A U.S. Space Program for Space Settlement

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I. Introduction

Imagine a space program based on a vision of settlement, rather than exploration. A vision of billions of people living in hundreds of thousands of orbital colonies serenely orbiting Earth, the planets and our Sun. The current vision is about putting small numbers of people very far away entirely at government expense. Space settlement is about putting very large numbers of people in space primarily at their own expense, and making sure it's nice enough that they stay and raise the kids. While the current exploration vision is expected to cost about $100 billion up to the first visit to the Moon, the settlement vision is many orders of magnitude more expensive, making government funding impossible. But government can play crucial role. Specifically, perhaps we could use something close to the current NASA budget to stimulate much larger private investments. In this vision, government funds are devoted to prizes, test facilities and technology development, along with NASA's traditional science and aeronautic activities. Operations are left to the private sector.

Princeton physicist Gerard O'Neill and others showed that orbital space colonies were physically possible.[1,2] Dr. O'Neill's analysis suggested that lunar mines could supply the materials, the Sun could provide the energy, and that our technology had nearly reached the point where we could build orbital cities. These cities could be placed anywhere in the solar system, although beyond Mars nuclear power might need to replace solar energy. Others have shown that asteroids may be superior to the Moon for materials[3] and that construction of orbital colonies is considerably easier than developing comparable Martian or Lunar colonies.[4] O'Neill speculated that we would be well on the way to building orbital colonies by now. We aren't.

At the moment we don't even have a plan to settle the solar system. This paper is intended to be a first step. The focus is on building the first orbital colony, then using the infrastructure developed along the way to turn the crank over and over, building new land for Life's expansion. To build the first colony, we lean heavily, although not exclusively, on prizes. Prizes have several excellent properties:

1. They are fixed cost. There are never any cost over-runs.
2. Funds are only expended for results, not failures.
3. Prizes can motivate large numbers of contestants. Even teams that fail provide valuable training to the participants.

What is needed to get the first settlement built? Major development requirements include:

1. inexpensive launch
2. lunar and/or Near Earth Object (NEO) mining
3. mega-ton materials transport
4. in-orbit materials processing and manufacture
5. hundred megawatt scale in-space power generation
6. kilometer scale in-orbit construction

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7. nearly-closed life support

We propose approaching each as follows:

1. inexpensive launch - to be catalyzed by prizes
2. lunar and/or Near Earth Object (NEO) mining - catalyzed by prizes
3. mega-ton materials transport - prizes
4. in-orbit materials processing and manufacture - prizes for ground work, with winners eligible for grants to use Apollo materials and those provided by mining and transport prizes
5. hundred megawatt scale in-space power generation - prizes
6. kilometer scale in-orbit construction - very small prizes for simulated orbital construction in a NASA supplied software environment
7. nearly-closed life support - grants for ground work and prizes for low-g in-space agriculture

Let us turn to a more detailed consideration.

II. Launch

Over the last 50 years a wide variety of launch vehicles have been developed up to and including the U.S. Space Shuttle, the most capable space vehicle to date. In spite of decades of development, Earth-to-Orbit transportation costs thousands of dollars per kilogram and suffers a catastrophic failure rate of a few percent. Worse, these figures have not improved with time. The Saturn V cost less, measured in man-hours per ton to LEO, than todays major launch vehicles[5] and never suffered a catastrophic failure, although there were many close calls.

It has been pointed out that aircraft developed much more rapidly in their first 40 years than launch vehicles have. Hundreds of thousands, if not millions, of aircraft flights occurred in those years, but we have only launched a few thousand vehicles into space. To really improve launch vehicles, we need tens of thousands of launches per year, not dozens. The only market for humans-in-space capable of sustaining thousands of flights per year is tourism; but without major improvements in cost and safety, orbital tourism will be limited to those wealthy enough to pay $20 million for a ride on the Russian Soyuz, and current development plans do not promise major change.

All human-capable orbital vehicles to date have been developed as national projects by the U.S., Russia/USSR, and now China. For sub-orbital vehicles the picture is quite different. Spurred by the $10 million Ansari X-Prize, Scaled Composites, LLC built and flew SpaceShipOne into space twice in as many weeks. While Scaled Composites reportedly spent considerably more than the purse to win, other commercial deals involving advertising and technology sales netted a small profit.[6] As a direct result, Scaled is now developing SpaceShipTwo for Virgin Galactic. Virgin Galactic is building a space port in New Mexico and intends to fly tourists into space for a few hundred thousand dollars per trip within a few years, and there are a couple of competitors. Not only did the X-Prize spur a promising effort to initiate a sub-orbital tourism industry, but over 20 teams competed for the X-Prize. Only Scaled won, but the other 20+ efforts provided training for well over a hundred individuals in human space flight development.

If $10 million may have jump-started the sub-orbital tourism industry, what prize might do the same for orbital flight? Orbital flight is far more difficult due to much higher Δv, longer exposure to the space environment, and high-speed atmospheric reentry. Also, failure is common, particularly during the first few launches of a new system. Only 5 of the first 9 Pegasus launches succeeded, 9 of 20 for Atlas, 3 of 5 for Ariane, 9 of 18 for Proton, and 9 of 21 for Soyuz. Thus, one might expect orbital flight to require a much larger prize. Indeed, Bigalow Aerospace has offered a $50 million prize for private development of an orbital vehicle,[7] but this has not generated a level of effort comparable to that expended for the X-Prize. Not only is the prize money apparently insufficient, a differently structured prize may be needed.

The X-Prize was intended to provide a large fraction of the development cost in a lump sum, with the hope that a derived vehicle could fly tourists for a profit. However, the lowest cost estimate to develop a Earth-to-LEO vehicle is $400 million for development and $20 million per four person flight, by Transformational

level	passengers	$/passenger	cost ($M)	Max income (1st competitor) ($M)
1	10	25,000,000	250	175
2	10	20,000,000	450	315
3	10	15,000,000	600	420
4	10	10,000,000	700	490
5	10	5,000,000	750	525
6	20	2,000,000	790	553
7	50	1,000,000	840	588
8	100	100,000	850	595
9	1,000	50,000	900	630
10	10,000	10,000	1,000	700

Table 1. Prize schedule based on t/Space pricing proposals. There are ten prize levels paid out for the first 10-10,000 passengers launched (second column), subject to the condition that no competitor may collect more than 70% of the prizes at any one level. Total cost is in the third column and maximum any one competitor could gross in the fourth.

Space Corporation (t/Space), and this may be optimistic. If t/Space met their cost targets and recouped all development costs from a prize, seats would still cost at least $5 million per passenger, which would continue to limit the market to a small number of extremely wealthy individuals. Furthermore, if all the prize money is expended on a few flights by a single entrant, there may be no competitive pressure to reduce prices to the $10-50 thousand range believed necessary to make a vacation in space accessible to the mildly wealthy.

We propose avoiding these pitfalls with a series of prizes for successive launch of people into orbit. The dollars-per-passenger ratio decreases as more and more passengers are flown; ending at the desired price point. Initial prize sizes can be adjusted to provide a profit after reasonable results are achieved. For example, Table 1 illustrates prizes based on the t/Space cost claims. A company meeting these cost and performance targets would be profitable after a few launches; and by the end of the program over eleven thousand people would have orbited Earth. Note that the total cost of all prizes is $1 billion, less than three month's shuttle operations.

However, suppose a competitor hires desparate people to ride in unsafe ships? Some may be killed, but a profit could still be realized on the successful flights. Fortunately, theres a simple solution based on an old French law. Crawford Greenwalt, former President of Dupont, is quoted as saying "My company has had a safety program for 150 years. The program was instituted as a result of a French law requiring an explosives manufacturer to live on the premises with his family." In the same vein, we propose requiring at least one major investor, top executive, or senior engineer from the competitor be on each flight. Also, any competitor suffering loss of life should be barred from further competition. Extreme measures are necessary since early fatalities could easily put space tourism back by decades.

There is at least one additional problem. A healthy market requires at least two, and preferably many, viable competitors. Limiting the prizes per company at each dollar-per-passenger level provides a mechanism to support multiple competitors. We suggest limiting any single competitor to no more than 70% of the prizes at any one level. This is enough to give a substantial advantage to the first winner, but leaves large sums for a second.

In nearly 50 years of space flight we have failed to lower the cost of transport to orbit or improve safety to the point where substantial numbers of people will pay their own way. Contest driven development of launch vehicles has been successful for sub-orbital flight. Perhaps something similar will work for Earth to LEO transportation.

III. Mining and Materials Transport

We propose encouraging space mining and materials transport with prizes for Lunar and/or NEO materials delivered to HEO (High Earth Orbit). HEO is chosen to avoid materials entering Earth's atmosphere. As a very large quantity of materials are necessary, it is important to maintain large safety margins against

level	tons	$/ton	cost ($)	total cost ($)
1	0.1	10,000,000,000	1,000,000,000	1,000,000,000
2	0.5	2,000,000,000	1,000,000,000	2,000,000,000
3	1	1,000,000,000	1,000,000,000	3,000,000,000
4	10	100,000,000	1,000,000,000	4,000,000,000
5	100	10,000,000	1,000,000,000	5,000,000,000
6	500	1,000,000	500,000,000	5,500,000,000
7	1,000	500,000	500,000,000	6,000,000,000
8	5,000	100,000	500,000,000	6,500,000,000
9	10,000	50,000	500,000,000	7,000,000,000
10	50,000	10,000	500,000,000	7,500,000,000
11	100,000	1,000	100,000,000	7,600,000,000
12	500,000	100	50,000,000	7,650,000,000
13	1,000,000	10	10,000,000	7,660,000,000

Table 2. Prize schedule designed to bring bulk materials costs down to $10/ton to HEO.

any conceivable harm to Earth.

The bulk of the materials needed for space settlement construction are for radiation protection. Conservatively, approximately 10 tons of material are needed for each square meter of surface area,[1] but almost any materials will do. This means we need several million tons for a colony of several thousand people. For example, the Kalpana One colony design for 5,000 residents requires approximately 15 million tons of material, or about three thousand tons per resident.[8] If we assume that each resident can afford a few tens of thousand dollars for shielding costs, then a price point around $10 per ton is required. This establishes a low point, or prize for the last ton of material, in the prize schedule. Actually, a higher price point is viable but it makes almost no difference to the prize system's total cost.

The high point, or prize for the first ton of material, is more difficult to determine. Ideally, a competitor should make a profit after a reasonable amount of effort, but there are no data on the cost for returning extraterrestrial materials to HEO. The Apollo program retrieved approximately 300 kg of lunar materials to Earth at a cost of approximately $25 billion in 1960's dollars, or about $80 million per kilogram ($80 billion per ton). However, the Apollo program was hardly optimized for bulk materials mining. Somewhat arbitrarily, we choose $10 billion per ton, about one-eighth the Apollo cost ignoring inflation (perhaps another factor of 10), for the first 100 kg of materials returned from the lunar surface or an NEO.

A draft prize schedule based on these two extremes is found in Table 2. A total purse of a bit less than $8 billion, the equivalent of six months of NASA's budget, is allocated to deliver 1+ Mton to HEO. This supplies about seven percent of the bulk materials needed for the Kalpana One design. At the final price point, bulk materials for subsequent copies of this 5,000 person colony should cost $30,000 per resident. As with the launch vehicle prize, no more than 70% of the prize money at any one level may be won by a single contestant organization, insuring that prize money will be available for at least two serious contenders. In addition, no more than 70% of the prize may be won by materials from a single source. This insures that at least one NEO is used for materials; which is important because the Moon lacks carbon and nitrogen; and has hydrogen in significant quantities only at the poles.

NASA is currently conducting a very productive search for NEOs. This search should be continued and expanded, particularly to smaller bodies. Current funding is quite modest and could be substantially increased without creating major budgetary problems. In particular, the ground based telescopes currently in use have great difficulty detecting NEOs inside the Earth's orbit due to the glare of the sun. This could be corrected, to a great extent, by a small space telescope dedicated to NEO detection. By placing the mirrors in a long tube such a telescope can point quite close to the Sun without ill effect.

From	To	Length (time)	Quantity (continuous power)
LEO	LEO	1 day	10 watts
MEO	LEO	1 week	100 watts
GEO	LEO	1 month	1 kw
MEO	Earth	3 months	10 kw
GEO	Earth	6 months	100 kw
Lunar Orbit	Moon	1 year	1 mw

Table 3. Prize schedule designed to developed beamed space solar power for use throughout the Earth-Moon system. The first column is the location of the solar power satellite, the second column the location of the receiving satellite. The third column is the length of time power must be supplied to win the prize, and the last column is the minimum continuous power transmission needed to win. Prizes are awarded for every combination consisting of one pair from the first two columns and one from each of the other columns.

IV. Materials Processing and Manufacture

NASA currently has a prize for materials processing of lunar regolith simulant. The MoonROx (Moon Regolith Oxygen) challenge will award $250,000 to the first team that can extract breathable oxygen from simulated lunar soil before the prize expires on June 1, 2008.[9] As regolith simulant is quite inexpensive, this prize system could be expanded to many other tasks. Teams that meet the challenge could then be eligible for grants including access to lunar materials returned by Apollo and meteorites found on Earth; extending their techniques to more realistic materials. These materials are in too short supply to be made available to large numbers of contestants.

Similarly, the first materials returned to HEO by the mining prize system would be too valuable to be made available to large numbers of contestants. Also, simply getting equipment to HEO is difficult and expensive. Thus, materials from the mininig prize system should be used in a traditional NASA technology development program at first. If launch costs come down and the to quantity of materials increases a prize system may be feasible.

V. Space Solar Electric Power

Space solar power is too expensive for terrestrial applications in the near- and mid-term. Indeed, until solar power satellites can be built almost entirely from extraterrestrial materials it is hard to imagine competitively priced space solar power for Earth. However, power in orbit is extremely valuable. Solar power satellites in high orbit, which will not decay for many centuries, could power LEO satellites, eliminating the drag extensive solar arrays cause and substantially reducing reaction mass for orbit maintenance. Also, lunar mines could benefit from solar power satellites to provide power during the lunar night, which could be used to keep equipment warm enough to survive the two week lunar darkness deep freeze.

Our draft prize system for space solar power is structured differently than the launch and materials prizes. We propose $10,000,000 prizes for each of 216 milestones defined by the end points of power transfer, the length of time power transmission is maintained, and the quantity of power transmitted. For example, the first prize to be won would probably be beaming 10 watts of power between two LEO satellites for one day. There are six cases for each of category, so all combinations gives us 216 cases (6x6x6). This leads to a total cost of $2.16 billion. Any given system may only win one of the prizes, and no firm may win two adjacent prizes in the length-of-time dimension. This insures that many systems will be built and that there will be at least two prize-winning competitors. By the time all prizes are claimed, we will have the ability to beam megawatts of power to nearly any location in the Earth-Moon system. Table 3 contains potential contest details. This particular approach has an end point of $1.14/kw-hour, about ten times the cost of electricity for the author's residence. While this is higher than desired, normal markets can be reasonably expected to keep driving the cost down given adequate demand.

VI. In-orbit Construction

In orbit construction will probably be a feature of later stages of space solar electric power prize winners. For colonies themselves, however, it makes little sense to start real in-space construction before launch costs come down and substantial product flows are available from the materials processing and manufacture element. The same is not the case for simulation.

Contests and very small prizes can work for in-space construction in software simulation. NASA could develop an open source simulator and run the contests, but any reasonably credible and capable organization could do it, given a small core of committed, and talented, programs and contest organizers. Since the contestants need only a free development environment and an inexpensive personal computer, prizes can be quite small. Indeed, the RoboCup[10] simulation league – where fully autonomous simulated robotic soccer teams compete – generates substantial participation with no monetary prizes at all. This is an element of the program could be executed by the National Space Society.

VII. Life Support

Sustainable colony life support can be simulated on the ground in closed chambers. For example, the Biosphere II project demonstrated closed life support system for eight people over 13 months in spite of a number of serious mistakes. Ground based closed life support systems are difficult to encourage with prizes because each entrant must be monitored carefully for months or even years to prevent cheating. Thus, ground based life support should be supported with a grant program rather than prizes. Even a few tens of millions of dollars a year would vastly increase the rate of progress in this arena.

In contrast to ground based life support, in space life support is easier to encourage with prizes. For example, if low-g agriculture is practical, then large mass savings in colony design are possible because agriculture can be conducted in the interior of a colony; requiring no hull space, and thus no additional shielding (assuming artificial lighting). In addition, lower g levels will enable development of crop varieties with smaller, weaker support tissue (trunks, branches, twige, etc.) that can therefor devote more energy to food production. The Lewis One[?] and Kalpana One[8] orbital colony designs take advantage of this. Since closure is required for the survival any plants and animals grown in space, close monitoring to prevent cheating is unnecessary.

We propose prizes of $100 million each for the first 10 food-crop plant species and the first four food producing animal species that are grown through one complete life cycle (e.g. seed to harvest) in space at between 1/6 and 1/3g. These are the lunar and martian levels respectively, both of which are easily accessible in orbital colonies. To prove multi-generation survival, we somewhat arbitrarily propose prizes of $100 million each for the first 10 plant species and the first four animal species grown through two complete life cycles. As with the other prizes, no more than 70% of the prizes may be won by any one organization. If successful, this program will definitively prove that low-g agriculture is practical and cut the required size of orbital colonies by a large factor for a total cost of $2.8 billion plus administration costs.

VIII. Conclusions

We have presented a U.S. government space program designed to develop key technologies to enable large scale colonization of the solar system. The program depends on private sector development supported by government funded prizes, test facilities, and technology development. This is intended to stay close to the present NASA budget; achieving much more ambitious goals than the current exploration program by catalyzing private efforts, much as the $10 million Ansari X-Prize catalyzed much greater development expenditures to achieve private sub-orbital flight.

As the proposed program is much more ambitious, the total cost of all prizes is approximately $14 billion, which, adding substantial administrative costs, is about one year's NASA budget. While there is no guarantee that these prizes will have the desired effect, prizes are only awarded for success. If the technology is not developed, only administrative costs are incurred. While the size of these prizes is plausibly sufficient, doubling or tripling would not make a successful program excessively costly. Indeed, solar system colonization is so beneficial even an actual cost ten times higher would be the deal of the millennium. What, exactly, are we waiting for?

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