Space Settlement: An Easier Way

Al Globus, San Jose State University
Stephen Covey, DSI, Inc.
Daniel Faber, DSI, Inc.
July 2017

"Come with me if you want to live," Kyle Reese in *The Terminator*, 1984

Abstract

To survive in the long run, we must settle beyond Earth. We are taking the first steps now, but there are major problems. Lunar or Martian settlements will be very far away and low gravity is a serious issue for children. Free-space settlement designs have typically been kilometer-scale spacecraft weighing millions of tons, requiring both large scale space construction and extraterrestrial mining and materials processing infrastructure before the first settler moves in. To utilize extraterrestrial materials these designs are typically located in orbits very far from Earth, at least as far as the Moon. Being so massive and distant makes construction impractical, at least for a long time to come.

Things are about to change. Two recent discoveries regarding space radiation and human rotation tolerance suggest that the first free-space settlements may have a mass measured in kilotons, rather than megatons, with dimensions around 100 m rather than half a kilometer or more. First, space radiation computations suggest that Earth orbits below about 500 km and close to the equator have radiation levels so low that little or no radiation shielding is required [Globus 2017a]. Second, a careful examination of the literature suggests that permanent settlers can tolerate much higher rotation rates than was commonly thought, allowing much smaller settlements to provide 1g artificial gravity [Globus 2017b].

Between these two studies, the mass of early free-space settlement designs can be hundreds of times less than previously believed and they can be located hundreds of times closer to Earth, vastly simplifying construction and logistics. Furthermore, extraterrestrial mining is no longer required to build the first settlements because of low mass and new, large reusable rockets under development. Also, the first space settlements may be very similar to large, advanced space hotels. Such facilities, in turn, may be developed incrementally from smaller, less sophisticated hotels and stations starting with the ISS (International Space Station), perhaps even at a profit. If the results of this paper are confirmed by further research, a herculean task requiring monumental effort will instead become a difficult but surmountable engineering challenge.

Acronyms

delta-v	change in velocity
g	gravity, 1g corresponds to gravity at the surface of the Earth
ELEO	Equatorial Low Earth Orbit
GCR	Galactic Cosmic Rays
HEO	High Earth Orbit
ICRP	International Commission on Radiological Protection

ISS	International Space Station
ITS	Interplanetary Transportation System
kg	kilogram
L2	Lagrange Point Two
L5	Lagrange Point Five
LEO	Low Earth Orbit
m	meter
mGy	milli-Gray
MPA	megaPascal
mSv	milli-Sievert
NEO	Near Earth Object
rpm	rotations per minute
SSP	Space Solar Power
T	metric ton

Introduction

This paper is about the very first stages of life's growth throughout the solar system and beyond. It is about a radically easier, perhaps the easiest, path to the first space settlements. For the purpose of this paper, a space settlement is a home in space where people go to work, live, and, for those who wish, raise their kids. Raising children onboard distinguishes space settlements from space stations, where astronauts go to work, and space hotels, where people go to play.

In the 1970s a series of studies at Stanford University and NASA Ames Research Center led by Princeton University physicist Dr. Gerard O'Neill suggested the feasibility of building and living in free-space settlements located at the Earth-Moon L5 point or other orbits [Johnson 1975] [O'Neill 1977]. Free-space settlements are essentially gigantic spacecraft in orbit, big enough to live in. L5 is a point on the Moon's orbit equidistant from Earth and the Moon. These studies produced, among other things, the Stanford Torus design, a structure almost two kilometers across, rotating at 1 rpm (rotations per minute) to provide 1g artificial gravity at the rim.

There is a great deal of radiation in space from which settlers inside the Stanford Torus would need to be protected by millions of tons of lunar regolith. This material would be provided by a lunar mining operation involving an electromagnetic catapult on the Moon and a catcher at L2. Progress towards this dream has been slow in large part because the system is so big (kilometer scale with a mass of millions of tons) and it requires an extensive extraterrestrial industrial base to take advantage of lunar materials before the first settler can move in. These materials are hundreds of thousands of kilometers away from Earth.

Building and operating such space settlements is a massive challenge, worthy of a great civilization. However, to date it has been too great a challenge to undertake with the resources available. We propose a three pronged approach to make the first few settlements much easier to develop:

1. Make them close.
2. Make them small.
3. Build up incrementally, ideally with profit at each step.

Building the first settlements close to home makes everything much easier. For the purpose of this paper, closer means Equatorial Low Earth Orbit (ELEO). Equatorial Low Earth Orbit refers to orbits close to Earth and at all points close to the equator[1]. This is much closer than the Moon, asteroids or Mars. A 500 km circular orbit is 760 times closer to Earth than the Moon or L5 and 100,000 times closer than Mars at closest approach[2]. Transportation cost, time and risk are accordingly lower. Unhappy settlers can return to Earth in a few hours. Telephone calls and video conferences can work since communication delays are short. New settlers can get to their new home relatively easily. Evacuation is at least theoretically possible if disaster strikes. The importance of distance is hard to overstate.

A key benefit of ELEO settlement is vastly reduced radiation levels [Globus 2017a]. The mass of previous free-space settlement designs is dominated by radiation shielding. Eliminating radiation shielding reduces the mass of cylindrical designs by a factor of at least 19 and toroidal designs by a factor of about 155 [Johnston 1975] (see Table 1). As we will show computationally, settlements in ELEO may need very little or no dedicated radiation shielding as they will be protected by the Earth's magnetic field and the mass of the Earth itself.

[1] This is a region with far less radiation than other orbits, or the surface of Mars or the Moon.

[2] A note on numbers: there are a lot of quantitative results in this paper. Almost all of them have been rounded off as excessive precision in the data presented here is pointless and misleading. Thus, you should expect to find many small, non-consequential inaccuracies.

Stanford/NASA Ames Mass Estimates

Mass model based on 1975 study	all mass values in metric tons			
shape	structure	air	shielding mass	factor by which the mass is reduced when radiation shielding is not necessary
multiple dumbbells	75,000	37,000	9,900,000	89
multiple torus	100,000	10,400	9,700,000	89
banded torus	112,000	13,200	7,000,000	57
single torus	4,600	1,900	1,000,000	155
cylinder	775,000	299,000	19,400,000	19
sphere	64,600	35,200	3,300,000	34
dumbbell	400	200	1,400,000	2,334

Table 1: Mass estimates from [Johnson 1975]. The first column lists various shapes a settlement could have. The next three are the estimated structural, air and radiation shielding mass in tons. The last column was added by the authors to indicate the factor by which the mass is reduced when radiation shielding is not necessary.

This huge reduction in total mass compensates for the greater energetic difficulty of launching materials from Earth to ELEO as opposed to launching from the Moon to L5, the design location of the Stanford Torus. In the early studies, the Earth-Moon L5 point was chosen as the location of a settlement for the energetic advantage of launching materials from the Moon. Going from the Moon to L5 requires a delta-v[3] of 2.3 km/sec, and going from Earth to 500 km ELEO requires 10 km/sec [Cassell 2015]. Using the velocity squared as our energy measure[4], Earth to ELEO requires 19 times more energy per unit mass. But Table 1 suggests that at least 19 times less mass is needed if no radiation shielding is required. Thus, the energetic advantage to launching the mass of a settlement with deep space radiation shielding from the Moon to L5 is balanced by launching far less mass from Earth if no radiation shielding is necessary.

---

[3] delta-v is change in velocity necessary to move from one orbit (or surface) to another.

[4] One could also use the rocket equation to make the comparison, but that makes the result strongly dependent on ISP and is much more complex. At high ISP (e.g., LOX/H_2) the difference compared to delta-v squared is not great.

Making the first settlements small directly reduces construction difficulty. A village is easier to build than a city. The faster a settlement rotates, the smaller it can be and still provide 1g of artificial gravity at the rim, as needed for children to grow up strong [Globus 2017b]. As we will show from an examination of the literature, settlers can probably tolerate 4 or perhaps even 6 rpm [Globus 2017b]. For the purpose of this paper we assume, based on the literature, that a diameter of around 112 m (corresponding to rotation at 4 rpm for 1g of artificial gravity) is adequate for settlement, as opposed to the 1790 m (1 rpm) or 450 m (2 rpm) diameter found in earlier designs. Since the mass of a torus or cylinder-shaped settlement scales somewhere between the square and the cube of the diameter, increasing the spin rate results in an enormous reduction in the total amount of material needed.

Building up capability incrementally is a time honored engineering tradition because it works. For example, the 1969 Moon landing was built up in stages:

1. one man suborbital flight.
2. one man orbital flight.
3. two man orbital flight.
4. docking and space walks.
5. three man orbital flight.
6. circumnavigation of the Moon.
7. “That’s one small step for (a) man, one giant leap for mankind.”

Similarly, we propose starting with the International Space Station (ISS), then building more, better, and larger revenue-generating space stations and hotels over time until the sizes approximate that of a 4 rpm settlement (112 meters diameter). The economics of space hotels should encourage operators to develop the life support to keep the crew and guests breathing, drinking and eating with minimal resupply from Earth. Eventually, building and operating the first space settlement may not be much more difficult than building another hotel.

This is economically difficult using current expendable launch vehicles, which cost at least $1,650 per kilogram [SpaceX 2017] from Earth to LEO and tens of millions of dollars to put a passenger in orbit. However, SpaceX is developing the ITS—Interplanetary Transportation System, a two-leg Earth to Mars transportation system based on large fully reusable vehicles [Musk 2017]. Target costs are $140/kg and $200,000 per passenger to Mars. The first leg of the ITS is to LEO and these costs should be significantly lower. If SpaceX is able to even approximate the target costs, building small space settlement in ELEO may be affordable.

This paper will compare slightly modified[5] versions of two published space settlement designs, the Stanford Torus [Johnson 1975], a 1 rpm design, and Kaplana One [Globus 2007], a 2 rpm cylinder, with versions having no radiation shielding and rotating at 3 or 4 rpm. Moving these designs to ELEO, making them as small as we dare, and launching all materials from Earth results in a system mass two or three orders of magnitude smaller, which will make such designs more practical.

[5] We will assume modern materials and radiation shielding requirements, thus focusing on the differences caused by location in ELEO and higher rotation rates.

A Tale of Two Studies

Our approach may have a chance to work because two recent studies strongly suggest that free-space settlements in ELEO can be far less massive than previously thought. These discoveries combined with improvements in launch vehicles necessary for any space settlement to succeed may allow space settlements to be built with components launched from Earth. This vastly simplifies the construction and operation of the first space settlements. We will examine these studies in greater detail below, but first we take a high level look at the results of each study and the implications for early settlement size.

The first of the two studies used sophisticated NASA radiation modeling software [OLTARIS 2011] to show that a settlement in ELEO below about 500 km may require little or no dedicated radiation shielding, based on radiation limits for settlements derived from an extensive literature search [Globus 2017a]. The Earth itself and the Earth's magnetic field protect this area from most space radiation. Staying close to the equator avoids passing through the South Atlantic Anomaly so radiation levels are much lower than for the ISS. Since radiation shielding is the vast majority (typically over 95%) of the mass of previous space settlement designs, and since total mass is a fairly good proxy for difficulty, placing settlements in ELEO makes construction of the first settlements much easier.

Figure 1 provides some ISS experimental data on radiation levels in LEO. Notice that a spacecraft in orbit near the equator will only encounter blue areas on the map, indicating low radiation levels. We will quantify these levels computationally below.

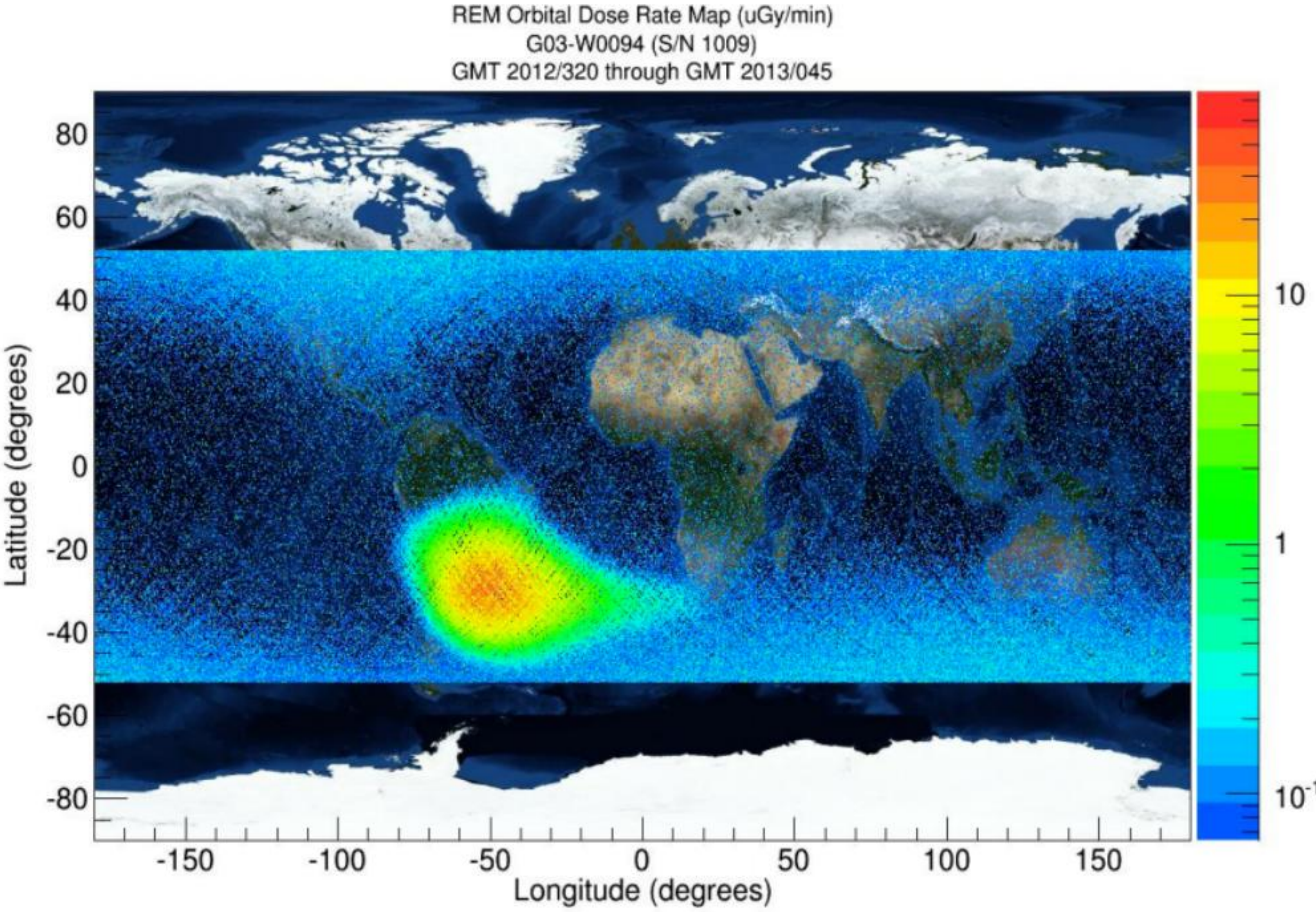

Figure 1: Radiation measurements taken on the ISS. Note the high levels of radiation over the South Atlantic and much of South America and very low levels near the equator. The ISS orbit is around 400 km, somewhat below the altitude of the computational data presented in this paper. Image credit NASA.

The second of these studies examined the literature on human tolerance of rotation [Globus 2017b]. Rotation is used in free-space settlement designs to provide something similar to Earth-normal gravity to the settlers. In the earlier designs it was assumed that a rotation rate of no more than 2 rpm is advisable as rotation can make people ill. Limiting rotation to 2 rpm means that the diameter of the settlement must be at least 450 m to achieve Earth-normal artificial gravity. Careful examination of the literature finds little basis for the 2 rpm limit. While people do get sick when rotated, they adapt quickly and there is an effective training regime. In fact, the literature suggests that 4 rpm (and perhaps more) is fine for settlers, requiring only a few hours to a day or so of adaptation or perhap six hours training. Thus, a 112 m diameter is acceptable (4 times less than Kalpana One and 16 times less than the Stanford Torus).

Note that the mass of a settlement design roughly scales by the inverse of the fourth to fifth power of the rotation rate. Thus, cutting the rotation rate in half leads to a roughly 16-32 fold reduction in mass, all else being equal. Why?

From the equation for centripetal acceleration

$$\alpha = \omega^2 r$$

α is acceleration
ω is rate of rotation
r is radius

the radius scales as the inverse square of the rotation rate given constant acceleration. The mass of a settlement scales with the radius as follows:

- Hull mass scales as the cube
  - the surface area scales as the square and
  - the required strength of a pressure vessel[6] scales linearly
- the atmospheric mass scales as the cube
- the furnishings in the 1g living area scale as the square

Thus, the furnishing mass scales as the inverse fourth power of the rotation rate and everything else scales as the inverse fifth power of the rotation rate.

Combining the mass reduction of eliminating the radiation shielding (19 times for Kalpana One and 155 times for Stanford Torus, as shown in Table 1) and increasing rotation to 4 rpm (a mass reduction of 16-32 times for Kalpana One and 64-128 times for the Stanford Torus), we get a total mass reduction of 300-20,000 times. The large difference is because the Stanford Torus is 1 rpm and Kalpana One 2 rpm. To check these analytic results, we have built two simple models of settlement mass, one for cylinders and another for tori.

[6] The settlement must hold an atmosphere!

Model comparisons of the mass of settlements similar to Kalpana One and the Stanford Torus at various rotation rates with and without radiation shielding are found in Tables 2 and 3, and are very roughly consistent with the analytic results. Note that the models are not quite the same as the original Kalpana One and Stanford Torus to make the comparisons with smaller designs more direct. This is particularly noticeable for the population size, which is quite a bit higher than in the original papers. A description of the models may be found in Appendix B and the models themselves at http://www.nss.org/settlement/journal/EasyModel.xls.

Kalpana One

Figure 2: Kalpana One. Image credit Bryan Versteeg, used by permission.

Kalpana One Mass Estimates

Measure	Shielding	No Shielding	No Shielding
rotation (rpm)	2	3	4
radius/height (m)	224	99	56
Hull (kT)	50	3	0.5
Internal Struct (kT)	63	12.4	4
Radiation shield (kT)	3,870	0	0
Non-struct (kt)	54	10.9	3.4
Air (kt)	42	3.7	0.7
Total Mass (kT)	4,100	30	8.5
Falcon Heavy Launches[7]	77,000	560	160
ITS launches[8]	14,000	100	28
Mass ratio	1	136	480
Population	7,850	1,550	490
Mass/person (T)	519	19	17
drag mass/area (T/m^2)	22	0.809	0.732
deorbit time 500 km (years)	NA	166	150

Table 2: This table examines the effect of mass and size as the modified Kalpana One design increases rotation rate, reducing radius, and sheds its radiation shielding. The numbers in red are the reduction factor for mass. Flat end caps are assumed. The population row assumes 1g residence area of 40 m^2/person, roughly the floor area per person of a smallish suburban house. Mass ratio compares the mass of each option to that in high orbit at 2 rpm. Orbital lifetime calculations (last row) are based on [Panwar 1999] as implemented by the Satellite Orbital Decay web site for a 500 km circular orbit (http://www.lizard-tail.com/isana/lab/orbital_decay/). The cross section is based only on that of the settlement, not solar arrays or thermal radiators. That will be the subject of a future study and the time will go down accordingly.

The original Kalpana One design was a 2 rpm cylindrical settlement. Thus the diameter was about 450 m. The original paper had a cylinder height of 325 m but for the purpose of the calculations in this paper the cylinder height is equal to the radius. Table 2 suggests that if we shrink Kalpana One down to 112 m diameter (4 rpm) and eliminate the radiation shielding by placing it in ELEO, the total mass of the system is reduced by a factor of about 480, consistent with our analytic results. The population is also reduced by a factor of about 16. Reductions are even larger if we go to 6 rpm but it is not at all clear that a 50 m diameter home can be a viable settlement. Indeed, now that it seems higher rotation rates are possible, the minimum size of a settlement is probably determined by other factors, perhaps psychological or social issues. This is an area that needs investigation.

---

7 The Falcon Heavy is a launch vehicle under development by SpaceX with a projected maximum payload mass to LEO of 54 tons [SpaceX 2017].

8 ITS is a very large launcher under development by SpaceX with a projected maximum payload to LEO of 300 tons in fully reusable mode [Musk 2017].

The last two rows of Table 2 (and Table 3) address a major safety issue with large LEO satellites. If they are abandoned they will eventually enter the atmosphere and impact the ground. We see that the time to deorbit, even if an ELEO settlement is completely abandoned, is so long (over 166 years for a cylinder) that any reasonably capable spacefaring civilization can easily address the threat. Thus, the only realistic situation in which an ELEO settlement would enter the atmosphere is if our civilization collapses completely. In this case, space settlements falling to Earth somewhere along the equator will be the least of our worries.

Stanford Torus

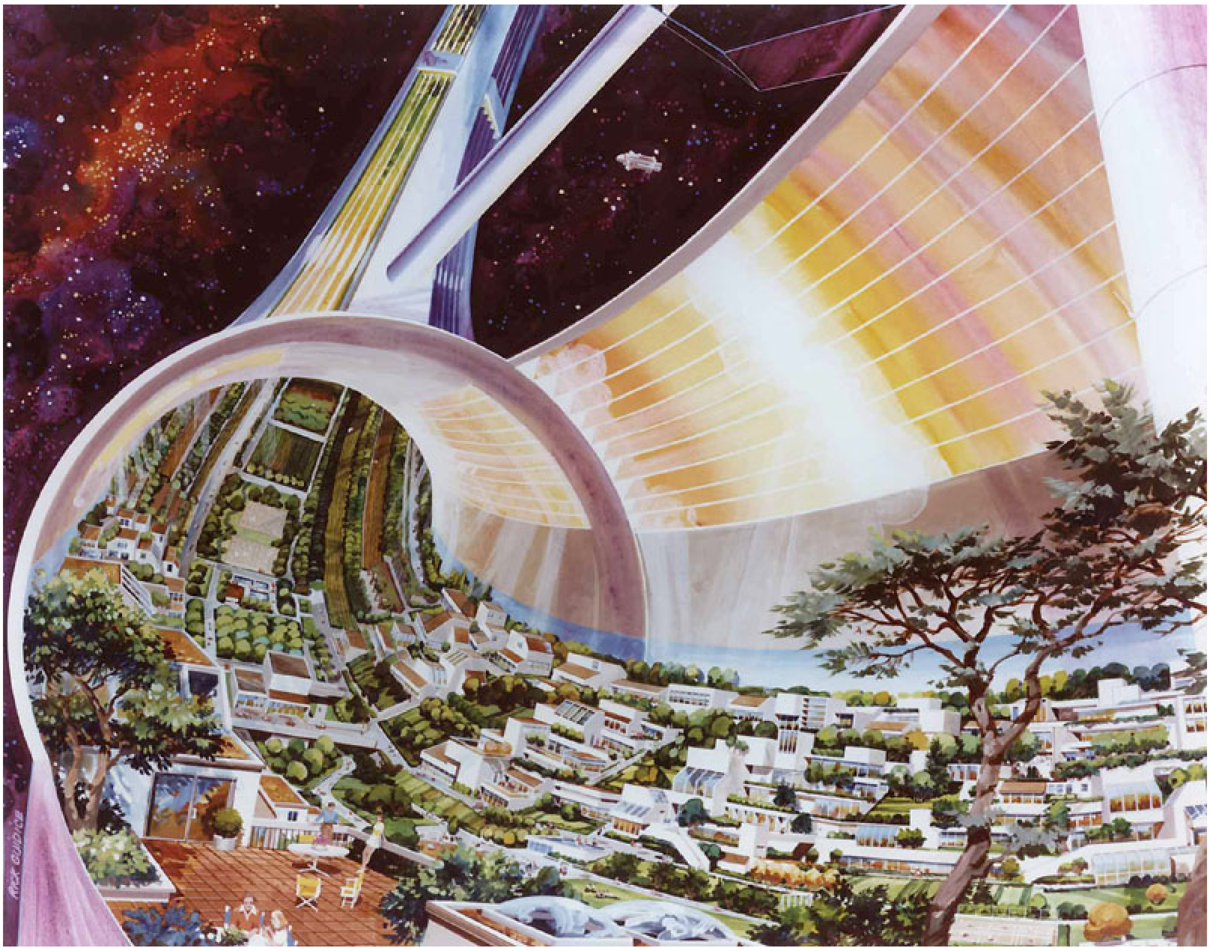

Figure 3: Stanford Torus, image credit NASA.

Stanford Torus Mass Estimates

Measure	Shielding	No shielding	No shielding
Rotation (rpm)	1	3	4
Outer radius (m)	895	99	56
Inner radius (m)	65	10	7
Hull (kT)	67	0.228	0.08
Internal Structure (kT)	145	2.5	0.98
Radiation Shield (kT)	12,740	0	0
Non-structure (kT)	127	2.1	0.86
Air (kT)	82	0.2	0.06
Total Mass (kT)	13,300	5.1	2.0
Falcon Heavy Launches	250,000	96	38
ITS launches	44,000	16	7
Mass ratio	1	2,600	6,650
Mass/person (T)	725	16.5	16.3
Population	18,000	310	123
drag mass/area (T/m^2)	15	0.325	0.311
deorbit time 500 km (years)	NA	67	63

Table 3: This table examines the effect of mass and size as the modified Stanford Torus design increases rotation rate, reducing radius, and sheds its radiation shielding. The numbers in red are the reduction in mass. The population row assumes 40 m^2/person for a residence. Orbital lifetime calculations (last row) are based on [Panwar 1999] as implemented by the Satellite Orbital Decay web site for a 500 km circular orbit (http://www.lizard-tail.com/isana/lab/orbital_decay/). The cross section is based only on that of the settlement, not solar arrays or thermal radiators. That will be the subject of a future study and the time will go down accordingly.

The Stanford Torus is a 1 rpm toroidal design with a 130 m inner diameter. The inner diameters for the higher-rpm calculations are less. Because we are starting at 1 rpm (Kalpana One was 2 rpm) and because a torus needs more radiation shielding for the same living area, eliminating the shielding and increasing the rotation rate leads to an enormous mass reduction. Note that the total mass of the 4 rpm version could be launched from Earth with about seven ITS launches.

We will examine the results of the radiation and rotation studies that drive this enormous improvement in the ease of building the first space settlements more carefully. But first we must explain why ELEO is an easier target for early settlement than the Moon or Mars.

The Moon and Mars

We know empirically that the Moon and Mars will likely be much harder to settle than ELEO because of our experience with space stations. The first space stations went into LEO in the 1970s. The ISS is up there now (Spring of 2017) and has been continuously inhabited since October of 2000. No stations have been built on the Moon or Mars not because no one wants them, but because they are much harder to access than LEO. This is primarily because a LEO orbit (assuming 500 km) is about 760 x closer to Earth than the Moon and 100,000 x closer than Mars at closest approach. This is a massive logistical advantage for LEO.

Note that there are at least three relevant ways to compare the difficulty of travel from Earth to places in space: distance, delta-v, and time. Table 4 provides these for the places of interest in this paper. The square of the delta-v is the energy necessary to change location which correlates with the amount of fuel necessary. Delta-v appears in the exponent of the rocket equation and so has an enormous effect on fuel requirements, although this can be reduced with fuel depots. Time is important if only because it limits the number of trips a single reusable vehicle can make.

Getting To and From ELEO is Relatively Easy

	distance (km)	delta-v (km/sec)	time, one way
ELEO	500	10	hours
L5	382,000	14.1	3 days
Moon	382,000	16.4	3 days
Mars (at closest approach)	54,600,000	20.2	260 days

Table 4: Distance between the Earth and potential settlement locations by different measures. The Mars distance actually varies a great deal over time. Here we list the distance at closest approach. The times are for current or near-term technology. All figures are approximate.

The Moon and Mars also have a big problem for early settlers. Children raised there will almost certainly have very weak bones and muscles, and possibly other as-yet-unknown maladies. This is because Mars and the Moon have a surface gravity much less than Earth normal (1g). The lunar surface is at roughly 1/6g and Mars about 3/8g. Muscles and bones develop in response to stress, and children raised in low-g cannot be expected to be strong enough to visit Earth except in extremis, or perhaps after an incredibly vigorous exercise program. Consider an individual who weighs 73 kg (160 pounds). If they went to a 2.7g planet, the equivalent of moving from Mars to Earth, they would weigh 194 kg (about 420 pounds) and probably could not get out of bed without assistance.

For children raised on the Moon or Mars, attending college on Earth, competing in the Olympics or performing at Carnegie Hall will be either extremely difficult or impossible. By contrast, free-space settlements can rotate to provide artificial gravity at whatever level desired. Although this is not true gravity it will load children's bones and muscles and there is every reason to believe they will grow up strong enough to return to Earth for a visit or even to live [Globus 2017b]. Space settlement does not have to be a one-way permanent commitment for the settlers or their children.

Mars and the Moon do have ample supplies of easily accessible bulk materials for radiation shielding and other purposes. Many tons of material per square meter can be used to bury living modules to provide a reasonable radiation environment, but such protection does not appear to be needed in ELEO. So, for early settlement the total mass of an ELEO settlement launched from Earth is roughly comparable to the mass that must be launched for a similarly sized surface settlement. This will only change when space mining, processing, fabrication and transport sufficient to build the more massive settlement components (e.g., pressurized modules) can be developed.

Structures can be a fair bit less massive on the Moon and Mars as they are not exposed to a full 1g. Also, oxygen for breathing can be extracted from the Martian atmosphere fairly easily. However, power systems on the Moon and Mars will likely be more massive than at ELEO. A lot of storage is needed for the two week lunar night and solar energy at Mars is more than twice as diffuse than at Earth orbit. There are also long duration dust storms. Nuclear power is possible but means settlements would be Earth-dependent for energy. Trading away in situ energy to gain in situ materials may not be advantageous as materials can be recycled but energy cannot.

Thus, radiation shielding being unnecessary in ELEO eliminates much, although not quite all, of the materials advantage the Moon and Mars provides for the earliest space settlements. The residual advantages may well be swamped by the fact that ELEO is 760 times closer than the Moon and 100,000 closer than Mars to the industrial might of Earth.

Finally, if humanity wants to grow and survive over the very long term, a civilization based on free-space settlements has a large advantage over one on planetary bodies and moons. If humanity were to completely settle the Moon and Mars we would be spread out over three locations and would roughly double our living area. If we build free space settlements co-orbiting with asteroids, there is enough material for living area of roughly 400 times the surface area of Earth spread out among perhaps a hundred million settlements. Furthermore, free-space settlements make excellent generation ships for traveling to nearby stars, and on arrival do not need a planet, just some space junk. If your answer to Kyle Reese's imperative that introduced this paper is 'I do,' then free-space settlements are for you.

We now examine in more detail the two studies that suggest that small ELEO space settlements may be the easiest path to early space settlement. There is an extensive section on radiation with the evidence suggesting that ELEO settlements below around 500 km may need no radiation shielding. There is then an extensive section on rotation tolerance. These are followed by a market-driven approach to solve the launch problem and learn how to build small settlements in an incremental fashion

Study One: Radiation Protection

This section is a relatively brief summary of the results reported in [Globus 2017a], where more detail and references may be found. That study is based on a series of radiation calculations using OLTARIS, NASA's web front end to their very sophisticated radiation codes [OLTARIS 2011, OLTARIS 2014]. These calculations suggest that in ELEO below about 500 km little or no dedicated radiation shielding is necessary. This reduces the mass of settlement designs by at least a factor of 19.

Space residents will be exposed to significantly more radiation than most, although not all, people on Earth. This radiation can be kept away from settlers by massive amounts of radiation shielding, but placing settlements in ELEO takes advantage of the Earth's magnetic field which would prevent many charged particles from reaching a settlement.

The primary health concern is radiation induced cancer, which can be expected to be more frequent in space settlers than on Earth. Interestingly, however, the closest approximation of space radiation found on Earth, the low level exposure of radiation workers and people in high background radiation areas, has not been shown to increase cancer rates in humans. However, animal experiments and atomic bomb survivor studies have shown increased cancer rates with much higher dose rates for short periods of time.

Much radiation in ELEO is low energy and can be stopped by minimal shielding, such as the structural hull of a settlement. On very rare occasions there are severe solar storms, consisting mostly of protons, that may require substantial additional shielding for a few hours or days, particularly if coincident with geomagnetic storms. Further research is necessary to evaluate the need for solar storm shelters in ELEO, which will not be addressed here. However, if settlements feature low-g swimming pools wrapping around the axis of rotation, the population could perhaps simply go swimming during storms since water is an excellent radiation shielding material.

However, the most dangerous ELEO radiation comes from Galactic Cosmic Rays (GCR). GCR consists of all kinds of particles at a wide variety of energies, but most of the light weight, low energy particles are diverted by the Earth's magnetic field leaving only heavy (e.g., iron ions) high speed particles to threaten ELEO settlements. These are at a very low level, but are very difficult to stop and come from every direction. Furthermore, small amounts of shielding can increase the damage from GCR when high energy particles collide with nuclei in the shielding, generating a shower of secondary particles.

To determine the amount of shielding necessary one must choose an acceptable level of radiation. For the general population [Globus 2017a] chose 20 mSv[9]/year based on an extensive examination of recommendations for radiation limits on Earth. For example, 20 mSv/year is the occupational limit for nuclear workers recommended by the International Commission on Radiological Protection (ICRP) [Wrixon 2008]. Although the average background radiation in the U.S. is only 3.1 mSv/year [Linnea 2010, NRC 2010], this is an average and in many areas levels are higher. In Europe, large parts of Spain and Finland

[9] The Sievert is a measure of the biological damage caused by radiation. mSv stands for milli-Sievert, one one thousandths of a Sievert. The mSv is calculated from the incident radiation, measured in Grays, weighted by the kind of radiation and the type of tissue affected.

experience more than 10 mSv/year [World Nuclear Association 2014] and in a few parts of the world background radiation is far above 20 mSv/year [Ghiassi-nej 2002] with no apparent negative effect. Thus, 20 mSv/year seems a reasonable and conservative requirement given current knowledge.

However, there will be children and pregnant women on space settlements and a radiation limit suitable for the general population may not be sufficient. The embryo and fetus are known to be particularly susceptible to radiation damage. A careful study of the ICRP studies on radiation and pregnancy suggests that 5 mGy[10]/pregnancy, the equivalent of 6.6 mGy/year, may be a reasonable limit [Wrixon 2008] [ICRP 2000] [ICRP 2003]. There appears to be no data to suggest that this level will cause damage, but the data are not very complete. For example, for the fetus and embryo there is no accepted approach to converting radiation of various types measured in mGy to biological effectiveness, measured in mSv, due to lack of knowledge and the fact that radiation damage is much greater in certain time windows than others.

Children are quite susceptible to radiation damage but [Globus 2017a] does not recommend limits lower than 20 mSv/year. However, this is an area requiring additional research.

There is one major caveat to the 20 mSv/year-6.6 mGy/year limits adopted here: there is very little data on the effects of high energy GCR at all, and that data is for much higher levels per unit time. Most of the data underlying the above limits comes from atomic bomb survivors, pregnant women receiving X-rays, and animals exposed to high energy particles in accelerators, particularly the Brookhaven National Laboratory/NASA Space Radiation Laboratory. The atomic bomb survivors and pregnant women receiving X-rays were exposed to vastly higher radiation levels for a very short periods of time and the radiation was not that characteristic of GCR. Although high energy iron and other heavy nuclei can be and are generated in accelerators for animal experiments, for practical reasons it is difficult to run experiments in an accelerator for long periods of time at low radiation levels, for example the 20 or so days needed for rodent gestation studies. For this reason, experimental protocols involve much higher dose rates for very short periods of time. This is not necessarily an accurate approach. For example, if you were to expose a person to a year’s worth of sunlight in a few hours, their skin’s reaction would be quite different from that of a year round sun bather.

We now examine the computational results from [Globus 2017a] that suggest that ELEO settlements will require little or no dedicated radiation shielding. All of these data are based on computations performed with OLTARIS. All calculations were done using the (simulated) 1977 Solar Minimum radiation levels. Since GCR levels near Earth tend to be higher during solar minima as the Sun’s magnetic field is weaker, these results are conservative, i.e., they report higher radiation levels than are usually seen. However, there have been some periods of even lower solar activity. This will not matter much for the general population where the limit is based on exposure over many years or even decades, but may be an issue for timing pregnancies, i.e., it might be wise to avoid being pregnant near solar minima.

[10] The Gray is a measure of radiation. A mGy is one one thousandths of a Gray.

Radiation Shielding in Deep Space

Large amounts of mass can be used to bring radiation levels inside a space settlement down to acceptable levels. Table 5 shows computational data for polyethylene[11], water and lunar regolith shielding above the Earth's magnetic field. Polyethylene is an excellent radiation shielding material, readily available, slightly more effective than water and much better than lunar regolith. A bit over six tons of polyethylene for every square meter of hull is needed to achieve our limits. This is a massive amount of material for a settlement of any significant size.

Radiation Shielding Required Above the Radiation Belts

	polyethylene		water		lunar regolith	
tons/m^2	mSv/yr	mGy/yr	mSv/yr	mGy/yr	mSv/yr	mGy/yr
~0	462	128	462	128	462	128
1	194	85	200	86	281	110
2	137	52	147	54	275	82
3	91	31	101	34	240	62
4	57	18.5	67	21	194	48
5	35	10.9	43	12.5	149	37
6	21.0	6.3	26.5	7.5	109	28
7	12.3	3.6	16.1	4.4	77	20.9
8					52	15.1
9					34.9	10.5
10					22.8	7.1
11					14.5	4.7

Table 5: Comparison of shielding materials in deep space. The rows indicate yearly radiation levels at a given shielding mass except the first row which calculated the radiation for one millionth of a gram of lunar regolith as a stand-in for no shielding at all (OLTARIS cannot calculate zero shielding levels). The first column lists tons of shielding per square meter; the other columns list different materials and measures. The mGy columns are a (computational) measure of radiation taken inside shielding; the mSv columns are biological effect. The red color indicates that values are less than 20 mSv/year or 6.6 mGy/year. Note that polyethylene is a bit more effective than water, and both are much more effective than lunar regolith. All values are calculated by OLTARIS.

[11] Polyethylene is made up of long carbon chains each with two hydrogens, except at the ends.

Notice that the radiation levels are monotonic, i.e., they always decrease with greater shielding. This is because the shield is massive, the smallest amount being a ton per square meter, so most secondary radiation is absorbed.

Radiation in ELEO

Table 6 presents computational data for a 500 km circular ELEO using polyethylene shielding. Notice that even at 10 kg/m^2 shielding, the equivalent of which is very likely to be provided by any reasonable hull and furnishings, the 20 mSv/yr and 6.6 mGy/yr are met. Indeed, with no shielding at all the general population limit is met and the pregnancy limit is very nearly met. This has an interesting consequence: spacewalks in ELEO may be safe enough from a radiation point of view to be a significant recreational activity. This is in stark contrast to the surface of the Moon and Mars where radiation levels with no shielding are quite a bit higher than ELEO, meaning walks around the surface must be limited to meet 20 mSv/year.

Notice, however, that unlike Table 5 the radiation levels are not monotonic, they sometimes increase with increased shielding. This is primarily due to secondary radiation generated by high-energy heavy GCR. However, the calculated radiation levels never exceed our limits at higher shielding levels.

Radiation Shielding Requirements in ELEO

tons/m^2	500 km mSv/yr	mGy/yr	600 km mSv/yr	mGy/yr
~0	17.7	10.2	40.1	1,559
0.01	17.1	3.6	29.8	101
0.025	16.4	3.7	24.4	50.6
0.05	15.3	3.9	19.8	21.8
0.075	14.4	4.0	17.4	12.5
0.1	13.7	4.0	15.9	8.9
0.15	12.7	4.1	14.1	6.1
0.2	12.0	4.2	13.1	5.3
0.25	11.7	4.3	12.6	4.9
0.5	11.9	4.6	12.6	4.9
0.75	12.7	4.8	13.4	5.1
1	13.3	4.9	14.0	5.2
1.25	13.6	5.0	14.3	5.2
1.5	13.8	4.9	14.4	5.2
1.75	13.7	4.8	14.4	5.1
2	13.5	4.7	14.1	4.9

Table 6: Yearly radiation levels calculated for circular equatorial orbits at 500 and 600 km altitude. The rows are for tons of polyethylene shielding with the exception of the first row which calculated the radiation for one millionth of a gram of lunar regolith as a stand-in for no shielding at all (OLTARIS cannot calculate zero shielding levels). Red indicates that the level meets the 20 mSv/year limit or the 6.6 mGy/year limit for pregnant women. All calculations by OLTARIS.

Radiation in Non-equatorial LEO

Table 7 illustrates the importance of ELEO (equatorial orbits) as opposed to the most commonly used LEO orbits at higher inclination. Notice the rapid rise in radiation as the inclination increases. Note that the ISS is in a 51.6° inclination orbit.

Radiation Shielding Requirements at Different Inclinations

Mass (tons/m^2)	0° (mSv/yr)	15° (mSv/yr)	30° (mSv/yr)	45° (mSv/yr)	60° (mSv/yr)	75° (mSv/yr)	90° (mSv/yr)
0.25	14.6	262.8	636.0	424.1	345.0	335.5	334.0
0.5	12.1	112.1	253.5	178.2	164.0	168.7	170.3
1	13.2	43.4	88.7	79.1	90.3	100.2	102.7
2	14.0	21.6	36.7	45.5	58.9	66.4	68.3
3	12.6	16.4	25.1	33.2	42.4	47.1	48.3
4	10.3	12.3	17.6	23.5	29.4	32.2	32.9
5	7.9	8.9	12.1	16.1	19.6	21.3	21.7
6	5.7	6.3	8.2	10.7	12.7	13.7	13.9

Table 7. This shows the effect of inclination and shielding on radiation levels. The rows indicate the amount of radiation inside a settlement with the given amount of water shielding. Thus, the levels are not directly comparable to other tables in this paper but the differences are small. The columns correspond to different orbital inclinations at a 600 km altitude. Red indicates that the level meets our 20 mSv/year limit for the general population. All calculations by OLTARIS.

Radiation levels for equatorial orbits are low because these orbits do not pass through the South Atlantic Anomaly, a region of high radiation over the South Atlantic and South America. Figure 1 provides some experimental data on radiation levels in LEO which we will repeat here as Figure 4 for your convenience.

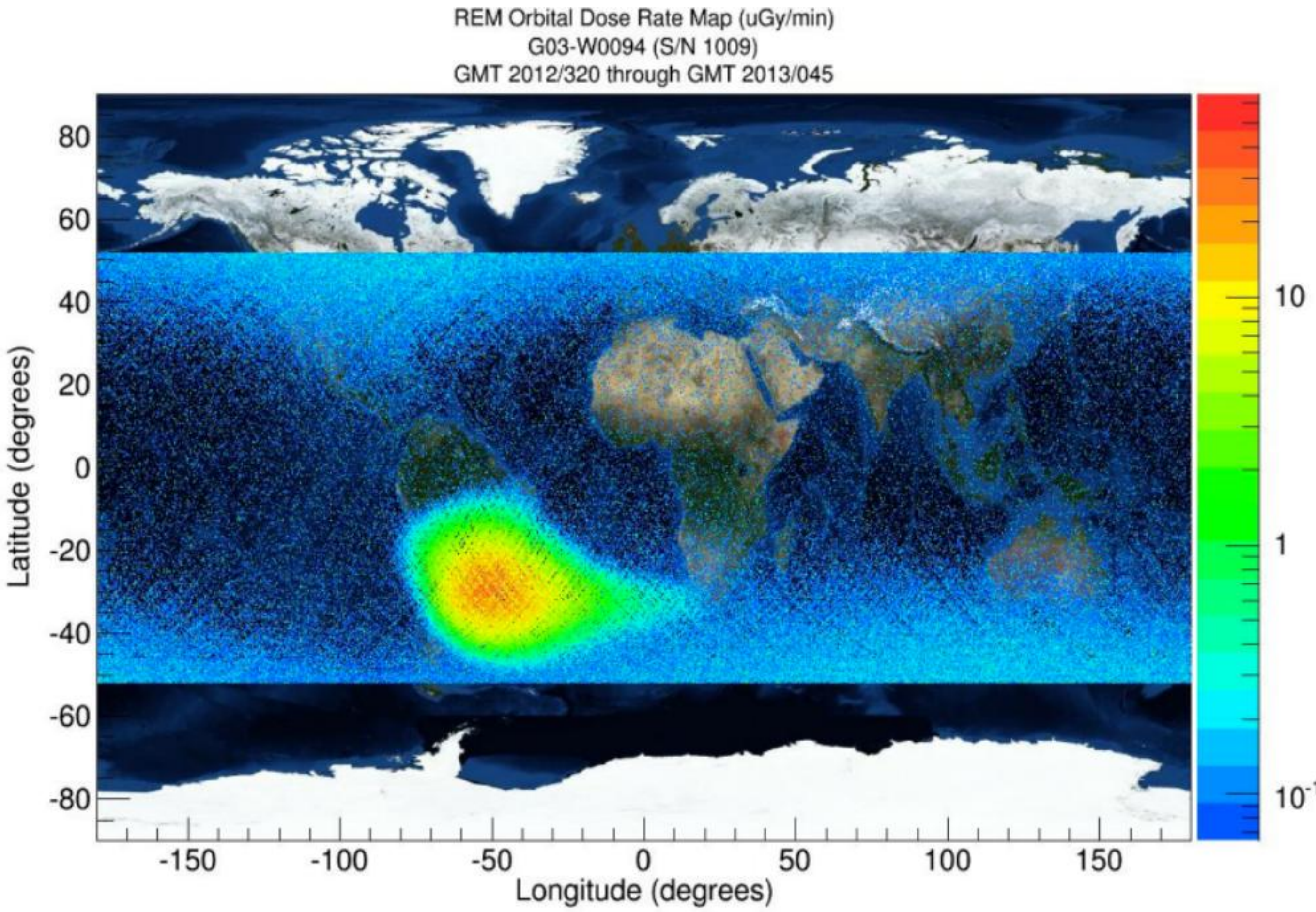

Figure 4: Radiation measurements taken on the ISS. Note the high levels of radiation over the South Atlantic and much of South America and very low levels near the equator. These low levels are well below our 6.6 mGy/yr limit, but the ISS orbit is around 400 km, somewhat below the altitude of the computational data presented in the paper. Image credit NASA.

Thus, it appears that we can live in space settlements in ELEO below about 500 km, and perhaps a bit higher, with no dedicated radiation shielding, as the structure, solar arrays, micrometeor shields and so forth are likely to provide the small amount of shielding needed. However, as mentioned above there are caveats:

- The limits chosen may not provide acceptable protection. Indeed, it is not clear what acceptable protection is. The pregnancy limit rests on particularly weak ground. Special limits for children may also be necessary.
- The radiation codes used are based on data that may not be sufficiently applicable. Very little of the experimental data regarding biological effect reflects the characteristics of GCR and what little is available is at much, much higher dose rates. Fortunately, this last fact means our results are probably conservative, i.e., that the space radiation environment may be less detrimental than we think.

Radiation Risk Reduction

Greater understanding of radiation risks will require significant study of organisms exposed to low levels of GCR for long periods of time. At the moment there appears to be no way to do this on the ground as very long studies are impractical. It may be enough to study radiation levels on the ISS, but the environment is not ideal. Radiation levels are much higher as the ISS passes through the South Atlantic Anomaly, and for most of the time GCR is lower since the ISS is generally at a lower altitude (around 400 km), deeper in the Earth's magnetic field and better protected by the Earth itself. Also, at present the ISS has no centrifuge capable of maintaining 1g for rodents so the effects of weightlessness, which are significant, would mask radiation induced changes. Smaller centrifuges suitable for smaller animals, e.g., fruit flies, and tissue are available.

Particle accelerators on the ground such as the Brookhaven National Laboratory can generate high energy iron particles very similar to the part of GCR of concern. Indeed, these facilities are routinely used to study space radiation effects on tissue and animals, including rodents. However, these accelerators are expensive, $7,000/hour in this case, and long term studies are logistically difficult. Experimental protocols usually involve exposing subjects to the same total quantity of radiation expected on, for example, a trip to Mars, in a very short period of time, then assuming that this will have a somewhat similar effect. Unfortunately, there is little if any evidence that they will have the same effect and some evidence to the contrary. In some rodent experiments, animals exposed to a little radiation preceding a larger dose had fewer negative consequences than animals exposed only to the larger dose [ICRP 2003, paragraph 424].

To really explore the radiation effects at ELEO a space station in such an orbit is necessary to expose subjects to exactly the target environment. Such a facility must either house centrifuges to expose test subjects to 1g or the entire facility must rotate. This last option is likely more expensive to build but staff can stay for longer tours as they will not be exposed to weightlessness for long periods of time. The station can be relatively small, 25 m radius or maybe less, as we shall see in the next section. Furthermore, data taken from the staff themselves will be more meaningful if the facility rotates. The facility must study different types of organisms, up to at least rodents, through multiple life cycles to throw light on negative radiation effects on pregnant mammals.

It should be noted that the negative effects of space radiation may become treatable by medical advances in the decades between now and the construction of the first settlements. For example, radiation can induce cataracts but affected eyes can be repaired by modern surgical techniques, and cancer treatment is rapidly improving.

Having examined the beneficial radiation effect of locating settlements in ELEO, we now turn our attention to the rotation rate in an attempt to reduce the minimum size of a viable settlement.

Study Two: Rotation Tolerance

This section is a brief summary of the results reported in [Globus 2017b] where more detail and references may be found. That study examined the literature on human rotation tolerance and found that settlement residents can easily tolerate up to 4 rpm, and 6 rpm is probably acceptable. At these rates, visitors may experience discomfort and nausea for a few hours or a day or two after arrival, but this is of minor consequence to settlers. However, at 6 rpm very short term visitors (e.g., family visiting for a weekend) may spend much of their visit feeling ill. There is an effective training regime that teach one to control their biological responses to rotation using biofeedback and other techniques.

Increasing the rotation rate reduces the radius of a spinning settlement to achieve 1g artificial gravity and thus reduces the size and mass of a settlement. For example, doubling the rotation rate reduces the radius by 4 times. Thus, if other factors, such as psychological and/or sociological issues, allow for smaller settlements, increasing the rotation rate can reduce size and ease construction difficulty.

Table 8 shows diameter vs rotation rate to achieve 1g:

Rotation Rate and Diameter

Rate (rpm)	1	2	3	4	5	6	7	8	9	10
Diameter (m)	1790	448	200	112	72	50	38	28	22	18

Table 8: Rotation rate and diameter required to produce 1g of artificial gravity at the rim of a space settlement. Notice that the diameter drops rapidly with increasing rpm and flattens out because the diameter scales with the inverse square of the rotation rate.

Rotating space settlements can provide artificial gravity to the residents and avoid a wide range of negative effects of exposure to microgravity. These negative effects include fluid redistribution, fluid loss, electrolyte imbalances, cardiovascular changes, red blood cell loss, muscle damage, bone damage, hypercalcemia, immune system changes and “aging,” vertigo and spatial disorientation, space adaptation syndrome, loss of exercise capacity, degraded vision, degraded smell and taste, weight loss, flatulence, changes in posture and stature, and changes in coordination.

Various countermeasures have been tried to address microgravity symptoms in a piecemeal fashion, but these do not resolve most of the issues and often have negative effects themselves. Rotation addresses the underlying problem—that we have evolved to live experiencing 1g acceleration nearly all the time. Artificial gravity by rotation is the only practical countermeasure that gets at the underlying cause.

Experiments with artificial gravity on small animals and cell cultures have yielded encouraging results. In the Soviet satellite Cosmos 936 in 1977, the lifespan of rats exposed to centrifugation was significantly greater than that of non-centrifuged control animals [Connors 1985]. In Spacelab D-1 in 1985, experiments showed that T-cell function—which is severely hampered in microgravity—is preserved in artificial gravity via centrifugation [Diamandis 1987].

However, rotation itself has negative effects. These include motion sickness, movement errors, throwing errors and illusions. Motion sickness is by far the most serious for space settlement. In experiments, and life, rotation can cause fatigue, stomach awareness, nausea and even vomiting. The effects vary a great deal from person to person and are increased by faster rotation, smaller radii of rotation and high g-level. It is possible to train people to reduce the symptoms.

The space settlement rotation rate recommendations of [Globus 2017b] are:

- Up to 2 rpm should be no problem for residents and require little adaptation by visitors.
- Up to 4 rpm should be no problem for residents but will require some training and/or a few hours to perhaps a day or two of adaptation by visitors.
- Up to 6 rpm is unlikely to be a problem for residents but may require extensive visitor training and/or adaptation over a few days. Some particularly susceptible individuals may have a great deal of difficulty.
- For up to 30 rpm and beyond adaptation has been achieved with specific training. However, the radius of a settlement at these rotation rates is so small (under ~20 m for seven rpm) it's hard to imagine anyone wanting to live there permanently, much less raise children. Rotation at high rates, however, may be useful for a radiation study station in ELEO.

Biofeedback augmented with autogenic training has been shown to give subjects control over up to 20 physiological responses related to motion sickness. Subjects learn to control the physiological systems affected by motion sickness and avoid discomfort [Cowings 2000][Cowings 2013]. Astronauts provided with several half hour sessions of similar training up to 30 rpm suffered less space sickness.

Note that there are two classes of people that must be accommodated: residents and visitors. For residents a few days of feeling ill at the beginning of a multi-year stay is of little concern. However, if a settlement expects many short-term visitors it may be best to keep the rotation rate under about 4 rpm.

Much of the data on the negative effects of rotation was gathered in rotating rooms, experimental facilities where subjects could be exposed to rotation on the ground for days or even weeks. Many of these studies were conducted in a facility including the Pensacola Slow Rotation Room led by Dr. Graybiel.

In 1960 Graybiel published a paper [Graybiel 1960] that is a good example of the data behind [Globus 2017b] recommendations for space settlement design. In this particular study there were five regular subjects and one deaf subject who had lost otolith[12] function. The deaf subject had no motion sickness symptoms at any time, suggesting that otolith response is the driver in rotation tolerance. Subjects were tested in two-day runs at five

[12] The otolith organs are structures in the inner ear that are sensitive to gravity and acceleration.

rotation rates. They were given a number of tests to complete, but there was no adaptation procedure.

The results of this study may be summarized:

1. 1.71 rpm: very mild symptoms.
2. 2.2 rpm: one subject threw up (he had a history of seasickness) but otherwise similar to 1.71 rpm.
3. 3.82 rpm: mild symptoms and subjects adapted within a day; adaptation was longer for the less resistant subject.
4. 5.44 rpm: highly stressful (except for the deaf subject) but most adapted in a day or so. Subjects with prior rotation experience did better than those without.
5. 10 rpm: highly stressful (except for the deaf subject); subjects could not complete all tasks. There was some adaptation over the two day run.

Note that these are very close to our recommendations. There are many other studies with more-or-less similar results.

At least five authors have surveyed the literature and come to conclusions similar, but not exactly, to ours. The results of these studies are summarized in Figure 5.

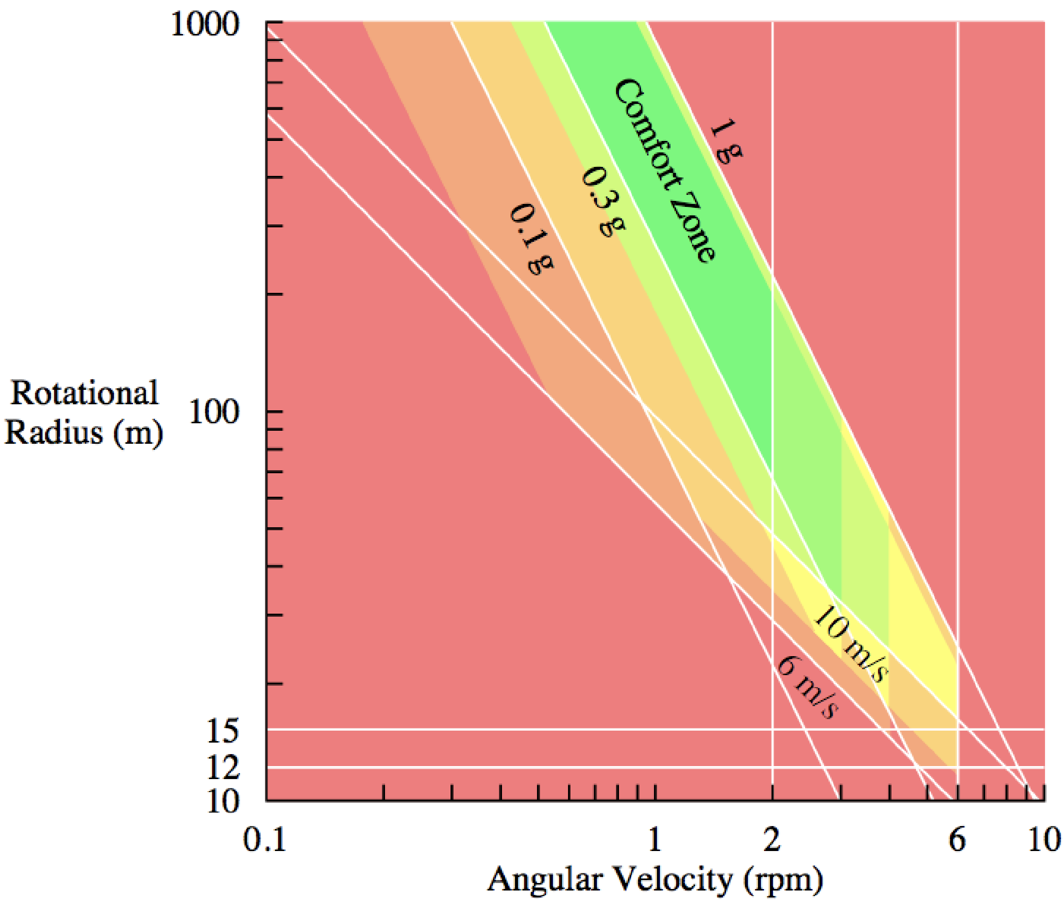

Figure 5. Note that we are only concerned with the 1g line. Green indicates all authors agree this rotation environment is acceptable. Red means no

authors thought so. Intermediate colors indicate disagreement between the authors [Globus 2017b].

None of these authors were looking at settlement related issues, but rather considering rotating spacecraft for much shorter periods of time; for example, on a trip to Mars. Note that most authors agree with our analysis that 4 rpm is acceptable, although there is less agreement between them at 6 rpm.

There are some caveats to these results. First are factors which might make our results more or less optimistic. These studies

1. have very few subjects, usually 10 or less.
2. show great variability in rotation tolerance from person to person.
3. sometimes chose subjects for higher than normal rotation tolerance.
4. have only adult subjects.
5. are only a few weeks or less in duration.

However, there is some reason to believe the ground based experimental results are pessimistic for space, particularly settlement, applications:

1. the experiments were conducted with very short rotation radii, usually under 3 m, and shorter rotation radii generally lead to more severe symptoms.
2. at least one very encouraging experiment strongly suggests that in orbit negative rotation effects may be much less than on Earth.

In the 1970s, SKYLAB experiments with a rotating chair took data before, during, and after flight. Eight crew members participated. Nausea levels were measured. All subjects experienced much less nausea in microgravity, as opposed to pre and post flight in 1g. On the ground many of the subjects could not complete the 150 prescribed head motions, but in orbit all did with few or, in most cases, no symptoms [Graybiel 1977]. Similar results have been obtained in parabolic aircraft flight.

The literature indicates that high-rotation-rate space settlements will be uncomfortable for people when they first arrive, just as arriving in a high-altitude city can be uncomfortable. However, within a few hours or days we can expect symptoms to pass, just as altitude sickness does. This is certainly acceptable for permanent residents who will stay for years.

To really nail down the effects of rotation in orbit, additional experiments along the lines of the SKYLAB experiment discussed above are in order. This could be supplemented by parabolic aircraft flights. If the results reported above on a small number of subjects extend to the general population, then high (4-6 rpm) rotation rates may be acceptable.

As noted above, the combination of the results of these radiation and rotation studies strongly suggest that space settlements can be far less massive (480 times or more) and much closer to Earth (760 times) than previously thought. Even with these enormous reductions in size and distance, there is a still a major barrier that ELEO shares with all space settlement schemes.

The Big Problem: Launch

The proposed approach to developing the first space settlements depends heavily on launching all the materials from Earth. The required improvements in launch for financially viable ELEO settlements are significant. It should be noted, however, that all other settlement locations also require much improved launch capabilities.

Space settlement is, at its core, a real estate business. We hope to build new communities in order to sell housing in them. This must be done above cost or be subsidized. To keep the subsidies to a minimum, we would like to be able to sell a house or apartment in space for something close to the cost of a very high end location on Earth today. For example, the average home price in Silicon Valley is well over $1 million today. Considering just the launch costs, since these are the easiest to quantify, how much improvement is needed to get a housing unit in a space settlement somewhere in the few million dollar per person range?

There are two parts to the transportation cost: delivering the materials and components for the settlement, and flying the proud owner to their new home.

Table 2 suggests that Kalpana One at 4 rpm requires 17 tons/person. The cheapest advertised price today for delivering mass to orbit is the Falcon Heavy, in late-stage development, at $90 million for 54 tons to LEO [SpaceX 2017], or $1.7 million per ton. For 17 tons that is about $29 million.

The cheapest advertised price to launch people to LEO is a bit over $26 million/seat on a Falcon 9/Dragon which included a stay at a Bigelow space station, also in development. This price was removed from the Bigelow website but it is still the best data we have. It is consistent with the $20-50 million the Russians have reportedly charged to fly tourists to the ISS.

Combining these two costs gives us (rounding up) $60 million per person. This does not include materials, construction or resupply costs. We assume that government or space tourism businesses (see below) will conduct most of the research and development cost other than actually building a settlement.

To get the transportation costs to close to one million dollars, leaving some small number of millions for everything else, we need to reduce the cost of launch by about a factor of 50 to around $1.2M/person. There is a system at the very beginning of development with targets in this range: the fully reusable SpaceX Interplanetary Transportation System (ITS), intended to provide a transportation system to enable Mars settlement [Musk 2017]. It will use the Raptor rocket engine, which is in development and ground test. In addition, a large carbon composite cryogenic fuel tank has been fabricated and is undergoing test. This is no mere paper study.

The system has two legs: Earth to LEO and LEO to Mars. The Earth to LEO leg involves two vehicles. The “rocket booster” with 42 Raptor engines (up from 27 engines on the Falcon Heavy) takes off from Earth, places a payload in orbit, and returns to the launch site ready for refueling and another trip. This booster can place 550 tons of expendable payload in LEO or 300 tons of “reusable payload.” The second vehicle is the “interplanetary spaceship” with nine Raptor engines, cargo capacity of 300 tons to LEO (when launched with the rocket booster) or, eventually, up to 100 passengers. The spaceship can take off from and land on Earth. There are also hardware and systems for the LEO to Mars leg but they are not of interest for ELEO settlements.

The ITS cost targets are $140/kg and $200,000 per passenger for transportation from the Earth’s surface to the Martian surface. The first leg of this transportation system, from Earth to LEO, should cost considerably less than half as a vehicle can make perhaps a trip per day as opposed to many months for a single transit to and from Mars. If we conservatively assume that the Earth to LEO leg is half the cost, that gives us $70/kg and $100,000 per passenger. At these prices the transport of necessary materials and components to ELEO will cost approximately $1.2 million and transport of the owner $100,000 for a total of $1.3 million, roughly the same as ELEO settlement requires. Note that the sunk cost is only the $100,000 for the owner; the $1.2 million (plus materials and construction costs) could conceivably be recouped or even increased by sale of the owner’s share of the settlement and, presumably, a dwelling there.

Reducing launch cost by a factor of 50 will be extremely difficult, but would have fantastic benefit for every use of space. The advantages of improved launch, well below a factor of 50, are recognized and are part of the reason we are in the midst of a golden era of launch system development with SpaceX, NASA, United Launch Alliance, Virgin Galactic, Blue Origin, Orbital ATK, the Europeans, Russia, India, Brazil, China and others all developing new or improved launch vehicles. In particular, the SpaceX Falcon 9, a relatively new vehicle, has reduced the launch price enough that their competitors are scrambling to follow suit. However, to reduce launch price by a factor of 50 will require more than any of the current efforts can possibly provide, with the notable exception of the ITS.

For any system to reach a 50 times price reduction, or anything close, will almost certainly require fully reusable launch vehicles, much improved technology and a very high flight rate, probably in the tens of thousands per year. The reusability and technology requirements are generally recognized but for some reason flight rate is often ignored. However, with today’s market of fewer than 100 launches per year, a single reusable vehicle capable of two flights a week could, theoretically, satisfy the entire launch market! Even 1,000 flights per year would only require 10 such vehicles. Large reductions in price will not come if vehicles are built in such small numbers. Launch vehicles only make money when they fly, so we need a very high flight rate, probably over 10,000 flights/year.

There are only two applications that, at the right price, could create a market requiring a flight rate of tens of thousands or more per year: space solar power (SSP)[13] and tourism. SSP requires a very large investment up front before any income is generated and is vulnerable to terrestrial competition, particularly as batteries improve. So we turn our attention to tourism.

[13] For our purposes, SSP refers to gathering solar energy in space and beaming it to Earth.

Tourism: the Killer App

How do we get from where we are now to the construction of the first high-rpm space settlement in ELEO? One word: tourism—a $2.3 trillion/year industry [Statista 2014]. Steady growth in a for-profit space tourism market could provide most of the development needed to enable construction of the first ELEO settlements.

Launch Rate

The first task is to drive the launch rate up to the point where prices are, very roughly, 50 times lower than today's prices. There have been a number of studies of the space tourism market [O'Neil 1998]. We present data from one of them in Table 9:

Relationship Between Space Tourism Price and Volume

price/ticket (2015 $)	passengers/year	Flights at 10 passengers per vehicle	Vehicles needed if flies twice per week	Gross revenue ($ million)
1,600	20 million	2 million	20,000	32,000
16,000	5 million	500 thousand	5,000	80,000
160,000	400 thousand	40 thousand	400	64,000
400,000	1,000	100	1	400
800,000	170	17	0.017	136

Table 9: From Crouch, G. I., "Researching the Space Tourism Market," presented at the annual Conference of the Travel and Tourism Research Association, June 2001. This study attempted to determine global demand for tourist flights as a function of price. Prices were converted to 2015 dollars and the last three columns added.

These are early estimates and require further research. However, there are three important take away messages from Table 9 that are justified even if the data are not quite right.

1. Demand is a strong function of price. As the price goes down the number of passengers per year increases very rapidly. This will reward those who can fly less expensively.
2. The market may eventually be quite large, perhaps tens of billions of dollars per year.
3. There is some point—$160,000/trip here—where demand skyrockets.
4. Even with demand exploding at $160,000/trip the number of reusable vehicles needed is not particularly large. Low vehicle price requires large volumes and to require truly large numbers of vehicles we need a very low customer price, perhaps in the tens of thousands of dollars per seat range.

The way to develop lower cost launch vehicles is to get the industry into a virtuous cycle where

1. Lower launch prices stimulates increased demand.
2. Increased demand provides economies of scale to lower launch costs.
3. Back to #1.

What Table 9 indicates is that such a virtuous cycle is possible if the necessary vehicles can be developed and we have a buyers market. The need to undercut the competition can drive incremental technology development, and government research has been effective in developing long term, breakthrough technology (the Internet is the classic case).

Note that the ITS, at $100,000 per seat may be in the vicinity of the price point that corresponds to a rapid increase in the market. This is in the range of the reduction necessary to build unsubsidized ELEO settlements. However, this may still not be enough to require more than a few hundred launch vehicles.

Fortunately, the tourist market is not just a matter of surveys and speculation, there is already a space tourism market with paying customers. The Russians have flown seven paying customers to the ISS for a week or two each, one of them twice. Prices are believed to have varied from about $20 to 50 million. Unfortunately, prices started some years ago at $20 million and have since gone up, which can only mean that right now space tourism is a sellers market. This is because in the last few years only one tourist seat into space has been available.

While only a single seat has been for sale in a number of years, over 700 people have paid a deposit for a short suborbital flight, at $250 thousand/seat, but the vehicles are not yet ready and have not yet flown in space. Nor are any American crew-capable vehicles ready for human launch to orbit, although two are in development. This leaves only the Russian Soyuz and only when an extra seat is available beyond what is needed to staff the ISS. Thus the $50 million/seat price. The cargo version of the Falcon 9 has reduced satellite launch prices and stimulated an industry-wide scramble to lower prices. If the human-rated Falcon 9 under development can do the same for tourist seats, our virtuous cycle may begin.

Space tourism can, at least in principle, provide the demand to develop the reusable, high-launch rate vehicles necessary to successful ELEO space settlements, or anywhere else for that matter. The tourist market can also drive the development of the technology and infrastructure necessary to construction and operation of the first space settlements.

Facility Development: Space Hotels

One approach to developing ELEO settlements is to start with where we are and build more, larger and better space stations and hotels to feed a growing market as space vacation prices come down due to improvements in launch vehicles. Leasing space in stations and providing hotel accommodations could provide near-term revenue to drive the market. The owners of space hotels will have a strong incentive to recycle air, water, and even food to reduce the cost of resupply. Higher volumes of tourist traffic will support larger and larger hotels. Some space hotels may even rotate to provide fractional-g to allow staff longer stays and make customer use of the toilet an easier task. Eventually, if all goes well, space hotels may approach the size of a 4 rpm settlement (112 m diameter and 2-8.5 kT mass, see Tables 2 and 3). At that point, building the first settlement may not be much more difficult than building yet another hotel.

Figure 6: The International Space Station (ISS) in orbit. It is around 100 m in length, not much less than the 112 m diameter required for a 4 rpm space settlement. The mass of the ISS is about 0.42 kT [NASA 2015], or about 5-20 x less than the 4 rpm versions of the Stanford Torus and Kalpana One (see Tables 2 and 3). The ISS has hosted 7 paying tourists. Image credit: NASA.

First, let us consider where we are. The ISS typically hosts six people. It is around 100 m long but does not rotate and is in a high-inclination, high-radiation orbit somewhat lower than our preference (about 400 km rather than 500 km). The ISS has hosted seven space tourists, one twice, for a price estimated at $20-50 million per person on trips of one to two weeks. In addition to paying a very high price, these tourists needed to learn Russian and train for many months in Star City in Russia. The reward has been fantastic views of Earth and the incomparable experience of microgravity. Some of these ‘tourists’ have also conducted important, and sometimes paid, experiments during their stay [Garriott 2014].

The U.S. government has no specific plans to develop additional space stations after the planned decommissioning of the ISS in 2024. There are indications that NASA would like private industry to develop commercial stations, but no firm commitment to help. The Russian and Chinese governments have both indicated that they will build and operate space stations of their own in the relatively near future. What might a U.S. led program to replace the ISS look like?

For a variety of reasons, NASA cannot fly rich tourists. NASA can help develop space stations though. One approach to getting started would be for the ISS to be augmented and eventually replaced by private space stations, commercially owned and operated. The

Alliance for Space Development (ASD) and the National Space Society (NSS) proposed that this be approached in a manner similar to to the COTS and CCDev programs [NSS 2015], where NASA provides partial development funding and subsequently becomes an anchor tenant, or at least an important customer. This approach successfully developed two cargo launch vehicles at a small fraction of the usual rocket development cost (COTS program) and is currently being used to develop passenger service to the ISS (CCDev).

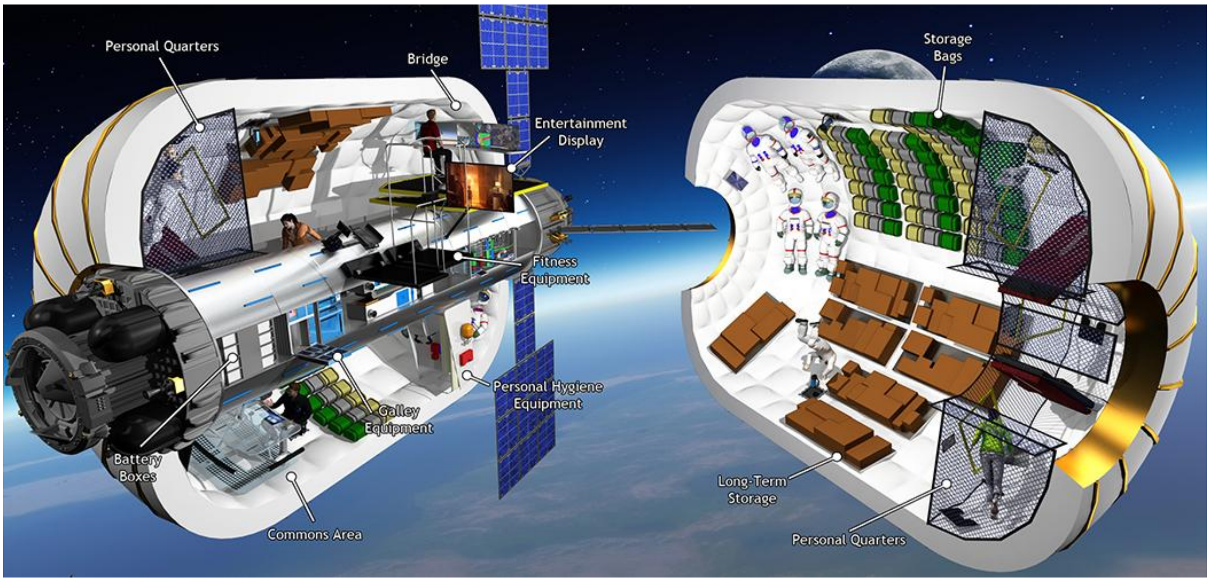

Figure 7: The B330 space station. Image credit Bigelow Aerospace.

There are at least two private companies, Bigelow Aerospace and Axiom Space, that are building space stations. Axiom Space is just getting started but Bigelow is more mature. The Bigelow modules are based on inflatable technology acquired from NASA and subsequently improved. Bigelow has flown two sub-sized test stations which are currently in orbit. Bigelow also sent the BEAM (Bigelow Expandable Activity Module) to the ISS under a $17.3 million contract with NASA for a two year trial. Finally, Bigelow is developing the B330 module, a six person, 20 ton, 9.45 m length, 300 m^3 volume, 20 year lifespan space station module that is being marketed as a tourist destination and to national space programs and companies for research and development [Bigelow 2017].

Two small companies making progress is hardly enough to declare victory and go home. However, there are a number of aerospace companies with the capacity to build space stations or hotels, and intelligent use of government development funds could both help Bigelow Aerospace and Axiom Space succeed and bring others into competition to generate a more vigorous market.

Let us assume, for the moment, that industry steps up to build and operate space stations in response to current opportunities and perhaps government inducements. It will not escape notice that space hotels are easier to build and operate than space stations. All that expensive science equipment—furnaces, glove boxes, centrifuges and so forth—is not needed. It is much simpler to have a large area for microgravity recreation and some first class windows for viewing. If someone can build and operate a profitable space hotel, then others will follow. Space hotels will need less expensive launchers to bring more and more customers, and launch companies need high launch rate to reduce prices. Hotels are key to to this virtuous cycle.

If a vigorous space hotel market is established, it is reasonable to expect that many of the technical and infrastructure problems associated with ELEO settlement will experience competitive pressure to be solved. For example,

1. Recycling air and water can lower costs significantly.
2. Growing food on board can not only save cost, but high end customers may not welcome freeze-dried food-like substances for dinner.
3. Rotation may be introduced, at low g-levels, to eliminate the customer training necessary to use microgravity toilets, a tricky proposition with significant downsides when things go wrong!
4. Modest artificial gravity levels might allow hotel staff to have longer tours of duty, substantially reducing costs. Microgravity recreation would still be available near the axis of rotation.

If the virtuous launch cost cycle can be established, over time it is reasonable to expect that space hotels will evolve into facilities near the size of a 112 m diameter space settlement with all or most of the necessary capacities: life support, artificial gravity, transportation, communications and so forth. At that point building the first true space settlement, a place to raise your kids, is not a lot different from building yet another hotel.

Thus, the first space settlement may not come from a heroic effort by an elite band of adventurers, but rather from the natural outgrowth of a profitable commercial market complete with the luxurious amenities expected by high-end tourists.

Immediate Tasks

The most important immediate tasks, as we have discussed above, are launcher development and private, commercial follow-ons to the ISS. These can work out the transportation, construction, and operational issues relevant to space settlement.

We have also indicated that an ELEO research station is necessary to investigate radiation issues, and experiments rotating people in micro-g may may be important.

There are other issues that should be addressed soon: the relevant orbits are home to very high velocity uncontrolled space junk, launch failure rates are too high for extensive tourism, high launch rates may impact the atmosphere, and we do not know how small a viable settlement can be.

Space Debris

The spacefaring nations of Earth have been creating debris in orbit for decades. As a result, there are over 20,000 tracked Earth-orbiting objects larger than 10 cm and perhaps half a million or more shrapnel fragments between 1 and 10 cm. These are traveling at speeds around 27,000 km/hour [NSS 2016]. It has been reported that 10% of LEO satellites have been hit and at least one communication satellite was destroyed by a debris collision, creating thousands of new pieces of shrapnel. A collision with many of these bits of junk could easily puncture the pressurized hull of a hotel or settlement. The problem is expected to get much worse as the probability of a collision is superlinear with the number of pieces so each collision significantly increases the probability of more collisions.

Figure 8 shows the number and mass of the debris as a function of altitude. Note that at the altitude we expect for early ELEO settlements and hotels, around 400-500 km, there is not a lot of debris. That is because debris at these altitudes decays and burns up in the atmosphere fairly quickly, unlike large and heavy settlements with high mass per unit of drag area. However, almost all of the debris generated in LEO will eventually pass through the 400-500 km altitude range and at that point constitute a serious threat to both hotels and settlements, and, for that matter, all other satellites in LEO. Thus, it would be wise to prevent additional space pollution and clean up the mess we have already made.

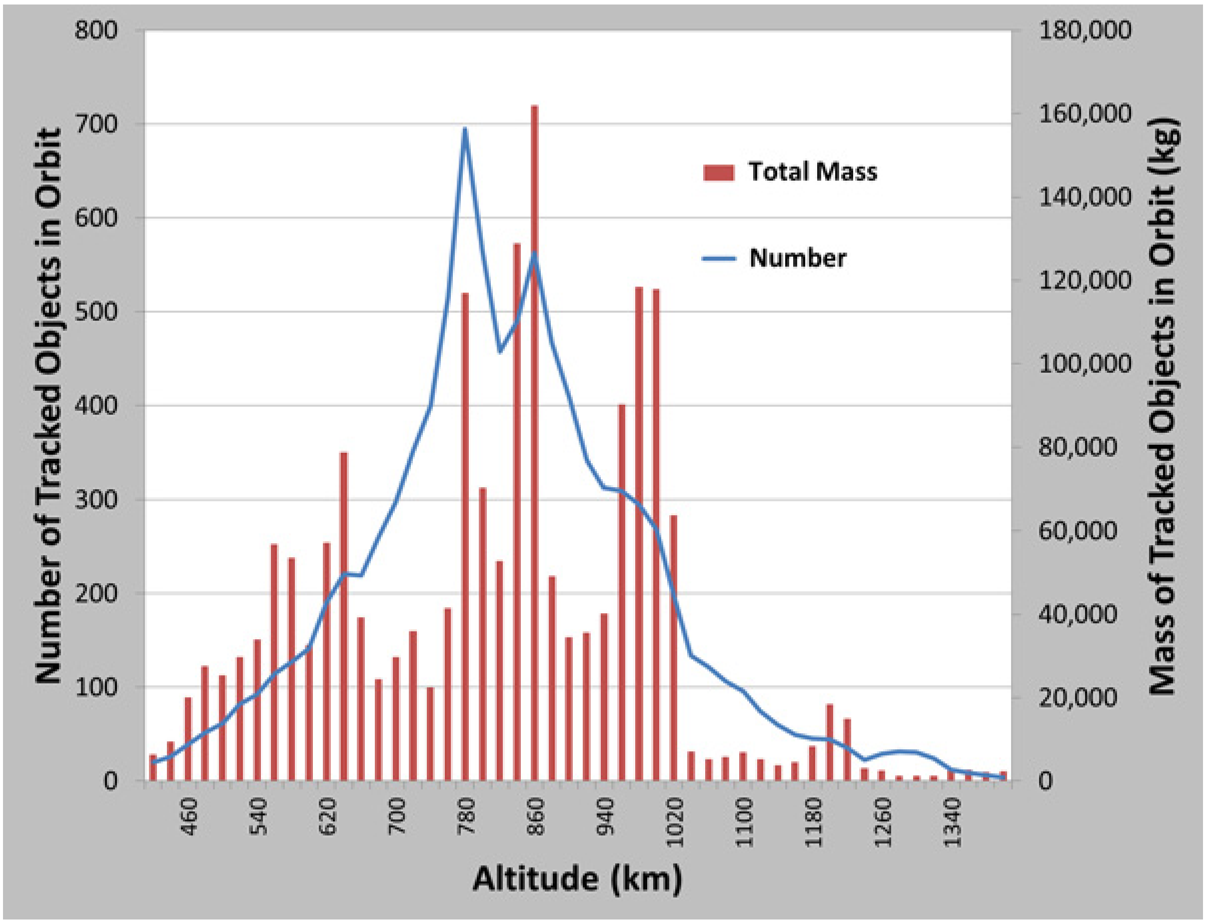

Figure 8: Number of tracked objects in LEO and the total mass as a function of altitude. Image credit Darren McKnight and Patrick Dingman [McKnight 2012].

Fortunately, it is not necessary to clean up all the debris for ELEO settlements to be practical. If there is a good system in place to detect a potential collision with some warning it is possible to move a settlement. The ISS has made a number of collision avoidance maneuvers to avoid potential collisions using docking thrusters, the Shuttle, and Progress supply ships. These maneuvers also boost the ISS into a higher orbit so they can help keep the station from deorbiting. The mass of the ISS is about 0.4 kTons or about 20 times smaller than a 4 rpm Kalpana-class settlement. Scaling up to this boost capability is a challenging engineering problem, but no more than that.

Launch Failures Rates

Launch vehicles have fairly high catastrophic failure rates. For example, the Space Shuttle had a 1.5% failure rate. This is fairly low compared to most other launchers. [NASA 2011] and [Lafleur 2010] report failure rates for a number of vehicles:

1. Shuttle: 135 launches with a 1.5% failure rate.
2. Soyuz: 1,698 launches with a 2% failure rate.
3. Delta: 347 launches with a 4% failure rate.
4. Ariane: 193 launches with a 5% failure rate.
5. Proton: 351 launches with a 11% failure rate.
6. Atlas: 347 launches with a 12% failure rate.

It should be noted that many of these failures were early in the vehicle’s lifetime and that failure rates in the future are likely to be lower. For example, the most recent version of the Atlas family, the Atlas V, has never had a catastrophic accident.

The maximum fatality rate a viable space tourism business can tolerate is unknown. However, as early space tourism is definitely adventure travel, comparisons with other adventure travel may be relevant. For example, the fatality rate for those climbing Mt. Everest is about 2% [Explorersweb 2006]. Assuming that early space tourists can tolerate as much risk as those climbing Mt. Everest the most reliable launchers appear to be good enough, or at least almost good enough.

Of course, there are important differences between the space tourism experience and climbing Mt. Everest. The climbers require great skill and must be in excellent physical condition to even consider the attempt. Training and fitness requirements for space tourism are much lower. Also, when climbing it is you against the mountain as opposed to being a passenger whose fate is in others’ hands.

In the longer term, if we achieve the desired 10,000 launches per year or more a 2% failure rate is completely unacceptable. That would be at least 200 fatal accidents a year or four per week. Space launch failures will almost certainly be well publicized as explosions make for high TV ratings. Thus, a vigorous program to reduce failure rates is imperative.

High Launch Rate Impact on the Atmosphere

Every space launch slightly alters the Earth’s atmosphere by inserting rocket exhaust at various altitudes. Vehicles returning to Earth usually use atmospheric braking which involves high temperatures and induces chemical reactions. These effects are particularly significant at high altitudes where there is little matter to begin with.

At today’s very low launch rates, under 100 per year, there is little concern with atmospheric pollution. The amounts are tiny compared to other sources. However, we have seen that space settlement, at any location, requires tens of thousands of launches per year to bring prices down to the point that very well off individuals might be able to finance their own relocation into space. At these high launch levels it is not a given that atmospheric damage is acceptable.

Fortunately, the cost of respecting the environment is usually low if environmental concerns are addressed early before there is a large infrastructure based on polluting technology. In the case of space launch, consider that H_2/O_2 is not only more powerful (higher ISP) than carbon based fuels but the exhaust is only water, not more complex compounds and CO_2.

A vigorous long range research program to understand potential threats to the atmosphere and avoid them would be wise.

How Small Can a Settlement Be?

Our study of the rotation literature revealed that the criteria used for early space settlement designs was unnecessarily conservative, although appropriate for those studies at that time. In fact, settlers can tolerate much higher rotation rates and this translates into smaller initial settlement size. However, rotation tolerance alone may not be sufficient to define the minimum size of a viable settlement.

Most of the early settlers will likely come from large cities as maintaining a gigantic, complex new machine such as a space settlement requires very high levels of technical expertise. We will be asking these people to live in a much smaller social and physical environment. How small can that be?

We don't know, and it is important. It is important because the smaller the settlement the easier it is to build, at least for the first few. In this paper we have assumed that a 4 rpm settlement with a diameter of 112 m would be big enough, which seems reasonable but there is very little data to back it up. Indeed, one might expect that the minimum size depends a great deal on exactly who inhabits the settlement.

We conducted an internet survey to throw light on the minimum size issue. Just over 1,000 people took the survey and 95% were self-described space enthusiasts. Approximately 6% of the respondents said they could be happy living in a space settlement the size of a large cruise ship (100 m diameter, 50 m length cylinder) with 500 or less people and were willing to devote up to 75% of their lifetime wealth to go. While hardly definitive, this suggests that some people would at least consider living in space in a 4 rpm settlement and with population of seven billion it should be easy to fill a settlement at the right price.

Settlement Growth Path

While the easiest approach to the first few settlements may be to use ELEO, this is not the end goal but rather a very large first step. See Appendix A for an extremely long term development path starting with the first ELEO settlement and continuing on to high Earth orbit, the Moon, asteroids, Mars, and eventually generation ships to the stars.

Conclusion

To survive long term, humanity and life itself must diversify beyond Earth. Of all species only homo sapiens is space faring and only humankind has the physical ability to settle space. However, developing true space settlements—where residents live, work and raise their children—is a daunting task. Surface settlements, on the Moon and Mars, are severely problematic for raising children due to low gravity and are also extremely far away making transport difficult. For forty years free-space settlements appeared to require mining millions of tons of material from the Moon or asteroids and constructing kilometer scale space systems at huge distances from Earth. In this paper we have shown how to make early settlement construction and operation significantly less daunting by making those first settlements close, small, and building up from the ISS incrementally.

We have seen that the task is much easier when the first settlements are built in ELEO around 500 km above the Earth's surface and directly over the equator. The radiation environment in this region of space is relatively benign as we have seen from both experiment and computation. In fact, a careful examination of the permissible radiation levels combined with calculation strongly suggests that ELEO settlements may need no dedicated radiation shielding, which is typically 95% or more of the mass of free-space settlement designs. In space, mass is a good, although not perfect, proxy for difficulty.

We have seen that the literature suggests that human rotation tolerance is much greater than the designers (including these authors) of earlier free-space settlements believed. This permits the construction of much smaller settlements. In combination with eliminating the radiation shielding the mass of free-space settlement designs can be reduced by at least two orders of magnitude, which is a complete game changer. It means that lunar or asteroidal mining, materials processing, and manufacture is no longer on the critical path to the first settlement, although they will be able to exploit the markets created by ELEO settlements launched from Earth.

We have seen that the primary barrier to space settlement is the cost of launch, as is true with all large-scale space development. The near term cost to launch a single settler and their share of the materials for an ELEO settlement is around $60 million, half just to launch the settler. To reduce this cost into the range of an expensive house on Earth requires somewhere around a 50 fold reduction in launch price. Fortunately, the ITS, a system in early development by a launch company with a history of low-costs vehicles, SpaceX, has cost targets that translate into transportation costs to ELEO settlements of around $1.3 million per settler, almost exactly what is needed, and only $100,000 of that cost is a seat for the settler, the rest for materials and components [Musk 2017]. It should be noted that other locations (Moon and Mars) have similar or greater mass requirements at least in the near term, with access to materials being balanced by greater transportation cost.

While a 50 fold reduction in launch price will be difficult to achieve, there is a market mechanism. The volume of space tourism is a strong function of price. Any reduction in launch cost can substantially increase the number of paying customers, and this can provide the increased volume needed to reduce the price, which can increase the number of customers and so on in a virtuous cycle. The key is converting the current sellers market into a buyers' market. As an important side effect to this dynamic, tourists will need an ever increasing number, size, and sophistication of space hotels, which may eventually evolve to the point that building a small space settlement is not much different from building a large hotel.

Thus, we see that the first major steps toward settlement of the solar system may not be driven by elite astronauts, but rather by ordinary people taking the most amazing and fantastic vacation of their lives.

Ad Astra!

Acknowledgements

Thanks to Al Anzaldua for the space debris information. Thanks to David Brandt-Erichsen, Joe Carroll, Gary Oleson, Tom Marotta and Joe Strout for comments and editing.

Appendix A: Settlement Growth Path

While the easiest approach to the first few settlements may be to use ELEO, this is not the end goal but rather a very large first step. In this appendix we sketch out an extremely long term development path starting with the first ELEO settlement and continuing on to high Earth orbit, the Moon, asteroids, Mars, the outer solar system and eventually generation ships to the stars. The rest of this appendix will outline this expansion.

Fill ELEO with Settlements

Once a few ELEO settlements have been built and successfully operated the next order of business is to fill ELEO with an industrial civilization. A 500 km altitude circular orbit at the equator is about 43,000 km long. Assuming a spacing of 1,000 km, that means there is room for 43 settlements. If we assume we can populate orbits every 50 km in altitude from 400 to 600 km we get about 200 settlements. While the first settlements should be as small as possible to take advantage of space hotel development experience, most people, particularly technical people, are accustomed to living in cities with large populations. Thus, it is probably desirable to build larger settlements as quickly as possible and decommission the early small ones once the slots fill up. If each settlement has at least a population of 10,000—the number chosen by the 1970's studies [Johnson 1975] [O'Neill 1977]—that makes for a total ELEO population of over two million.

ELEO Settlement Enables Lunar and/or Asteroidal Mining and Settlement

All of the current approaches to lunar and asteroidal mining suffer from the same weakness: small markets in space. It is difficult for extraterrestrial materials to compete on Earth as the same materials can generally be mined on Earth for a small fraction of the cost of developing and operating mines in space and transporting the resulting materials to Earth. By far the best markets for extraterrestrial materials are in space where transportation costs work against Earth materials.

However, the current in-space market for materials consists of six people in the ISS and about 1,300 robotic spacecraft, only one of which to date has been designed to be refueled or repaired—certainly not enough to justify lunar or asteroidal materials to do so. The most common market cited by space mining enthusiasts is oxygen and sometimes hydrogen for use as rocket fuel. This market doesn't exist at all right now, and even in rosy future projections is quite small compared to tourism. One exception is the United Launch Alliance proposal to build space solar power satellites using materials mined on the Moon and transported by rocket fuel also mined from the Moon [ULA 2016].

Once extensive settlements in ELEO are established this will change. Instead of six people in space there may be millions. These people will need water and atmosphere replacement, reaction mass for orbit maintenance, and materials for manufacturing and for building additional settlements. This may be enough to get lunar and asteroidal mining operations started. Unless these mines can be entirely automated, including maintenance, a crew will be necessary for each mine. These mining camps may, as they often have on Earth, become the nucleus of new settlements.

Although lunar mines are the closest in distance, asteroidal materials may play a role at this stage as some asteroids can be brought into lunar or even Earth orbit at low delta-v using very efficient solar electric propulsion and lunar gravitation assist [Brophy 2012].

Thus, rather than space mines being essential to initial settlement construction, settlements may create the conditions for successful extraterrestrial mining.

Lunar and/or Asteroidal Mines Enable High Earth Orbit (HEO) Settlement

Once there are lunar and/or asteroidal mines in operation it may become feasible to build settlements beyond ELEO in the more intense HEO radiation environments that require many tons of shielding per square meter of hull. Then the same problems faced by the designers of the Stanford Torus will have to be overcome, but those tasks will be made much easier by a large, experienced workforce in space, industrialization of ELEO, and existing lunar and/or asteroidal mining operations that need to be scaled up, not created from scratch.

Thus, ELEO settlements may enable the lunar and/or asteroidal mines which in turn enable delivery of the materials required by HEO settlements. This space is vast and can support an extremely large population—certainly in the billions, but there is more.

Asteroid Mining Enables Solar System Wide Settlement

Although the resources of Earth orbit (space and sunlight) and lunar materials are enormous they should not hold humanity forever. Indeed, for survival it will be prudent to push beyond Earth orbit, even HEO, to become independent of the Earth-Moon system. The obvious approach is to build settlements co-orbiting with asteroids that supply the necessary materials.

The first asteroid-based settlements will undoubtedly be close to Near Earth Objects (NEOs) as they are the easiest to reach. At 2 rpm a cylindrical Kalpane-One-like settlement including deep space radiation shielding has a mass of about 4 million tons according to Table 2. At a representative asteroidal density (3 ton/m^3 [Carry 2012]) a spherical 140 m diameter asteroid has about that much mass. There are roughly 15,000 NEOs at least that large [NASA 2013] and roughly 1.7 million main belt asteroids one km or greater across. More large large asteroids can be found in Jupiter’s orbit, but that’s not all.

Outer Solar System

Beyond Neptune stretches a vast region of icy bodies including the Kuiper belt and Oort Cloud. The furthest bodies in the Oort Cloud may reach halfway to the nearest star, Proxima Centauri. Indeed, if Proxima Centauri has similar icy bodies they may overlap with those orbiting Sol. In any case, by some estimates these bodies could support a population in the trillions, or perhaps even more.

If a sizable fraction of the asteroids and icy bodies are developed into space settlements mankind will have an enormous industrial base, perhaps sufficient to launch the next step.

Generation Ships Enable Galactic Settlement

If you and your family have lived for 500 generations in free-space settlements, how important is proximity to Sol? For some, it may not matter much whether their settlement is in orbit around the Sun or on the way to Proxima Centauri, four light years away. It does not matter if Proxima Centauri has a habitable planet, as our distant descendants will only need asteroids or comets to provide materials. If suitable propulsion, power source and extremely efficient recycling can be developed in the next few tens of thousands of years[14], there is every reason to believe that groups of co-traveling settlements (for redundancy should something serious go wrong) may head out into the galaxy. As we are near the edge of the galaxy where interstellar distances are relatively large, if we can get to Proxima Centauri we can get anywhere in the galaxy given enough time [Globus 2012].

Appendix B: Free-Space Settlement Models

This section provides a description of the Microsoft Excel models that feed Table 2 (Kalpana One cylinders) and Table 3 (Stanford Tori). The source spreadsheet may be found at http://www.nss.org/settlement/journal/EasyModel.xls.

Both tables use a set of “knobs” that may be ‘turned’ to define the basic parameters driving the calculations for a series of columns of the various size habitats. Some values are derived from others, but of course may be overridden.

Note that for simplicity, the models hide certain rows and columns not needed for this discussion, but interested parties may unhide them and try additional knobs and settlement sizes. They are further documented in the spreadsheet.

The basic comparison values for the reduction factor going to ELEO merely change the shield mass from 6 tonnes/m^2 to 0. The other parameters are unchanged, yet are (in general) different from the original settlement designs, so a direct comparison to, for example, the original Stanford Torus, would require additional changes (such as the population density, structural materials strength and density, etc.).

For the Kalpana One cylinders, the aspect ratio is fixed at 1.00 (versus the 1.3 of “Kalpana One Revised” [Globus 2007]). For the Stanford Torus, the original 6.9 aspect ratio of the 1 RPM torus is preserved for comparison, but the other tori each have a knob for aspect ratio, and they vary from 6 down to 2 for the various sizes, in an effort to provide minimally acceptable populations. Note that a still smaller aspect of 1.5 (3:2, equivalent to a donut) may be used, but less material is required for a cylinder.

The chosen hull material is a carbon fiber composite with a very high strength (2,400 MPA) and a relatively low density (1.3 g/ml), an appropriate choice for Earth-launched habitats.

[14] Or millions of years, if you are worried about insufficient time for R&D.

An internal structural mass value of 0.2 tonnes/m^2 is sufficient to provide an extra level of structure with walls and a ceiling that can support the weight above it (thus there is an outer rim and a level above; one would be for residence and the other for equipment, storage, agriculture, work areas, and the like).

A non-structural per-person mass allowance of 7 tonnes is specified, which includes:

1.5 of plants (per the NASA 1977 study) for food and recycling of air and water
+ 1.0 of H2O drinking & hygiene & recycling
+ 0.5 of H2O for recreation (pools) & aesthetics (fountains, streams, and ponds)
+ 1.0 for furniture & fixtures
+ 1.0 for lighting & equipment (includes plumbing & power & cooling)
+ 0.5 for paper & plastics & textiles
+ 1.5 for agriculture & recycling overhead and equipment

A rich allowance would be 14 (double everything). A minimum allowance would be 3.5 (half everything). The population capacity is defined as 40 m^2/person of projected 1g area.

There is also a design structural strength margin for the hull. This is initially set to 300%, and a bare minimum of 50% may be acceptable. This margin is used to calculate the hull stress requirement which includes the contributions from air pressure, the 1 g weights of the shield, internal structures and the total non-structural masses in tonnes/m^2 of hull. Note that air pressure alone is 10 tonnes/m^2. The margin applies to all of these.

Calculations are made for the drag cross section (m^2) and density (tonnes/m^2) used in an external calculation for the lifetime of the habitat assuming no orbit-raising maneuvers and an initial altitude of 500 kilometers.

Here are the knobs and resulting tables (a portion of the tables are used for Tables 2 and 3 above):

KNOBS

1.00	Cylinder aspect ratio (width to radius)
0	Shield mass (tonnes/m^2)
2400	Hull structural strength in MPA
1.3	Structural materials density (tons/m^3)
0.2	Internal rim structures mass (tons/m^2 of cylinder rim)
0	Internal endcap structures mass (tons/m^2 of cylinder end caps)
7	Non-structural mass in tons/resident
40.0	Cylinder area per resident (m^2) (population density) - they don't all have to live along the rim!
0.0	Endcap area per resident (m^2) (population density) - additional population
300%	Design Structural Strength Margin

Row Values & Formulas
RPM: an input value, is the only parameter defining the cylinders
Radius: $1/((pi*rpm/30)^2/9.8)$ in meters for 1.0 G
Width: radius * cylinder_aspect_ratio
Design_Population: rim_area/cylinder_area_per_resident
+ endcap_area/endcap_area_per_resident
Shell_Mass: (paraphrased) density*2*pi*radius^3*(1+aspect_ratio)
design_stress/(hull_strength-density(9.8*radius))
this is essentially the density * volume * stress * aspect_ratio_correction_factor
/ (strength - gravity_self_stress) (all in proper units)
from Space Settlements: A Design Study (NASA 1977) p66
For a torus, the correction factor of an infinitely long cylinder (1.5)
is used instead of (1+Ar), and the formula for the volume of a torus is
applied instead of the volume of a cylinder.
For both, the minimum mass is set as the minimum_thickness * hull_area
Hull_thickness is simply hull_mass / hull_area.
Internal_structures is the projected_1G_area * internal_rim_structures_mass
plus a similar endcap calculation for cylinders only
Shield is simply hull_area * shield_mass (in tonnes/m^2)
Non_Structural_Mass is the population * non_structural_mass_allowance
Air_Mass is 1.2 kg * total_volume (as all, converted to kilotonnes or kT)
Total_Mass is simply hull+shield+internal+non_structural+air masses
Reduction_factor uses an iteration to compute the total mass including 6 t/m^2 of shield for the “original” settlement size (2 rpm for cylinders, 1 rpm for tori), then plug in that value for the other calculations using other shield masses.
Drag_Cross_Section used an iteration to determine the angle presenting the maximum area for drag, which turns out to vary slightly with aspect ratio but is close enough to 55^o for our purposes. Then the calculation is sin(55^o)*pi*r^2+cos(55^o)*width*diameter
Drag_Mass_per_m^2 is total_mass / drag_cross_section
The torus_aspect_ratio is another input value varying per torus.
Additionally, the mass, area, and volume for spokes and hubs is computed for each torus, assuming six 2-meter-diameter spokes and a 4-meter-diameter central hub (for docking), all with a thickness the same as the hull.

Kalpana One-style habitats

RPM	1.00	2.00	3.00	4.00	5.00	6.00
Radius m	895	224	99	56	36	25
Width m	895	224	99	56	36	25
Design Population	125,637	7,852	1,551	491	201	97
Shell (kT or kiloTons)	2,030.79	31.62	2.77	0.49	0.13	0.05
hull thickness (m)	0.155	0.039	0.017	0.010	0.006	0.005

Internal Structures (kT)	1,005.10	62.82	12.41	3.93	1.61	0.78
Shield (kT)	0.00	0.00	0.00	0.00	0.00	0.00
Non-structural mass kT	879.46	54.97	10.86	3.44	1.41	0.68
Air mass kT	2,698.72	42.17	3.70	0.66	0.17	0.06
Total Mass (kT)	6,614.07	191.57	29.74	8.51	3.32	1.56
Reduction Factor	1	21	137	479	1,230	2,613
Drag cross section m^2	2,977,356	186,085	36,757	11,630	4,764	2,297
Drag Mass/m^2 (tonnes)	2.221	1.029	0.809	0.732	0.696	0.680

Stanford Torus

RPM	1.00	2.00	3.00	4.00	5.00	6.00
Outer Radius m	895	224	99	56	36	25
Aspect Ratio	6.9	6	5	4	3	2
Tube Diameter m	130	37	20	14	12	12
Shield Mass kT	0	0	0	0	0	0
Population	18,208	1,309	310	123	67	48
Shell Mass kT	66.968	1.379	0.228	0.088	0.046	0.030
Thickness m	0.024	0.007	0.005	0.005	0.005	0.005
Internal Structures kT	145.666	10.470	2.482	0.982	0.536	0.388
Non-structural mass kT	127.458	9.161	2.172	0.859	0.469	0.339
Air mass kT	82.587	1.687	0.209	0.057	0.025	0.017
Spokes & Hub kT	1.069	0.079	0.026	0.015	0.010	0.007
TOTAL MASS kT	423.748	22.775	5.116	2.000	1.086	0.781
Reduction factor	31	580	2581	6602	12158	16901
Drag cross section (m^2)	871,357	64,259	15,741	6,431	3,596	2,610
Drag mass/m^2 (tonnes)	0.486	0.354	0.325	0.311	0.302	0.299

References

[Bigelow 2017] "Bigelow Aerospace | B330." http://bigelowaerospace.com/b330/. Accessed July 10, 2017.

[Brophy 2012] Brophy, John, and Fred Culick. "Asteroid Retrieval Feasibility Study." Keck Institute for Space Studies, April 2, 2012.

[Carry 2012] Carry, Benoit. "Density of Asteroids." *Planetary and Space Science* 73, no. 1 (2012): 98–118.

[Cassell 2015] Cassell, Chris. Personal communication based on calculations using AGI's STK.

[Connors 1985] Connors, Mary M.; Harrison, Albert A.; Akins, Faren R. *Living Aloft: Human Requirements for Extended Spaceflight* (NASA SP-483). NASA Scientific and Technical Information Branch.

[Cowings 2013] Cowings, Patricia S. "Psychophysiology of Spaceflight and Aviation." *Polish Journal of Aviation Medical Psychology* 19, no. 3 (2013): 9–16.

[Cowings 2000] Cowings, Patricia S., and William B. Toscano. "Autogenic-Feedback Training Exercise Is Superior to Promethazine for Control of Motion Sickness Symptoms." *The Journal of Clinical Pharmacology* 40, no. 10 (2000): 1154–1165.

[Diamandis 1987] Diamandis, Peter H. "Reconsidering Artificial Gravity for Twenty-First Century Space Habitats." In *Space Manufacturing 6: Nonterrestrial Resources, Biosciences, and Space Engineering*, B. Faughnan, G. Maryniak (Eds.), 6:55–68. AIAA, 1987.

[Explorersweb 2006] Explorersweb. "AdventureStats," 2006. http://www.adventurestats.com/tables/EverestAgeFat.shtml.

[Garriott 2014] Garriott, Richard. "Opening the Floodgates to Entrepreneurial Space Exploration." Luncheon talk presented at the 33rd International Space Development Conference, Los Angeles, CA, May 14, 2014.

[Ghiassi-nej 2002] Ghiassi-nejad, M., S.M.J. Mortazavi, J.R. Cameron, A. Niroomand-rad, and P.A. Karam. "Very High Background Radiation Areas of Ramsar, Iran: Preliminary Biological Studies." *Health Physics* 82, no. 1 (2002): 87–93.

[Globus 2007] Globus, Al, Nitin Arora, Ankur Bajoria, and Joe Strout. "The Kalpana One Orbital Space Settlement Revised," April 2007. http://alglobus.net/NASAwork/papers/2007KalpanaOne.pdf accessed January 2017.

[Globus 2012] Globus, Al. “Our Solar System, Our Galaxy, then the Universe,” April 2012. http://space.alglobus.net/papers/Expansion.pdf accessed December 2016.

[Globus 2017a] Globus, Al, and Joe Strout. “Orbital Space Settlement Radiation Shielding,” *NSS Space Settlement Journal*, June 2017. http://www.nss.org/settlement/journal/NSS-JOURNAL-Orbital-Space-Settlement-Radiation-Shielding.pdf accessed June 2017.

[Globus 2017b] Globus, Al, and Theodore Hall. “Space Settlement Population Rotation Tolerance,” June 2017. http://space.alglobus.net/papers/RotationPaper.pdf accessed June 2017.

[Graybiel 1960] Graybiel, Ashton, Brant Clark, and J Zarriello. “Observations on Human Subjects Living in a ‘Slow Rotation Room’ for Periods of Two Days.” *Archives of Neurology* 3, no. 1 (July 1960): 55–73. doi:10.1001/archneur.1960.00450010055006

[Graybiel 1977] Graybiel, Ashton, Earl Miller, and Jerry Homick. *Biomedical Results From SKYLAB: Experiment M131. Human Vestibular Function*. NASA, 1977.

[ICRP 2000] Valentin, J. *Pregnancy and Medical Radiation*. Annals of the ICRP. International Commission on Radiological Protection, 2000.

[ICRP 2003] Valentin, J. “Biological Effects after Prenatal Irradiation (Embryo and Fetus).” Annals of the ICRP. International Commission on Radiological Protection, 2003.

[Johnson 1975] Johnson, Richard, and Charles Holbrow. *Space Settlements: A Design Study*. NASA, 1975. http://space.alglobus.net/75SummerStudy/Design.html.

[Lafleur 2010] Lafleur, Claude. “Spacecraft Stats and Insights,” *The Space Review*, April 5, 2010. http://www.thespacereview.com/article/1598/1.

[Linnea 2010] Wahl, Linnea. “Environmental Radiation.” Health Physics Society, January 2010. http://hps.org/documents/environmental_radiation_fact_sheet.pdf accessed July 31, 2014.

[McKirdy 2014] McKirdy, Euan. “Fukushima Residents Cleared to Return Home amid Ongoing Contamination Fears.” CNN, April 1, 2014. http://www.cnn.com/2014/04/01/world/asia/fukushima-miyakoji-return/index.html.

[McKnight 2012] “We’ve Already Passed the Tipping Point for Orbital Debris” *IEEE Spectrum*. http://spectrum.ieee.org//aerospace/satellites/weve-already-passed-the-tipping-point-for-orbital-debris accessed September 24, 2015.

[Musk 2017] Musk, Elon. “Making Humans a Multi-Planetary Species” New Space. June 2017, 5(2): 46-61. https://doi.org/10.1089/space.2017.29009.emu presentation materials at http://www.spacex.com/sites/spacex/files/mars_presentation.pdf accessed October 2016.

[NASA 2011] NASA. “Space Shuttle,” 2011. http://www.nasa.gov/mission_pages/shuttle/shuttlemissions/index.html.

[NASA 2012] “NASA Orbital Debris FAQs.” Accessed September 26, 2015. http://orbitaldebris.jsc.nasa.gov/faqs.html.

[NASA 2013] “Ten Thousandth Near-Earth Object Discovered,” June 2013, accessed 9 November 2015, http://science.nasa.gov/science-news/science-at-nasa/2013/24jun_neo/

[NASA 2015] “About the Space Station: Facts and Figures | NASA,” 2015. http://www.nasa.gov/mission_pages/station/main/onthestation/facts_and_figures.html.

[NRC 2010] “NRC: Fact Sheet on Biological Effects of Radiation,” October 2011. Accessed July 31, 2014. http://www.nrc.gov/reading-rm/doc-collections/fact-sheets/bio-effects-radiation.html.

[NSS 2016] NSS. “Orbital Debris: Overcoming Challenges.” Position Paper. National Space Society, May 2016. http://www.nss.org/legislative/positions/NSS_Position_Paper_Orbital_Debris_2016.pdf accessed January 2017.

[O’Neil 1998] O’Neil, Daniel, Ivan Bekey, John Mankins, Thomas F. Rogers, and Eric W. Stallmet. “General Public Space Travel and Tourism - Volume 1 Executive Summary.” NASA Marshall Space Flight Center, March 1998. http://www.spacefuture.com/archive/general_public_space_travel_and_tourism.shtml.

[OLTARIS 2011] R Singleterry, S Blattnig, M Clowdsley, G Quallis, C Sandrige, L Simonsen, T Slaba, et al. “OLTARIS: On-Line Tool for the Assessment of Radiation in Space.” *Acta Astronautica* 68 (2011): 1086–97.

[OLTARIS 2014] “OLTARIS Home Page.” Accessed June 13, 2014. https://oltaris.larc.nasa.gov/.

[O’Neill 1977] O’Neill, Gerard K. *Space Resources and Space Settlements*, NASA SP-428. NASA, 1977. http://space.alglobus.net/spaceres/index.html.

[NSS 2015] “NSS Position Paper Next Generation Space_Stations 2015.” National Space Society, April 2015. http://www.nss.org/legislative/positions/NSS_Position_Paper_Next_Generation_Space_Stations_2015.pdf.

[Panwar 1999] Panwar, Rakesh. “Satellite Orbital Decay Calculations.” The Australian Space Weather Agency, 1999.
http://www.ips.gov.au/Category/Educational/Space%20Weather/Space%20Weather%20Effects/SatelliteOrbitalDecayCalculations.pdf

[Space Adventures 2015] “Circumlunar Mission.” Space Adventures, Ltd. | Circumlunar Mission. Accessed September 7, 2015.
http://www.spaceadventures.com/experiences/circumlunar-mission/.

[SpaceX 2017] “Falcon Heavy” 2017. http://www.spacex.com/falcon-heavy

[Statista 2014] Statista. “Travel & Tourism: Global Economic Impact 2014.” Accessed September 28, 2015. http://www.statista.com/statistics/233223/travel-and-tourism--total-economic-contribution-worldwide/.

[ULA 2016] United Launch Alliance, Transportation Enabling a Robust Cislunar Economy, presentation,
http://www.ulalaunch.com/uploads/docs/Published_Papers/Commercial_Space/2016_Cislunar.pdf. Accessed July 10, 2017.

[World Nuclear Association 2014] “Naturally Occurring Radioactive Materials NORM,” June 2014. http://www.world-nuclear.org/info/Safety-and-Security/Radiation-and-Health/Naturally-Occurring-Radioactive-Materials-NORM/.

[Wrixon 2008] Wrixon, A D. “New ICRP Recommendations.” *Journal of Radiological Protection* 28, no. 2 (June 1, 2008): 161–68. doi:10.1088/0952-4746/28/2/R02.
http://iopscience.iop.org/0952-4746/28/2/R02/pdf/0952-4746_28_2_R02.pdf