Towards a Minimal-Cost Artificial Gravity Architecture for the 2020s-2030s: The LEO Platforms

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Abstract— Since the early 20th century - well before the first crewed spaceflights - strategic planners and engineers alike have been exploring the development of artificial gravity (AG) structures in space. While many visions have been painted of AG at space-settlement scale, few viable pathways have been proposed to construct this infrastructure absent massive nation-state demand and funding – this demand has not materialized and seems unlikely to materialize barring a black swan event. Here, we propose an alternative pathway which could be pursued in its initial stages with small seed investment, grow into addressing the viable business case of providing small-scale AG stations to commercial customers by the mid-2020s, and eventually set the stage for the construction of the first space-settlement scale AG space station – all without the need for nation-state support and funding of such a megaproject. The insight enabling this pathway is that while AG provides obvious health benefits, it could also provide non-obvious cost benefits – making it a cost-effective competitor to static space stations when microgravity is not required.

I. Introduction

The concept of rotational artificial gravity (AG) as an aid in the human exploration and settlement of space was first proposed by Konstantin Tsiolkovsky in 1903 [1] [2]. In the ensuing decades, the idea gained more and more prominence [3], including serious consideration at NASA and within the Soviet space program [4] [5] [6] [7] – peaking with the mid-70s work of Gerard O'Neill, who laid out technologically plausible and NASA-endorsed plans to build city-scale AG space stations in high earth orbit [8].

The sociopolitical factors which O'Neill laid out as likely to spur the construction of these megastructures – namely, the population and energy demand explosions [3] – did not play out as he predicted. Global population growth slowed markedly in the decades following his proposals [9], and energy demand proved easily addressable by terrestrial means [10]. This, combined with the failure of the Space Shuttle to provide the rapid and cost-effective access to space that O'Neill's plans counted on [11], meant that none of his space colony architectures ever developed beyond the conceptual phase.

In the nearly fifty years since O'Neill's plans captured the public imagination, AG has become a topic of little interest to most of the operators of actual space missions, both in government and in the private sector. To date, the largest AG system put in space has been the rodent-scale centrifuge of Kosmos 936 [12], and only one such system ever flew. There have been only two notable indicators of interest in AG by NASA since the start of the 21st century – the first being a concept for a "Nautilus X" AG module aboard the ISS [13], and the second being the inclusion of "Artificial/Partial Gravity Services" as a "Stretch" goal in the 2021 request for Commercial LEO Destinations proposals [14]. In the former case, the plans for this module were abandoned, and in the latter case, none of the Commercial LEO Destinations proposals selected by NASA included any plans to meet the AG stretch goal [15].

While the apparent demand for AG solutions has collapsed in the past half century, the last ten years have seen a radical improvement in the feasibility of their supply. To be sure, novel ideas for city-scale AG continue to be developed and improved [16] [17] [18] [19], but the most economically significant developments have occurred at much smaller scales.

Perhaps most prominently, the work of Al Globus and his collaborators showed first that space settlements could be protected from cosmic radiation if they remained in a sub-500km Equatorial Low Earth Orbit (ELEO) [20], eliminating the need for heavy radiation shielding and allowing them to be built with an order of magnitude less mass than previously thought possible [21]; and then that the rotational tolerance of humans is significantly higher than previously believed, allowing space settlements to be much smaller than in prior concepts while still reaching the same levels of AG [22]. Globus combined these two insights into his proposal for Kalpana Two [21], a 400-person AG space station with a mere 112m diameter and almost no dedicated radiation shielding to speak of. These concepts were popularized in the book Globus co-authored with Tom Marotta in 2018 [23].

At the same time, the cost of getting mass to orbit has continued to drop from the $65,400 per kilogram that Space Shuttle achieved, reaching an estimated $1,500 per kilogram thanks to the innovations of SpaceX [24] – and is predicted to reach somewhere around $100 per kilogram within the current decade [25] if their fully-reusable Starship system succeeds (and the SpaceX track record suggests that it will).

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The combination of Globus' small-diameter ELEO architecture with the unprecedentedly low cost-to-orbit afforded by Starship enables the construction of AG space stations for dramatically lower sums than ever before proposed – in fact, a later section of this paper contains a plan to build a minimum viable human-habitable AG space station for around \$16 million USD. In addition to this paradigm shift in the basic inputs for viable AG, the recent proliferation of commercial space companies has created a wide array of off-the-shelf systems that make constructing and operating spacecraft (including space stations) significantly cheaper than ever before [26]. And the growth of the market around cubesat components and services has opened a sub-\$100,000 entryway for the orbital testing of the few novel systems and concepts needed to build such AG stations.

Thanks to all these developments, it is becoming increasingly feasible to envision a commercially-funded pathway to AG space settlement, which does not rely on investment by nation-states or on social factors here on Earth causing urgent demand for human populations in space. In other words, it is becoming increasingly feasible for a single modestly funded private company to bring to fruition the century-old dream of AG space settlement.

Globus and others have already pointed out the increasing viability of such a pathway [21]. However, to our knowledge, no rigorous plans have been laid out for how a company could start from almost nothing and grow to the scale of constructing Kalpana Two-style space settlements while maintaining a viable business case (and therefore access to capital) along its entire journey.

In this paper, we aim to lay out just such a plan – which we have entitled the LEO Platforms plan. The critical insight of the plan is this: While AG has been primarily discussed and desired due to negative effects of microgravity on human health [27] [28] [29], we believe that AG space stations could be built and maintained for a much lower cost than their microgravity counterparts. The reason for this comes down to the simple fact that most of humanity's technologies, ranging from plain toilets to advanced climate control systems, were built to take gravity for granted; and adapting these basic systems to microgravity is only done at immense expense. By providing Earth levels of AG in space, low-cost systems developed to work on Earth could easily and cheaply be adapted to work in space, eliminating the need for much costly specialized hardware.

With the number of humans in space expected to grow substantially in the coming decades [30], there will be growing demand for on-orbit housing across a wide range of mission lengths. Of course, many of these humans will be employed in microgravity applications, but this does not mean that their housing needs to be in microgravity – the previously mentioned NASA Nautilus X concept, for example, proposed mating an AG ring to the microgravity ISS.

If a company can provide the most healthy and cost-effective housing for this growing number of space residents by employing AG structures, there will soon be a profitable business case for building such structures. This very prediction, in turn, implies a venture capital case *today* for the creation of pathfinders towards such structures, so that the company building them can be the market leader when significant demand begins to materialize.

The first section of this paper outlines the two technological pathfinders such a company could undertake today, requiring a very modest amount of seed funding (under \$200k) that should be easy to obtain given the possibility of even a small market for AG orbital housing developing within the next decade. This financing assessment draws on our personal experience with venture capital, having raised millions of dollars for a prior startup [31].

The second section of this paper outlines the three stages of AG space station that this company could progress through once the existence of this market becomes more apparent, starting with a \$16MM project – well within the financing range of a typical Series A [32] – and growing into systems that will meet the housing demands of dozens of residents.

The last section of this paper outlines two final stages needed to reach the first Kalpana Two-style AG space settlement of approximately 400 residents.

Critically, each stage along this pathway will fulfill not just an aspiration for human life in space, but also profitably meet an expected market demand.

Taken together, these sections lay out LEO Platforms as a business plan to get from zero to AG space settlement with no nation-state mandate or financing; considering current technologies and their costs, the present availability of capital for various types and stages of business, and the expected growth of the space economy.

II. The First Phase: Technological Pathfinders

a. Platform A: ECLSS on the Ground

The most unintuitive aspect of LEO Platforms is the theory that AG space stations (or substations) could be built and operated for a lower cost than microgravity space stations. As such, the first priority of a company pursuing the LEO Platforms architecture would be to both practically demonstrate the plausibility of this theory, as well as to gain engineering experience in developing the cost-effective AG versions of systems that any space station would require.

The greatest distinction between a general satellite / non-human spacecraft and a space station (meant to house humans) is the need for the latter to sustain life – the systems needed for this are broadly categorized as the Environmental Control and Life Support Systems (ECLSS).

As more satellites launch to orbit each year [33], the non-ECLSS systems available to the builders of spacecraft will continue to increase in availability and decrease in cost. The unique challenge for any company aiming to enter the market of space housing, then, will revolve around ECLSS. Unlike microgravity space housing systems, AG space housing systems (or at least many of their ECLSS components) can be fully tested and proven on Earth, since they are here subjected to the same earth-normal gravity that they will operate in once on orbit.

As is laid out in the "Platform 0" section later in this paper, the first orbital ECLSS of the LEO Platforms plan will be fully expendable, and so a company following this plan should begin by validating an expendable ECLSS here on Earth. In practice, this could be accomplished by the long duration stay of a resident in a fully hermetically sealed environment, incorporating as few or as many systems of the potential Platform 0 station as the company's seed budget allows.

Table 1 summarizes the high-level systems needed for a Platform 0-level space station, with those that would be possible to demonstrate on Earth indicated in the second column. The third column indicates which systems we believe would most likely be appropriate for a seed-stage demonstrator, which we have dubbed Platform A (our habitable space stations follow a 0-indexed numerical naming, while our technological pathfinders follow an alphabetical naming).

In short, while Platform A could incorporate just about every system that doesn't explicitly require an orbital structure in microgravity for real-world testing (i.e. just about every system pertaining in any way to ECLSS, including power and pressure structure), restricting ourselves to just the systems unique to a human-habitable station would yield an extremely affordable test proposal.

While the exact "mission profile" of Platform A would depend on the investor, PR, and capability-building considerations of a company following the LEO Platforms plan, we will now explore an execution which assumes a monthlong stay on Platform A by a single resident, implementing only the systems indicated in the third column of Table 1. A stay of longer duration, or with more residents, is entirely feasible – and the economics of this could be estimated by extrapolating the figures below. A broader demonstration of the systems, to include those indicated in the second column of Table 1, could be achieved at this stage or during the development of Platform 0, and could scale in complexity all the way up to placing a sealed Platform 0 module in a large vacuum chamber, with external lamps powering solar panels on said module. We will not attempt to estimate the cost of such a broader demonstration, though depending on the aforementioned company needs and abilities surrounding investors, PR, and capability-building, a company may choose to pursue this more ambitious implementation of Platform A.

Living in a hermetically sealed ECLSS for one month is, outside of the history of actual space stations, both a novel and a not entirely unprecedented proposal. At this very moment, thousands of sailors are living aboard submarines submerged in oceans around the world, tens to hundreds of feet below the nearest human-survivable natural environment. Submarines are not entirely 'sealed', however – fresh oxygen is provided within them by the electrolysis of seawater [34]; something that space stations would not have easy access to. A closer analogy may be mine survival shelters, which, like Platform A, are fully sealed and require no external inputs for their ECLSS to function. These shelters, however, are designed to house miners for hours to days before rescue can arrive, and we have been unable to find any that are designed to sustain human life for even a week, much less a month. This means that (including the far more involved exoplanet base simulators Biosphere 2 [35], Yuegong-1 [36], and SIRIUS [37]), Platform A will be one of the first terrestrial fully-sealed environments to house a human for a full month.

TABLE 1: SYSTEMS DEMONSTRATED ON PLATFORM A (PA)

System	Possible for PA	Likely for PA
GNC / Avionics	-	-
Propulsion	-	-
Communications	-	-
AG Mechanics / Tether	-	-
Pressure Structure	Yes	-
Thermal Management	Yes	-
Power Generation	Yes	-
Pressure Management	Yes	-
Oxygen/CO_2 Management	Yes	Yes
Humidity Management	Yes	Yes
Trace Contaminant Removal	Yes	Yes
Human Waste Disposal	Yes	Yes
Water Supply & Recycling	Yes	Yes

A basic potential implementation of Platform A would require no more and no less than the components laid out in Table 2. The second column of this table estimates the cost of each of these components, with the third column providing an example of a sufficient way to procure any less easily available component at the estimated price.

Structurally, Platform A would be a fully-sealed 'bubble' of perhaps 8' height and a 15' x 15' base, likely made of non-porous plastic film, housed in a warehouse that can provide a stable temperature and an electrical connection (recall that we are exploring an execution that only demonstrates the station systems laid out in the third column of Table 1, and may assume/simulate the effective functioning of the other systems, such as power and thermal management, through other means - e.g. by housing Platform A in a temperature-controlled warehouse with a connection to the electrical grid).

The most ambitious aspect of Platform A would be atmospheric management. Here, we are helped by the fact that we are designing a system meant to be adapted into the ECLSS of Platform 0, where expendable (single use) components are part of the plan. It is important to understand that Platform 0 will not be significantly mass-constrained, as is discussed later in this paper. This means, for example, that we can afford for our system to rely on stored oxygen and fully dispose of all captured carbon dioxide, rather than recycling the oxygen atoms in CO_2 back into breathable O_2 as the costly Sabatier System on the ISS does [38].

Atmospheric management on Platform A would need to include:

- Providing adequately high levels of O_2
- Keeping CO_2 levels below a certain threshold
- Maintaining an appropriate humidity range
- Removing trace gas contaminants

Outside of frequently venting the atmosphere and providing a replacement stream of standard (~80% N_2, 20% O_2) air to keep O_2 adequate and CO_2 low (while our mass constraints are generous, they do exist – this approach would be infeasible), the simplest way to keep these two gasses in their target ranges would be to continuously introduce pure O_2 to replace that consumed by Platform A's resident, and to capture this resident's exhaled CO_2 before it reaches harmful levels in the air. NASA estimates that an average person consumes 0.84kg of O_2 and produces 1.00kg of CO_2 each day [39].

TABLE 2: COMPONENTS OF PLATFORM A

Component	Cost	Rationale
Warehouse to host environment	$2,000	Sublease rates for the space needed are on this order in Durham, NC
Environmental seal/envelope	$3,000	
Primary gas monitor / controller	$10,000	The approximate cost of a SCUBA rebreather
Backup gas monitor	$1,000	
Pure O_2 supply	$2,000	The approximate cost of SCUBA tanks filled with 26kg of O_2
CO_2 capture material	$1,000	The approximate cost of 110kg of Sofnolime
Dehumidifier + Air Filter	$1,000	
Potable Water	$20	
Camp Shower	$500	
Camp Toilet	$1,000	
One month of food	$500	
Furniture	$500	
Total cost:	**$22,520**	

0.84kg of O_2 per person-day as well as the weight of the tanks needed to store this compressed oxygen fall well within the mass constraints of Platform 0 (as discussed later in this paper) – meaning that we can meet our oxygen needs using a system of compressed pure oxygen. CO_2 capture can be accomplished even more simply – by using expendable CO_2 capture materials. Lithium hydroxide is a common choice in historical expendable ECLSS systems [40], though a more attractive alternative for Platform A may be Sofnolime, a sodium hydroxide and calcium hydroxide compound used commonly in SCUBA and submarine applications, which makes it readily commercially available. 1kg of Sofnolime can capture 0.296kg of CO_2, and this approach again falls within the mass constraints of Platform 0.

As such, Platform A would require ~26kg of O_2 and ~105kg of Sofnolime, as well as tanks and tubing for the former. The control mechanism for this system could be adapted from SCUBA rebreathers, which maintain a breathable gas mixture by passively capturing all present CO_2 in an open (unmetered) bed of Sofnolime and introducing compressed O_2 gas when sensors indicate that O_2 levels are falling below the target range. Table 2 includes cost estimates for these three components – 26kg of pure O_2 in compressed gas cylinders, 110kg of Sofnolime, and a SCUBA rebreather as the oxygen regulation system. A redundant O_2/CO_2 monitor is included for safety. Together, these systems accomplish the first two goals of atmospheric management.

In a closed system, a human would be a net producer of humidity, so maintenance of an appropriate humidity range would require a dehumidifier. Here, our earth-normal gravity environment provides a tremendous cost advantage, as off-the-shelf commercial dehumidifiers are easily up to the task and cost very little.

The commercial dehumidifier utilized in Platform A would also provide the environment's primary means of air circulation (facilitated by convection, another benefit of the earth-normal gravity environment), and so would be a natural host for trace gas contaminant removal systems. Even in costly microgravity ECLSS systems, these have often consisted of little more than expendable activated carbon filters [41] – such filters come standard with many commercial dehumidifiers, and so trace gas contaminant removal does not need to be addressed separately in Platform A.

With atmospheric management handled, the only remaining components of a full ECLSS are the supply of fresh water, and the removal of dirty water / human waste.

NASA estimates that a single human uses 4.17 kg of fresh water each day and creates 5.57 kg of dirty water [39] — the difference being made up through moist food and the fact that human metabolism is a net producer of water, to the tune of 0.35 kg/day [39]. At these masses, no recycling of dirty water is needed to meet the mass constraints of Platform 0; however, it would be trivial to collect potable water from the evaporator coil of the dehumidifier to reduce mass need by over half, as 2.28kg of the daily human-expelled water is in gaseous form (coming from humid breath and the evaporation of sweat). Whether the company building Platform A chooses to start their mission with 34 gallons of water (4.17kg per day) or to reuse dehumidifier condensate (lowering water need to less than 16 gallons) will likely come down to their particular considerations.

In microgravity, the removal of dirty water (from washing) and human waste poses a considerable and expensive challenge. This is another area in which our earth-normal gravity environment will lower costs to near nothing - in this environment, camp showers and sealed camp/RV toilets fully satisfy the mission requirements. Allowances for the costs of these are made in Table 2.

Including a reasonable allowance for a month of food and for furnishings within Platform A, the total mission cost estimated in Table 2 comes in at around $23,000 – an exceptionally low figure for an ECLSS system, even one meant to only be used by a single person for a single month.

The successful demonstration of Platform A by any company building it as their first step along the LEO Platforms framework would prove, in very real terms, the massive cost savings afforded by operating a space station within an earth-normal gravity environment. Of course, the expendable and mass-generous nature of this ECLSS would complicate the analogy to existing space ECLSS implementations; but the company could point to the Platform 0 concept as a priced-out and feasible implementation of this concept in a real human-habitable space station.

The building of Platform A would thus make real the possibility of human life on Platform 0 – the first actual space station of the LEO Platforms plan – and help the company building this pathfinder to raise the engineering capabilities, publicity, and investment needed to proceed to the second

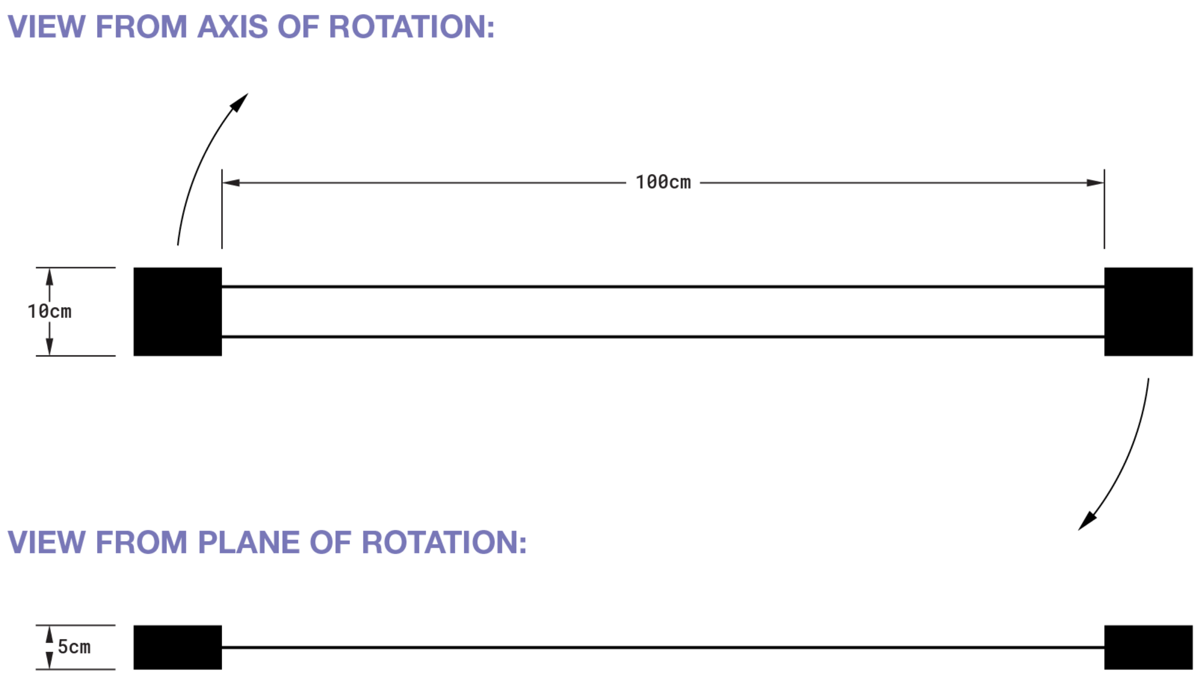

Fig. 1: Platform B dimensions

phase of this plan.

b. Platform B: Scaled-down AG in Orbit

An AG space station is (broadly) the union of an AG spacecraft and an ECLSS. In addition to developing and demonstrating ECLSS capabilities, therefore, any company following the LEO Platforms pathway should develop and demonstrate their ability to control and operate an AG spacecraft in actual low earth orbit.

This does not need to be costly – the physics of a rotating AG spacecraft are consistent regardless of scale, and modern miniaturized technology would allow even a cubesat to demonstrate most of the non-ECLSS functions of such a spacecraft.

It is therefore a cubesat which we propose to launch at this stage of development. We refer to this spacecraft as Platform B – though it may be developed in parallel with or even before Platform A.

Platform B would launch as a 1u cubesat, measuring 10cm x 10cm x 10cm in its initial configuration – at this size, launch to a non-selective orbit would cost approximately $45,000 (per an industry source quoting summer 2022 launch prices). Once released into orbit, the cubesat would separate into two 5cm-thick halves, held together by twin 1m-long tethers of thin but rugged wire – creating a bola configuration. One of the two separated modules would accelerate to impart a spin to the system, generating AG in both.

Much like Platform A, Platform B is both novel and yet not unprecedented. It would be the first orbital AG spacecraft since Kosmos 936 [12], and likely the largest one ever operated for more than a few minutes (excepting the brief attempt of Gemini 11 at creating a 36m-long bola [7]). It could, however, draw on the handful of cubesat AG designs that have been proposed in the past two decades, including a 2008 proposal by the Mars Society [42], a 2017 proposal by an engineering lab at Cornell University [43], and separate 2014 and 2017 proposals by a team at Arizona State University [44] [45]. These proposals lay out reasonable expectations for what Platform B could do and how it could be designed - the Cornell proposal in particular includes a rigorous cost analysis, estimating the total expense of building such a satellite (excluding launch) to be under $50,000.

Rotation is not an intuitive mechanical reference frame – while the physics of an AG bola are well understood, there exists almost no practical knowledge or experience regarding how to best control one, as well as what challenges could arise in its operation and how these challenges could be overcome. For example, how would the shifting of mass at the base of one of the separated modules (a walking human, in the example of a full-scale AG space station) affect the rotation and orientation of the system? What kind of resonances and oscillations would be potentially destabilizing, and how could these be managed? How could precession best be countered?

For Platform B to be more than a PR / investor relations proof of progress for the company building it, the spacecraft must be designed to answer these questions, and in doing so build the practical knowledge necessary to optimally design the first human-habitable AG space station – Platform 0. To that end, it would be useful for Platform B to roughly emulate the planned characteristics of Platform 0, simply at a much smaller scale.

This begins with the spacecraft's general size and structure.

Platform 0 will consist of two cylindrical modules – about

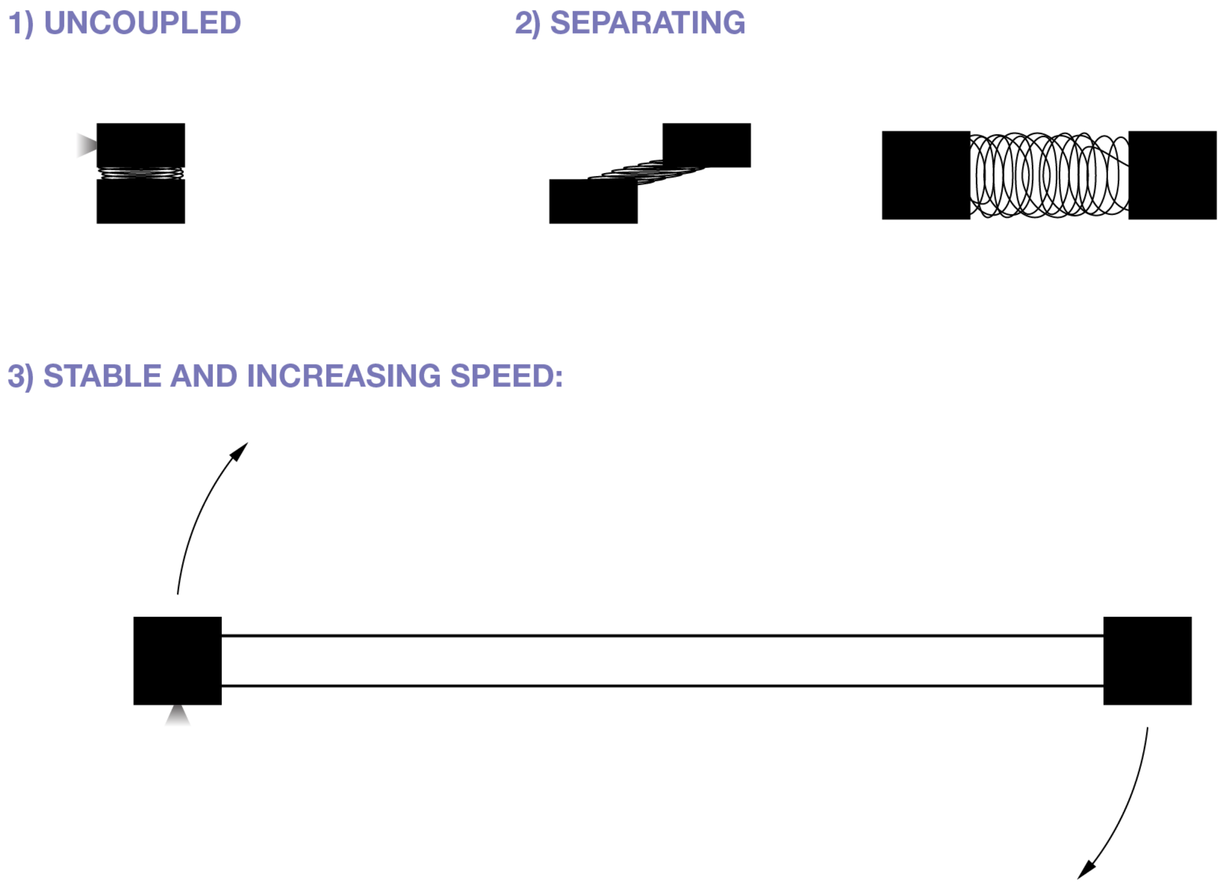

Fig. 2: Platform B spin-up

9m in length and 4m in diameter – separated by a 112m tether. This is roughly approximated by two rectangular modules – 10cm long, 10cm high, and 5cm wide – separated by two 1m tethers. Note that due to the intermediate axis theorem, these modules must rotate such that the 5cm width is orthogonal to the direction of rotation (i.e. parallel to the axis of rotation) for the system to be dynamically stable. The precise number of tethers can be determined in the actual execution of Platform B (the base design of Platform 0 calls for four), but having more than one tether will allow for greater stability if mass is shifting within one or both of the modules. Figure 1 illustrates the general size and rotational direction of Platform B.

Upon being deployed in orbit, Platform B can extend from its base configuration (10cm x 10cm x 10cm) to the split-module configuration by releasing a magnetic clasp holding the two modules together. Spooling out the tethers is needlessly complex – the two halves can be arranged to enclose between them the full length of the tethers while Platform B is in its base configuration, and immediately expose these tethers at their full length when the modules separate.

At this stage, the tethers could be extended simply by spinning up the modules. In fact, only one module would need to be accelerated (likely with a small cold gas thruster, though any type of thruster would do given that there is little time constraint involved) for the system to begin spinning symmetrically. With proper modulation of the thruster's firing, this can even be accomplished without any net change to the translational velocity of the spacecraft [46]. Some additional modulation may be needed due to elasticity within the system – for example, the spin thruster may need to fire very softly for initial separation, then much harder as the tethers reach full extension, so that rotational momentum overwhelms any 'bounce' that may bring the modules back together from their initial separation momentum. This spin-up approach is illustrated in Figure 2.

Once spinning stably, the system can be brought up to its target rotational velocity and therefore target level of AG by continued firing of the primary spin thruster. The level of AG that is targeted can be determined in the actual execution of Platform B – earth-normal gravity would require the system to spin at approximately 39rpm, and while this is certainly achievable, a more likely target may be the 4rpm that Platform 0 will need to spin at for that larger system to achieve earth-normal gravity. At 4rpm, Platform B would generate 1% of earth-normal gravity; a small force, but one sufficiently strong to test the control characteristics of a bola in free space.

This control will most likely be provided by small cold-gas thrusters located on various faces of the two Platform B modules – while reaction control wheels may be a more conventional choice for a satellite of this size, these would not scale well to Platform 0; and the lessons we hope to learn from Platform B should be prioritized around their applicability to that larger space station. Additionally, it may be beneficial to include a movable mass at the base of one or both of the modules, which could be repositioned mechanically or magnetically, so as to test the characteristics of a bola when mass is shifting or oscillating within one of its ends (as would be the case when a human walks along the length of a Platform 0 module), and to develop control methods that could handle these dynamics appropriately.

The successful spin-up and control of Platform B will be a tremendous milestone not only for the company that builds it, but for the entire space exploration community – this will be one of the biggest steps yet towards AG in real-world execution. While the engineering and control lessons derived from the operation of Platform B and the tests undertaken by it while in orbit will be a tremendous source of practical knowledge for the company, the stage for Platform 0 will be set not only by the lessons of Platform B, but by the proof of capability it will represent. Alongside the demonstration of a reliable yet low-cost gravity-based ECLSS in Platform A, the demonstration of Platform B will be crucial in helping the company to raise all the funds needed to build and launch Platform 0, and so move into the second phase of the LEO Platforms pathway: The construction of actual human-habitable artificial gravity space stations.

III. The Second Phase: Initial Human-Habitable Stations

a. Platform 0: The First AG Space Station

As this paper has suggested multiple times, the primary purpose of all the work in the first phase of the LEO Platforms plan would be to make possible the construction of Platform 0: the first human-habitable AG space station. This station would advance the program from technological demonstrators to a 'minimum viable product' – while Platform 0 would still be a proof-of-concept above all else, it would be a complete demonstration that life in orbit can be achieved at great comfort and low cost by employing an AG architecture.

Platform 0 thus represents a pivot point in the LEO Platforms pathway; transitioning the project from completely speculative venture funding to proof of a viable commercial proposition in functioning space housing. It is to the company pursuing LEO Platforms what Falcon 1 was to SpaceX. In the latter case, after three failed launches, SpaceX flew a single successful mission on Falcon 1, delivering a dummy payload to orbit – and this proof of orbital capability allowed them to secure the NASA contracts needed to build Falcon 9, which then became the sole focus of the company.

Similarly, the successful operation of Platform 0 will be the proof of space housing capability that will open the LEO Platforms project to many paying customers, and in turn, to much broader capital markets than were previously afforded it – but like the mass simulator that served as the payload on the successful Falcon 1 launch, a "simulated human" is all that is necessary for Platform 0 to achieve its objective. In fact, given the risk any novel life support system would pose to a human, it is all but guaranteed that a space station concept would need to prove itself capable of sustaining human life before actual human lives were entrusted to it. As such, Platform 0 will be designed such that a human could spend a year aboard it, but in the cost and mission planning considerations that follow, we will assume that no human will actually be present, and that instead the systems aboard Platform 0 will be put through their paces however any customers that may have expressed interest at this point (such as NASA or the US Department of Defense) would like to see them proven.

In short, Platform 0 will be a human-habitable space station on a yearlong mission, with the goal of demonstrating that a human could've safely and comfortably lived aboard for that full year, and with the purpose of securing the contracts and funding necessary for the development of Platforms 1, 2, 3, and 4, which are discussed later in this paper.

What follows is a brief outline of the systems, considerations, and estimated costs of Platform 0, summarizing our previous, more detailed article which first introduced the Platform 0 architecture [47]. Readers are invited to refer to this prior work for additional information. Notably, unlike Platforms A and B, which could conceivably be built and operated by a small founding team, Platform 0 will require moderate engineering and management resources to execute, and so allowances are made for staffing and related business expenses in our cost estimates below.

1. The Critical Input: Starship

Platforms A and B have been designed in the context of technologies and costs as they stood when this article was written (May 2022) – in other words, nothing would prevent them from being built today at roughly the costs estimated in their respective sections of this paper. Platform 0, however, relies on one critical technology that has not yet reached market: the SpaceX Starship. This launch system thus becomes the limiting factor of when Platform 0 can reach orbit – and while SpaceX has made estimates of commercial flights by 2024, we have spoken with insiders at the company who believe that 2026-2027 is a more realistic possibility. This doesn't mean that work on Platform 0 cannot begin before these years if a company following the LEO Platforms pathway is ready, but it does mean that Platform 0 will likely not reach orbit until the latter part of this decade.

Once Starship is ready, however, it becomes the driving factor of Platform 0's affordability – unlocking the possibility of systems that will act as savings multipliers far and beyond the cost-per-kg-to-orbit reductions that the launch system will provide.

Over the past few decades, improvements in computer hardware have made it possible to run old software much faster – yet this old software is rarely used, as the faster hardware has enabled newer software to dramatically multiply the impact that better silicon has on the world. Similarly, while legacy systems could hitch a cheaper ride to orbit on Starship, the systems of Platform 0 will be far lower-cost and more robust than these legacy systems, even though they would not be possible without Starship.

The cost of this Starship ride to orbit has been estimated by Elon Musk to be on the order of \$1-2MM per launch [25], though we must be careful to recognize the possibility that true costs will be somewhat higher, and to factor in a profit margin for SpaceX. As such, we will tentatively estimate a cost of \$5MM to utilize the full launch capacity of a Starship

TABLE 3: ESTIMATED COSTS OF PLATFORM 0

	Parts	Labor	HM weight (kg)	SM weight (kg)	HM volume (m^3)	SM volume (m^3)
Orbital Launch	$5,000,000					
Module Bodies	$210,000	$260,000	9,500	9,500		
Tethers	$10,000		1,000	1,000		
Spin Thrust	$400,000	$200,000		17,000		9.6
Stationkeeping	$100,000	$200,000	50	50		
Oxygen	$25,000		1,700		1.2	
Sofnolime	$10,000		1,250		2	
Air Management	$10,000	$200,000			0.25	
Cooling System	$100,000	$200,000	1,000		0.5	
Trace Contaminant Control	$10,000		10		0.25	
Water	$10,000		700		3.8	
Power	$100,000	$200,000	500	400	0.1	
Food	$10,000		300		1	
Docking Adapter	$1,000,000		1,000			
Interior Finishing	$90,000		2,000			
Avionics	$10,000	$200,000				
Warehouse	$600,000					
Technicians		$200,000				
2nd Year of Labor		$1,460,000				
Mission Engineer		$600,000				
Project Lead		$2,000,000				
Taxes + Benefits		$2,290,000				
Totals	**$7,695,000**	**$8,010,000**	**19,010**	**27,950**	**9.1**	**9.6**

for a ride to orbit. The total estimated cost of Platform 0 is summarized in Table 3, and the components of this cost will be discussed in turn below.

The total LEO payload capability of Starship is still unknown, but present estimates range from 100T – 200T. As discussed in the introduction to this paper, Platform 0 and its successors will need to be placed into an equatorial low earth orbit to eliminate the need for radiation shielding [20]; so given the possible need for plane change maneuvers, we will restrict ourselves to just below the lower limit of these payload estimates, and plan for Platform 0 to weigh no more than 90T.

2. The Basic Structure

While FEMA recommendations for minimum closed-quarters living space range as low as 60 sqft per person [48], 200 sqft is a common target, and so we will provide this amount of habitable floor space on Platform 0. Utilizing the bola architecture explained above in the context of Platform B, it is possible to fit an equally-sized habitat module and service module into the officially published Starship payload bay dimensions [49], the former of which delivers the target amount of floor space along with 7' ceilings and ~10" of usable hull thickness, as illustrated in Figure 3. This hull thickness is more than sufficient to accommodate the Whipple shielding needed to protect against micrometeorite strikes [50].

As shown in Figure 3, the two modules of Platform 0 would be held together by four tethers, each measuring roughly 106m long. These would be coiled in the Starship payload bay for launch, and unravel after orbital deployment in the same manner as the tethers of Platform B.

This tether length would allow the living area to be kept at earth-normal gravity with a station rotation rate of 4rpm, which the previously mentioned research of Al Globus suggests as an upper limit for human comfort [22].

Note that while the module floors are – for simplicity – depicted as flat in most figures here, the actual floor of any habitat module would have a slight curvature so as to remain orthogonal to the centripetal force at all points along it; i.e. so that the artificial gravity would always push a resident directly into the floor. This actual degree of this curvature is shown in Figure 4.

The costs for this structure are summarized in Table 3. The two modules would be built with the same construction method as Starship – rolled steel sheets welded into tanks; specifically, three layers of 12-gauge rolled steel to approximate the Whipple shielding layout of the ISS [50]. The tethers, meanwhile, would be steel ropes selected for a 5:1 safety factor, which a 1.25" diameter would provide even if the modules' weight utilized the entire launch mass budget [47]. Figure 5 shows a completed Platform 0 from a particular angle to better illustrate its structure.

3. The Propulsion

Figure 6 shows a number of options for the initial spin-up of Platform 0, of which Option 3 – the same one utilized by Platform B – is by far the simplest, and therefore likely the most cost-effective.

While we do not expect an actual human to ever live aboard Platform 0, the demonstration of its function requires a design that would allow for this. Since a human would not be able to dock with and enter the habitat module after the station has spun up, and since the ECLSS assumes at least some level of gravity in its design, the station must spin up somewhat quickly to keep a human who entered before spin-up comfortable. This is in contrast to Platform B, which has no constraints on its spin-up speed and could even use a

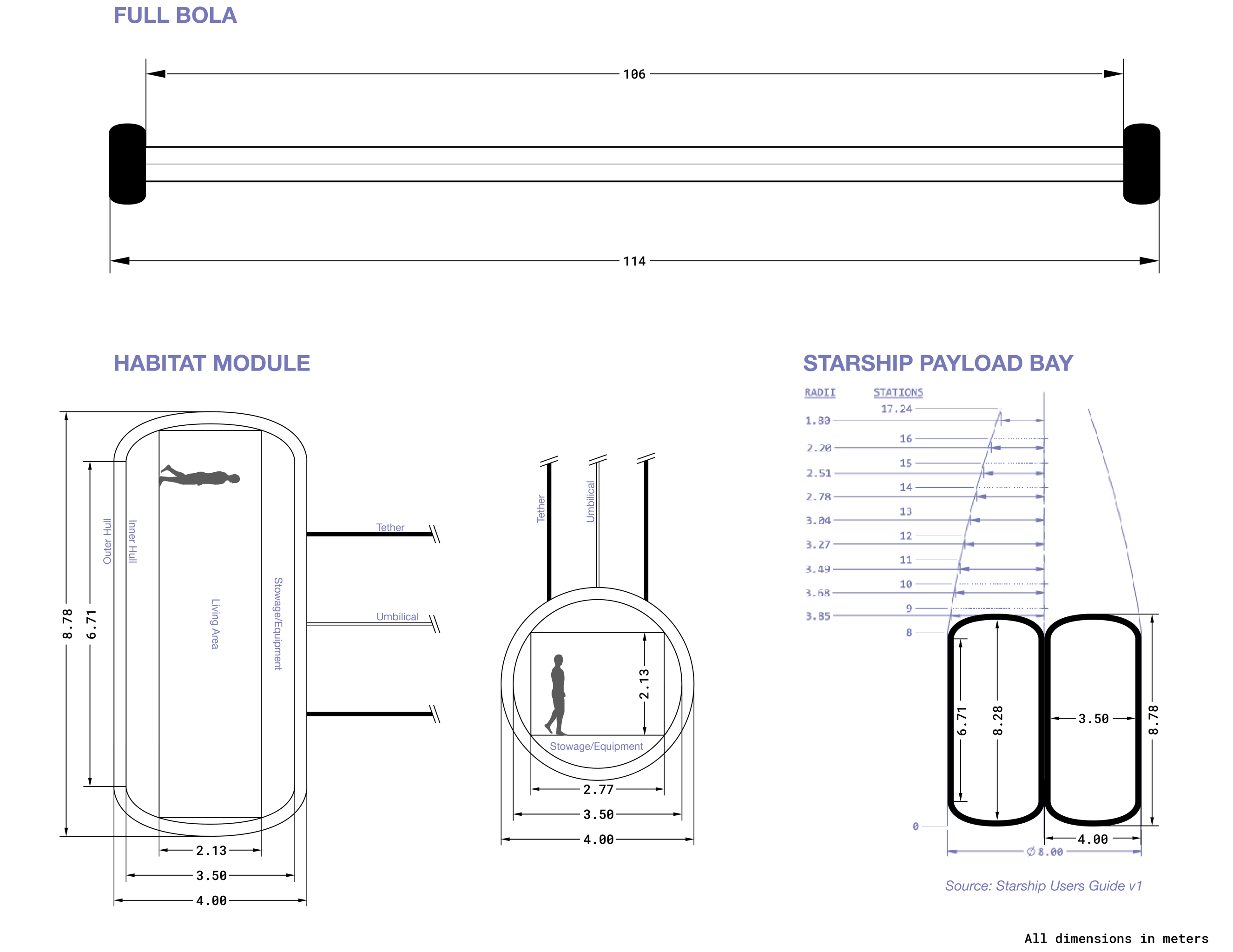

Fig. 3: Platform 0 Basic Structure

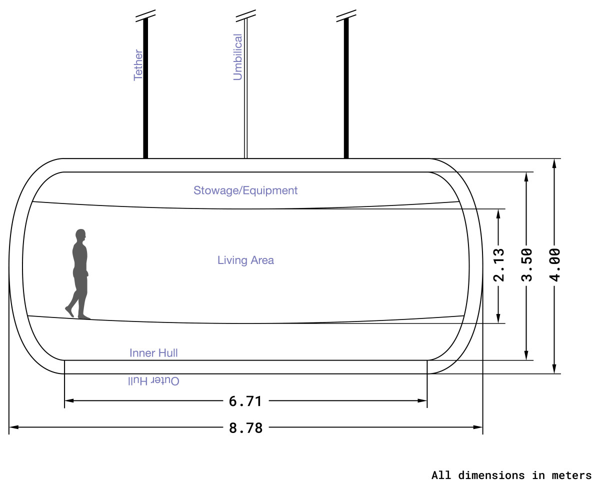

Fig. 4: Habitat Module Floor Curvature

slow ion thruster if doing so proves most viable. The end of Platform 0's mission poses a simpler constraint – the tethers need only be severed for the habitat module to become a temporary microgravity space station in an orbit just 23m/s (the modules' linear speed at 4rpm) away from its original, allowing a spacecraft to easily dock and pick up the hypothetical resident at the end of their stay.

Thus, Platform 0 requires at least one moderately powerful thruster (as illustrated in Figure 6, Option 3) to successfully accomplish its mission. To reach a quarter of earth normal gravity within 6 hours of spin-up beginning, and full earth normal gravity within 12 hours (this is likely sufficiently fast for the ECLSS and theoretical resident), this thruster must be capable of producing 48N of thrust and imparting a delta v of 23m/s to the design limit wet mass of 90T [47].

Constrained far more by cost than by mass, Platform 0 could meet these requirements with a cold gas thruster system rather than the more conventional (for a spacecraft of this size) hypergolic motor. This requires 3T of propellant and a quite significant 14T of 7500 psi steel tanks – but the mass budget allows it, and the cost is minimized. The cold gas system could be extended to a number of thrusters around the two modules, which would maintain desired station orientation and rotation based on the lessons in rotational dynamics learned from Platform B.

4. The Life Support

Platform 0's ECLSS will be a direct descendant of the systems first developed for Platform A. While many of the cost savings described so far stem directly from the nonlinear ef-

Fig. 5: Platform 0 in LEO

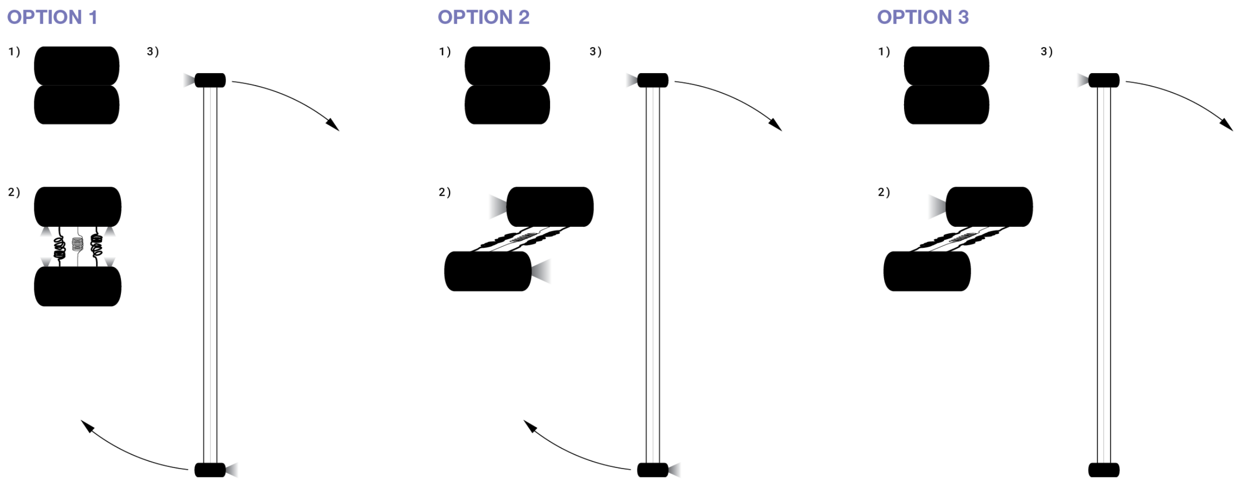

Fig. 6: Platform 0 Spin-up

fects of the drastic reduction in cost-to-orbit that Starship will provide (e.g. a welded steel body is somewhat heavier than one made of machined aluminum, but orders of magnitude cheaper), ECLSS is the arena where dramatic cost savings begin to likewise stem from the earth-normal gravity environment that the habitat module will be exposed to – as Platform A itself demonstrates.

In particular, atmospheric management – perhaps the most intimidating component of ECLSS – will be handled on Platform 0 exactly as it is handled on Platform A. Bays of Sofnolime will remove a year's worth of CO_2 from the air (LiOH remains an alternative option), while fresh O_2 will be metered in from compressed gas tanks throughout the yearlong mission duration. Extrapolating the figures calculated in the Platform A section of this paper, 307kg of fresh O_2 will be needed, for a mass impact of 1.7T when including 7500psi steel tanks. The Sofnolime needed for a year of CO_2 capture will weigh in at 1.25T and occupy 2 m3 in the habitat module. The cost, weight, and volume impacts of these systems are summarized in Table 3, and their volume/arrangement can be seen in Figure 7.

A central air handler will, as in Platform A, deal with trace gas contaminants by using expendable activated carbon filters. It will also dehumidify the air by running it over evaporator coils – though in the case of Platform 0, these coils will not be part of a dedicated dehumidifier, but rather part of a temperature management system. The heat-expelling radiators of this system (space stations in LEO are net producers of heat) will be located under lips that run along the sides of the habitat module, as can be seen in Figure 7. With the station oriented to rotate about an axis orthogonal to the sunlight (note the bottom right illustration in Figure 7, as well as

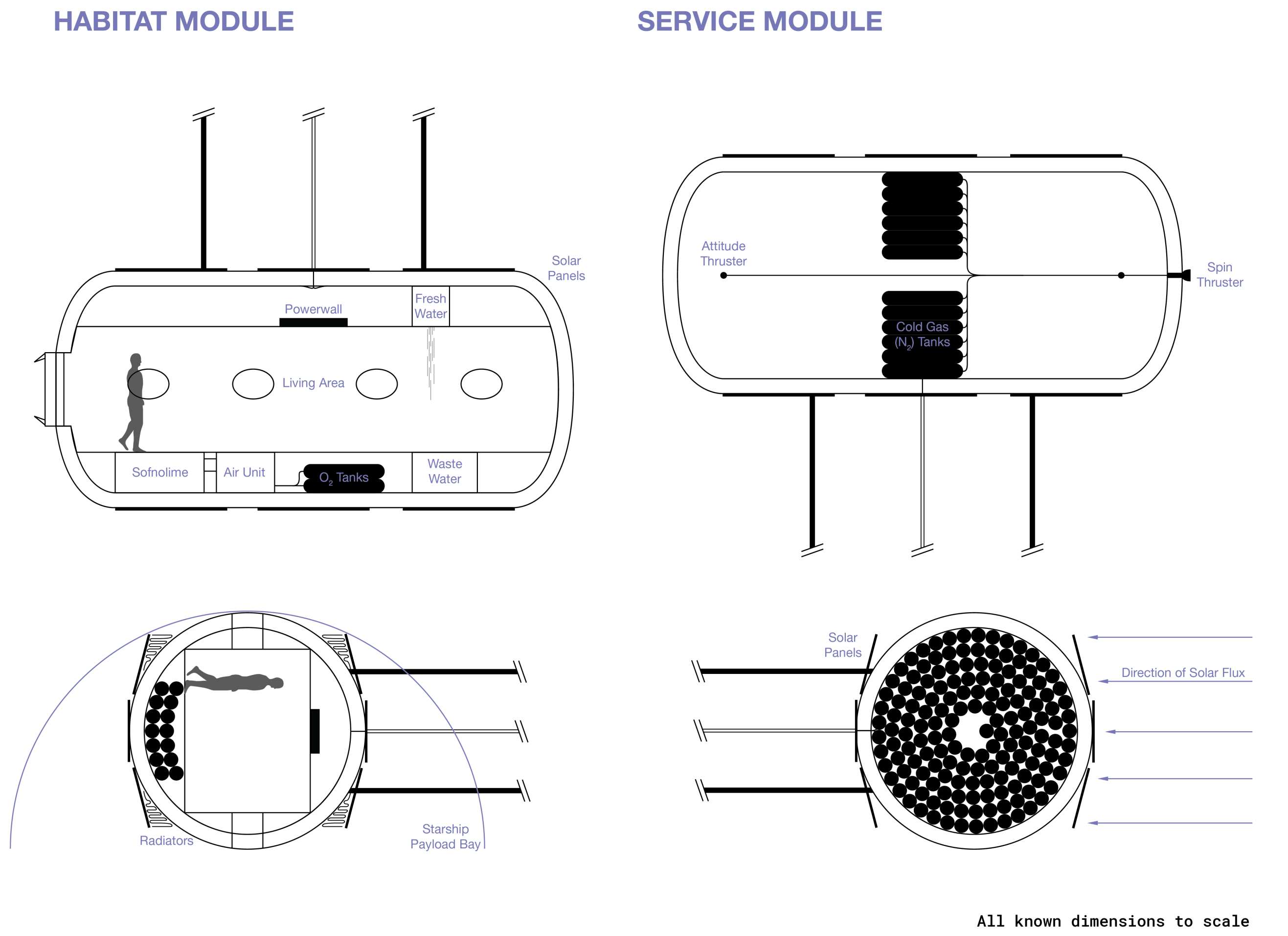

Fig. 7: Layout of Platform 0 Systems

the shadows in Figure 8), these radiators will remain in permanent shade, which is necessary for optimal function. In Figure 8, the radiators are illustrated with a slight red hue.

The evaporator coils of the heat management system, on which moisture from the air of the habitat module will condense, illustrate yet another significant cost saving afforded by the earth-normal gravity environment. In microgravity, moisture must be removed from these coils in complicated and expensive ways (such as specialized coatings and suction). On Platform 0, it will simply drip off, exactly the way it does in analogous systems (air conditioners) on Earth.

Water and waste will be managed on Platform 0 similarly to how they are managed on Platform A. Using NASA estimates for water need on long-duration missions [39] and recycling the cooling system condensate as drinking water brings the total freshwater need for the mission to 0.7T, along with space prepared for 1.2T of wastewater storage [47] (recall that humans are net producers of water – the 0.5T of new water will be a downstream product of the oxygen and food aboard the station). The NASA estimates include wash water – so like Platform A, Platform 0 will have both a simple (tank) toilet and a shower. In microgravity, both of these systems would be prohibitively expensive. Aboard Platform 0, they will require only basic valves – even the shower can be gravity-fed if the fresh water is stored in the upper part of the habitat module, as illustrated in Figure 7.

5. The Power

Like most spacecraft currently in LEO, Platform 0 will draw its electric power from solar photovoltaics. As explained above, the station will maintain its axis of rotation orthogonal to the sun in order to keep its radiators shaded; this means that the tops and bottoms (as well as the ends) of the modules will be exposed to the sun, each point in these regions receiving a sinusoidal amount of solar flux as the station rotates. Figure 9 illustrates the base of one of the modules near peak solar flux.

Off-the-shelf photovoltaic systems decline significantly in price each year, and the minimalist (gravity-assisted) ECLSS of Platform 0 will require little power – an estimated 1.5kW at peak draw [47].

This demand can be adequately met with a single Tesla Powerwall and 13 standard Tesla solar panels (providing 3kW of power generation during orbital day and adequate power storage during orbital night) [47], arranged as depicted in Figures 7 and 9. Briefly – these are 19.8% efficiency panels [51] with an operating temperature range suited to orbital demands [52], capturing an average of 16 square meters of solar flux in this arrangement.

6. The Assorted Systems and Overhead

In addition to the primary systems outlined above, Platform 0 will need a few more components in order to be fully mission

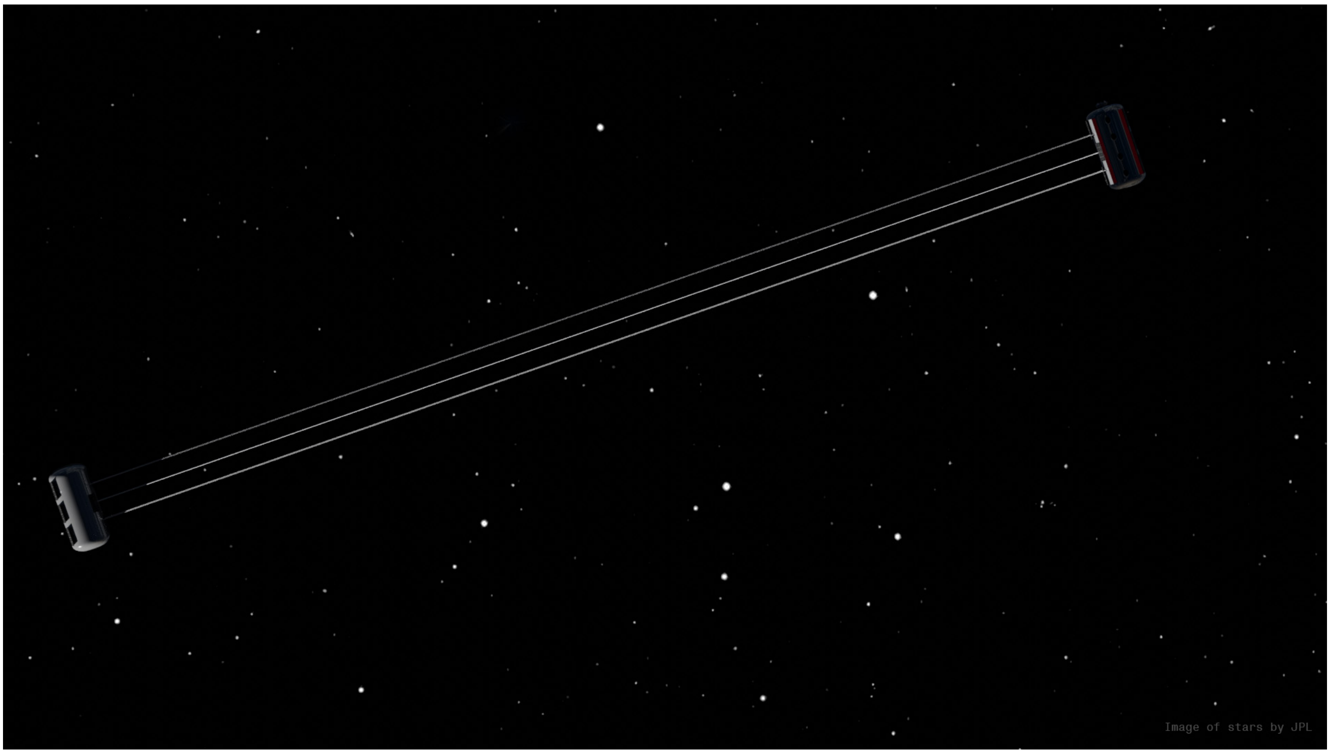

Fig. 8: Platform 0 in its Rotation Orientation

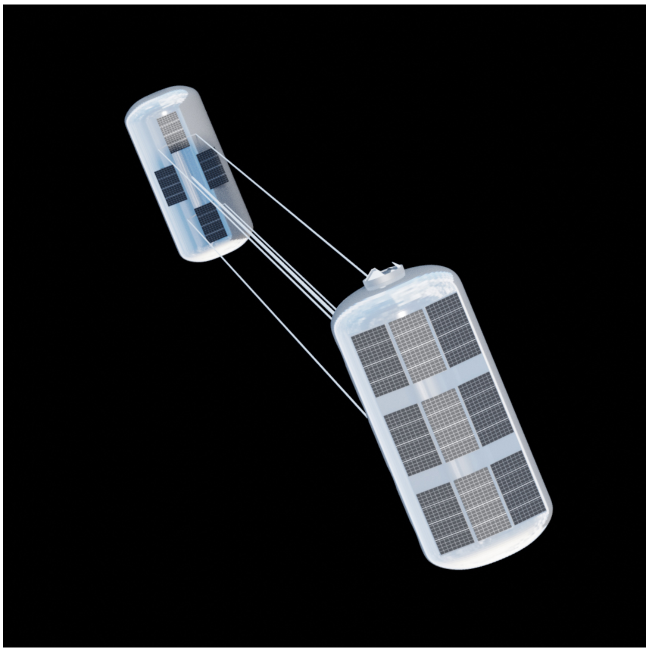

Fig. 9: Platform 0 from Module Base

viable. Again, the costs of these are summarized in Table 3 and briefly discussed below.

Even with no real human to consume it, the station would need to stock a year's worth of hydrated food, as the water calculations assume. Given a reasonable diet, the mass and cost of this food would be a rounding error in the total station plan.

A docking port would need to be installed in the habitat module. To save cost, no associated airlock would be provided, and any docking spacecraft would be expected to pressurize the interspace before opening the station's hatch. A standard International Docking Adapter can be procured for around $22MM [53], but this is the sticker price of a human-rated system from a major contractor; and machining a similar assembly from open NASA plans would cost far less.

Finally, avionics exceeding the standard of Platform B and furniture exceeding the standard of Platform A would need to be provided – the budgets for these are correspondingly higher for Platform 0 than for its pathfinder counterparts.

As shown in Table 3, the materials costs of the mass-liberated design of Platform 0 will consume a minority of its budget. Most of the expense will come from designing and building the system – and so Table 3 attempts to capture the entire organizational cost of the project. The exact rationales for these labor cost estimates can be seen in the original paper on Platform 0 [47] - in reading Table 3, it should be noted that the system-delineated parts of this table assume one year of engineering work on their corresponding systems.

Near the bottom of the table, additional costs are added to estimate the expense of leasing and maintaining a warehouse near Boca Chica for two years; of hiring additional technicians to aid in the assembly of Platform 0; of retaining the engineers and technicians for a potential second year of work; of hiring a mission engineer for a two year build phase and yearlong mission; of hiring a very seasoned project lead for four years; and of paying the payroll taxes and benefits for this combined workforce.

7. The Inflection Point

The operation of Platform 0 for one year in orbit will be a success for the company which builds it, and for many others as well – for the first time in history, AG will be proven in a real-world example as the ideal form of human housing in space. While this will likely draw new suppliers to the AG space station market (further advancing our ultimate aim, which is the human settlement of free space), the company which builds Platform 0 will have a tremendous first-mover advantage, both in its unique practical knowledge of how to make viable AG space systems as well as in its highly visible position as the leading provider of these.

As such, the possible customers for AG space stations will likely turn to this company before anyone else; and the capital markets will respond in turn to profit from the opportunity presented by owning a significant share of this rapidly growing market of critical infrastructure. With the success of Platform 0, investment in the company will be significantly de-risked, and securing the funding necessary for the further stages of the LEO Platforms plan will be much easier than before. In the Platform architectures that follow, we will not delve into costs with the detail we afforded these in Platforms A, B, and 0; though we will continue to refer to high-level customer economics (as the project will continue to become more profitable with each stage) and recognize that continued investment will likely be required.

b. Platform 1: The First Customers

By the time Platform 0 has completed its year in orbit, likely not before 2028 given the timetable-limiting requirement of commercial Starship launches, real and immediate demand will exist for the orbital housing provided by the LEO Platforms.

The space economy grew by 55% from 2010 to 2020 [54] but is expected to more than triple from 2020 to 2030 [55]. At a rough estimate, this would increase the population in orbit from around 13 in 2020 to around 40 in 2030; but the recent advent of commercial human spacecraft in the US, some of which have begun flying private astronauts, suggests that the number of orbital residents may be much higher than this by the time Platform 0 has proven itself.

While the exact reasons these astronauts will have for being in orbit are difficult to predict, it is reasonable to assume that some will be there as tourists, some will live aboard the three Commercial LEO Destinations space stations that NASA has selected for this program [15], and some will be employed maintaining the orbital factories of the rapidly-growing space manufacturing companies which aim to establish these in the coming years.

Each of these three industries (tourism, government space presence / research, and manufacturing) would benefit from and be interested in the affordable and healthy orbital housing that AG space stations could provide. A flight-proven Platform 0 architecture could conceivably serve some of these interests, but a slightly augmented architecture could serve them all.

Specifically, such a station would need to be accessible from microgravity while rotating – whether connected to a microgravity station at its center of rotation, as the proposed Nautilus X module would've connected to the ISS [13], or simply providing an always-accessible docking port there – which would allow indefinite access and resupply without stopping the rotation. This could be accomplished with a small docking module at the center of the station, and pressurized cylindrical tunnels leading from this hub to the two rotating modules. If Platform 1 is indeed connected to a microgravity station, its center of rotation would need to stay fixed as astronauts move from hub to habitat module and back – pumps transferring unused consumables in the direction opposite astronaut motion could facilitate the required balance of mass distribution.

Additionally, it would make sense for some of the systems tested aboard Platform 0 to be made more robust and easier to maintain – for example, a system for venting wastewater as harmless aerosol could be set up, and the carbon dioxide absorption pellets replaced with a regenerative system cycling amines or metal oxides, like the systems used aboard the Space Shuttle Orbiter or modern submarines [56]. The low mass cost afforded by Starship would likely mean that oxygen regeneration and water purification, however, would remain less economical than refilling the expendable oxygen and water reserves with infrequent resupply visits.

Note that Platform 0 has a lot of unutilized design mass, as shown in Table 3. On Platform 1, some of this would be taken up by the introduction of the expandable tunnels and hub module, though mass optimizations learned from Platform 0 would likely mean that Platform 1 could be filled with more consumables, allowing for two or three people to live aboard a single station before space constraints become an issue.

Most importantly, however, the lessons learned from Platform 0 will enable the company executing the LEO Platforms plan to develop improvements to their architecture and systems that are difficult for us to predict today. All of these improvements – combined with the persistent microgravity access – will come together as the Platform 1 architecture: effectively a Platform 0-style station ready for actual commercial use. Figure 10 depicts how such a station might be arranged.

Platform 1, like Platform 0, will launch fully assembled in a single Starship payload bay. Depending on the strategic focus of the company developing it, each unit will likely be built and launched at a profit for the company, and the company may choose to further profit by providing these units as a continuing service (much as launch companies provide their spacecraft) rather than a sold asset meant for a customer to own and operate.

Platform 1 may fully satisfy the orbital housing market for anywhere between a year and a decade, depending on the growth of demand. With time, one or more 'neighborhoods' could be established where individual Platform 1 stations orbit in a line, spaced hundreds of meters apart, each owned by a nation, company, or wealthy individual, the constellation accessed through regular Starship launches that visit each station in turn before returning to the Earth.

At some point, however, demand will emerge for a single AG station that can support more than two or three astronauts at a time – and it will behoove the company building the LEO Platforms to answer this demand in the simplest and most cost-effective way possible.

c. Platform 2: Expanding to Dozens of Residents

As soon as more astronauts need to be housed in a single location than Platform 1 allows, a need will emerge for a larger architecture – since the Platform 1 system does not lend itself to modular growth.

Consider the simple modular case – connecting two Platform 1 stations along their axis of rotation, such that their

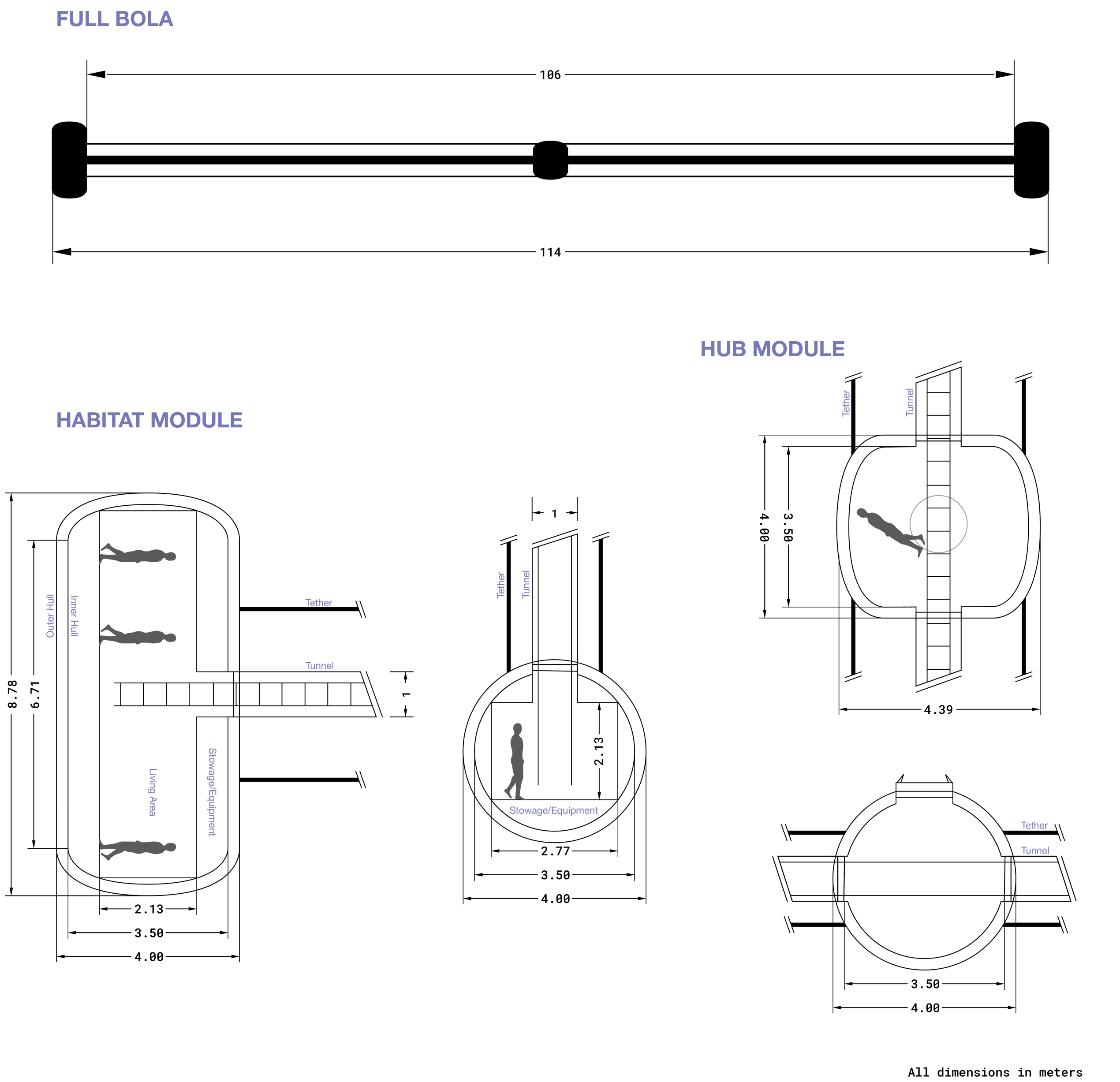

Fig. 10: Potential Platform 1 Structure

central hubs, habitat modules, and service modules are each docked to their counterparts. Depending on the precise mass distribution within the modules, the axis of rotation will likely no longer be the axis with greatest moment of inertia (and if three Platform 1 stations are so connected, the axis of rotation will certainly not be the axis with greatest moment of inertia), but rather the intermediate axis. This leads to dynamically unstable rotation – a situation that only worsens as more Platform 1 stations are docked together.

Of course, incorporating as much as possible of the Platform 1 systems and designs into a larger station would lead to savings in engineering cost, validation time, and design risk – the key is that the modularity must exist not at the level of multiple Platform 1 stations joined together, but rather at the level of Platform 1 modules (habitat, hub, and service) joined together in an entirely new arrangement. To avoid rotation about an unstable intermediate axis, these modules must be arranged in a single plane orthogonal to the axis of rotation.

While a design joining these modules end to end (a 'circular chain of hot dogs') would work, a design that pivots the axis of rotation 90 degrees from the Platform 0 and 1 designs (the 'bullets in a revolver') would be preferable. This is primarily because even a single plane of this new Platform 2 design would allow each module to extend a central 'hallway' bisecting two private spaces – while an end to end (chain of hot dogs) design would require that the entire module serve as the hallway, eliminating the possibility of sizeable private space without the costly addition of additional planes of modules along the axis of rotation. While the ISS is arranged principally in this 'everything is a hallway' manner, and many future space stations will likely be as well, the possibility of meaningful private spaces would allow for multiple disparate tenants aboard a single Platform 2 station – be they residents in a space hotel, researchers working in separate labs, or even astronauts from varied countries engaged in non-public work.

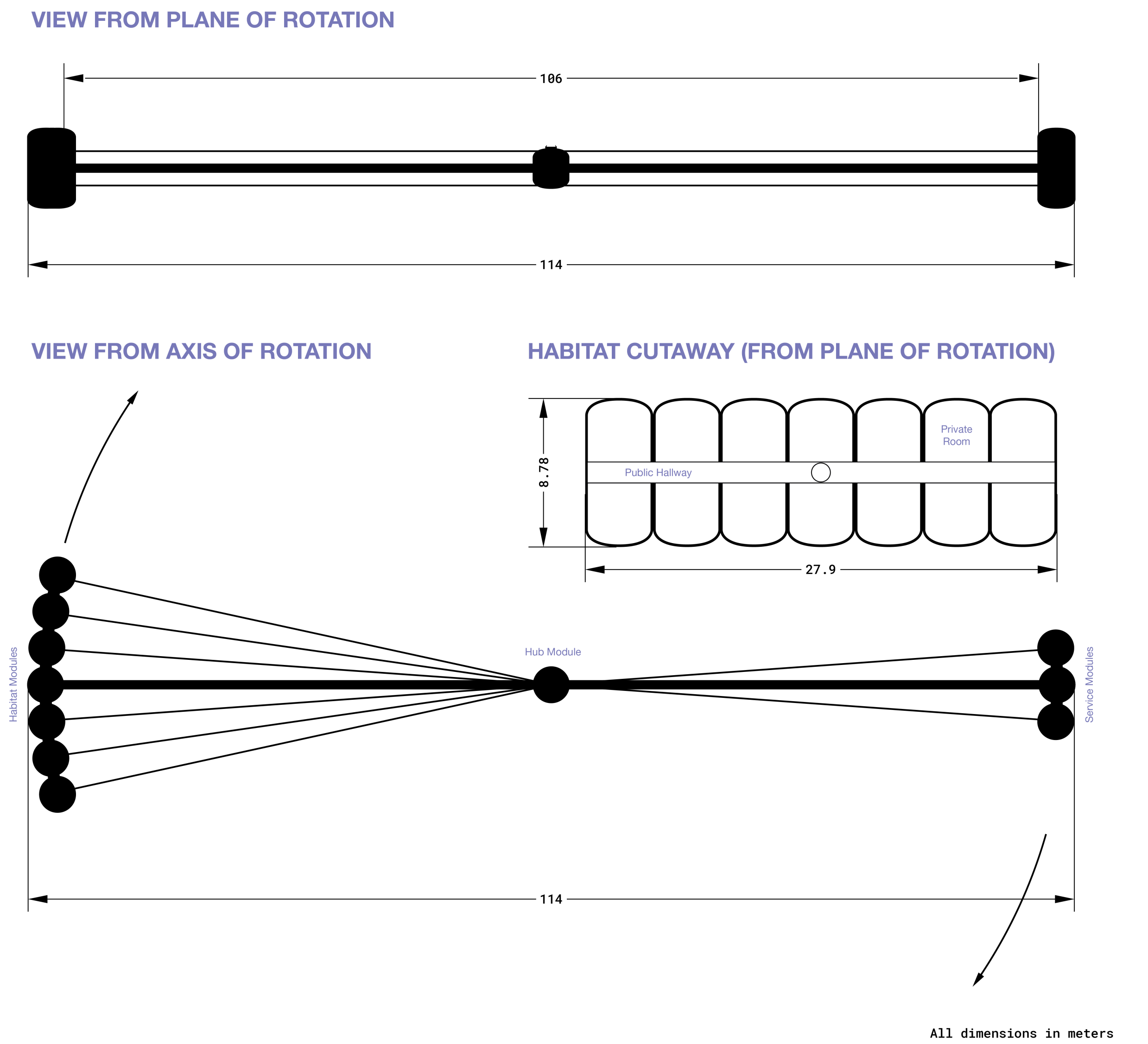

Fig. 11: Potential Platform 2 Structure, 11 Modules

This proposed design for Platform 2 is depicted in Figure 11, showing an example seven habitat modules connected to a single hub module and three service modules. A one-to-one ratio of habitat module to service module would likely be unnecessary, though this would depend on the precise employments of the habitat modules and how much resources they would require from the bank of service modules. Figure 11 depicts these modules connected by a system of tethers, though as the number of modules grows, perhaps even to multiple planes of modules, a truss system may become more appropriate.

As currently proposed, the Starship payload bay could hold three of these modules, along with a significant amount of tether and collapsible tunnel. As such, the depicted 11-module (7 habitat, 3 service, plus a hub) Platform 2 would require four Starship launches. It will be physically possible but in practice extremely difficult to add modules once the station is already rotating, so all of these modules will likely be connected prior to station spin-up. This means that the modules will need to be designed for rapid and simple docking and launched in quick succession – with the station spinning up only when fully assembled, using propellant thrusters but probably not cold gas thrusters.

A completely filled circle or plane of modules will consist of one hub module and a total of roughly 88 habitat and service modules. Approximating one resident per ‘private room’ (as defined above and depicted in Figure 11), and a roughly 2:1 ratio of habitat to service modules, this means that a single Platform 2 plane will be able to house up to 120 astronauts.

This will likely be sufficient for all conceivable commercial needs for quite some time – and when a greater resident capacity per station is finally needed, it will be possible to spin up another Platform 2 plane and dock it with a primary plane. While this will be a maneuver requiring precision, there is nothing excessively risky about it (unlike the prospect of docking a single module into an already rotating Platform 2 plane). Since a full plane (i.e. an object with full rotational symmetry about one axis) is not prone to dynamic instability so long as it rotates about its axis of symmetry, any number of planes could be ‘stacked’ in this way, extending a single Platform 2 station to a size limited only by its rather narrow hallways, and the tendency of chokepoint congestion to grow exponentially as more planes are added.

It is likely that the company pursuing LEO Platforms will be able to reach significant profitability and enterprise value at this stage, developing largely Platform 1 and Platform 2 stations for a variety of clients across a growing space economy in the years 2030 through 2050. Indeed, due to the large population limit of a single Platform 2 plane and the possibility of the architecture to transcend even this limitation through the addition of further planes, nearly any commercial use case considered in the coming decades could have its needs fully met by this architecture – serving space workers and tourists alike.

The demands most likely to drive development of yet more accommodating architectures will be those for leisurely housing: While workers and adventure-seekers will not mind the cramped quarters of Platform 2, the true possibilities for vacation homes and even settlement in orbit will only be met by more open and engaging spaces. This, then, will be the impetus for the third and final phase of the LEO Platforms pathway.

IV. The Third Phase: Initial Space Settlement

a. Platform 3: The First Monohull Station

At a certain point in the growth of the human population in orbit, demand will shift from the purely functional (furthering tourism or space work) and begin to include a desire for home or 'land' ownership in space. This novel type of demand is unlikely to develop absent a robust space tourism industry, as those curious about the experience of spending time in space would be, for a period, adequately served by the accommodations of facilities like Platform 1 and Platform 2. But at a certain point, those with the resources to aspire towards a greater personal presence in orbit – be it something akin to a vacation home or even a semi-permanent residence – will create a market for the type of space residence that the habitat modules of a Platform 2 would simply be too cramped to provide.

This demand for more accommodating spaces will not be limited to private individuals. As the possibility of time spent in space transitions beyond the merely functional and towards the luxurious, governments and corporations will want to show their prestige and inspire their executives with board rooms on 'floors' higher than any skyscraper could ever reach.

A demand for comfort and luxury cannot easily be met with modular units – this will be the first time, then, that it makes business sense to construct a cohesive monohull (single pressure vessel) space station, divided into wide, comfortable spaces for any number of tenants.

This deep into the LEO Platforms plan, it is difficult to predict the specific designs that the lessons of stations built to date will lead to – we aspire only to set a strategy for the LEO Platforms plan, and believe that a key step in this strategy will be moving beyond modularity and building the first, simplest monohull station in Platform 3. Besides the aforementioned demand pressures for a monohull station once Platform 2 stations are commonplace, it is clear that the final stage of the LEO Platforms pathway – a Kalpana Two-style station – will not be modular; and so it makes sense for the company pursuing the LEO Platforms plan to gain experience in monohull construction via an architecture smaller and simpler than Kalpana Two. What follows is one possible way that this Platform 3 – the first monohull station – could be designed.

In meeting the goal of providing more expansive space than could a full-ring Platform 2, it will likely make sense for Platform 3 to nonetheless roughly preserve the dimensions of its predecessor, so that control and other systems are a known quantity, and the novel challenges are restricted to the transition from modular to monohull construction. As such, Platform 3 may follow a design similar to that shown in Figure 12.

This design calls for a floor diameter (112m) and thus 1g rotation rate (4 rpm) consistent with all Platforms so far. Its living spaces are of the same height as those in the preceding Platforms and allow for the same mechanical space above and below. The differences begin with the cross-width of the spaces, which grows from the approximately 9 meters that a Starship payload bay could handle to a full 20 meters, a breadth impossible to achieve with modular construction. The spaces are capped with floor-to-ceiling pressure hull windows, and they are bisected along the plane of rotation by a hallway leading to tunnels to the central hub – both the hallway and the tunnels being double the width of their Platform 1 and 2 predecessors, allowing for a comfortable elevator ride to the hub. The hub itself has twice the diameter of previous hubs, requiring the full breadth of a Starship payload bay at launch.

Critically for our goals of personal and business luxury, this design could afford rooms with 7 foot high ceilings and a 27 foot floor span. The total floor circumference would be about 1150 feet, for a total private floor area of 62,000 square feet. This in turn would be sectioned as commercial demand dictates – whether that be 6 offices of 10,000 square feet each, 60 residential units of 1,000 square feet each, or something in between. Each private unit would be pressure sealed from the others in the unlikely event of a hull breach, but the residents would otherwise live in a single cohesive structure.

Platform 3 would represent the greatest technological challenge since Platform 0. The modularity of Platforms 1 and 2 means that these predecessor models can launch fully assembled (in the case of Platform 1) or assemble quickly and easily in space, from fully built modules, by using docking ports and standardized tether attachment points (in the case of Platform 2). Platform 3, however, would launch as pre-fabricated hull slabs at most – and these would need to be assembled and pressurized in space before the station could spin up.

Nor would this assembly be restricted to welding (or latching) hull segments together – plumbing, electrical, flooring, and all manner of other components would either need to be installed in orbit or seamlessly connected between prefabricated segments. In either case, the amount of labor needed to assemble even a single Platform 3 approximates that of a modest construction site on Earth. This means that assembly would require either a large team of astronauts or of specialized assembly robots. The latter seems more likely, but no present technology comes close to meeting the need.

Surmounting the technological barrier of monohull assem-

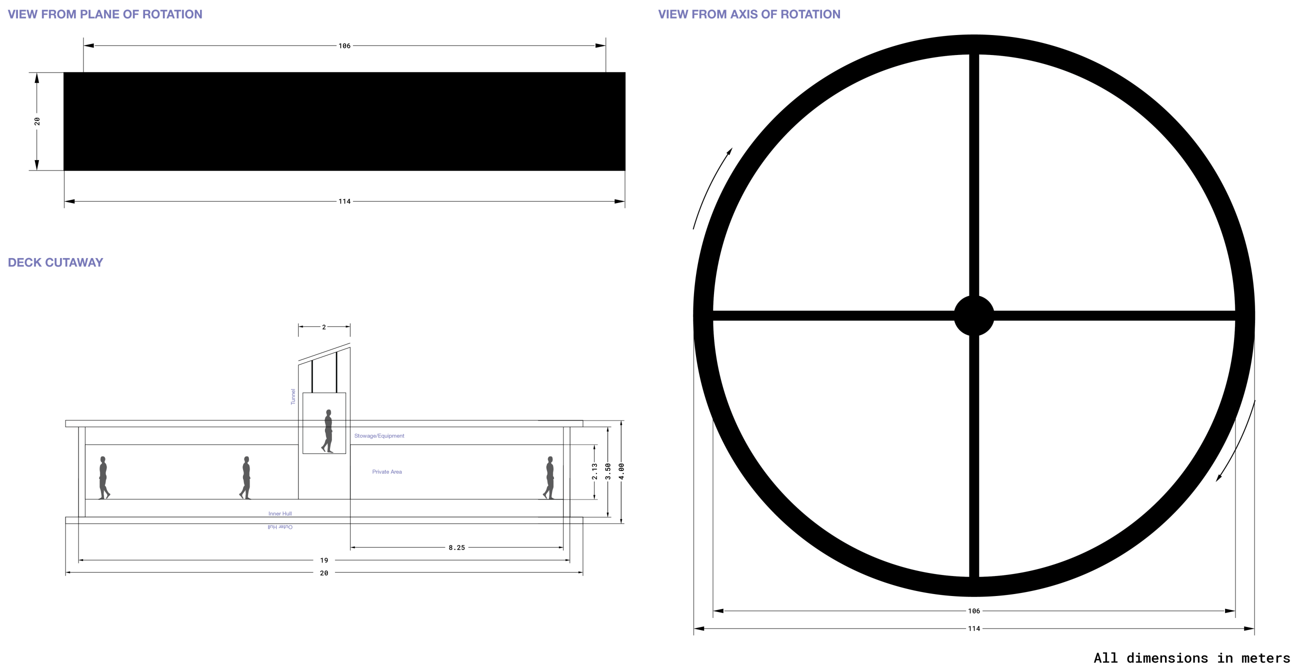

Fig. 12: Potential Platform 3 Structure

bly in space, however, would build a formidable moat for the company pursuing LEO Platforms, and make directly possible the end goal of the pathway: The construction of the first space-settlement scale AG station.

b. Platform 4: The First Settlement

While Platform 3 will provide a standard of living in space that far exceeds anything which came before, it will still ultimately constrain residents to rooms within a circular building – with only the elevator tunnels extending more than 7 feet in height. As the idea of luxury living in space is shown to be possible, and becomes more accepted and desired, demand will begin to emerge for the open-air habitats envisioned since the times of O'Neill – sufficient demand to finally present a business case for the construction of the smallest such viable habitat. With the experience gained in building and operating one or more monohull Platform 3 stations, the company pursuing the LEO Platforms plan will be perfectly situated to fulfill this demand and complete the pathway.

As of the writing of this paper, no smaller viable habitat has been proposed than the Kalpana Two design set forth by Al Globus in 2017 [21] and expanded upon by Tom Marotta in 2018 [23]; so we proceed with this as the structural concept for Platform 4.

Platform 4 will thus be a cylinder approximately 112m in diameter, rotating at 4rpm to produce 1g of AG at its primary 'floor level'. The 'bare' cylinder will have a floor space of approximately 424,000 sqft, though a second residential story will nearly double this, and a third 'communal deck' of ponds and grassland will provide access to the open space of the settlement from the residences below [57]. Life support and other equipment can be housed below these three stories, or closer to the central hub. Figure 13 presents an artist's conception of how such a station may look from the inside.

It is likely that the first Platform 4 stations will be luxury residences for those who seek an even more exclusive experience than that afforded by Platform 3. It is difficult to estimate the rate of demand growth for life in AG space habitats, as this will be a social phenomenon. However, placing the mass of such a station into orbit is estimated to require only 140 Starship launches; and the construction costs will come down with each succeeding station built, as the company building them gains additional experience and economies of scale. In other words, the supply should quite rapidly grow to lower the barriers to life aboard a Platform 4, allowing people of more and more modest means to purchase residences as more Platform 4 stations are built. This will only be furthered by the fact that an operational track record for one or two Platform 4 stations will likely open the door to reasonable insurance prices, and therefore mortgage-assisted ownership aboard later Platform 4s.

Eventually, life aboard a Platform 4 will go from being a billionaire vacation retreat, to a conventional choice for a remote office worker. Somewhere along that transition, the first families will choose to come up to a Platform 4 with no intention of returning to the Earth. Some of these people will decide that they are ready to raise children aboard these stations – and so the first generation of space settlers will finally be born.

V. Conclusion

The dream of artificial gravity space settlements has been a guiding aspiration for many people in the century since the concept was first proposed – inspiring space enthusiasts, many works of science fiction, and quite a few serious engineering studies among NASA and its international counterparts. While perhaps esoteric in a short term view, the need for space settlement is clear in the long term – the Earth will

Fig. 13: Interior Concept for Platform 4 / Kalpana Two | Credit: Bryan Versteeg

become uninhabitable one day, and the sooner that viable populations in space can be established, the lower the risk that humanity will be extinguished by a single event aboard the single planet we currently inhabit. This fact has been cited by Elon Musk and Jeff Bezos (among many others) as the greatest driver of their work, and by philosophers as an argument for putting immediate priority on the development of human life in space [58].

While much has been said, planned, and designed regarding large space settlements [3] [8] [16] [17] [18] [19] and, recently, smaller space settlements [21], there has been, to our knowledge, no viable pathway proposed for a sustainable business case that confronts the modest space station demand of today and enables the growth of that demand until the first AG space settlement can be built – relying purely on profitable investment returns rather than on any public or philanthropic funding. This paper has attempted to show – in the LEO Platforms plan – that such a pathway is possible.

In the long run, space settlement is inevitable (except in the case of human extinction) and will eventually grow to support a large portion of the total human population. The companies that capture the space settlement market are therefore poised to return tremendous gains to their investors – and the LEO Platforms plan shows how this market's first mover can begin its journey today.

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