Gravitat: Proposal for a Standard Design Vessel for Space Settlement

Dr. Pietro Calogero
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pietro@calogero.us

Abstract

In this paper I propose a "gravitat" as a two-pod vessel rotating around a central truss. I argue that a standard vessel design can serve multiple roles for extended crewed missions: as a vehicle, as an orbiting station, and as a surface base mounted on low-gravity planetary bodies. These roles share substantially overlapping design constraints: low total mass for both delta-V and station-keeping; spin-gravity for crew health and simplification of system design; and a nearly-closed environmental life-support system with significant fault-tolerance. Furthermore, a common design enables the most rapid accumulation of field-test time to identify strengths, weaknesses, and overall risk management of a complex vessel.

The proposed design includes two pods enclosed in three concentric fabric envelopes, tethered to a central truss by cables arranged to minimize oscillation. The pods consist of internal trusses, parallel to the axis of rotation, that support their dwelling decks and multiple garden shelves. The structural design is deliberately simple, to maximize reliability and durability. Complexity emerges in the details of long-term life-support, which requires years of empirical testing and observation to enable actual settlement of space.

1. Introduction

This paper is a proposal for a program to develop a general purpose space vessel for long term habitation with spin gravity: a *gravitat*. This vessel can serve multiple types of crewed missions: as a station in orbit of planets or at Lagrange points, and as a vehicle for long-duration interplanetary exploration. Unlike designs for short crewed missions, the gravitat employs the concept of *space settlement* to re-think the relationship between risk, duration, propulsion systems, and mission design (Johnson & Holbrow 1977).

Biomedical research on the International Space Station (ISS) has revealed fundamental challenges for keeping a crew healthy for more than one year in space. And yet with current technology, crewed exploration to even our closest neighboring planets will exceed one year. For long-duration voyages—and most especially for permanent settlement in space—we need to begin field-testing spin-gravity, radiation shielding, and at least partially closed-loop life support systems. The gravitat program is a proposal for both a vessel and a process of technology development. The overall geometry of the vessel is deliberately simple, to minimize long-term risks, maximize durability, and to create a platform for the development of technologies that we *don't* understand yet.

To be effective, this program needs a very definite mission. NASA famously developed many technologies during the Moon program, because the specific goal of lunar landing and return maintained institutional focus and public support. The shuttle program was also technologically prolific, but less fondly remembered because the goal of 'heavy freight to LEO' was not as compelling for the public and for political leaders who control program funding. Therefore I propose the following goal for the gravitat program: keep explorers healthy for five years in deep space. If we can do that, we can not only get to Mars; we can also *stay* in Mars orbit for at least a year and then return healthy crew to Earth. The same design can serve as a permanent orbital station at Luna, and also as a mounted base on an asteroid. Furthermore, the gravitat program would develop some of the key technologies for far greater goals: permanent space settlement, and interstellar exploration.

The first version, Gravitat-α, should be built in equatorial low earth orbit (ELEO) as a successor to the International Space Station, and serve as a research and development platform for the following technologies:

1. To determine long-term spin-tolerance, and thereby to find the minimum feasible radius for practical spin gravity.
2. To develop a nearly-closed environmental life support system (N-CELSS) for the optimum compromise between low mass, fault tolerance, and independence from external inputs (Sadler et al. 2011).
3. To design an environment with sufficient active and passive radiation-shielding to maintain the long-term health of the crew and the organisms of the N-CELSS.
4. To simultaneously develop competence in fabrication and in-situ resource use (ISRU), by retrieving expired satellites and rocket upper stages and recycling them.

The gravitat is a space *vessel* in the general sense: a container that can function both as a space *vehicle* and as a space *station.* To function for long missions, the life-support system needs to be mostly closed-loop. Based on the estimates of Meyer (2017) and Soilleux (2017), this means a growing area of about 180 m^2 per person, and a habitat mass of 66 metric tons per person. The gravitat is designed with twin pods for two persons per pod, so the N-CELSS alone would mass at 264 metric tons, with our current understanding. It may be possible to reduce the mass of the N-CELSS significantly by reducing the total water of the system, but such a reduction needs to be balanced against the role of that water as a passive radiation-shield which protects the crew. Therefore the trade-offs of N-CELSS mass and the design of the radiation-shielding system are also linked. The principles of each of these systems are already well understood in isolation; however we are at the point where we need to empirically test the integration and practical trade-offs of all of these systems under field conditions.

Once the design of Gravitat-α is fully resolved, it is the template for a generation of essentially identical gravitats that can be used as both deep-space vessels and as remote stations. Flaws in a remote vessel can be analyzed and hopefully solved in a nearby counterpart. Likewise, improvements to one vessel can be applied to all of them, if materials are available. Eventually the technologies developed through this proposed gravitat program will be useful for a wide variety of vessels in the process of space settlement. But for this program, I propose a set of nearly-identical vessels in order mitigate risks until we have more experience with humans in deep space.

This design is not likely to be the first crewed vehicle to get to Mars. However, if this reliability-centric approach succeeds, gravitats are more likely to be the first crewed vehicles to reach the solar-system gas giants. If crews can be kept healthy for five years or more, then gravitats can take advantage of the specific-impulse efficiencies of either electric plasma or nuclear thermal propulsion for extreme long-distance travel. Design for long-term reliability also means that the gravitat can be used as a rescue-vessel, or for follow-up forensic analysis to study catastrophic mission failures of hastier, higher-risk missions.

2. The Basic Structure of the Gravitat

The gravitat consists of two equal-mass pods**,** suspended on tethers, rotating around a central truss that we will call the *axle*. At the fore end of the axle is a non-rotating foredeck oriented perpendicular to the axle, and attached to it with a bearing (figure 1, shown in cyan). The dock is located at the center of the foredeck, which also holds at least one manipulator arm and the ISRU workshop. The docking tube extends through the bearing. Immediately behind the bearing is a Transfer hub (figure 1, shown in red), which can ‘spin down’ and mate to the back of the docking tube, and ‘spin up’ and move along the fore halyard out/down to either of the pods. A dynamic mass-balancing system (not shown) exchanges mass with the Transfer Hub to maintain rotational balance of the gravitat. Along the middle of the axle, each pod is suspended via tethers from winches: one halyard and two side-stays to the fore lock, and two side-stays and one halyard to the aft lock on each pod (Rousek 2010). The fore halyard also serves as the guide-cable for the Transfer-Hub and counterbalance masses. Aft of the pod mount-points, a second non-rotating platform holds communications equipment, the main photovoltaic panels, and the main radiators. A power plant is attached to the ‘stern’ end of the axle, along with propellant tanks and an engine. The axle, tethered pods, fuel tanks, and engine all rotate together.

The pods are 18 meter diameter spaces, enveloped in three concentric fabric layers with radii of 9, 10, and 11 meters, respectively (figure 1, shown in gray). The crew area within each pod is a 3m x 3m x 18m Pratt truss, oriented parallel to the axis of rotation (figure 1, shown in blue). This truss supports not only the crew deck within it, but also the hydroponics shelves, bio-digesters, and all other equipment contained in the pod. Airlocks at the fore and aft of each pod are attached to the pod-truss (figure 1, shown in orange). Each airlock serves as an anchor point for the three pressure-envelopes and the tethers to the central axle (figure 1, dotted lines). A viewing cupola and Transfer Hub dock are mounted to the fore airlock (figure 1, shown in green), and an emergency atmosphere-entry capsule is mounted to each aft airlock (figure 1, shown in red).

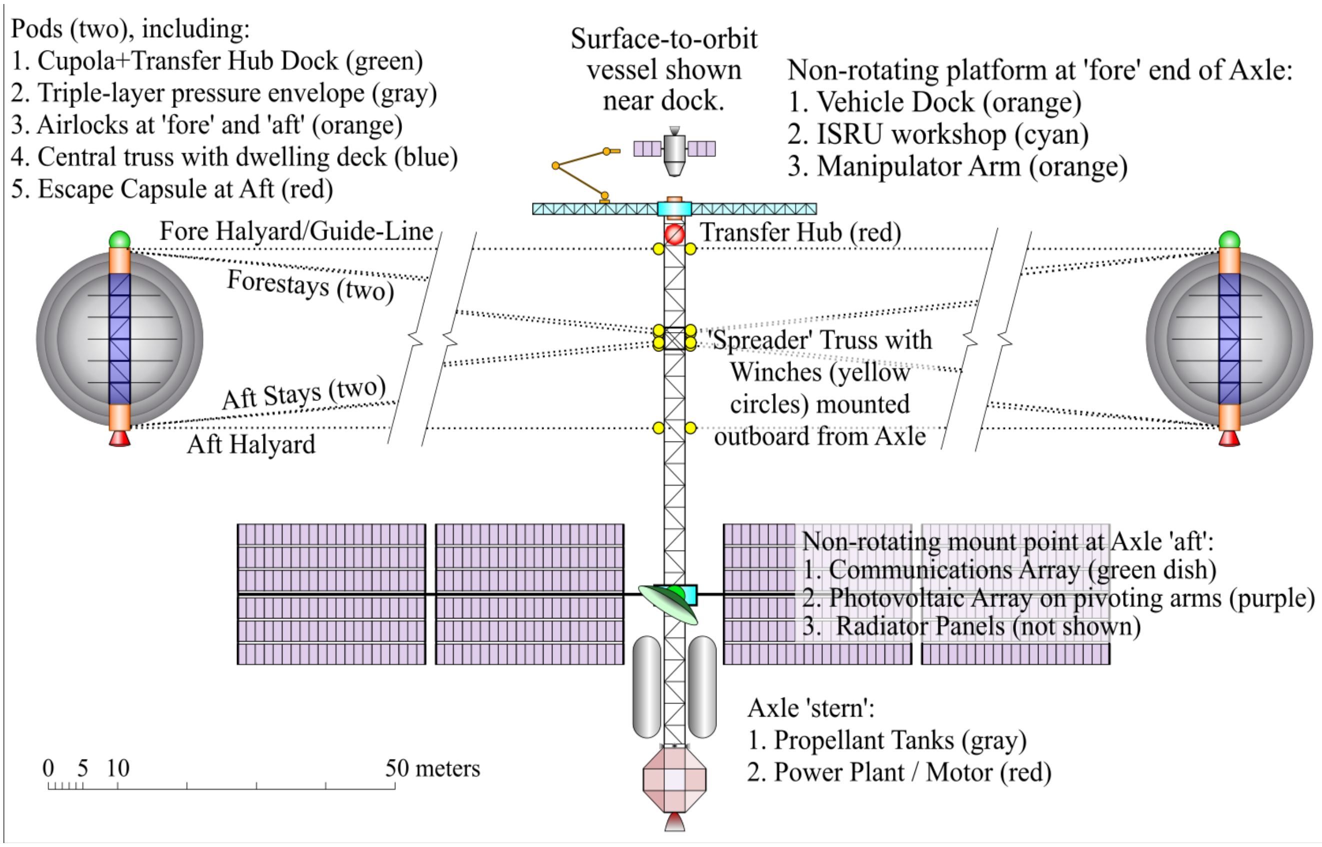

Figure 1: General components of the gravitat. Distance between pods and central axle not shown to scale. Illustration by the author.

Aside from the pods, the configuration of the vessel is similar to the Davis “Manned Mars Mission Concept” (1986) and the Nautilus-X proposal of Henderson and Holman (2011). The habitat components are similar to the RASC-AL proposal of Krishnamurthy et al. (2016).

The designation of rotating and non-rotating components of the gravitat is driven by the need to maintain stability of axial rotation for some components, and stability of orientation toward external objects for other components such as the communications-array and the photovoltaics array. The rotating portion of the gravitat will need an active counterbalancing system to maintain stability, similar to the dampeners used in high-rise buildings and recent models of passenger jets. This will enable crew and supplies to move forward, aft, and between pods without generating whole-structure oscillations. This is also why the forward dock is designed as a non-rotating component of the fore-deck. Although capsules (Soyuz, Crew Dragon, Orion, Starliner CST) all appear radially symmetrical, they are designed with deliberately asymmetrical mass-distribution to maintain stability during atmospheric re-entry. Each of these designs is also different, so there is no one docking position that would align the aggregate mass of any and all surface-to-orbit capsules to the axis of rotation of the gravitat. It is more practical to dock capsules to a non-rotating deck. The center-of-mass of the foredeck will need to be aligned with the rotational axis while the gravitat is under thrust; so it will also need a dynamic counterbalance system. But this design avoids the need for a constant re-centering of mass for every docking/undocking and capture of orbital debris for recycling.

The dwelling-decks within each pod are oriented with their long axes parallel to the axis of rotation. This follows Hall’s (1999) recommendation to minimize prograde and retrograde movement of the crew, to minimize coriolis-induced discomfort and vertigo (Newsom 1972, Hall 1994, 1999, and 2016). The pods are suspended from cables in a double-triangle geometry so that the cables are both redundant and minimize oscillation of the pods (Pengelley 1966). The two winches shown adjacent to each other at the mid-point of the axle are actually four winches, mounted at the ends of a cross-truss that holds them away from the axle. Each pod is therefore suspended by a triangle of three tethers at the fore airlock and a triangle of three tethers at the rear airlock. If spin-tolerance testing shows that the radius can be reduced, reduction will not require any significant redesign of the structure, only a winching-in of the cables.

In addition to the inhabited truss running through the center of each pod, the remaining volume is taken up by shelves of hydroponic gardens suspended from a mast-and-yardarm support network, resembling a "ship in a bubble" structure (figure 2). The intent is to provide the maximum growth-surface area for environmental life-support, within the most efficient volume. The use of two nearly-identical pods enables each to act as a control for the other, and as a lifeboat if necessary.

The hydroponics, bio-digesters, and filtration systems are the most complex part of the gravitat. More than any other component, the N-CELSS requires extensive field-testing in space because the nature of its complexity is iterative. How will soil microbe communities be affected by cosmic rays and the conditions in such a vessel? Unlike classical engineering problems, the emergent complexity of micro- and macro-biomes is a problem of dynamic balance between billions of partially-symbiotic organisms. Will these communities remain in balance, absorb sufficient carbon dioxide, emit sufficient oxygen, support food production and break down biological waste for years? These questions can only be answered empirically, in field conditions. And we must answer these questions with very high confidence in order to evaluate the risks of environmental imbalance and LSS collapse on multi-year missions.

Gravitats can be tested initially in near-earth environments: LEO, lunar orbit, and Earth-Luna Lagrange points—locations close enough to mount a rescue in cases of catastrophic systems failure. Once sufficient reliability, durability, and fault-tolerance are established, no change is needed in the design for either existing or new gravitats to be used as deep-space vessels. An engine capable of propelling the gravitat will need to be tested even on the first Gravitat-α, so there is no design difference between the orbiting-station role and the deep-space vessel role. If a gravitat is intended to be mounted to a low-gravity body (asteroid or small moon), an additional base-attachment bearing would have to be tested.

The following sections explain the design rationale for the components of the gravitat.

Why three concentric fabric pressure-envelopes?

Each pod consists of a 'triple-envelope' design for several reasons.

First: the multiple-layer fabric design minimizes risk of catastrophic decompression. Rigid vessels are vulnerable to rupture and splitting even from low-energy impacts such as the Progress/Mir docking accident of 1997 (Sawyer 1997). Multiple layers of fabric are less likely to be torn open simultaneously, and more likely to fail slowly enough for the crew to survive and respond. Furthermore, multiple layers separated by distance produce the "Whipple Shield" effect, in which a high-velocity impact with the outermost shell disperses the energy of the impactor over a larger area by the time it hits each subsequent layer (Whipple 1947).

Second: fabric envelopes are also more practical for initial launch to orbit. Bigelow Aerospace demonstrated that a large-diameter fabric enclosure can be packed within a narrow-diameter launch vehicle, and then inflated once in orbit.

Third: fabric envelopes and their differential pressurization are designed for fault-tolerance. I propose that the innermost space replicate the Earth's atmosphere of 78% nitrogen, 21% oxygen, and 1% trace gases, at 1.0 Bar pressure. (If it is possible to replace the nitrogen with argon, that would eliminate the hazard of 'bends' in case of decompression or for transition into low-pressure EVA suits; but plants might do poorly in an argon/oxygen atmosphere). The cavity between the innermost and middle envelopes should be 100% argon at a lower pressure, about 0.5 Bar. The outermost cavity should be filled with water vapor at about 0.1 Bar (so that it remains in a gaseous state). The water-vapor is part of the passive radiation shielding of the pod. Water has a high proportion of hydrogen (2/3), which is effective at absorbing cosmic radiation (Globus 2017). Water is also less hazardous than other hydrogen-rich gases that could be used: methane (CH4) or ammonia (NH3). Because of the difference in gas-mixtures in each cavity, leaks between each envelope would be easily detectable by chemical sensors. The material of each fabric envelope will also differ. The innermost envelope needs to endure oxygen, moisture, and low-speed impacts from dropped tools or other crew activities. The outermost envelope needs to be opaque and reflective to visible and ultraviolet light.

Fourth: the envelope needs to support an active electromagentic radiation shield. One possibility is an electrostatic shield (Buhler and Wichmann 2005). The second is an electromagnetic shield. Battison et al. (2012, Chapter 4) recommend creating an EM shield with a double helix dipole cylindrical coil of superconducting magnets as the most weight-efficient configuration. If so, the pod-envelopes would not be spheres as shown in this paper, but shaped as round-ended "fat" cylinders. There is still some disagreement about whether an electromagnetic or an electrostatic shield would be most practical (Clark 2015). Fortunately, the question of a spherical or fat-cylinder shape of the pods will not change the overall pod-tether-axle configuration of the gravitat. Answering this, and other complex-systems questions, is the core purpose of the gravitat development program.

Ironically, the one off-world location where the gravitat's proposed radiation-shield is unnecessary is the place where I propose it be built: equatorial low-earth orbit (ELEO). In any low orbit, the body of a planet blocks almost half the solar and galactic cosmic radiation. As for the side exposed to space, Globus & Strout (2017) point out that Earth's magnetic field protects an equatorial orbit far better than inclined orbits originating in Kazakhstan (Soviet/Russian missions) or Florida (American missions). I propose ELEO for initial assembly and testing of the gravitat in order to protect builders *before* proper shielding is developed. Like the N-CELSS, the radiation-shielding needs to achieve a balance of reliability, durability, fault-tolerance, and an optimal compromise of mass with effectiveness. During the development process, the organisms of an N-CELSS developed at ELEO will be protected from most hard radiation even before the shielding system is resolved.

Why provide one full gravity of spin-force?

There are several reasons to design a habitat with 1-gravity centripetal acceleration. First and foremost, to maintain the health of human crew on very long missions. American and Soviet/Russian extended missions in microgravity have shown serious and increasingly harmful effects to human health, summarized by Globus and Hall (2017). Human health may be maintainable at lower forces, but we do not know nor can we test such possibilities on Earth (Carroll 2010). Human physiology is complex and subtle enough that low-g tolerance can only be tested empirically, in a spin-gravity habitat of the same or similar design as the one proposed here. For long missions, reduction of physiological stress on the human crew is a critical risk-reduction. Current technologies cannot prevent long-term exposure to cosmic radiation in a low-mass vessel; so the feasible minimization of all other stress-factors is especially important.

The second reason for a 1-g environment is to reduce the cost of designing the systems within the pods. The design and testing of systems able to function in microgravity has been a major challenge for the development of both vehicles and stations since the 1950s. For the gravitat, many systems such as water filtration and toilets can be developed and tested on Earth, at much lower cost. This enables focus on other priorities: the balance of low mass with durability and reliability. In order to accumulate testing experience as quickly as possible, mockups can be operated in parallel at multiple terrestrial sites at a feasible cost.

The minimum feasible radius to produce 1.0g centripetal acceleration without causing serious crew discomfort and vertigo is still unknown (Globus and Hall, 2015). Part of the purpose of the Gravitat-α in ELEO is to refine our understanding of the factors that lead to an optimal compromise of radius and angular velocity for all components of the vessel. The current minimum-radius estimate is 225 meters, resulting in 2rpm rotation (ibid.). Gravitat-α is designed at this radius. With this proposed configuration, different options of spin-rate and radius can be tested without any significant redesign of the overall vessel.

The Pod design: erecting ship-rigging in a bag

Meyer (2017) envisioned many aspects of farming in space which influence this proposed gravitat design. Beginning with a truss running through an 18-meter diameter space, the most low-mass way to build a series of agricultural shelves is to erect masts and booms that support them (see figure 2).

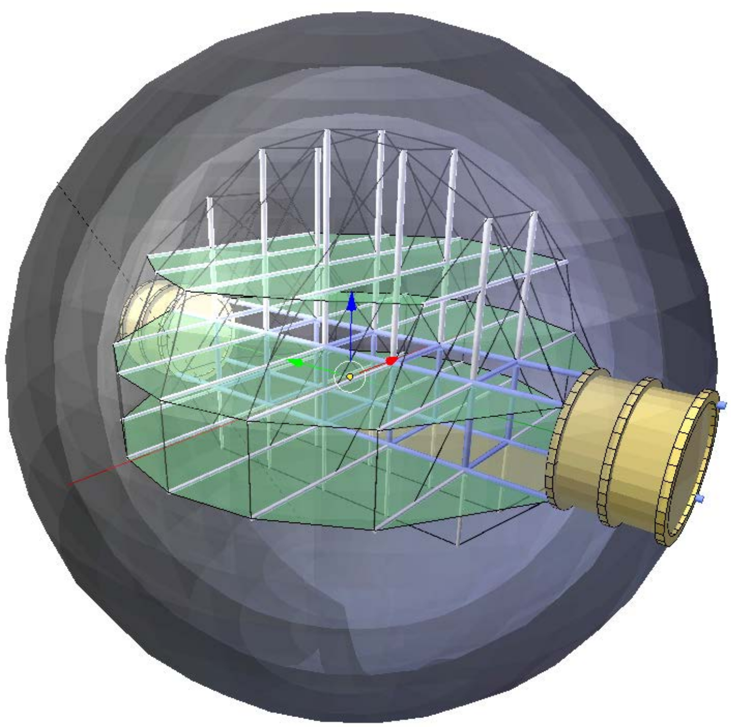

Figure 2: interior structure of the Pod. Design and illustration by the author.

Figure 2 shows a rough model of one of the two pods. The three concentric fabric pressure-envelopes are shown in gray; the fore and aft airlocks in yellow-orange; the main truss members in blue; the garden shelves in green. Masts and booms which support the decks are white, and the cables that suspend these components are shown in black.

This structure is designed to hold 360 square meters of garden, which consists mostly of hydroponics trays for growing vegetables. A series of basins underneath the main deck (not shown) would reprocess urine and greywater. One basin is a carp pool; an elegant way to convert wastes back into protein. Cosmic ray absorption plays a major role in both the positioning of water-basins and the selection of structural materials within the pod. Water, polyethylene, and polypropylene are all chemicals with high proportions of hydrogen. Globus (2017) points out that hydrogen is effective at absorbing high-energy cosmic rays without rescattering them as harmful Brehmsstralung X-rays, the way that metals do. Therefore I propose that all structural members and the three fabric envelopes be made of polypropylene, polyethylene or other hydrogen-rich compounds, and that water basins be positioned to provide the maximum passive shielding of the crew deck.

LED grow-lights will replicate the intensity, duration, and shifting spectra of daylight in a diurnal and seasonal pattern. If feasible, LEDs will be supplemented with sunlight collected and relayed through fiber-optic cables (Giacomelli et al. 2012). This illumination system is designed to support the circadian rhythms of both crew and plants. As with spin-gravity and atmospheric gas mix, this design follows the same logic of biological stress-minimization for a long-term habitat.

The crew deck within each pod truss is 2.8 meters high, 2.8 meters wide, and 17.8 meters long. The floor area is therefore 50 square meters (slightly over 500 square feet) for a crew of two. This area is comparable to two-person apartments in major cities across the Earth. Equipment and instrumentation can be attached to the outer side of the truss to maximize the floor area within the truss. The design of the crew space is beyond the scope of this paper. However as a designer of urban housing, I am confident that this floor area is sufficient for comfortable habitation. I also recommend that several cabin designs be developed by high-profile organizations with experience in comparable spaces: the U.S. Navy, Airstream, IKEA, and Chris Craft.

Why Two Equal-Mass Pods?

A spin-gravity vessel could be designed with only one occupied pod, and an equal-mass counterweight containing supplies, or perhaps a constant-mass exchange of waste-products from the occupied pod. However in the proposed gravitat design, each pod acts as a control-counterpart in an ongoing experiment in long-term life-support systems. And, in the case of catastrophic failure of one of the pods, the second is the backup to maximize the chance of retrieving the whole crew.

The nearly-closed environmental life support system (N-CELSS) is the most complex and least-understood system of the gravitat. Rather than attempt to design a completely closed-loop system, this approach is to achieve an optimal balance between (1) minimal mass, (2) system stability and (3) fault-tolerance. Such a balance will involve thousands of variables: the mix of plants, fungi, algae, and bacteria needed to develop a stable environment; and a determination of which parts of which ‘loops’ will need to be left partially open and supplemented with supplies produced on Earth. For example, spices are highly prized by ISS crew because their food is generally bland. On an extended mission, it might be more practical to carry Earth-grown peppercorns rather than attempt to grow pepper trees in the habitat. Cologne, chocolate, and chemotherapy medications could all be shipped to a remote gravitat via low-mass, high-speed drone ships.

Developing an optimally balanced N-CELSS will require thousands of days of empirical testing. This process can be accelerated through parallel testing in multiple spaces on Earth, especially since the gravity and gas mixture will be the same within the gravitat. However ground-based testing, and even long-duration testing in equatorial LEO cannot truly duplicate the conditions (such as hard radiation) of a multiple-year deep space mission. Micrometeroid punctures, or a slow, cascading failure of the gardening system could cause one of the pods to fail with ample warning, in which case the other pod would become a lifeboat for the whole crew. Or, a more subtle imbalance in the environmental mix could be studied and perhaps corrected by observing similar (but inevitably non-identical) conditions in the other pod.

3. Gravitat Program as a Step Towards Space Settlement

In space, now, we don't just work there. As human beings, we live there.
—Nicole Stott, interviewed on TMRO, September 23, 2018.

The tortoise of deep space settlement, not the hare of a space-race

The core design intent of the gravitat is to thoroughly test a standard, high-reliability vessel that can serve both as an orbital station and as a vehicle for very long crewed missions. The first gravitat, Gravitat-α, should be posted in low Earth orbit (LEO) for years as its systems are tested and refined. The gravitat is not likely to be the first crewed vehicle to travel to Mars and back. The two most likely propulsion systems for turning this vessel into a vehicle would be either electric plasma propulsion, or nuclear thermal propulsion. Both of these technologies have been well tested, and deliver about three times the specific impulse of the best chemical rocket engines. However, neither of these propulsion systems delivers high momentary thrust, so delta-V with these systems would be very gradual. Space-X or a national space agency could build rocket-propelled vehicles that could get to Mars much faster than a gravitat.

The advantage of the gravitat is that, given enough time (meaning a stable N-CELSS), the thrust-to-mass ratio of this system as a vehicle might make sense for longer missions to Jupiter and Saturn. Furthermore, upon arrival at Mars or Venus, the same vessel can act as a crewed, long-term orbital station. In other words, this design conforms more closely to the principle of space *settlement* rather than a short-term, unsustainable space *race*.

A platform for testing differing gravity environments

A fundamental gap in our understanding of human physiology is the long-term effects of reduced-gravity environments. Caroll (2010) argues that we need to conduct extensive testing of both biological and mechanical systems under reduced-gravity conditions, and that the surface gravity of Mars (0.38g) and Luna (0.16g) are good levels to test, in order to prepare for long-term surface exploration of both of those worlds. We do not know if human or plant health can be maintained even at 0.9g, let alone 0.38g or 0.16g. Long-term emulation of low-g environments is not possible on Earth (Young et al. 2009). The least-cost place for building a testing laboratory is low Earth orbit. Carroll proposes pods at different radial positions on the same tether, in order to conduct simultaneous tests at different levels of emulated gravity.

This is not the primary purpose of the gravitat; the N-CELSS design requirements mean that this has to be a much more massive vessel than what Carroll proposes for this specific purpose. However the gravitat could be used to test how humans, other organisms, and equipment function at reduced gravity, either by changing the tether radii or rate of rotation, or both.

Deploying gravitats near, but not onto, objects of exploration

Although the gravitat could be used to test much lower-g environments emulating the surface conditions of Luna and Mars, this design is proposed to fill a role which is not often discussed in space exploration: stationing humans near to, but not on, other planets. One reason is to avoid human exposure to dust. The 'dust fines' of Luna, Mars, and asteroids pose a serious problem for human respiratory health. During the Apollo Lunar missions, fine dust adhered to EVA suits and was therefore brought back into the Lunar Module. On future planetary missions, crews are likely to operate a variety of drones: semi-autonomous remote machines. Drones may be adjacent to the crew, or several light-seconds away. This eliminates the challenge of operating probes with long signal-delays, and increases the possibility of both field repairs and field modifications of probe capabilities. Furthermore, in order to respect the ongoing effort to determine whether life emerged independently on other planets, we need to quarantine other planets in our solar system from our own terrestrial biology. Human bodies alone are complex micro-biomes, and environmental life-support systems include a far wider array of organisms, some of which might be able to survive on Mars.

From two-pod vessel to space settlement

Hermann Noordung (1995, pp 102-112) proposed a "Habitat Wheel" in 1929, and von Braun (1953) expanded on Noordung's proposal in the early 1950s. And yet these proposals have not yet been implemented, almost a century later—and decades after the harm of long missions in microgravity have been clearly documented. I argue that this gravitat program may be a way to sell the cost of developing critical technologies for space settlement by explaining the multiple missions that can be achieved with this one design. It could serve as the Lunar Gateway; as the means to get to Mars and Venus and remain in orbit; even to get to Jupiter and Saturn with known feasible propulsion-systems. The technologies that need to be developed in the gravitat program are mostly refinements and extensions of well-established existing projects: CELSS, active shielding, nuclear thermal propulsion.

The technologies necessary for the gravitat are also critical technologies for permanent space settlement. Many of the practical details are understood in principle, but need to be tested to the point of extreme reliability, feasibly low cost, and maintainability. Several questions that need to be answered through the development of the gravitat illustrate the overlap with space settlement technologies more generally:

1. How is power generated, stored, and distributed in a durable, sustainable way?
2. How is mass actively distributed to maintain rotational stability, to allow for transfer from axle to pods and back?
3. How does an extreme-long-term crew work together and in relation to people on Earth? What are complications and mitigations?
4. Is this the most pragmatic design for docking to a rotating station?
5. How is a distributed, parallel system of ELSS tests managed? Seti@home may be the model, and public volunteer participation may be a powerful method of promoting and maintaining public support. But how does it work in practice?
6. Does the gravitat give us sufficient information to develop robust risk-assessment models for space settlement?

Athough I have proposed developing the first gravitat in ELEO, this is one space environment that does not need all the technologies the gravitat will require. Much larger stations, with far less shielding and less-closed life-support systems, can be stationed permanently at ELEO, such as the Kalpana-One (Globus et al. 2007) or The Gateway Spaceport (Gateway Foundation 2019). Gravitats, in contrast, are designed to endure the harsher conditions of permanent settlement in deep space. However, development of the gravitat for first missions to Jupiter (perhaps even the first survivable missions to Mars) can bring sufficient mission-focus to justify the resource-expenditure needed to develop essential technologies and practices for space settlement as a whole.

Conclusion: Gravitat as design approach

This paper is an argument for a specific design approach to long-mission crewed vessels. Whether in transit as a vehicle, or in orbit as a station, the design requirements of such vessels are substantially the same. The overwhelming priority is to maintain a reliable, durable, healthy habitat for human crew. This design priority is simple in principle, but extremely difficult in practice due to the iterative and emergent nature of artificial ecosystems acting as human life-support systems. This type of design problem requires numerous cycles of empirical testing. The total time for testing can only be reduced by running dozens—if not hundreds—of tests in parallel, in conditions as close as possible to the interior of the vessel.

Once deployed, gravitats can serve not only as a core technology of space settlement, but also a process-environment for adapting the culture of space-program management to allow for innovation and improvisation of technologies and practices in field conditions.

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