Considerations for Large-Scale Construction in Orbit

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Abstract

To sustain and expand the human presence in space, a space-based economy must be developed. This in turn requires the development of infrastructure to utilize extra-terrestrial resources. This paper revisits concepts for large-scale construction in space from the 1970s, in the context of developing a space-based economy. Developments in robotics, solar power generation, microgravity manufacturing and earth-based launch costs significantly alter the models envisaged in the '70s. These changes are illustrated by considering the assembly of the outer shell of a 1 km-radius rotating cylindrical habitat.

Introduction

Forty years after the first human reached space, the space-faring industry is at a cross-roads. The Cold War and missile development no longer provide imperatives. Commercial expenditures in space exceeded government expenditures for the first time in 1997 [1] and a "gold rush to Low Earth Orbit" [2] was expected. The spectacular success of robotic missions to Mars and the outer planets lent credibility to NASA plans for a human mission to Mars. However, some high-profile business failures underlining the basic economic realities of the "High Frontier" and recent losses of Mars missions have changed that picture [3]. The International Space Station is operational, but has not yet become a business success. The launch cost from Earth continues to be the single most formidable obstacle to space utilization. It is becoming clear that for business to succeed in Space, this obstacle must be overcome. There is growing consensus on the need for infrastructure built away from earth, whether on the Moon or in orbit, and for a substantial portion of the mass needed for operations to be extracted from sources other than Earth. A space-based economy must develop, with many businesses whose suppliers, value addition processes and customers are all located away from Earth.

Since the 19th century, speculations of increasing technical depth have laid out plans for human settlements beyond Earth. After the Apollo successes, the basic feasibility of such settlements was shown through detailed studies[4,5]. The stated objectives of such projects have evolved. Early concepts were advocated on the basis of our species' urge to explore new frontiers. In the 1970s, Space settlements were advocated based on demographic imperatives of humanity: they promised access to unlimited power, room and resources [4]. In the 1980s, Space was seen as the next frontier in the Cold War. In the 1990s, communications technology and the miniaturization of electronics heralded an era of micro-satellite constellations in LEO; the idea of humans venturing further slid down in priority. Exploration of distant worlds was delegated to remote observations, and visits by robotic craft.

Given recent economic history, it appears that no single market initiative, however huge its apparent potential, will result in sustainable expansion into Space. Instead, it will take a broad realization by people of many professions and business interests that Space offers opportunities, similar to previous developments of areas considered hostile to human habitation (e.g. Alaska). This is needed for two reasons: (a) to mobilize public support for public investment on the

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necessary scale to build infrastructure, and (b) to generate the initial market base which will ignite expansion of the wide array of trades and businesses which underpin a civilized society.

For business plans to develop, a knowledge base of technological discussions and cost estimation models is needed. This paper is an effort to contribute to such a discussion. We started with the consideration of a technology for building panels and pressure vessels in microgravity, using granular or powdered raw material and tailored acoustic fields [6-9]. The process of developing businesses based on this technology was considered through a NASA program and the Space Resource Utilization community [10,11]. At each level, the interdependence of various problems, technologies and resources became increasingly obvious. Support for the smaller, low-risk steps of the space program cannot be maintained unless there is a strong vision of a much greater space-based economy in the future.

Test cases were undertaken to investigate the issues in developing a space-based economy. In Ref. 10 we presented a non-contact method to produce panels of desired shape using various kinds of materials. We showed how the uncertainty in Net Present Value of a company planning to enter space-based manufacturing depended critically on the existence of space-based infrastructure and NASA support in technology development. In Ref [11] a Delivered-Cost Approach enabled preliminary costing of the construction of the outer shell of a Mars Cycler craft. This showed the cost-effectiveness of space-based manufacturing using extraterrestrial raw material, argued on the basis of market prices. The present paper considers the second test case: assembly of the outer shell of a 1 km-radius rotating cylindrical habitat.

Previous Work

Various visionaries have studied the dream of "Outposts" in space: great space cities which will act as stepping-stones to economic utilization of extra-terrestrial resources, and to systematic exploration of Space. Models for human settlements in space have followed two major paths: artificial structures in orbit [4,5], and terraformation of neighboring planets [12]. Most work in the recent past has been done in the area of building settlements on Mars after changing the composition of the atmosphere.

O'Neill [4] considered in detail the issues in developing large settlements in Space. He recognized the fundamental obstacle of earth-based launch costs. He identified economic opportunities as the correct motivator for development, and Space-based solar power as the first large-scale commercial product from Space. This offered order-of-magnitude savings in building a space power station versus building added power-generation capacity on earth in the last quarter of the 20th century. He saw the Moon as the only viable source for extraterrestrial resources, because of the existing knowledge on the composition of the Moon. He identified the Lagrangian Point L5 as the logical location for the settlement. O'Neill primarily focused on a spherical "city" named the "Bernal sphere", with toroidal agriculture stations attached on either side. The Bernal sphere would spin co-axially with the toroids to generate artificial gravity close to one Earth 'g' near the equator of the sphere. O'Neill envisaged the sphere shell being made of aluminum and glass (to admit sunlight), with a support structure made of aluminum ribs and/or steel cables. Radiation shielding dominated the mass of the settlement; the structural mass was a small fraction of the total. Even at projected earth-LEO launch costs of $110/lb, O'Neill saw that the material would have to come from the Moon. He postulated a lunar-based mass driver to send much of the required mass into Space.

Ref. [5] was the result of a 10-week expert study at Ames Research Center, of technologies for settlements. From comparisons of various configurations, a toroidal shape was selected to provide the highest artificial gravity at the lowest rotation rate, with the lowest overall mass and cost of construction for a small human settlement. The toroidal shape could also be used to generate magnetic fields to help deflect charged particles.

There are six important differences between the assumed models of 1975, and today.

1) The 1975 studies assumed earth-LEO launch costs of $110 per lb, and Earth-L5 costs of $440/lb. Today's estimates are $1300 to $14000 per lb to LEO in present dollars.
2) The above studies assumed human labor to construct the outer shell including the radiation shield, as well as to operate the lunar facilities and launchers. Today, the Pathfinder and Voyager missions, as well as robotic manufacturing, miniaturized digital electronics and fuzzy-logic control all enable us to assume that the vast majority of work in extraterrestrial environments will be automated. Human operators will be needed for initial control and verification, and for trouble-shooting and redirection, but even these can be accomplished to a large extent, whether in GEO, L2 or the lunar surface, by direct control from Earth.
3) The mass driver on the Moon was postulated to be powered by hydrogen-oxygen systems, with the hydrogen shipped in from earth. Today [13] robotic, large-scale manufacture of solar power-generating capacity on the lunar surface is feasible, allowing us to assume solar-powered launchers distributed around the lunar equator to enable launches at a high rate.
4) The launchers are assumed sized to launch railcar-sized payloads rather than baseball-sized payloads. This is thermodynamically less efficient, and results in a lower effective specific impulse for the mass driver. However, it makes "catching" the launched payloads using propulsion/control units easier. It also avoids the problem of millions of dirtballs orbiting the Moon and posing unacceptable collision threats to other traffic.
5) Our own technology of Acoustic Shaping [7-9] shows promise as a means of building solid walls of desired shape, upto 2mx2m in panel area, using automated processes amenable to microgravity processing. Smaller panels can be constructed on the lunar surface as well, though these require liquid-based processes.
6) Both the Bernal sphere and the Ames torus assume pressurization of the entire interior space to allow "shirt-sleeves" conditions. We assume pressurization of only the 10 to 30 meters adjacent to the inner surface of the radiation shield. A transparent membrane can be used to hold this pressure, with 30-meter bubbles adequate to provide micro-climates as needed.

These differences are significant enough to justify a new look at the process of building a "city" in space. As a start, we look at the process of building the massive outer shell and radiation shield. Our "city" is a hollow cylinder, 1 km in radius, and 2 km long. In this paper we leave open the issue of whether the ends should be capped, and with what material. The 2km-long cylinder can be a segment of a much longer "space tunnel. The 1km radius permits a gravity level of 1-g with 0.95 rpm: this is within the comfort parameters of the vast majority of humanity [4]. It thus removes one of the prime obstacles to the popular appeal of the space program: the idea that one has to be a super-fit youngster trained to military pilot levels to be allowed to participate in Space.

Building the Outer Shell of a 1km-diameter Space City

The purpose of the following discussion is to present a credible method of automatically and efficiently building the massive radiation shield and outer shell of the "city", and estimating the cost of this project. Our model is as follows:

1. The net output rate of the lunar mass drivers controls the time needed to build the city shell. The basic unit used in building the outer shell is a rectangular container similar in size to an open-top railroad box car: the 2-meter depth was selected to satisfy the need for 2m of lunar regolith to provide adequate radiation shielding [5]. The cars are loaded with compacted lunar regolith and

launched from the lunar surface. Standard orbiting propulsion units will each be equipped with gas thrusters (assumed to be solar-heated hydrogen) and a trio of fuel-cell powered electromagnets. Two of these units will be attached to each pair of box-cars in lunar orbit, and will propel them to the entrance to the 1km-dia cylinder. We assume that the shell is built at L-2, close to the Moon, and then propelled slowly to L-5 at a later date.

2. The structural strength of the cylinder will be provided by a grid of cables. Cable rings 1km in radius, spaced 4 meters apart, will be connected by longitudinal cables. Every node of the grid will be an electrical switching unit, so that a strong electric current can be passed through any segment of the grid independently. Rotation about the axis, initiated using small thrusters, holds the grid in tension during the construction of the shell. The grid is powered by solar panels, with hydrogen or helium thrusters to provide orbit corrections.

3. In a refined version, a radial arm which can be moved along the axis and around the azimuth holds an inner grid segment, rather than have a full inner grid. These current-carrying segments help guide the cars during construction.

4. Each "train" is assumed to enter the grid along a longitudinal trajectory with respect to the grid, at a relative speed of 1km/h. The electromagnets on the propulsion units are activated as needed to decelerate and position the boxcars to be attached to the grid. Once the boxcars are in position, the propulsion units are released for their journey back to low lunar orbit to catch new box cars and form the next train. Radial force due to rotation keeps the boxcars in position until connectors are automatically activated and they are fixed permanently to the grid.

5. With 2-meter-high boxcars filled with lunar regolith, adequate radiation protection is provided. The floors of the boxcars form the outer skin of the cylinder.

6. With good orbital mechanics and adaptive control as the construction proceeds, the ΔV needed for the orbit-transfer and positioning operations can be continuously minimized; just how close to zero it can come remains to be seen.

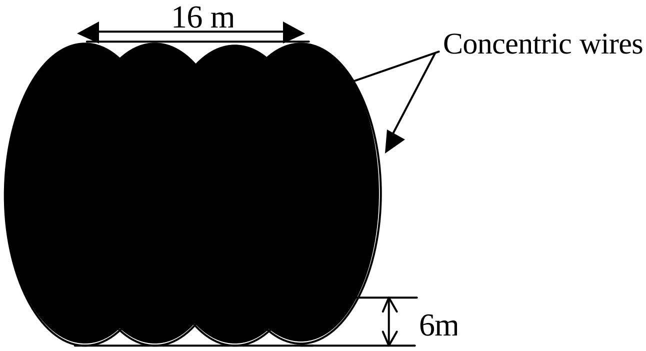

Figure 2. Schematic of a 16 m portion of the 2000m total grid system. The inner grid is shown as a complete cylinder for simplicity.

The figure above shows the layout of the wires and the city would lie between the two concentric grids. Details of the propulsion units and the grid will be considered in the presentation of this paper, using computer simulations. Construction parameters are listed in Table 1

Table 1: Construction Parameters:

City Radius = 1km Length = 2km Shield Depth = 2m Rotates at 0.945 rpm for 1g	
Current through large coil = 35 amps Windings on large coil = 500 turns (1/4 turn per meter)	Boxcar dimensions: 2mx2mx 20m Mass = 160,000 kg (regolith sp.gr.=2) No. of launchers = 10

Wire diameter = ½ inch Solar Panel area required to power grid = 350 m^2	Propulsion unit current required: 5 amps Total time to build = 4 years of actual construction/assembly work.

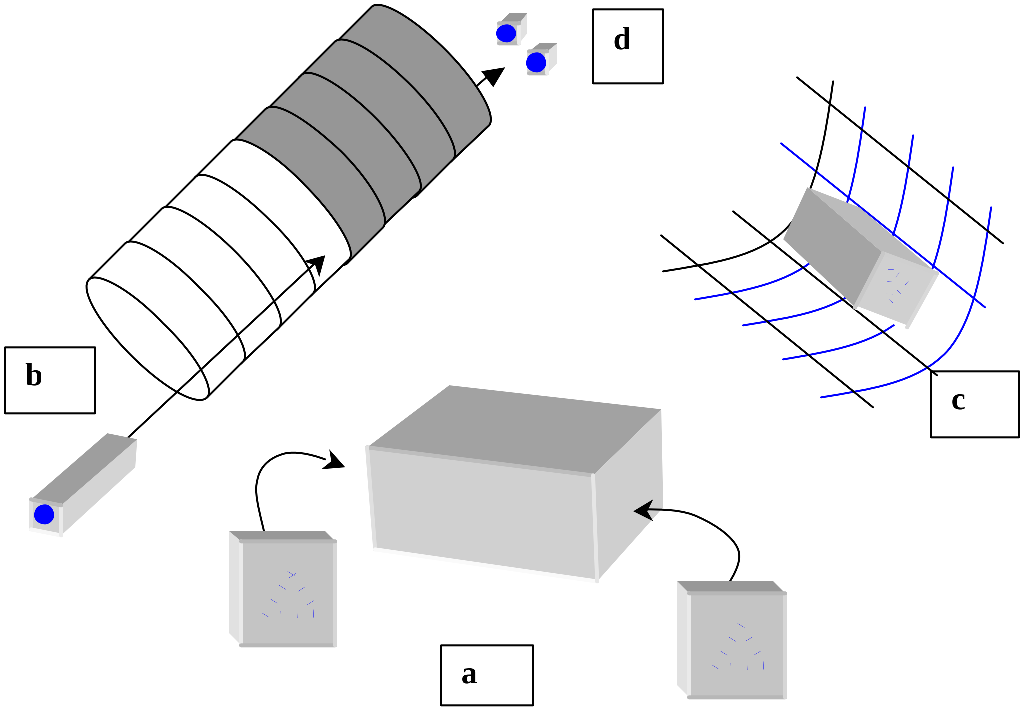

Figure 3. Schematic of construction procedure: Load approaches grid after being caught in the catcher. In step a, propulsion units attach to the load. In step b, the "train" enters the grid at 1km/h. Once it is decelerated to its correct position, step c, and the load located in position, the two propulsion/control units are removed and guided back to receive more loads, step d.

Cost Estimation

The construction of the Space City incorporates the various space technologies, constrained by the lack of assured returns in putting together a coherent business plan. It acts as an enabler that brings together the considerable resources generated by various 'space entrepreneurs'. This helps in providing assured sources of income for organizations such as the lunar mining and lunar launch industry. The symbiotic relationship helps in hedging risks for investors, who are often put off by the huge initial investment and long gestation periods. The main cost drivers in this approach are the shell mass and the launch costs associated with it. The main problem is the lack of past data about construction with extra-terrestrial materials. A parametric method of cost estimation has been used in this paper to factor in the uncertainties.

A parametric method of cost estimation is ideal for cases where the uncertainty is high, where factors have to be modified with new developments, and when previous analogies do not exist. We used the approach of Ref. [5] to identify cost items, but revised some of the methods used there. The cost of Earth launch to Moon landing is taken as $12,000/kg based on published figures of $2381/kg to LEO for the Proton launcher, with a factor of 7 assumed between LEO and the lunar surface. This gave a cost of $610 million for items other than the wire grid and the shield. As seen below, this is very small compared to the cost of building the massive shell which is also the radiation shield.

The cost of lunar launch was derived at using a new approach. Past analogies for cost of a lunar launch system do not exist, and estimation of the costs of lunar launch is extremely uncertain. To get around this problem, we propounded the 'Delivered Cost Approach' [11] to estimate costs of material delivered to the site of a much smaller construction project: the shell of a Mars Cycler spacecraft. The approach was to look at the pricing that would be set by the developers of the launcher, arguing that in the near term, the price would be dictated by the lowest cost from available Earth-based alternatives: this gave a figure of $2200 per kg. Here this approach is modified to account for the synergy required for such a massive project as the construction of a Space settlement. The settlement project will provide the dominant motivation for the development of multiple launchers around the lunar circumference. This project is itself a large undertaking, but it will open the way to routine mining and production operations on the Moon. Once the cost of this project is estimated, the pricing for material delivery to the settlement is set by the gross revenue needed to cover cost of operations and debt service plus return on investment. If this project cost is conservatively estimated, an upper bound can be obtained for the cost of the shield for the settlement. This works because the launcher is automated and uses solar energy, so that routine operation occurs at minimal operating cost, negligible compared to the capital investment. We pegged the lunar launcher project at $1 trillion. At 25% per year of gross revenue, the launch cost per kilogram starts at $45 /kg, decreasing by 5% per year to $37 /kg by the 4th year. This yields a Delivered Cost for the shield of $2.5 trillion. Refs. [4] and [5] confirm that the shield is the dominant cost item in the entire project to develop a Space Settlement. This cost estimate is conservative because we do not presume revenue from other uses of the lunar launchers such as the export of oxygen, minerals and finished panels, including solar panels for other projects, or beamed power from Moon-based solar plants.

Risk Reduction Strategies

As mentioned above, the vast majority of the construction of a space settlement can be accomplished by automated means, with the Sun as the energy source, at minimal recurring cost. However, no government, not to mention private entity, will undertake to invest 2.5 trillion dollars in a project which promises payoff only at the end. The approach to minimize risk is as follows:

1. The entire scope of the space-based economy must be communicated to the populace so that planning to exploit opportunities can proceed in parallel in millions of entrepreneurial minds. This will generate tens of thousands of ideas to reduce costs and increase payoffs.
2. The steps to be taken must be listed in detail, and wherever possible, alternative markets and uses must be devised for each step of expenditure and each technology developed. Some of this is obvious: robotic systems and techniques; non-contact manufacturing, solar cell development, magnetic levitation combined with mass-driver transportation, in-situ resource utilization systems, imaging and measurements for process control, all find earth-based uses. In this manner, even a project cancellation at the very end due to some catastrophe such as an unforeseeable meteor

impact, would leave the investors with a reasonable return in investment, and the project can be picked up where it was left off, later.

Discussion

It should be noted that the total cost of $2.5 trillion, while immense, is itself a space-based economy, with roughly 10% of it going to operating profits which in turn get invested in other space ventures. Of the remainder invested, a large portion goes into the development of infrastructure which includes several advanced technologies: robotic production of solar plants on the Moon; robotic construction of much of the launcher, small human habitations on the Moon, orbit-transfer vehicles, a plant to extract iron from the lunar soil and produce cables; fault-tolerant control systems, communication and electric power lines, as well as launcher systems all around the lunar equator, and a large radiation-shielded station at L-2. The subsequent steps of building the interior of the Space settlement can proceed gradually, as needs arise and resources flow in from other operations.

Will following settlements also use lunar launches of regolith for radiation shielding? Given the cost, it appears probable that a mission to capture a small asteroid and tug it back to L-5 may be a better alternative. This requires large space propulsion units, as well as new ways of robotic mining in the near-zero gravity of an asteroid, and of transfer to the new settlement.

Concluding Remarks

This paper has taken a new look at the problem of building settlements in Space, as a test case in developing a Space-based economy. Unlike in the 1970s, automation of most of the tasks is possible within existing technology, and solar power can be used for nearly all of the continuing energy needs of the project. The construction cost of such a settlement is dominated by the task of building the massive outer shell which must serve as a radiation shield. A scheme for building this shell is laid out in simple physical terms: it is probable that more elegant concepts will replace this scheme. Cost estimates show that most of the project cost is spent on the infrastructure and technical capabilities to be developed on the Moon, all of which will continue to be used to expand the Space-based economy by various industries and customers. The project uses core competencies of industries and professions far outside traditional aerospace regimes: this implies that broad-based support for the Space-based economy can be generated. Risk mitigation in the project is achieved by developing multiple markets for each technology developed. While the initial investment is on a scale where only major government initiatives can enable the project, this is seen as natural for a step which will generate an economy at least as large as the total of today's Earth-based economy.

The final version of this paper presented at the Space Congress can be found at www.adl.gatech.edu/archives/

References

1. Covault, C., "Global Commercial Space Business Sought for ISS". Aviation Week & Space Technology, May 11, 1998, p. 26-27.
2. "The Gold Rush to Low Earth Orbit". Scientific American, January 1999.
3. NASA Plan for Mars Exploration, 2001. http:// www.hq.nasa.gov/office/codez/plans.html
4. O'Neill, Gerard K., "The High Frontier: Human Colonies in Space". William Morrow and Company, New York, 1977

5. Johnson, R.R., Verplank, W., O'Neill, G. K., (co-directors): "Space Settlements: A Design Study". Report of a NASA-ASEE Engineering Systems Design Summer Program, Ames Research Center, CA, June-August 1975. Web version, December 1999 Globus, A., Yager, B., Sezen, T., Globus, R., http://lifesci3.arc.nasa.gov/SpaceSettlement/75SummerStudy/Table_of_Contents.html

6. Matos, C., et al, "Developing the Space-Based Economy: An Architecture for NASA Mars Customer Engagement". Proposal by the Georgia Tech / Emory team in the 2001 "NASA Means Business" program. See www.adl.gatech.edu/nmbhome.html

7. Wanis, S., Akovenko, J., Cofer, T., Ames, R., Komerath, N., "Acoustic Shaping in Microgravity". AIAA Paper 98-1065, 36th Aerospace Sciences Meeting, Reno, NV, January 1998

8. Wanis, S., Komerath, N.M., Sercovish, A., "Acoustic Shaping in Microgravity: Higher Order Surface Shapes". AIAA Paper 99-0954, 37th Aerospace Sciences Meeting, Reno, NV, Jan. 1999.

9. Wanis, S., Matos, C., Komerath, N.M., "Acoustic Shaping: Application to Space Based Construction", AIAA Paper 00-1020, 38th Aerospace Sciences Meeting, Reno, NV Jan 2000.

10. Komerath, N.M., Matos, C.A., Coker, A., Wanis, S., Hausaman, J., Ames, R.G., Tan, X.Y.,"Acoustic Shaping: Enabling Technology For A Space-Based Economy". Proc. First Space Resources Utilization Roundtable, Golden Co, Oct. 1999

11. Ganesh, B., Matos, C.A., Coker, A., Hausaman, J., Komerath, N.M., "A Costing Strategy for Manufacturing in Orbit Using Extraterrestrial Resources". Proceedings of the Second Space Resources Utilization Roundtable, Golden Co, Nov. 2000

12. Zubrin, R.M., Wagner, R., "The Case for Mars: The Plan to Settle the Red Planet and Why We Must." The Free Press, 1998.

13. Ignatiev, A., Freundlich, A., "Production of Solar Cells on the Moon from Lunar Regolith" . Proceedings of the First Space Resources Utilization RoundTable, Golden, CO, October 1999. See http://www.mines.edu/research/srr/first_srr.html