Large-Scale Construction for a Space-Based Economy

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Abstract

The paper articulates the need for a coherent plan for a Space-Based economy. Such a plan would allow all segments of industry and the public to participate as stakeholders rather than as spectators. The architecture as laid out provides the argument to synergize efforts directed at the Moon, NEO, Mars and the Asteroids, and identifies the engineering roles of the construction, mining and transportation industries in enabling such an economy. Long-term human habitation beyond Earth requires radiation shielding. This requirement drives the design of orbital habitats, which are an essential component of a Space-based economy. Past attempts to design such habitats have been hindered by the lack of suitable construction means for such high-mass, large structures. This problem is revisited in the light of advances in lunar power production, metal extraction, robotic manufacturing, solar-heated propulsion for orbit transfer vehicles, and telepresence. It is shown that the construction of a 1km-radius cylindrical radiation shield is both feasible and cost-effective when done as part of a coherent plan for a Space-based economy. The architecture presents a scheme for bootstrapping resources on the Moon to provide power, metal extraction, and an electromagnetic mass driver, followed by a process for automated construction of the massive radiation shield and essential internal structure. Methods for costing and financing such a project are considered. It is seen that when set in the context of a coherent plan for a Space-based economy, the level of public investment comes down to levels of present public infrastructure and environmental projects. In addition, risk assessments for each of the component entities shows that risk is brought down to levels which can appeal to investors.

Introduction

The human presence beyond Earth today is limited to a very few dedicated government employees and robots who are dependent on Earth-launch of all resources. While commercial spending on Space, worldwide, surpassed government spending as of 1997 (Ref.1), and the satellite business generated over $81B in revenue (Ref.2) in 2000, the Space industry and the exploration/ utilization programs cannot be described as being "healthy". The "Gold Rush into Low Earth Orbit" (Ref.3) seen in 1999, has stalled. The Mars program has seen a dramatic drop in ambition level from "Permanent bases by 2018" in 1985, to "robotic

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exploration missions to Mars Orbit until 2020" in 2001 (Ref.4). Cost "growths" (Ref.5) on the ISS have forced NASA to cut into even these modest plans in 2001. In an environment of declining public interest and funding, the scientific debate about Space priorities pits proponents of various approaches in conflicting positions, perhaps destroying support for all missions. Surveys (Ref.6) show that people want to see NASA completing the ISS program before undertaking new ones.

Space Based Economy

This paper expands the idea of a Space-Based Economy and discusses the construction of a large space-based structure to illustrate changes in technology and the possible effects of a comprehensive plan on public support for such an Economy.

The literature on Space Commerce has focused on transportation and communication. "Infrastructure" has usually been taken to mean Earth-based infrastructure (Refs.7-12). Table 1 summarizes the differences in concept between today's Space Industry, and a true Space-Based Economy (SBE). The SBE follows a 'policy resilient approach', which builds up infrastructure to support multiple uses.

Table 1: Today's Space Enterprise versus a Space-Based Economy

Current models of Space Enterprise	Space-Based Economy
• Earth as the only possible market. • Launch cost reduction as key enabler. • Lack of infrastructure for repair or re-supply sharply heightens risk for all investors. • Support constituency: NASA Centers, Space launch companies, space science community • Limited and decreasing interest and funding.	• Space-based materials & products • Large Space-based infrastructure and manufacturing • Exchange of products and services between space-based enterprises. • Support constituency: diverse businesses, professions and public

Revisiting the Space Settlement Problem

We postulated (Ref.13) that with a concerted effort, a Space-based development plan supported by a majority of humanity can be outlined. In this paper we describe some of the first steps, and explore how the associated risks can be brought down. We then describe a technical approach which addresses the most daunting issues in building human settlements beyond Earth, in order to highlight the benefits of synergistic planning.

To illustrate how such a plan can bring about revolutionary change, we start by reconsidering the mega-project of building the radiation shield of a cylindrical "settlement", 1km in radius, and 2 km long, built at the L-2 Lagrangian Point of the Earth-Moon system (Ref.2). An example is "Island One", a 1-km-radius orbiting community, described by O'Neill (Ref.14). The "Bernal Sphere" would spin co-axially with toroidal agriculture modules, with artificial gravity close to one Earth 'g' near its equator. Two fundamental obstacles to building such communities are: *(a) the need for human or human-like robotic labor, and (b) transportation and cost of the immense mass of the radiation shield. A shield made of sand or soil would be 2 meters thick* (Ref.16). Even at projected STS launch costs of \$110/lb to LEO (Ref.14), versus today's \$12000/lb, this was prohibitively expensive and dangerous to build with human labor. A 1976 expert study of technologies (Ref.15) considered a toroid, but this too remained impractical.

Table 2: Important Differences Between 1975 and Present Model

#	1975 models	Present model using Tailored Force Fields (TFF)
1	\$110/ lb Earth- LEO	\$1,300 to \$14,000 per lb to LEO
2	Human labor on-site	Robotic with Earth-based telepresence supervision
3	Construction at L-5	Shell construction at L-2 followed by slow move to L-5
4	Lunar mass driver powered by H_2 Baseball-size loads. 30g; 10km run (Refs. 16, 17)	Lunar-equatorial Solar-power fields. 20 launchers; round-the clock launches; fuel is lunar-generated electricity. Railcar-sized loads. 8-g, 40km track.
6	Entire interior pressurized.	10 to 30 meters at rim pressurized, using membrane with 30-meter bubbles to provide micro-climates.
7	Machinery required to make panels etc.	Non-contact shape formation with solar-heated powder sintering & furnaces. Robotic assembly of payloads.

Table 3: Construction Parameters of 1km cylinder radiation shield:

- Radius = 1km; 0.945 rpm for 1g
- Length = 2km
- Shield Depth 2m
- Grid current = 35 amps
- 500 loops of cable; Wire dia =12.5mm
- Solar Panel area to power grid = 350 m^2
- Boxcar dimensions: 2mx2mx 20m
- Regolith Mass/ load: 160,000 kg.
- 10 launchers operational at any time (20 total around lunar equator)
- Shepherd unit current: 5 amps
- Time to build: 10 yrs.

In Ref. 13, we chose a simple, scaleable cylindrical geometry. For the 1km-radius shell, the 2m thick shield had a mass of 5-x10^{10} kg. A solar-powered electromagnetic positioning scheme was devised to guide loads of lunar regolith into position and form the shield. The construction scheme is summarized in Tables 2 and 3 and Figures 1 and 2.

Implications

The cost of building the City is dominated by that of the radiation shield and outer shell. With our proposed automatic technique, the cost of actually building the shell is made negligible in comparison with that of delivering the huge amount of material to L-2. The operating cost for this delivery is negligible. The key to making such an immense project affordable is to ensure the congruence of various needs for such launchers on the Moon. Prior work on Space Manufacturing looks at manufacturing in space using non-Earth based resources and energy (Refs.19-22).

Cost Estimation Approaches

Several levels of estimation can be considered. An upper bound is obtained by the 'Delivered Cost Approach' (Ref.18), where the cost of materials delivered at a given point in Space would be limited (a) from above by Earth based material cost and (b) from below by the supplier demanding the most that the market will bear. This approach will result in few projects being feasible. Secondly, one can estimate the capital cost of constructing the entire Space-Based Economy. A third approach is to bring in all players at the outset, and figure the costs and risks to each, given the presence of the rest. Ignatiev (Ref. 23) estimates a robotic 10,000 MW solar power plant on the Moon at $ 62B in year-2000 dollars. This will have a multi-customer base, including mining, fuel extraction, manufacturing and launch services. The cost for strip mining on the Moon is estimated as $ 3 B in year 1979$ (Ref.24), extrapolated using Consumer Price Index Inflation to $ 8B in 2000$. The Lunar Launcher System cost in 1977 dollars (Ref.25), adjusted for inflation, gives a Present Value estimate of $8B. Table 4, compares these to the costs and benefits from historical data on the development of the State of Alaska (Ref.26), and the present-day Space-related economy.

Figure 3 summarizes the drop in public funding required, as more businesses are enabled by the "assured market" of the Radiation Shied project. The requirement drops from $110B if the Shield is the only end-product, to $80B if it buys power from the lunar power plant while assuring the power-producers of demand during the initial decades of their production. With power, and materials available, the launcher cost comes down, again with an assured and diversified market to reduce risks in its development. The horizontal axis of Figure 3 makes the point that the drive towards one-shot missions and "3-to-5-year ROI" can be replaced by a planned, sensible pace of development, with its benefits clearly visible. Thus, the vision of a SBE can bring the various business enablers together, and enable them to articulate business plans that seem realistic and achievable.

Table 4: Cost Elements, Sources, and Points of Comparison

Cost Elements of SBE	Points of Comparison
•Cost of Lunar Power: **$0.39/KwH** • Strip Mining on the Moon:**$8B** • Lunar Launcher: **$ 8.3 B** • Cost of Shield (Assured Survival Pricing): ***$110B***	–Development cost of Alaskan oil facilities: **$67B**, total revenue to-date **$267B**, incl. **$55B** Fed. Tax. (revenues from known precious resource) –Space Business total annual revenue 2000: **$116B** (AW&ST, April 2001) (revenues from industries & technologies which were created by the new capability)

Articulation for Public Support

The concept of a Space based Economy can bring various businesses together. The business plan of a single industry that may appear risky and unsubstantiated when viewed by itself, can become realistic when patched into the network of a Space based Economy. From discussions with various graduate classes on Strategic Marketing, we conclude that the key to attracting public interest is the provision of clear knowledge and methods to reduce risks and calculate business models. This process involves technical, economic and political aspects, which we summarize below. A detailed form of the Fishbone diagram shown in Figure 3 can be used to develop every step needed for the SBE project. Technical risk can be reduced, and calculated, by developing alternative markets/ uses for all the technologies, which require large investment in the process. The availability of knowledge on what has been tried before, and on all the studies which have been performed, is a vital step towards such risk-reduction, and is being undertaken at Georgia Tech's **Center for a Space-Based Economy (CSBE)**. The political support can only be generated by systematically educating businesses and professionals of the payoffs from a coherent vision of the SBE, so that lawmaker support develops across the nation.

Table 5: Steps in Articulating a Space-Based Economy

Setting up a space based Economy:	Key Requirements
• Give businesses a vision of the new markets to be explored in space. • Bring together authorities from tourism, construction, aerospace, and other businesses to work towards realizing this goal of a Space-Based economy. • Outline key requirements needed to establish a space-based economy. • Educate people about benefits to standard of living. • Inform lawmakers of improved tax base, and economic development of the nation	• A clear vision of a Space-based economy, showing how most people and industries can consider themselves to be stakeholders in this endeavor. • Concrete examples of ventures in space, and predicted returns to attract industry interest. • Project planning, cost estimation and risk-reduction strategies • Communication of mutual interests: NASA, industry and lawmakers.

Concluding Remarks

This paper takes a look at the requirements for setting up a Space-Based Economy. The technical issues in building the massive radiation shield for a human settlement are reviewed in the light of today's capabilities for robotics and communication. By including the visions of several concepts such as lunar-based power, mass drivers and resource extraction, it is shown that the overall cost of such a major project can be brought down to imaginable levels. As more business visions are enabled by the assurance of a massive market provided by the infrastructure project, the level of public funding needed for the infrastructure comes down, even before tax revenues begin. The process for gathering public support for such an Economy is considered. Unlike today's exploration-focused government Space program, and isolated business plans for private ventures, the SBE can unite the public in supporting the Space enterprise.

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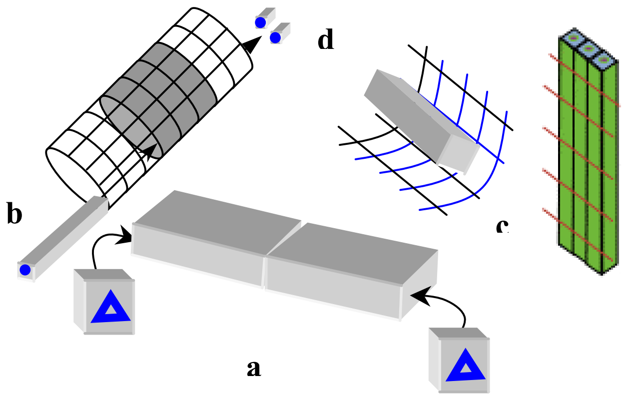

Figure 1: Construction sequence of the cylinder. (a) Shepherd units connect two loads into a load-train. (b) Train arrives at wire Grid (c) loads are delivered into place, (d) Shepherds leave to pick up another pair of loads. (e): loads fastened to cable Grid and each other, forming support structure.

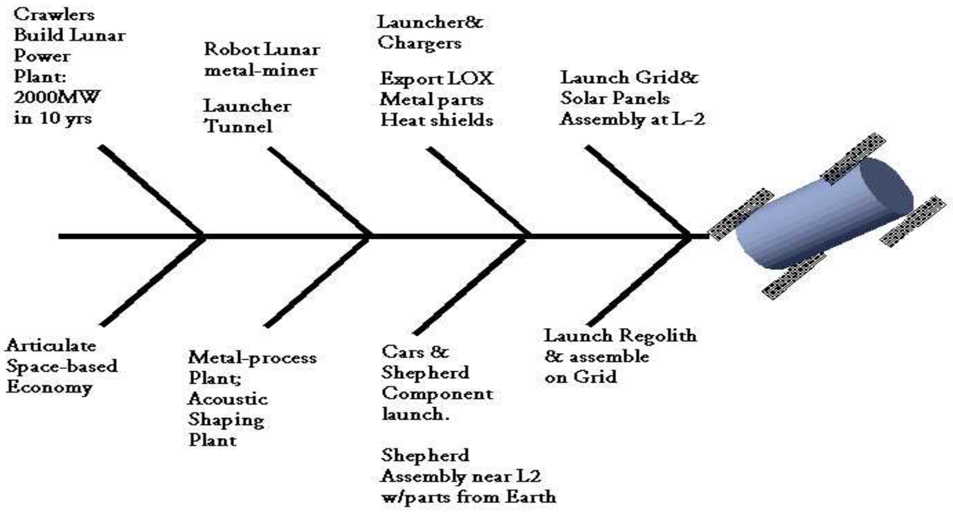

Figure2: Architecture of the infrastructure for the Space-Based Economy

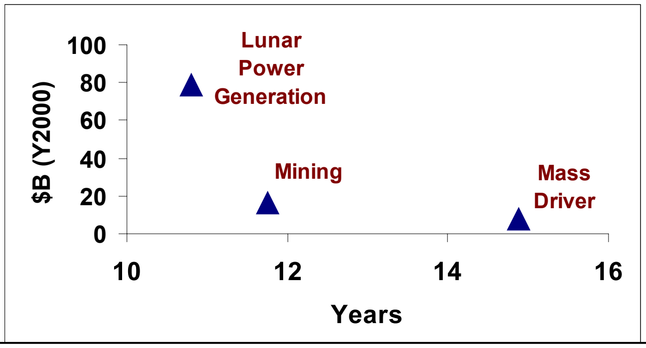

Figure 3: Reduction in public expenditure due to private space based industrial corporations