Near Term Policy and Research Priorities to Enable the First Space Settlement

Al Globus
Member of the Alliance for Space Development Board
Policy Forum on Space Settlement
An Examination of Policy Options
International Space Development Conference 2019
Arlington, VA
June 5, 2019

Abstract

We present a number of preliminary policy options and research directions intended to enable construction of the first space settlement starting in two or three decades. Most of the necessary technology development can be driven by either Earth-bound applications or the construction and operation of a series of ever more capable space hotels as space hotel requirements are very similar to those of space settlements.

This paper examines policy options for the necessary development that will not be catalyzed by terrestrial needs or space hotels. The options include making space settlement an official goal for the relevant agencies, developing launchers a factor of 20 or more less expensive than today, and debris cleanup.

We will also describe an applied research program to better understand the Equatorial Low Earth Orbit (ELEO) radiation environment, space farms, psycho-social issues, and unique settlement construction and operation issues.

Introduction

Starting in the 1970s Princeton physics professor Gerard K. O'Neill lead a series of studies indicating that free-space settlements, spacecraft large enough to live in, including raising children, were feasible and very beneficial for an expanding technological civilization [Johnson 1975][O'Neill 1977]. A series of designs were produced which are still of great value today. They rotate to provide 1g of pseudo-gravity at the outer hull, use lunar regolith shot from an electromagnetic mass driver for radiation shielding, and grow their own food. However, four decades on no free space settlements have been built and there is no near-term, or even medium-term, expectation that one will be.

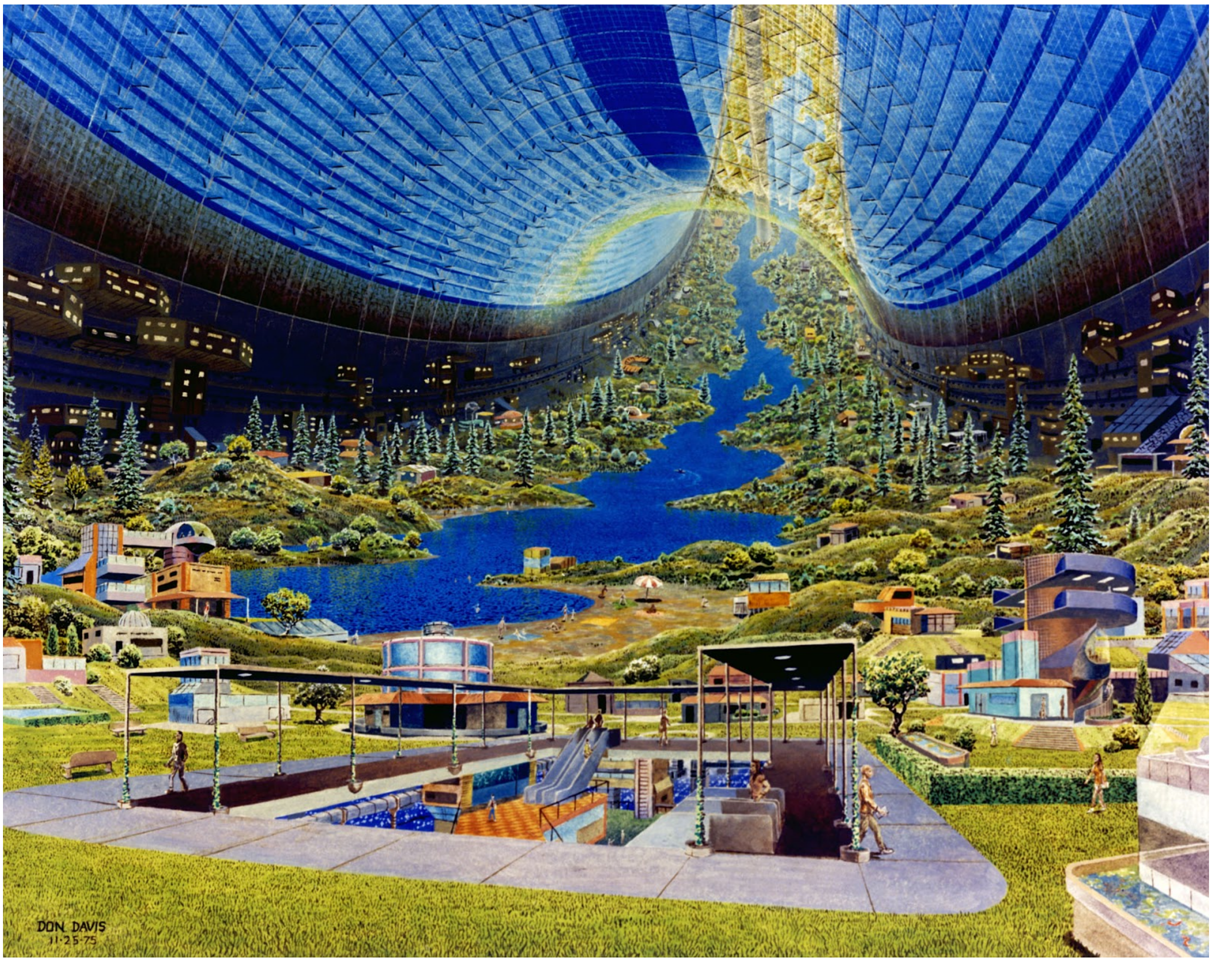


Figure 1: Stanford Torus developed in the 1970s, image credit Don Davis.

The most likely explanation is that building these systems is simply too difficult given the resources applied to the task. It is not hard to see why. The designs are

1. too big (kilometer scale)
2. too massive (millions of tons)
3. too far away (lunar distances)
4. And have no incremental path with income much less profit from where we are today to construction of the first settlement.

The net result has been no settlements.

[Globus 2017a] argues that there is an easier way. A path with four keys to a settlement that is orders of magnitude smaller, less massive, and closer. This path requires no extraterrestrial materials development and there is an incremental approach with income, and perhaps even profit, along the way. Furthermore, the next generation of launch vehicles currently under development may have the required physical and financial properties.

Figure 2: Kalpana Two interior. Note the extreme curvature as the diameter is short, about the length of a football field. Image credit: Bryan Versteeg.

The four keys are:

1. Place the settlement in Equatorial Low Earth Orbit (ELEO), a circular LEO with very low inclination. Up to about 600 km such orbits have very little radiation by space standards [Globus 2017b] eliminating most or all of the radiation shielding mass. This reduces mass by as much as a factor of 100.
2. Spin the settlement fast, up to about 4 rpm. This means the settlement can be much smaller than the 1 rpm Stanford Torus, roughly a factor of 16 less. When they first arrive, many settlers will get motion sickness, but the vast majority will recover within a few hours to a few days [Globus 2017c].
3. Take advantage of the fully reusable, low cost launchers under development. For example, the SpaceX Super Heavy and Starship which are expected to radically reduce the price of launch. To achieve this reduction engineering is not enough, we must also develop applications that can potentially support tens of thousands of launches per year. These applications are:
    a. Earth point to point
    b. Space solar power
    c. Tourism
4. The space tourism business will likely use space hotels. The requirements for a space hotel are very similar, although not identical, to those of a space settlement. A successful tourism industry will develop large and larger hotels, some perhaps with spin-induced pseudo gravity for guest convenience, until the size of Kalpana Two, a cylindrical settlement design incorporating these keys, is reached. After building and operating a few hotels in this size range, building the first settlement is a relatively small step requiring mostly a higher spin rate to achieve 1g at the hull.

	ISS	Kalpana Two	Stanford Torus
Mass (Kt)	0.4	8.5	13,000
Size (m)	100	112	1,790
Population	6	500	18,000
Distance (km)	400	500	384,400
SpaceX Super Heavy launches	3	60	90,000
Lunar/NEO mining	No	No	Yes
Inspace transport	No	No	Yes

Table 1: Comparison the ISS, Kalpana Two designed with the four keys, and the Stanford Torus. Note that the Stanford Torus numbers reflect the population and mass models in [Globus 2017a] not the mass and population models used for Stanford Torus design in the 1970s.

From Table 1 we see that applying these keys reduces mass by three orders of magnitude, size by one order of magnitude, and distance from Earth by two orders of magnitude. While building and operating the first space settlement is a difficult task, using these keys makes it is vastly easier.

The Policies

As mentioned above, most of the issues that need to be resolved are best developed in the course of technology improvement for on-Earth applications or space hotels. A small hotel suitable for a few tourists is a lot easier to build than a settlement. This means incremental development with income from each new hotel provides a relatively easy implementation path and early operationalization, always a benefit. We now examine some of the policy options that range from helpful to essential.

Make Space Settlement an Official Goal

Right now NASA has a mandate to explore, observe the Earth, pursue space science, and so forth, but neither NASA nor any other federal agency has a mandate to pursue space settlement. That means that when a bright young NASA engineer has an idea for a major improvement to the state of settlement art nothing will happen, at least on work time. The author was a contractor at NASA Ames and in multiple cases had promising settlement work shut down because it was not within NASA's purview. No money can be allocated to settlement work and no facilities constructed to directly further space settlement. This is also true at the Department of Transportation and Department of Commerce, both of which have space related responsibilities.

Note that making settlement a goal does not necessarily mean funds will be allocated or work will be done. Rather, it allows settlement work in those cases where management and/or Congress deems it appropriate. A bill to make settlement a goal is currently in work under the title Advancing Human Spaceflight Act (May 2019).

Order of Magnitude Plus Reduction in Launch Cost

The tallest pole in the settlement development tent is launch. Launch is enormously expensive, in great part because most vehicles are abandoned after a single use. The cheapest currently advertised launch price is $1,400/kg to Low Earth Orbit (LEO) using the partially reusable SpaceX Falcon Heavy [SpaceX 2019]. The generally accepted mantra is that fully reusable vehicles are the key to the order of magnitude or more reduction in cost is needed.

[Globus 2017a] suggests that current prices need to go down by a factor of 50 to make construction of a small settlement financially just barely feasible given the most optimistic somewhat reasonable assumptions. The next generation of SpaceX vehicles, the Super Heavy and Starship, are expected to be very large and fully reusable. Taking the most optimistic assumptions, these vehicles can reduce cost by a factor of about 20. Given the (in)accuracy of cost projections there is little real difference between reduction by a factor of 50 vs 20.

One might be tempted to proclaim that the most important policy is to shovel government money into the launch companies, particularly SpaceX and Blue Origin. However, right now is a golden age of rocket develop with something like 100 companies developing launchers. There is plenty of activity aimed at engineering solutions to the problem of launch cost and, to a lesser extent, safety. The missing piece where policy could step in is market development.

One cannot reduce prices by an order of magnitude or more unless there is a fairly large market to spread development costs and justify construction automation. Right now the world-wide launch rate is less than 100 flights per year. Consider a vehicle that can fly once a week. Two such vehicles could satisfy the entire current launch market. Even at 1,000 flights per year only 20 vehicles are needed to meet the entire demand. Something like 10,000 flights per year is probably the absolute minimum flight rate to sustain demand to keep fully reusable vehicles busy earning money.

Unfortunately, there are not a lot of markets that that can utilize 10,000 or more launches per year. In fact, there appear to be only three:

1. Earth point to point.
2. Space solar power.
3. Tourism

Earth Point to Point

A vehicle capable of reaching orbital velocity can reach any point on the Earth's surface in less than an hour, and most of the Earth within 30 minutes. Consider a financial worker in Manhattan who needs to close a deal with their counterpart in Shanghai. Our Manhattanite can hop on the regular rocket shuttle in the morning, close the deal over an extended lunch, and get home in time for their daughter's soccer game.

While such travel will certainly be expensive at first, as we gain experience in building and operating such systems prices will come down, just as jet travel from, say, California to Hawaii, has over the last several decades. Billions of people fly on jets each year and prices are reasonable. If the price is right and rocket travel is well integrated into the rest of the transportation system, such travel could easily create a market of well over 10,000 launches per year.

Ask: To reduce total trip time the rockets must be well integrated into the local transportation system. The current practice of excluding large swaths of airspace for lengthy periods [Murray] must be replaced with something much more efficient, but just as safe, for all rocket launches. This will require regulatory help and independent safety expertise.

Space Solar Power

Space solar power (SSP) refers to gathering energy in space and beaming it to Earth. SSP can, at least in principle, deliver very large quantities of energy to the grid. As the energy market is measured in trillions of dollars, if SSP becomes profitable a flight rate of greater than 10,000 per year should be easy to maintain until the space segment can be built from lunar or asteroidal materials.

Ask: SSP development requires substantial research and development but government research support has been very minimal. Meanwhile, nuclear fusion research has received hundreds of millions of dollars (or more) over the years, never produced commercial power, and is at least as risky as SSP. A balanced energy policy would fund SSP research at a rate similar to fusion.

Tourism

While increasing tourism may be an excellent approach to generating the required flight rate, using taxpayer funds to subsidize joy rides for very rich individuals is a political non-starter, and for good reason. Thus, government policy cannot help tourism directly. However, government policy can be directed towards space stations, indeed all the stations so far were built and owned by governments. Many of the requirements of space stations are similar to space hotels, the biggest difference being that hotels do not need expensive scientific equipment, so government policy can indirectly assist space hotel developers.

As with Earth point to point, space tourism launches must be integrated into airspace management.

Ask: An airspace regulatory regime that integrates aviation and a much higher tempo launch industry carrying passengers into space.

Debris Cleanup and Survivability

There is a great deal of debris in Earth orbit, particularly GEO and LEO. Around 34,000 pieces larger than 10 cm and 900,000 1-10 cm are in Earth orbit [ESA 2019]. The largest pieces are the most dangerous for settlements as strikes by small pieces of debris are unlikely to be fatal.

A settlement at, say, 500 km will eventually be exposed to collisions by all the LEO debris with a 500 km apogee or greater. At this altitude, debris will be cleaned out by atmospheric drag but most of the debris is at somewhat higher altitudes (around 800 km) and will slowly come down through the altitude of space settlements presenting a collision risk.

It will be difficult to dodge an imminent collision the way the ISS does, by boosting into a higher orbit, although not impossible. Even the smallest settlements will be very large and heavy. For example, Kalpana 2 has a projected mass of about 8,500 tons, about 20 times that of the ISS and thus 20x harder to move. On the other hand, large systems should tend to survive strikes by small pieces of debris. In any case, a significant reduction in large LEO space debris would make the first settlement significantly safer.

Research and development aimed at debris survivability can be undertaken in the name of space station and satellite safety, which will benefit both the space tourism industry and space settlement.

Ask: 1) a coherent approach to limiting new debris and removing existing threats, funded by those who benefit from LEO spacecraft, and perhaps modelled on the policy paper produced by the National Space Society [NSS 2017]. 2) a program to remove the largest pieces of debris in LEO above 500 km apogee. 3) a grant and contract program to improve system tolerance of debris strikes.

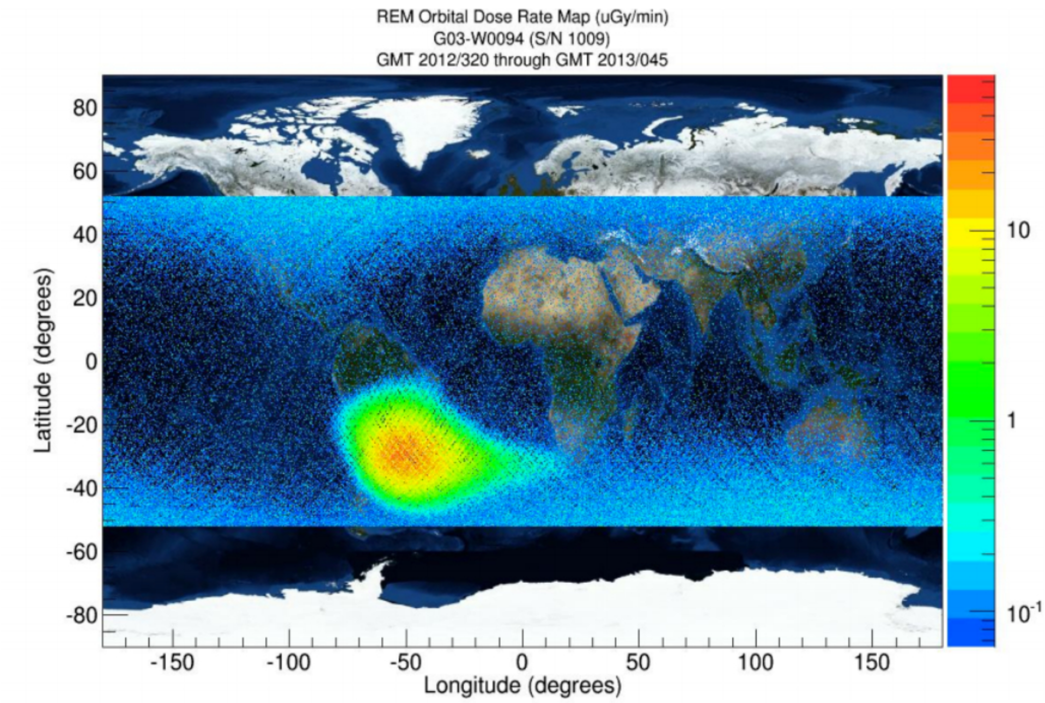
Applied Research Program

A great deal of applied research and development will be necessary to enable starting construction of the first space settlement. Some of this work requires answers soon as a negative result may mean that fast spinning ELEO settlements are fatally flawed. Other results are not essential for a few decades but much of this work needs to start now to deliver in time.

As we have mentioned, most of the new technology development necessary can be reasonably expected to be motivated by terrestrial concerns. Most of the rest can be motivated by space hotel development. Assuming a 4-5 year generation time for hotel development it might be 20 years before the fruits of this development are ready for settlement use. Thus, the research program specifically motivated by space settlement should aim to deliver the relevant technology at high TRL (Technology Readiness Level) in about 20 years.

Equatorial Low Earth Orbit (ELEO) Radiation

The heart of our approach to the first space settlement is the low radiation environment discovered using Oltaris [Globus 2017b] to calculate radiation levels one should expect in very low inclination orbits up to about 600 km. With so much riding on this result it makes sense to take in situ measurements to verify calculations. In addition, the location of the South Atlantic Anomaly (SAA) must stay below the equator for ELEO radiation levels to be low. It is not clear how to predict the location of the SAA over the next, say, 100 years, but we need to at least try. Both of these tasks should be executed as soon as possible as a negative result would invalidate the Kalpana Two concept.



Each dot is a radiation measurement taken on the ISS at about 400 km. The SAA is a region of relatively high radiation over the South Atlantic and South America. At its peak, in the center, radiation levels are about 1000x those of the rest of the planet. Image credit NASA.

One could verify the Oltaris calculations with one or more smallsat (even cubesat) missions to measure radiation levels 400-800 km. 400 because one can compare with ISS measurements, 800 because that is almost certainly higher than settlement apogee radiation levels will allow with small amounts of radiation shielding.

Predicting the future motion of the SAA is a difficult task, but [Heirtzler 2000 figure 8] suggests that while the SAA will be much larger by 2100 it will stay in the southern hemisphere. We also know that the SAA has been around for at least 400 years [Pavon-Carrasco 2016] and “Thanks to the present high resolution geomagnetic models we know the inner origin of the SAA. The SAA at the Earth's surface is the response of an inverse flux path at the core-mantle boundary (CMB) of the radial component of the geomagnetic field located approximately under the South Atlantic Ocean generating the hemisphere asymmetry of the geomagnetic field." [Pavon-Carrasco 2016].

Finally, the quality of the radiation in ELEO is unique, consisting of a low level continuous stream almost entirely made of very high energy high mass nuclei. The continuous nature is all but impossible to reproduce in accelerators and the low level means experiments must run for a long time.

Ask: 1) a series of small sat missions to characterize ELEO radiation at about 400-800 km with measurement in addition to computation and 2) a grant program to develop insight into probable changes of the South Atlantic Anomaly over the next few centuries. 3) A grant program to understand radiation effects and quality unique to ELEO.

Space Farms

Providing reliable, nearly closed, life support is probably the most difficult technical task in space settlement after launch. The farm in a settlement must not only provide food, but also convert CO_2 into oxygen, clean the water, and consume human, crop, and animal waste. Current space-based life support cannot even approach these goals. On the ISS, CO_2 is removed from the atmosphere only to be dumped overboard, some of the water is recycled, and a few leaves of lettuce have been grown and eaten.

Fortunately, there is a historical example of a system doing all life support, and it worked fairly well for the first try: Biosphere 2 [Nelson 2018][Poynter 2006]. Although there were lots of problems, the bottom line is that eight people lived in a nearly air tight facility for two years, grew most their own food on a half acre, recycled their waste, and ended with the same water they started with. O_2 had to be replenished after about a year as it was being absorbed by the concrete -- which proved that the system was nearly air tight.

The approach Biosphere 2 used was to mimic a number of terrestrial biomes. While this was effective it is somewhat high mass as a great deal of soil and water was needed (for eight people there were 1.7 tons of soil per person and 3,790 kg -- half a ton per person -- of water condensed out of the air every day [Poynter 2006 pp. 185]). For early settlements some way to reduce mass would be helpful, and there is one.

Arranging for natural sunlight to illuminate a space farm is geometrically difficult as the system is rotating to provide 1g of pseudo-gravity at the hull. Recently there has been an explosion in intensive, artificial light, (sometimes) soilless, agriculture around the world particularly in the Netherlands. One can, for example, purchase a standard sized shipping container, plug into water and power, and produce baby greens and lettuce for neighboring restaurants regardless of the weather or time of year[1]. Analysis by [Bryce 2017], [Bryce 2018], [Soilleux 2018] and others suggests that using artificial light and soilless agriculture

1 https://www.fastcompany.com/3063275/take-a-3d-tour-of-a-vertical-farm-packed-inside-a-shipping-container

for a space farm may be practical from a menu, power, space, and mass perspective, although a great deal of optimization will be required.

While commercial development can be expected to solve many of the problems associated with artificial light agriculture, there is no similar economic driver for recycling human waste, which will be essential.

Ask: 1) Grants and contracts to develop human waste recycling for terrestrial implementation. This approach could meet the needs of current societies, thereby developing a broad based technology with many trained personnel. 2) Building a Biosphere 2-like facility, ideally in the farm belt to access local expertise, to practice living in closed environments while on the ground and a single door from safety.

Psycho-Social Issues

In Biosphere 2 the eight biospherians reported an extraordinary emotional tie with the living environment they created and maintained. None-the-less they broke up into two antagonistic groups of four [Nelson 2018][Poynter 2006], which is a common occurrence in confined environments. The disagreements were so severe that former good friends would walk by each other without so much as a glance between them. This conflict never seems to have gone to the point of interfering with maintenance of their environment, but strategies to avoid this sort of antagonism are needed.

The nature of psycho-social issues is likely strongly influenced by population size. Kalpapa Two has a population size (500) similar to McMurdo Station in Antarctica, which has a summer population around 1,200 with 250 in winter. There has been some conflict and violence at McMurdo. Alcohol-fueled fights are fairly common and there have been a few incidents of extreme violence[2], including attacks with hammers and a knife. While difficult and perhaps expensive we need a better understanding of psycho-social issues before commiting 500 people to space.

Ask: 1) a grant program for academics to study analogous environments. 2) a facility that can be configured to study different population sizes, crowding, effect of controlling one's own biosphere, and other issues. This might be integrated with the space farm facility.

Rotating Environments

While there is substantial evidence to believe that people will adapt to being in a 100 m scale structure rotating at 4rpm [Globus 2017c], we cannot assume that serious issues will not arise. Thus, a program to understand the effects of rotation on people, animals, plants and even plumbing is necessary.

2 https://www.smithsonianmag.com/smart-news/russian-faces-antarctica-attempted-murder-charge-180970632/

Some work can be done exclusively on the ground. In the 60s a number of on-Earth rotating rooms were used to examine rotating human subjects. This work has continued at some level in, for example, the Ashton Graybiel Spatial Orientation Laboratory's[3] research into adaptation to coriolis forces due to rotation.

Other work requires ground and orbit coordination. For example, the rotating chair Skylab experiment [Graybiel 1977] should be repeated and setup to be as analogous to the situation facing settlers as possible. This experiment found that astronauts in orbit suffered very minor effects when exposed to very high rotation rates, whereas before and after the mission they became extremely ill with the same rotation rate.

Still other work requires a substantial facility in orbit. There is no other way to get partial-g and plants, animals, and humans need to be tested in a variety of rotating speeds to insure that the very limited testing done so far does not miss something important.

Ask: 1) grant program involving both studies and ground infrastructure such as rotating rooms and 2) a facility in LEO to test plants, animals, humans and equipment at various g levels below 1. This can be configured to lunar or martian g levels but must also present the range of g-levels one might find in a spinning settlement (everything from 0g to 1g).

Settlement Construction and Operation Issues

There are a number of research and development issues specific to space settlement that cannot be expected to be resolved in the next few decades by general improvement in knowledge or as driven by space hotel development. These include, but are not limited to

1. Long life hull and other structures
2. Ultra-recycling
3. Special purpose robotics
4. Detailed radiation models of settlement interior
5. Wobble control

Long Life Hull and other Structures

Settlements are, among other things, real estate projects. Most spacecraft have a design life of a few decades, if that. Nobody buys a house expecting that the land it is on will disappear in 20 years. Thus, we must learn to build very long lived structures in space. There are at least two strategies:

1. Build thick, massive structures that can degrade significantly before losing functionality
2. Constantly rebuild and discard structure always keeping a functional system in place. This is how bone stays strong for many decades without wasting mass. Some specialized cells build up bone in response to mechanical demands while others eat away bone if it's not needed.

[3] https://www.brandeis.edu/graybiel/

Ultra-recycling

Accumulation of trash is a bit of a problem for today's space stations. It must either be stored in the limited space available or sent to a fiery demise in the atmosphere. This second option requires a vehicle to burn up as well. This will not be a practical option if the in-space population grows from a few astronauts to hundreds, if not thousands, of settlers.

One solution is to recycle virtually everything. Germany, a global leader in recycling, recycles about 80% [Brassaw 20017] of total waste and 70% of municipal waste. Thus there is room for significant improvement.

One approach not available on Earth is to turn whatever cannot be otherwise recycled into radiation shielding by providing a mechanism to pack arbitrary trash into containers on the hull established for that purpose. Over time the hull will expand as trash is generated but that rate should slow down as more and more items can be recycled to purposes other than radiation shielding.

Special Purpose Robotics

Robotics is developing rapidly and over time more and more of space settlement construction and operation can expect to be handled by robots without any particular effort on the part of space settlers beyond learning to use what others have developed. However, there are certain issues that are unlikely to be addressed by the general state of the art or even space hotels. For example: robots intended to work in weightlessness.

Detailed Radiation Models of Settlement Interior

While Oltaris calculations are sufficient to assume that the overall levels of radiation are acceptable, the radiation at any given point in a settlement may be significantly higher due to secondary particles created by cosmic rays striking nuclei in the materials of the settlement and other effects. There could, at least in principle, be significantly elevated levels of radiation in someone's bedroom, which could cross the radiation limit to unacceptable [Globus 2017b]. While for specific locations radiation can certainly be measured and countered by trial and error, it would be best to know in advance. This requires detailed simulation and software integration with CAD software used for settlement design.

Wobble Control

Our target space settlement rotates at 4 rpm. As people and things move about the interior the structure will tend to wobble. If not well controlled this wobble could change the axis of rotation and/or simply demolish the settlement. Thus, strategies for continuous, long term, wobble control are needed.

Ask: 1) Research grant programs in each of these areas and, where appropropriate, instantiating them in software. 2) Use of the ISS and future space stations for test and demonstration.

Conclusion

Much of the research and development needed for the first space settlement can be expected to be accomplished by normal, world-wide technical developments. Most of the rest may be driven by the development of space hotels. However, there are some issues that will not be addressed by either of these mechanisms. Using hotels to develop most of the necessary technologies could easily take 20 years or perhaps more. Thus the research plan should aim to come to fruition in about two decades.

Most of the R&D paths sketched in this paper could benefit from grant and contract programs. In addition, some new (or refurbished) facilities will be needed. These include:

1. SmallSat (perhaps cubesat) missions to verify the ELEO radiation environment computed by Oltaris.
2. A mostly closed facility for full scale space farm research similar in some ways to Biosphere 2.
3. A facility, perhaps integrated with the space farm facility, to simulate the isolation and crowding expected on the first space settlement.
4. A LEO facility for variable g research.

While establishing these facilities and programs will not be particularly cheap, it can be expected to be small part of the current space budget and a tiny fraction of the federal government's expenditure. One major task left undone is to estimate the cost of these programs in addition to identifying other paths that should be followed.

References

[Brassaw 2017] Brassaw, Brian. "Germany: A Recycling Program That Actually Works | Earth911.Com." Accessed April 13, 2019. https://earth911.com/business-policy/recycling-in-germany/.

[Bryce 2017] Meyer, Bryce L. "Mass and Volumes for a Spectrum of Multistage Evolving Space Farms." *NSS Space Settlement Journal*, Issue no. 3 (November 2017). https://space.nss.org/media/NSS-JOURNAL-Multistage-Evolving-Space-Farms.pdf

[Bryce 2018] Meyer, Bryce L. "Electrical Requirements for a Spectrum of Multi-Stage Space Farms." *NSS Space Settlement Journal*, no. 4 (December 2018): 42. https://space.nss.org/media/NSS-JOURNAL-Space-Farm-Electrical-Requirements.pdf

[ESA 2019] ESA. "Space Debris by the Numbers." Accessed April 13, 2019. https://www.esa.int/Our_Activities/Operations/Space_Safety_Security/Space_Debris/Space_debris_by_the_numbers.

[Globus 2017a] Globus, Al, Stephen Covey, and Daniel Faber. “Space Settlement: An Easier Way,” NSS Space Settlement Journal, February 2017. https://space.nss.org/media/NSS-JOURNAL-Space-Settlement-An-Easier-Way.pdf.

[Globus 2017b] Globus, Al, and Joe Strout. “Orbital Space Settlement Radiation Shielding.” NSS Space Settlement Journal, 2017. https://space.nss.org/media/NSS-JOURNAL-Orbital-Space-Settlement-Radiation-Shielding.pdf.

[Globus 2017c] Globus, Al, and Theodore Hall. “Space Settlement Population Rotation Tolerance.” NSS Space Settlement Journal, January 2017. https://space.nss.org/media/NSS-JOURNAL-Space-Settlement-Population-Rotation-Tolerance.pdf.

Globus, Al, and Theodore Hall. “Space Settlement Population Rotation Tolerance,” January 2017. https://space.nss.org/media/NSS-JOURNAL-Space-Settlement-Population-Rotation-Tolerance.pdf.

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

[Heirtzler 2000] Heirtzler, J. R. “The Future of the South Atlantic Anomaly And Implications for Radiation Damage in Space.” NASA, 2000. https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20000085550.pdf.

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

[Murray] Murray, Daniel P. “The FAA’s Current Approach to Integrating Commercial Space Operations into the National Airspace System,” https://www.faa.gov/about/office_org/headquarters_offices/ast/reports_studies/media/REMAT-Murray-FAA-FINAL.pdf accessed April 13 2019.

[Nelson 2018] Nelson, Mark. *Pushing Our Limits: Insights from Biosphere 2*. University of Arizona Press, 2018.

[NSS 2017] National Space Society. “Orbital Debris: Overcoming Challenges.” National Space Society. Accessed April 13, 2019. https://space.nss.org/media/NSS-Position-Paper-Orbital-Debris-2016.pdf.

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

[Pavon-Carrasco 2016] Pavón-Carrasco, F. Javier, and Angelo De Santis. “The South Atlantic Anomaly: The Key for a Possible Geomagnetic Reversal.” *Frontiers in Earth Science* 4 (2016). https://doi.org/10.3389/feart.2016.00040.

[Poynter 2006] Poynter, Jane. *The Human Experiment: Two Years and Twenty Minutes inside Biosphere 2*. Basic Books, 2006.

[Soilleux 2018] Soilleux, Richard, and Stephen Gunn. “Environmental Control and Life Support (ECLSS) for Large Orbital Habitats Ventilation and Heat Transport,” January 2018. https://space.nss.org/media/NSS-JOURNAL-ECLSS-for-Large-Orbital-Habitats-Ventilation-and-Heat-Transport.pdf.

[SpaceX 2019] “Falcon Heavy Pricing.” SpaceX. Accessed April 13, 2019. https://www.spacex.com/about/capabilities.