity turns out to be essential to a human Mars transit mission, how would a flight vehicle actually be configured as a centrifuge capable of taking transfer maneuvers while under spin? Or should the vehicle spin-down for transfers? How would docking be accommodated? How would the vehicle accommodate a dynamic, shifting center of mass?

Establishing a variable-g artificial gravity centrifuge outside of Earth's gravity well will allow us to: 1) run human factors experiments at 1g to verify whether Earth-bound experiments have equivalent results; 2) perform all those same experiments in target gravities, such as lunar, Mars, or some other partial-g body; and 3) explore the lower-g limits for maintaining crew health. If a variable-g platform could be designed for greater than 1g gravities, an additional benefit might result: 4) perform all the human factors experiments at higher-g limits for extended durations to discover how the human body adapts. Though high-g experiements may more efficiently be done on the ground, having the capability to verify results in space may be an added advantage.

Though research using a space-based artificial gravity centrifuge can be completed anywhere outside the gravity well (LEO, cislunar, etc), ISS cannot be rebuilt to accommodate or counteract extraneous forces and accelerations. Therefore, an independent variable-g facility is needed, capable of spin-up, spin-down, and able to perform transfer maneuvers. Since the core purpose of the LOP-G is to extend human reach into deep space, and is not yet design frozen, LOP-G provides the soonest, and perhaps only, and therefore the best opportunity to explore the various combinations of artificial gravity parameter space.

III. Artificial Gravity Architecture Options

The essential feature of an artificial gravity centrifuge is a structure rotating about its center of mass to the degree that "centripetal acceleration induces pseudoweight" (Sherwood 2009a). "Rotating systems with internal energy-dissipation (friction) settle naturally into the lowest-energy state, which is rotation about the axis of maximum moment of inertia . . . The rotation axis remains fixed in inertial space unless acted upon by an external torque". The two most common potential spacecraft configurations for artificial gravity are mass balanced on the ends of a tether or truss, or mass balanced in a ring or cylinder around the center of gravity (Figure 1).

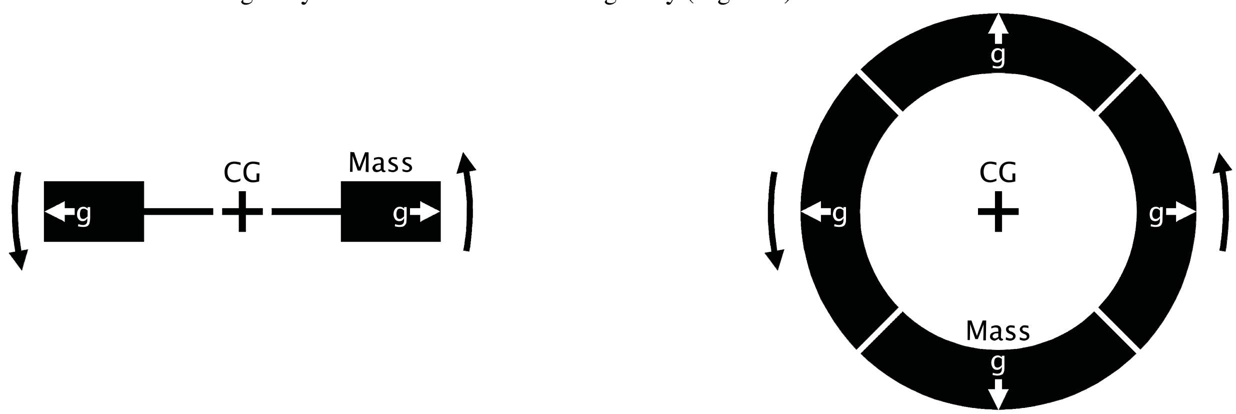


Figure 1: Common artificial gravity configurations: LEFT mass balanced on the ends of a tether or truss; RIGHT mass balanced in a ring or cylinder around the center of gravity

In a non-rotating spacecraft stack, acceleration, maneuvers, station keeping, docking, undocking, organization of pressurized volume, and grouping of masses are relatively straightforward. However, a rotating structure presents various challenges that may add complexity to the design:

- Extra mass / launches required to create a large diameter centrifuge
- Economic spin-up / spin-down
- Accommodation for docking of multiple vehicles who all want to be on the exact center of rotation
- Procedures for docking under spin
- Propulsion – through the center of mass, or eccentric?
- Dynamic management of mass distribution while under spin
- Orientation of solar panels / radiators
- Spin / counter-spin interfaces, if any
- Extra-Vehicular Activity (EVA) under spin
- Internal layout of ladders, partitions, floors, and walls
- Ergonomics of activities to be performed by crew in a rotating environment

Unfortunately, we do not have a good understanding of the requirements for artificial gravity, and what parameter values would provide a healthy environment to live and work in. Out-of-plane rotations cross-couple with the rotation of the environment to cause vestibular illusions of rotation around a third axis perpendicular to both (Sherwood 2009a). For example, yawing the head around the up-down "vertical" axis in an environment pitching around its "north-south" axis leads to a vestibular illusion of roll around the "east-west" axis. In-plane translations, radial or circumferential, encounter Coriolis forces that combine with the centripetal force to alter the magnitude and direction of the apparent gravity. In the literature, authors differ in their opinions on ideal radii, angular velocity, tangential velocity, and centripetal acceleration (Hall 2009; Cramer 1985; Stone 1973; Gilruth 1969; Gordon & Gervais 1969; Hill & Schnitzer 1962). Hall points out that at smaller radii, the physics of seemingly intuitive ergonomic actions like dropping an object result in counterintuitive results, but increasing the radius brings some of these results into closer alignment to what we experience in actual gravity fields (Hall 2009; Sherwood 2009a).

In a separate but related effort, Hall (2000) has taken many of the published data and combined them into an artificial gravity calculator called SpinCalc, as a simple online tool to show where authors agree or disagree on human comfort levels. New designers who explore the engineering parameters for artificial gravity, without first studying the human-factors literature for microgravity as well as artificial gravity, are sometimes put off by the large radius needed for "optimal" immediate comfort. They fail to consider that microgravity is also not immediately comfortable, requires a period of adaptation, and is ultimately very unhealthy even after adaptation.

An adequate exploration Mars transit vehicle may not need to be prohibitively large in order for the crew to take advantage of the health benefits of artificial gravity. Also, it may not be necessary to maintain a full 1g for a small exploration mission, and still reduce or eliminate deconditioning at the destination – it may be possible to scale back artificial gravity to meet exercise, nutrition, or pharmaceutical approaches in some sort of combination that tightens the radius or reduces the rotation rates. Upon entering microgravity, about half of all astronauts endure "space adaptation syndrome" that lasts from one to three days (Connors, Harrison & Akins, 1985; Merz, 1986). A similar period of adaptation to artificial gravity seems reasonable, considering the substantial health benefits that it offers versus prolonged weightlessness. However, it will not be known whether such a period of adaptation would apply until a suitable variable-g platform has been constructed and tested to find out.

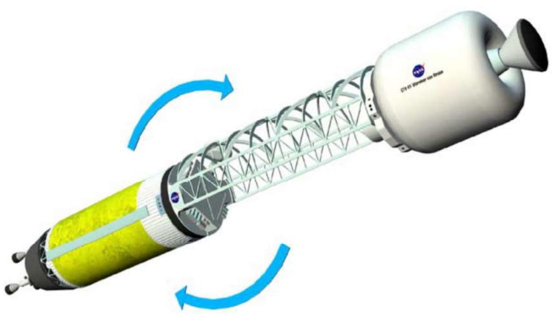


Figure 2: A tumbling stack (Borowski 2004) may be optimistically too short of a radius, but until a variable-g platform can perform experiments such proposals cannot be verified as practical or not

Borowski (2004) proposed an short 21.2m radius vehicle that simply consisted of a stack of habitat, propulsion, and mission modules that tumble end over end during transit, but de-spins for acceleration and destination operations (Figure 2). Borowski's concept proposed 4-6rpm, 0.38g Mars gravity outbound with near Earth gravity inbound, and is optimistically small and compact. But until a variable-g platform is built and tested, such proposals cannot be verified as practical or not.

A more conservative Joosten (2007) chooses to use a maximum of 4rpm, setting the 1g radii at 56m (Figure 3).

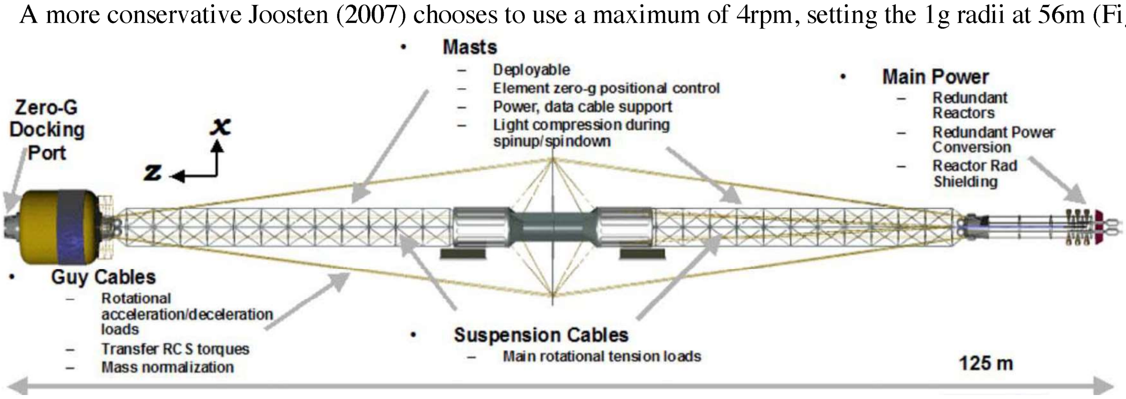


Figure 3: Artificial gravity transit habitat at around 56m radius (Joosten 2007)

Combinations of AG and traditional countermeasures cannot be known if all the testing occurs in Earth's gravity field. It is also unknown whether some author's recommendation of 2rpm is optimal, or if the rotation can be pushed to Joosten's 4rpm or greater. These unknowns dictate that the radius of a variable-g platform for rigorous testing of the entire parameter space of artificial gravity between 0-1g at 2rpm be adjustable to at least 224m – anything less than that would yield incomplete data.

Several examples of proposed artificial gravity systems should be analyzed as applicable to the scale of the LOP-G. Most artificial gravity proposals accommodate spin-up and spin-down procedures, assuming that some aspects of a mission would need to be conducted in one or the other condition. Propulsive spin-up / spin-down can be extremely costly for fuel, particularly if the procedure needs to be conducted many times during the mission. An alternative method that uses only electrical motors and flywheels for spin-up/spin-down was proposed by Sullivan (2002; 2003) assuming a 56m radius and 4rpm rotation for 1g, shown in Figure 4. This concept was expanded to a variable-g research platform a year later (Sullivan 2003).

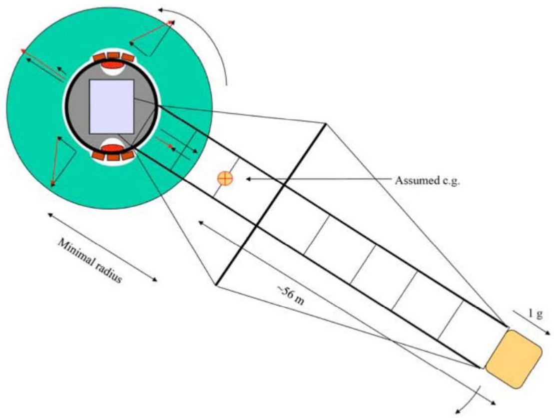


Figure 4: Spin-up/spin-down using electric motors and flywheels (Sullivan 2002)

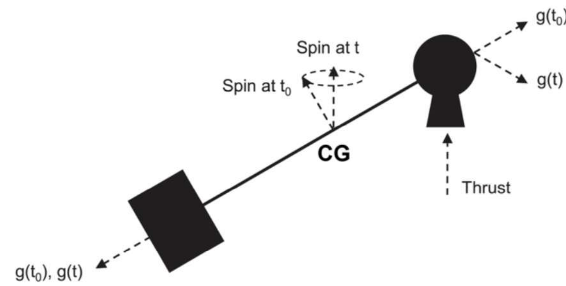


Figure 5: Maintaining AG during continual thrust and maneuvers (Landau 2008; Martin, Landau, Longuski 2016)

Sullivan's concept, depending on implementation, may result in a Center of Gravity (CG) offset from the location of major mass elements. Martin, Landau & Longuski (2016) proposed a method for offset or eccentric acceleration of a rotating artificial gravity centrifuge during transfer maneuvers without de-spin of the system (Figure 5). The mathematical analysis pioneered by Landau (2008) originally aimed at tethered spacecraft, but can be applied to a rigid truss structure as well.

Respecting the heritage and forward momentum of NASA's LOP-G vision, an artificial gravity version will need to accommodate a Solar Electric Propulsion (SEP) or other Power & Propulsion Bus (PPB) stage, two or more habitat modules, an airlock, and docking locations for Orion, logistics modules, and crew capsules from international partners or commercial participants.

IV. LOP-G AG Technology Demonstration Concept

We propose low-cost ways of architecting the Gateway vehicle so that it can meaningfully and operationally demonstrate the technology of AG at human scale in flight. No other extant or candidate flight system can do this, yet doing it is essential to retire a fundamental knowledge gap for human planetary exploration: the gravity level needed to preclude or forestall debilitating microgravity deconditioning. Incorporating AG capability into Gateway would be highly relevant and timely; and provide the program an incontrovertible feed-forward purpose.

A Gateway Gravity Testbed (GGT) demonstration would: 1) use Gateway flight elements already envisioned, 2) require minimal additional developments, 3) uniquely and definitively obtain flight data on both physiological and system performance in AG regimes of interest for extended-duration human exploration missions, 4) critically inform planning for extended stays on the Moon or potential missions to Mars or elsewhere that require durations longer than demonstrated on the ISS, and 5) provide key performance data needed to design AG-optimized subsystems.

A. Technical Description

We propose a range of architecture configurations – starting with just one additional Gateway element and progressing through graded options up to a protoflighted Mars transfer vehicle – and assess their benefits and penalties. We describe how electric propulsion (EP), already baselined for the Gateway, specifically allows validating two key operations: efficient spinup/spindown; and "thrusting while spinning" for Mars transfer vehicle applications.

Even the simplest option could test critical features of AG: spinup/spindown operations; physiological and system effects as a function of g-level and spin rate; perceptual, habitation, and operations issues in a rotating system; countermeasure effectiveness as a function of rotation time and duty cycle.

In addition to yielding key physiological data and engineering experience, AG technology demonstration might become vital for programmatic sustainment of the Gateway itself. Since no other foreseeable platform can perform a useful AG investigation, a GGT could bolster the argument for Gateway being essential for future exploration.

B. AG Architecture Options

A habitable AG space vehicle should allow: 1) correlating 1-g human factors experiments to determine capabilities and limits of Earth-bound experiments, and methods for flight system verification and validation; 2) conducting those same experiments in exploration-relevant target gravities, 1/6 g for lunar and 3/8 g for Mars; and 3) determining the lowest-g limit, and the parameters for duty-cycling super-g weight, that can forestall or manageably mitigate human deconditioning.

The most thorough investigation of AG operations, physiological and perceptual effects, impacts on subsystem performance, and utility of AG as a microgravity deconditioning countermeasure would require an inhabited vehicle capable of varying radius, spin rate, AG duration, spinup/spindown rate, relative orientation of habitation facilities; and of testing traditional and anticipated operations like docking, logistics transfer, robotic servicing, and perhaps EVA while spinning. Optimally it would be an open-ended architecture so that validation of equipment and outfitting concepts could be designed after the first tests, then added, tested, and removed. Such complete flexibility, while compelling from a scientific and engineering standpoint, would however pose significant disruption to the current Gateway concept.

"Rotating systems with internal energy-dissipation (friction) settle naturally into the lowest-energy state, which is rotation about the axis of maximum moment of inertia ... The rotation axis remains fixed in inertial space unless acted upon by an external torque" (Sherwood 2009a). The simplest spacecraft configurations for artificial gravity are masses separated by a tether or truss.

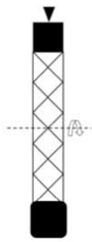
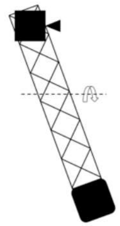
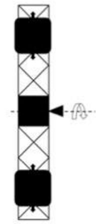
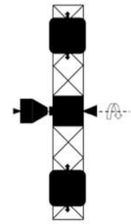
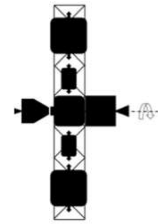
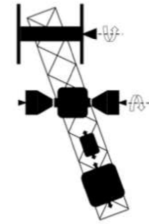
A rotating vehicle poses various system-level challenges:

- functional relationship of counter-masses separated by a distance of 10s to 100s of meters
- economical spinup/spindown
- accommodation of docking while spinning, even of multiple vehicles
- thrusting while spinning
- management of dynamic mass distribution while spinning
- orientation of solar and radiator arrays
- spin/counter-spin interfaces
- exterior maintenance operations while spinning, including EVA
- interior habitability including orientation, views, ergonomics, and outfitting.

These issues are present even with a rigid-truss armature; tethered schemes introduce yet more. A successful GGT architecture would include all the baseline Gateway elements: PPE, Deep Space Hab (DSH), Airlock, node-type accommodation of partner modules, Logistics Module(s), RMS system, and visiting vehicles starting with Orion. Table 1 depicts a gradation of AG complexity for potential Gateway demonstration and utilization:

- **Rigid Truss –** While this option cannot test the full range of AG parameters, it has three major advantages: 1) minimum "price of admission" to the first human-scale demonstration and investigation of artificial gravity including perceptual fundamentals (Hall 2009); 2) truss element could be based on ISS heritage; 3) avoids all complications of dynamic coupling and rendezvous operations, as AG demonstrations would occur during dedicated periods. Spinup/spindown is achieved with the gimbaled PPE EP thrusters. Minster, et al (2018) found that this scheme provides propulsively efficient, gradual spinup/down over a period of hours-to-days, easing mode transitions for the crew.
- **Thrust-n-Spin –** This option demonstrates continuous EP thrust while the vehicle is spinning, including offset compensation for propellant consumption (Landau 2008; Martin et al 2016). This capability allows AG investigations to occur simultaneously with other vehicle activities relevant for Mars transfer, including continuous thrust-vector reorientation (Figure 5).

Table 1: Gateway options to support AG investigation/demonstration span large range of complexity; simple options are very feasible.

	Rigid Truss	Thrust-n-Spin	Mobile Truss	Logistics Exchange	Crew Exchange	Electric Spinner	Protoflight MTV
							
Technology demonstrated	1st human-scale AG	Propulsive maneuvers in AG mode (Landau 2008)	CG location control Full AG parameter control	Docking in AG mode Cargo xfer in AG mode	Crew xfer in AG mode Radial crew translation	Simultaneous operation of μg and AG systems	Readiness for Mars-class mission
Features	Fixed elements, non-interfering ops ω=4rpm attains 1 g @ r=56m EP spinup/down over days	EP offset thrusting Non-interference ops except prop	Major elements reposition on truss carriages Non-interference ops except prop	Docking hub at CG	Crew hub at CG	Motorized despin	Complete exploration vehicle (e.g., RASC-AL 2017)
Major Pros	Simplest config $0 \le g \le 1$ by varying ω No new elements: 112-m ISS-heritage truss	No new elements Test coupled-force system behavior Trajectory change while spinning Gradual (days) spinup/spindown	No extra modules Vary r and ω to envelope Coriolis range	Robotic resupply without spindown Test rendezvous with AG system	Crew on/off without spindown Validate design/ ops of fully flexible system	Optimized AG testbed: vary ω Most flexible to accommodate partner module contributions Feed forward for LEO commercial systems	Full qualification flight-testing of mission hardware and modes Potentially shortest time to Mars missions
Major Cons	Cannot vary r	Cannot vary r	New element: mobile truss with power xfer	Limited to RMS vacuum xfer of supplies	New element: "elevator" cab	Major new element: flywheel/motor despin mechanism Complex config	Most expensive Longest to flight Program not ready to baseline MTV

- **Mobile Truss –** This option leverages ISS truss mobile trolley heritage to add mobility along the radius for the major mass elements (primarily Hab assemblage and PPE). This allows positive control of the CG location independent of consumables balance, but requires developing a design solution for transfer of power and thermal fluids across the mobile interface.
- **Logistics Exchange –** This option adds a logistics module docking interface which is actively maintained at the CG. This allows demonstration of rendezvous and docking/berthing of cargo vehicles along the rotation axis. With the first level of demonstration, the crew would access the logistics delivery after despinning from AG mode, A second level of demonstration, imposing design requirements on the RMS system and protocols, would use the RMS to remove vacuum-packaged units from the Logistics Module, and transfer them along the radius for insertion into the Hab's Airlock.
- **Crew Exchange –** This option would demonstrate rendezvous and docking/berthing of Orion while in AG mode. Crew transfer from Hub to Hab would require a pressurized "elevator cab" that docked to both at each end of the radius. With such a demonstration, all elements and operations needed for even very large-scale vehicle designs would be validated (Sherwood 2009b).
- **Electric Spinner –** This option represents a large class of AG-optimized configuration types, including both large-scale, mechanically-despun interfaces and the use of electric motors for arbitrary spinup rate (Sullivan 2002). The departures from today's Gateway architecture and element designs are significant, but allow the most flexible, progressive demonstration of potential designs and flight element prototypes by multiple partners, including international and commercial.
- **Protoflight MTV –** We include this option for completeness: it would adapt the Gateway into the actual vehicle intended for the first crewed Mars transfer. It would "shake down" the full range of subsystems in AG conditions, but require committing the MTV design, and therefore delay launch and IOC of the Gateway itself.

The table demonstrates several principles that should be considered for the Gateway program:

1. A Gateway Gravity Testbed could be incorporated into the Gateway program without undue technical or programmatic complications, and without requiring development of novel structures or mechanisms.
2. Human-scale AG, and investigation of key AG parameters, could therefore be one of the Gateway Technology Utilization demonstrations:
    a. Finally yielding critical feed-forward flight data that cannot be obtained any other way
    b. Giving the Gateway a unique identity certain to attract widespread attention and support.
3. Key innovations make AG demonstration by the Gateway practical:
    a. Offset EP thrusting configuration (Landau 2008; Martin et al 2016), which minimizes operational complexity by avoiding repeated spinup/spindown cycles.
    b. Use of EP for spinup/spindown (USC RASC-AL 2017; Minster, et al 2018), which makes the cycles efficient.
4. Straightforward new developments (primarily, a functional carriage mechanism capable of carrying the major Gateway elements on a rigid truss at 1-g) would open almost the complete range of AG parameters to investigation by the GGT.
5. Demonstration of shirtsleeve radial transfer among modules would establish technology potentially useful for commercial development of the LEO tourism market.

C. Technology Readiness Level

For the simplest option in Table 1, all essential technology elements (habitation systems, truss, and electric propulsion) are demonstrated to Technology Readiness Level (TRL) 9. Since AG cannot attain TRL 6 on Earth, but all components get tested under enveloping 1 g conditions, the combination of these technologies into a human-rated, deep-space, AG vehicle is arguably at TRL 4 based on analysis.

D. Accommodation and operations requirements

Human crews and all Gateway subsystems are the GGT payload. All subsystems, system-level interactions, and behavior require accommodation analysis (in design) and test (on orbit). Operational use comprises the technology demonstration. The dominant operational requirement is elapsed time in AG regimes with crew onboard. The highest-priority regime is 1/6 g, since zero data exist to validate that indefinite human stays on the Moon avoid or suppress microgravity deconditioning. The next priority regime is 3/8 g, to emulate Mars-surface conditions. The third-priority regime, depending on the findings of the first two, is cycling between regimes, including duty cycle.

A successful system architecture will enable these regimes to be tested over durations to be identified by the NASA Chief Medical Officer in collaboration with the biomedical community, while still enabling all other conventional functions and utilization proposed for the Gateway (e.g., radiation exposure study, validation of ECLSS reliability and repair in deep space, teleoperation of lunar-surface assets, and various technology demonstrations).

E. Public-private partnership

It is conceivable that a Public-Private Partnership (PPP) might arise to fund one of the more advanced AG options. While the GGT demonstration we propose is specific to NASA's needs to inform potential future human planetary exploration, it is also possible that private commercial entities pursuing space passenger travel markets (like LEO hotels) might see high value in a GGT, and be willing to co-fund development of a sophisticated demonstration.

V. Gateway Gravity Testbed (GGT) Configuration Studies

We propose a dual parallel deployable truss with internal rails, where all elements mount to carriages that can move along the rails to adjust spacing and distances.

Our proposed "Sling" Option, implmenting an Electric Spinner in Table 1, will use a parallel frame, placing habitat modules at one end and the PPB stage at the other (Figure 6, Figure 7). The PPB stage will be fixed on gimbaled attachments between the two trusses with a rotating flywheel radiator panel deck (Sullivan 2002) powered by electric motors. At the other end, two habitats will ride up and down the rails to adjust the diameter of the artificial gravity. Since the mass of the PPB is at one end, and the mass of the habitat modules are at the other, the center of gravity (and thus the center of rotation) will lie somewhere in between.

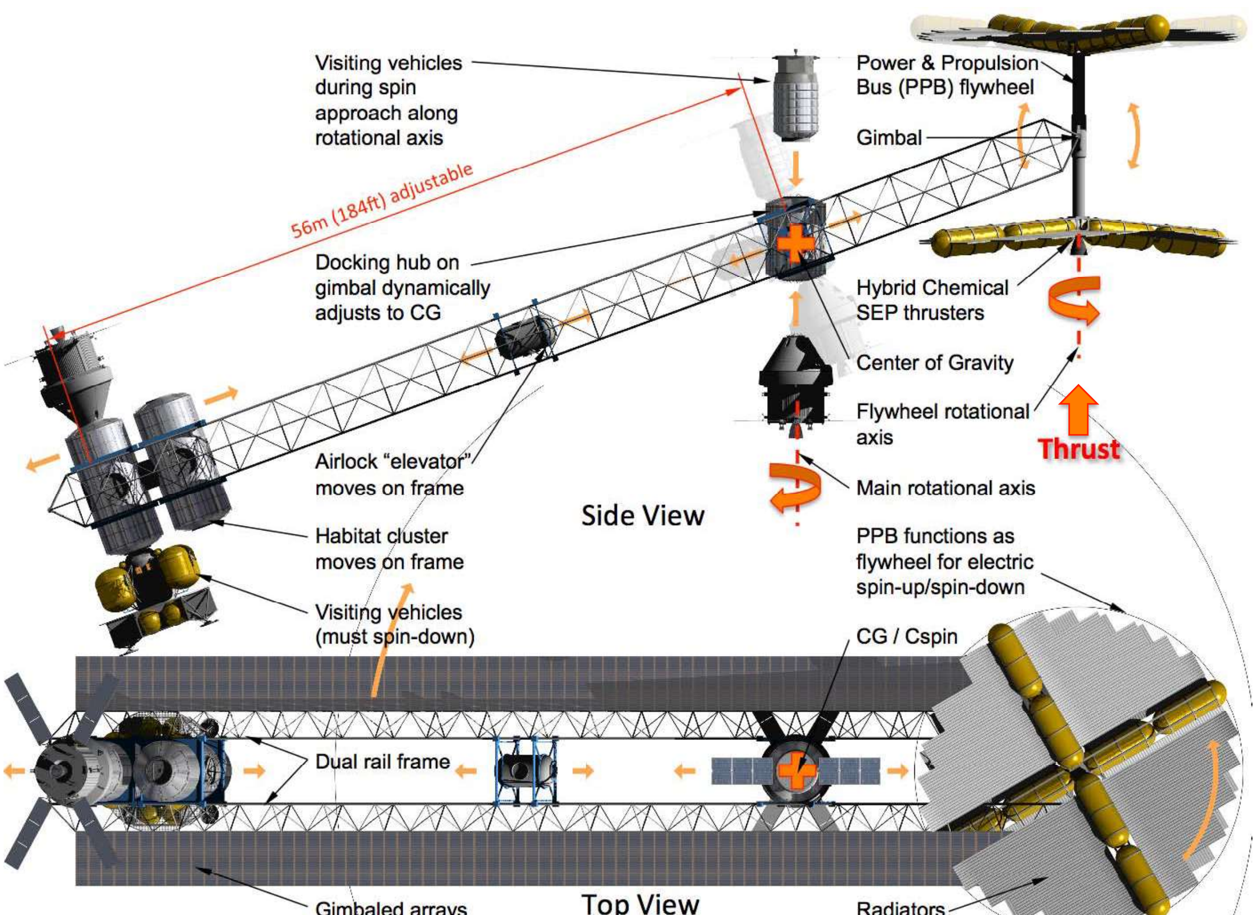


Figure 6: Our proposed "Sling" Option GGT side view and top view in spin configuration

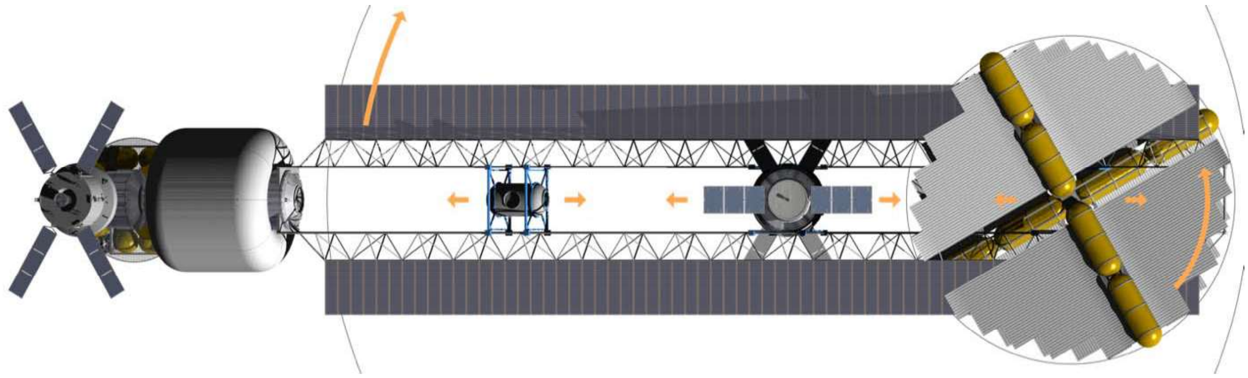


Figure 7: "Sling" Option GGT using a TransHab/Bigelow inflatable habitat type, which may require anchoring the truss to the habitat core structure – other elements can be designed to dynamically move along the truss

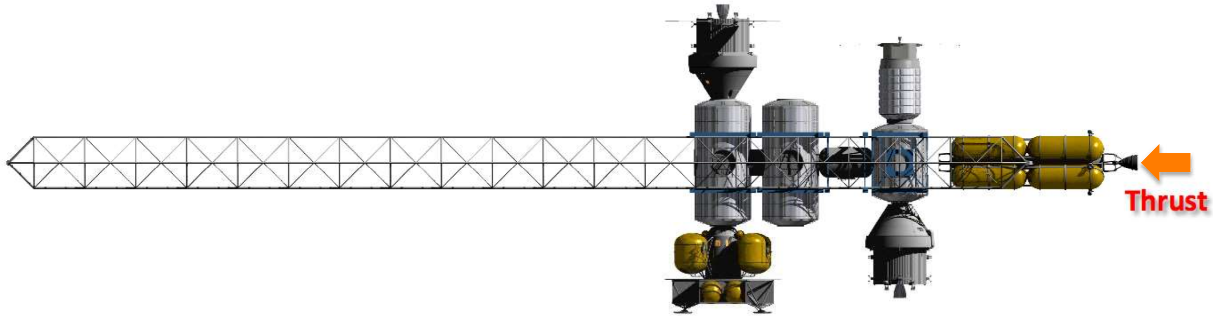


Figure 8: Our proposed "Sling" Option GGT out of spin, where Power & Propulsion Bus (PPB) flywheel stowed can be configured as a conventional stack

An additional hub module will be placed on gimbals at this CG location, with forward and aft docking ports to allow docking along the spin axis during spin. The docking hub will dynamically follow the CG as masses shift during the mission (expenditure of propellant, shifting of docked vehicles, adjustment of centrifuge diameter, etc). While docking during spin, the hub will be capable of rotating itself out of the truss plane in order to align itself with the main rotational axis. Once the docking has been completed, the hub can rotate back into the truss plane to allow for docking with airlock elevators traveloing along the truss back and forth between the pressurized elements.

The airlock will then function as an elevator (Sherwood 2009b) that runs up and down the rails between the docking hub and the habitats, allowing "shirt-sleeves" transfer between them. During spin, the two major masses will oppose each other around the CG. During acceleration and transfer maneuvers, the gimbaled PPB will thrust eccentrically from the moment arm distance away from the CG, but because the entire system is rotating, all the forces and masses will balance themselves and stabilize (Martin, Landau, Longuski 2016).

Electric motors on the flywheel on the PPB stage can be used to spin-up or spin-down as needed without the use of propellant (Sullivan 2002). The "Sling" Option will only allow for the docking of two vehicles at a time during spin. Additional docking would require de-spin to zero-g to open up waiting docking ports that do not lie on the rotational axis. All modules can be compactly docked to each other at one end of the frame as a conventional stack configuration for acceleration or maneuvers out-of-spin (Figure 8). The "Sling" Option would require a redesign of the PPB stage in order to incorporate a flywheel approach and berthing mechanisms would need to tolerate lateral loads from docked spacecraft cantilevered at 1-g, but otherwise uses all the other Gateway elements roughly intact as NASA has proposed them.

In the "Sling" Option, the PPB stage / flywheel would stow as a conventional stack element on the end of the truss, similar to the proposed LOP-G configuration as proposed by NASA (Figure 8).

Our proposed "Propeller" Option, implementing a Crew Exchange option on Table 1, will use full-length parallel frames, with all elements able to move up and down the frames (Figure 9). This option uses all the NASA Gateway proposed elements mostly intact.

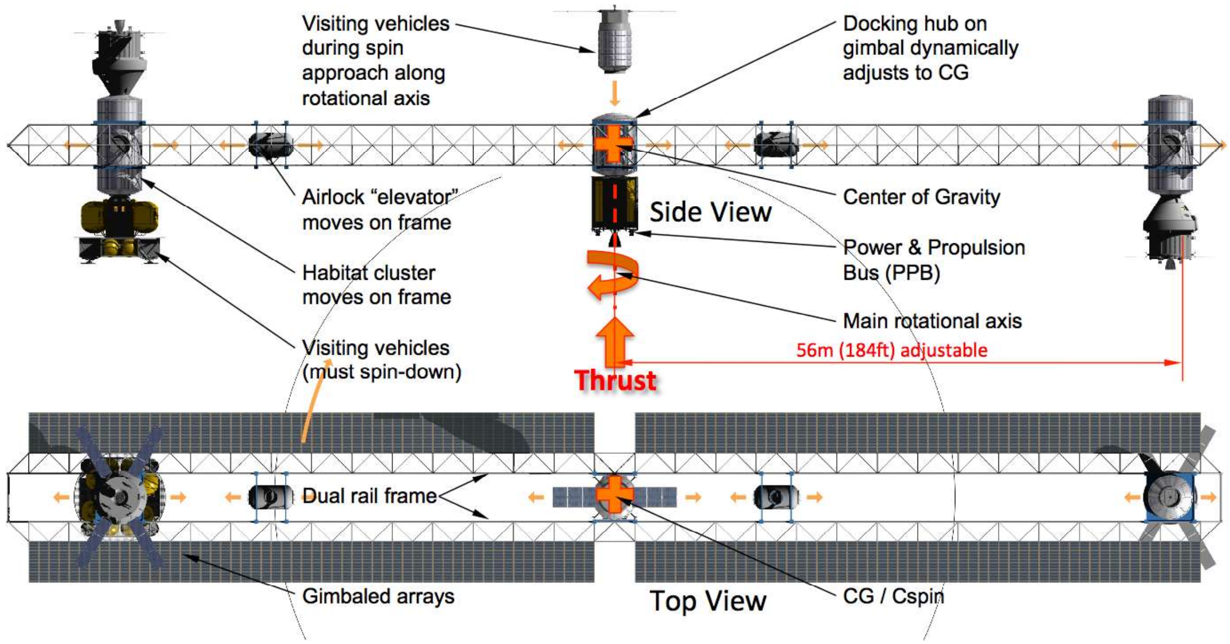


Figure 9: Our proposed "Propeller" Option GGT uses a longer truss, but all elements are able to move along the dual rail frame

The PPB stage will dynamically seek the CG and stay at the center of rotation during acceleration and transfer maneuvers, but will only be capable of allowing for a single docking vehicle along the rotational axis during spin. Other docking locations will require de-spin to perform in zero-g. All elements on the frame will dynamically shift to maintain balance and small airlock-like elevators will move up and down the frame between the larger elements. The "Propeller" Option can only perform spin-up / spin-down using propellant rather than an electric motor flywheel.

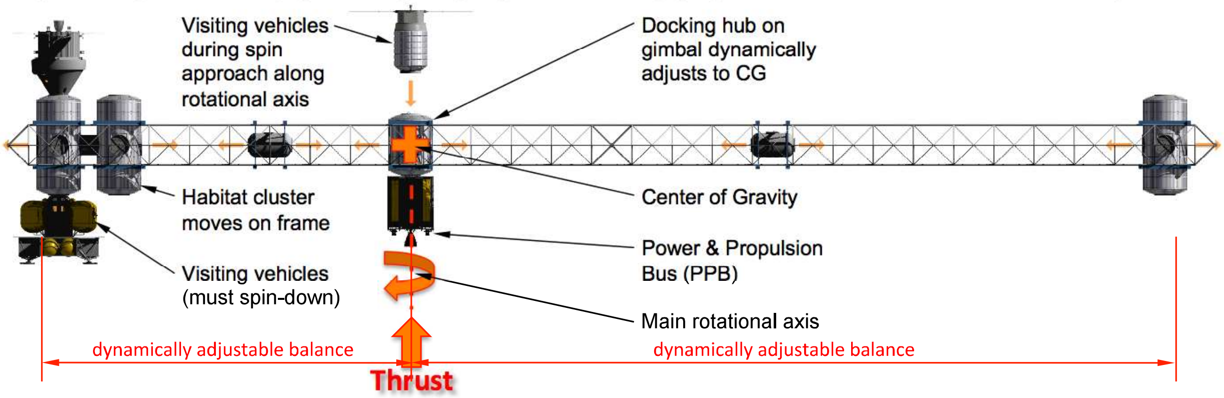


Figure 10: Our proposed "Propeller" Option GGT can shift the rotational axis to dynamically follow the CG whenever the mass changes, such as adding another habitat module (on the left)

The entire artificial gravity parameter space can be investigated, using the "Sling" configuration or "Propeller" configurations, where fully adjustable distances, radii, angular velocity, tangential velocity, and acceleration can approximate 0-1g or any gravity in between. AG can be in effect during transfer maneuvers, and the gravity can be adjusted either through changing the radius or rotation rate. As with the "Sling" Option, the berthing mechanisms on all modules would need to be designed to tolerate lateral 1-g loading during spin.

VI. Conclusion

We recommend adding a centrifuge truss element and adjustable AG hardware to the LOP-G configuration to allow the investigation of artificial gravity in this, perhaps only, opportunity to inform a future Mars or deep space transit vehicle. Since proposed LOP-G elements have not been finalized in their design and construction, now is the time to implement minor changes in the structures and interfaces and provide scarring to accommodate loads and resolve forces that would act upon them under centrifugal loading. Strategic scarring and structural reinforcement would be insignificant in cost, yet could be accomplished in such a manner as to address any number of future AG design options. Taking an example from the intermodal shipping container standards, four common lugs at the corners, along with requirements for forces passing through the container become scarring for any number of handling methods at dockyards, transportation, and shipping. In a similar manner, approximate force vectors and magnitudes for an AG centrifuge is either known or easily calculated, and would add very little to the cost of the proposed LOP-G elements.

We propose two AG concepts that make use of proposed LOP-G elements that could provide for dynamic loading, docking of vehicles, adjustable gravity, economic spin-up / spin-down, and thrusting while under spin.

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