Modeling The Evolution of a Space Economy

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Abstract

This paper revisits the question of how a logical progression towards a self-sustaining space-based economy might be predicted from today's various space missions and technological programs. It builds on projections made in 2008 and 2006, and considering the effects of interactions between enterprises. Interactions with the reboost, refueling and orbit transfer vehicle enterprises are considered. Recent advances in on-orbit servicing and electric propulsion have taken large steps shortening the time needed to reach a self-sustaining space-based economy.

Introduction

In 1997, roughly 40 years after the first artificial satellite was put in orbit, annual commercial space expenditures exceeded government and military expenditures [1]. A "Gold Rush to Earth Orbit" [2] was predicted around the turn of the century, based on the growth of demand for launches to build up telecommunications constellations, but this did not happen for various reasons. In 2008, global revenues [3] from the Space industry exceeded $257B, with roughly $139B in the USA. The industry has many segments: satellites of many kinds, developing propulsion units and parts, fuel cells, solar photovoltaic cell arrays, semiconductor and related device manufacturing, propellants, geophysical surveying and mapping, flight navigation systems, telemetry and tracking, satellite television and radio. However, the growth of commercial activity beyond Earth continues to be a process of extreme competition and attrition rather than monotonic, co-operative expansion. Political and economic uncertainties have hobbled the pace of the Russian space program, while a climate of indecision appears to have gripped the US human spaceflight program despite dire predictions and urgent calls to action from several high-level studies [4,5 ,6].

In 2011 national space programs around the world appear to have reached a valley with a choice of various paths each requiring a climb into tall mountains. The US government space program appears to be exiting the business of putting humans into Space. Plans to send humans to Mars [7], the Moon [8], or even to build up the International Space Station [9] and move it to the high orbit required to achieve the clean microgravity for it's research promise, all appear to have been dropped. Commercial launch activities are starting up, but few appear to have plans to develop into large economic expansion beyond Earth. Tight economic times on Earth make it difficult for national leaders to embark on risky ventures that commit massive resources. In 2009, 15% of funding for commercial ventures came [10] from the government, 52% from individuals or "angel investors", 30% from private equity, and 4% from reinvestment.

On the other hand, we may project with reasonable certainty that humans will not always be content with staying within the immediate environs of our planet. The natural resources available on Earth are a tiny fraction of those available in the near solar system. Activities in space will lead eventually to an extensive, self-sustaining space-based economy, which we define as an economy where the suppliers, production enterprises and customers are all located beyond Earth.

This paper continues a venture started in the late 1990s [11,12]. The postulate is that the meandering nature of development beyond Earth is guided by logical but compartmentalized planning based on the development of science and engineering. It is guided, driven and sometimes constrained by economic, political and military objectives. Given this postulate, the sequence of progression should be predictable in general terms. Such a prediction can then be used to develop detailed technological and economic roadmaps. In turn this should lead to business planning with reduced uncertainty. One can be reasonably sure of what support and competition might exist at different points in time, and use those in planning for new or altered markets, the right time to enter and exit, the rate of investment return that might be expected, and alternative paths to reduce risk. These plans then provide impetus to help sharpen the logic and efficiency of the progression, and perhaps greatly accelerate the process of development.

Much optimism is no doubt involved in this postulate, because it envisages a large reduction in the entropy of economic development, which is by nature a process that involves tremendous attrition through competition and digression. The development of the great commercial centers and markets on Earth have followed such paths, and we are asking how the path could be shortened and the progression facilitated with minimal waste, by good planning. Predicting political and global economic trends is quite beyond our scope; however, thinking about the logic of technical advances is a viable undertaking. While readers may understandably be skeptical at the outset, we hope that once they see the convergence of numerous technologies and programs discussed here, they may see that the state of progress is much further advanced than what they might have suspected.

In the 1970s, space enthusiasts fired up by the successes of the lunar missions imagined a swift progression of human development into the near solar system. The pioneering work of Professor Gerard O'Neill and others generated much interest in building large-scale habitats beyond Earth. Such habitats would be the equivalent of cities, with populations on the order of 10,000 to 300,000, becoming self-sufficient to the point where Earth would become just a tourist destination within a few generations. Visionary thinkers started developing descriptions

[13,14,15,16,17,18] of the commercial enterprises needed to support such a spread of civilization beyond Earth.

Today these efforts are dismissed as teenage science fiction, or as being too many decades away by most people, including some of the reviewers of the draft of this paper. We submit however that the relevance is not necessarily so far away. Actions that are or can be taken in the immediate future can help to bring that eventual reality much closer in time.

Figure 1 shows the anticipated progression of the space economy, left unmodified from Reference [**Error! Bookmark not defined.**] which was written at a time when the US "Moon-Mars" Constellation program was underway, and similar "we-

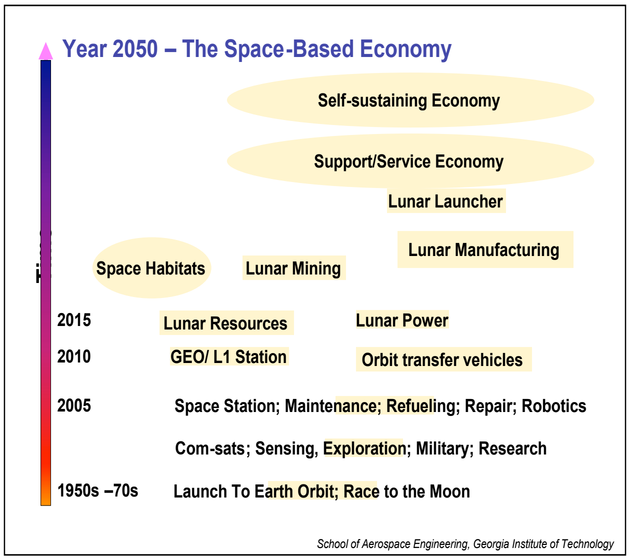

Figure 1: Progression to a self-sustaining space-based economy set out in Ref. [**Error! Bookmark not defined.**].

too" Moon-Mars strategic plans were declared by the space agencies [19] of Russia, Europe, Japan, India and China. The US has turned at least 90 degrees away from that direction since.

Evidently, there is no GEO/L1 station in place, and not much hope of getting to lunar resources by 2015, since the US Constellation program has been aborted before liftoff, and there is no ISS replacement from either the US or China. The gist of Figure 1 is a 4-stage evolution of the Space Economy. From the 1950s to the 1980s it was mostly a set of isolated missions and exploratory demonstrations fueled by the military race between the US/NATO alliance and the Soviet Union. From the 1980s there was a determined effort to put up constellations and larger stations, with a stated aim of commercial development in low Earth orbit, the second stage of the process. The notions of resupply, repair and even reconfiguration started with Mir and have advanced with the International Space Station. The commercial business plans around the ISS, with few exceptions, did not pan out, as the ISS took too long to complete, and could not be moved to its high final orbit until it was completed. Although NASA has funded at least 19 distinct space commercialization centers, few space enterprises have successfully spun off from those. This record should cast some doubt on the venture capital approach to space business, except where the development and launch cost dip of several billion dollars is covered by outright government largesse or military contracts. This may explain the preponderance of Angel Investors in Ref. [10].
In 2000-2010 the technologies required for the second stage have been advancing with surprising rapidity and purpose. There are numerous efforts to develop formation flying, on-orbit resupply, recovery, repair and refueling, debris removal, and reconfigurable swarms of satellites.

What comes next? The progression can be stated in general terms. Ref. [12] argued that large infrastructure development beyond Earth is a pre-requisite to organized and efficient economic expansion. Such infrastructure can only be developed through governmental programs. Yet, it is beyond the reach of any one government. An organized global effort is required. Thus a model was developed for such a global Consortium, drawing on existing examples in Europe, the USA and the United Nations treaties. The interplay of security and economic considerations was laid out, and it was shown that the heightened security concerns of the early 21st century, in fact provided a unique opportunity to set up a global consortium, where access was based on individual vetting rather than citizenship of particular nations. This model was published in the peer-reviewed archival literature.

The second step was to attempt a logical progression of the first N enterprises that would develop beyond Earth, where the total number N was extended beyond 20. Ref. [21] used the definition of "space-based economy" was defined as one where the majority of suppliers, value-adders and customers are located beyond Earth, and trading between them occurs for the most part without transiting Earth.

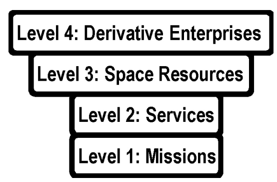

Figure 2: 4-level postulated development of Space-based economy from Ref. [12]

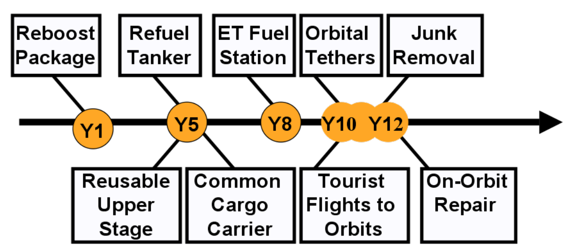

Figure 3: Sequencing of the first enterprises. From Ref. [21]

The approach taken was to consider a fully developed space-based economy as the final steady-state outcome, and consider how to get there from the present situation. The 4 levels of economy evolution were classified as follows:

Level 1: Missions
These included the development of ever larger and more reliable launch vehicles for human missions, the Hubble telescope, science missions to the outer planets, earth-orbiting satellites for military reconnaissance, remote sensing,

communication satellites in Geostationary Earth Orbit, telephone / internet consellations, the Global Positioning System, GALILEO and GLONASS navigation satellite constellations, sounding rockets, and suborbital tourism. The defining characteristic for our purposes is that each of these missions was completely self-contained, the satellites being unable to derive or provide any assistance or services to or from one another. Interactions were primarily with Earth, except for the case of communications between a mother ship or command module, and the spacewalker astronaut or the lunar or other lander/return modules.

Level 2: Interactive Services.

In level two, there were interactions between entities in Space. The first such missions started with rendezvous between the Gemini missions and unmanned vehicles, to demonstrate the capabilities needed for the lunar and SkyLab missions that were to follow. Robotic missions to the Moon, Mars and Venus, human-carrying missions to lunar orbit and then to the surface of the Moon, lunar exploration, and the development of the Shuttle Transportation System (STS) of reusuable vehicles, all involved such interactions at some level. The Apollo missions included setting up experiments and geological exploration of the lunar surface, with samples returned to Earth. The SkyLab and Mir space stations demonstrated long-term habitat functions and resupply and some onboard science experimentation. These examples inspired dreams of commercial enterprise and long-term habitats beyond Earth. The International Space Station, severely downsized from the initial plans for L1 or GEO stations, maintained the dream of commercial enterprise directed at high value products and processes. The STS demonstrated many steps such as use of a robotic arm, deployment, retrieval and refurbishment of some satellites by humans, experiments with electric power extraction using tethers, and construction, resupply and crew exchanges of the International Space Station (ISS). Mir and ISS demonstrated numerous rendezvous, resupply and repair capabilities, and even crew survival through solar storms.

However, interactive services suitable for commercial operations received a real impetus only with the advent of robotic or tele-presence demonstrations in the first decade of the new century. This fills out the Level 2 interactive services classification with orbit reboost packages, refueling, repair, and limited tests of orbit transfer vehicles and common cargo vehicles. The military services are rumored to have demonstrated or developed orbit-on-demand vehicles. Demonstrations of tethers, and new earth-based enterprises are imminent. None of these services have as yet become routine, with the possible exception of reboost for GEO communication satellites. One may argue that the few on-orbit repair missions constitute "routine" capability since such missions are by nature highly specialized.

Level 3: Extraterrestrial resource exploitation

In level 3 there will be commercial enterprises that actually extract and deliver resources from beyond Earth. Lunar oxygen, a space solar power station, lunar mining, production of metal parts, radiation shielding production, lunar landing and launch facilities, a lunar orbit transit station and Mars / Asteroidal cyclers are all anticipated missions. It is possible that a routine space telescope constellation program to identify and track Near Earth Objects (NEOs) and comets as an early warning system of objects on a collision course with Earth might become a commercial enterprise, since it is argued that the cost of missions to divert such objects is inversely and exponentially proportional to the time remaining until impact. Closer to Earth, space debris removal is likely to become a commercial enterprise that is urgently needed, with its payoff coming from insurance cost reduction and hence being shared by all space operators. These are not estimated in the present paper because they are essentially standalone enterprises that can be started at any time, independent of other capabilities.

Level 4: Derivative Enterprises.

Once the interactive services enable primary resource extraction enterprises, there will be derivative enterprises that exist primarily to serve these primary enterprises. These include long-term habitats, food growth, food supply, water supply, a fuel transfer depot, facilities to conduct repairs or to store spare parts, waste removal, tourist hotel facilities, lunar, Martian and asteroidal prospecting and sampling laboratories, and space training facilities for the rising number of space travelers and workers. Once such derivatives come into being, higher-order derivative enterprises will also arise, and the space-based economy eventually becomes self-sustaining and their link to Earth becomes weaker. Figure 2 shows the initial projected sequence of evolution.

Progress in On-Orbit Servicing

The major development towards a Space Economy in the past decade is the coordinated effort to develop and demonstrate technologies towards On Orbit Servicing integrating the ideas of reboost, refueling, repair, and removal from orbit. The US military's Responsive Space Initiative provided the impetus for much of the work that led to the DARPA demonstration missions. References [21,22 ,23 ,24] survey initial efforts in this area. Ref. [22] sets out some economic considerations to decide when repair missions are viable. Briefly, their criteria are that the repair mission must cost less than a replacement satellite, which implies that there must be a market need for the remaining or extended life of the satellite, and a 50% cost savings would probably be needed to get the owners to buy into the more risky repair mission. Below we lay out several discrete enterprises and their interactions.

Reboost Packages

Autonomous Reboost packages consisting of an engine, fuel, controls and communications can extend the lifetime of satellites which are not designed to handle refueling. The life extension to a revenue-generating satellite greatly reduces the investment risk (or military mission capabilities) by enabling the satellite to reach or exceed its design life despite draining fuel in efforts to correct launch errors or commanded military orbit plane changes. Ref. [25] describes a Chinese reboost-capable system with commercial potential. Several studies appear to have been done towards reboosting ("life extension") of Radarsat-1 satellite with an upgraded attitude control system. Figure 3 shows results from [14] for the projected Net Present Value (NPV) of a reboost enterprise. Assuming that its development cost is covered from military contracts, the launch

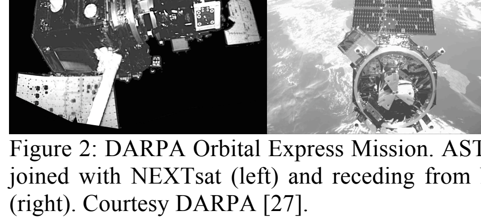

Figure 2: DARPA Orbital Express Mission. ASTRO craft joined with NEXTsat (left) and receding from NEXTsat (right). Courtesy DARPA [27].

cost dip is small. The commercial market consists mostly of existing GEO communication satellites. Reboost is clearly an opportunity whose window is limited by its own success in safe rendezvous, which will encourage satellite development for on-orbit refueling, rendering reboost moot.

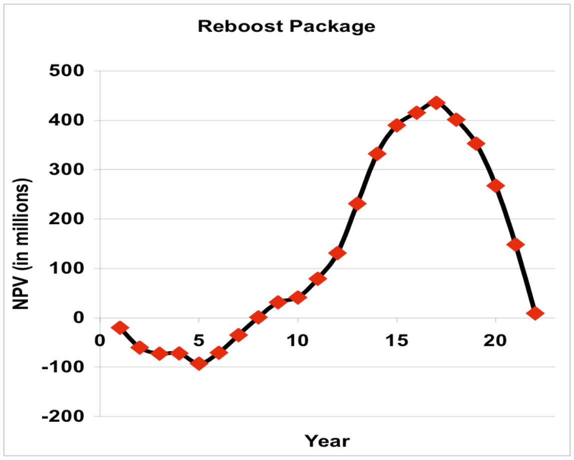

Figure 3. The NPV of the reboost enterprise becomes positive in 8 years, and peaks in 17. From [20]

Refueling
The rendezvous experience from reboost has two implications. It increases confidence in refueling spacecraft using fuel brought up in relatively inexpensive launch vehicles. It also opens the door to capture the excess fuel in external fuel tanks or used boosters before those are allowed to burn up in the atmosphere. The DARPA Orbital Express mission [26] in 2007 demonstrated several relevant feats. The Astro craft joined up with the NextSat craft in orbit, connected a fuel pipe, checked for leaks and transferred hydrazine fuel under pressure. It then transferred a replacement battery and installed it on the NextSat. It then separated and circumnavigated the NextSat craft at close range, including some approaches in directions requiring extreme orbital dynamics precision. It used a robotic arm to grapple and move the NextSat [27]. The mission was brought to a successful close [28].

This mission proved many of the capabilities needed for refueling and also to remove fuel from used launchers. With inherent collision risks and large delta-v requirements, the refueling business is surprisingly difficult to justify on the basis of return on investment, and may require initial intervention from the Consortium or national agencies. This is obvious in retrospect from considering that much of the fuel load on most satellites (except military reconnaissance satellites) is for reaching the initial stable orbit, but the main long-term need for fuel is for orbit-correction purposes. Thus a refueling vehicle will spend a very substantial amount of fuel getting to the rendezvous orbits and returning, but can only get paid for the small amount of fuel that the receiver craft needs for the next several years. However, development of a refueling enterprise is crucial to justify lunar and NEO-based fuel extraction enterprises which are postulated to be precursors to a true breakout from Earth orbit.

Reusable Upper Stage Orbit Transfer Vehicle
The next major step is the Orbit Transfer Vehicle or Space Tug, to ferry satellites between LEO and GEO. In-space refueling enables OTVs to carry out many missions. OTVs render the expensive and risk-prone cryogenic third-stage motors of many GEO missions superfluous. A much smaller orbit correction engine and a supply of fuel is all that is needed, with the OTV performing the LEO-GEO delivery. In the short term, this would hurt the manufacture of third-stage engines, but in the longer term, the demand for OTVs should more than replace the lost business. Several OTV concepts have been advanced [29,30].

External Tank Fuel Depot
The idea of boosting the external tank of the Space Shuttle to a stable low earth orbit has been considered for many years [31]. The reason why there are no such tanks left in orbit is said to be the concern over space debris, with NASA taking the position that it will allow commercial entities to take over such tanks if there is adequate guarantee that these will be responsibly managed and utilized, and moved to high stable and uncrowded orbits. The refueling business provides the motivation for a fuel collection depot to be assembled from main tanks, or other large rocket parts. Ref. [12] suggested that in contrast to the refueling business, this fuel depot enterprise may be the most lucrative long-term enterprise because the fuel and the technology for refueling might be robust to changes in fuel sources. These sources might change from dedicated supply missions to salvage from launchers, to fuel from lunar or other sources. The difficult demonstrations of rendezvous from arbitrary attitudes, attachment to tumbling craft and other maneuvers appear to have been passed under the On-Orbit Servicing demonstration missions, thereby greatly reducing the uncertainties in this enterprise.

Orbit-on-Demand Common Cargo Vehicle
This was envisaged as a relatively minor departure from the Progress series of Russian cargo launchers. Reusable launchers with airbreathing stages may become viable at some point. The first European Automated Transfer Vehicle ATV-1 "Jules Verne" was launched in March 2008, docked with the ISS in April, and was de-orbited in September 2008, followed by other ATV demonstrations [32].

Orbital Tethers
Much work has been done on the application of tethers in Space. Solar-powered LEO systems develop electrodynamic propulsion from the earth's magnetic field, and serve to move orbiting objects from one orbit to another [33]. Orbiting tethers are close to implementation for space junk removal [34]. Orbiting tethers could also swing small payloads from a suborbital flight into an actual orbit. This would be a breakthrough for renewable launchers of the sounding rocket class, most of the energy required for orbit coming from the tethers in space. This could collapse the launch cost from earth, and generate strong demand for the OTVs discussed above.

Tourist flights to orbit
While the orbital tourist industry has started with a handful of astronauts, good infrastructure in space will be needed before the industry becomes sizeable. The economics of this enterprise have been studied extensively [35,36,37,38,39]. We do not project that tourism will be a major driver of the space economy.

On-orbit repair

We projected in [21] that this enterprise would start with specific high-value spacecraft rescue/repair missions, but evolve to a more routine space-based maintenance/servicing enterprise, based at the fuel depots. Technical progress in this area has been rapid, driven by DARPA initiatives. The Orbital Express mission has already demonstrated impressive capabilities. The Hubble and other space telescopes pose initial markets and technology drivers in this area [40]. The prospects for setting up service depots in LEO or GEO have been studied in an Operations Research investigation [41]. Service tours reaching up to 20 satellites were considered, with obvious advantages if they are in nearby orbits. Repair missions to Mars were also considered. The above suite of enterprises comprises the technical core of the Level 2 Interactive Services infrastructure in space: refueling, reboosting, repair, tethers, junk removal, with resupply and tourism to provide a growing market for space launch. The next set of enterprises is more ambitions, and builds on this infrastructure.

The Space Power Grid

Energy has long been considered the first major extraterrestrial resources that will find a large market on Earth. We have proposed that a low-earth orbit constellation of 36 to 64 satellites will enable real-time beamed power transactions between points on earth, thereby enabling rapid growth in renewable-energy plants on earth which are currently handicapped by having to compete against the established earth power grid [42]. This would be followed by ultralight collector satellites in high orbits, beaming sunlight to converter spacecraft in low earth orbit [43].

Beamed Power to Space

At present each spacecraft has to carry its own solar arrays, whose deployment has been a problem area on several launches. Arrays degrade over time. Thus, space-based assets can afford to pay premium prices for beamed electric power. Our recent study shows that beamed power is best implemented as part of the comprehensive earth-space power grid development towards Space Solar Power [44].

Another 15 to 20 enterprises have been listed in our previous work [21]. A self-sustaining Space Economy may be assumed to have several hundred such enterprises as the derivative enterprises combine with their suppliers develop new markets and businesses in the progression to a large and expanding space-based economy.

Lunar Oxygen, Hydrogen and Steel

The fuel industry infrastructure becomes the expansion market for lunar oxygen [45]. Initial customers for lunar oxygen will of course be on the moon, associated with planned bases. This business is also tied into the lunar water and lunar steel industries. Hydrogen from the fuel depots, delivered to the moon will be used in extracting steel and other metals, also generating water for use on the moon. This requires several flights to the lunar surface. The moon is an abundant source to generate steel, aluminum and titanium. The lunar steel enterprise was discussed in Reference [21], where we argued that the potential for this industry is unlimited, once lunar transportation is established, hydrogen is brought in (or power becomes cheap) and a market exists for the byproducts of metal production.

Lunar Shuttle

As lunar oxygen extraction gets underway, the market for delivery of hydrogen and equipment to the moon, and fuel and steel from the moon, justify establishment of lunar launch/lander services, connecting perhaps to orbiting stations in lunar orbit, or rendezvous with OTVs for transit to GEO or earth-moon L2, L4 or L5. Initially, the demand is for delivery of many tons of equipment, supplies, and hydrogen to the lunar surface, with high-value cargo for return being such things as crystallized lunar rocks and perhaps geology samples.

DISCUSSION: INTERACTIONS AND THEIR EFFECTS

Interactions between enterprises can be predicted to some level, and these have a dramatic effect on the development of the economy. The interaction effect is already seen above, where the prospect or advent of one business has a huge effect on the market or the relevance of others. In addition, the secondary or side products of one enterprise may be extremely valuable, and have make-or-break effects on the costs and profits of another. One interaction effect that we have already shown in [21] is on GEO launch cost. The cost per unit functionality was shown to be reduced by one to two order(s) of magnitude, by the presence of reboost, refueling, orbit transfer vehicles and on-orbit repair services. Other interactions occur in the development of lunar industry, tying steel production to water, oxygen, hydrogen and lunar transportation industries, as considered in Reference [46]. Results to-date show that a staged sequence of enterprises can each break even at very substantial rates of return on investments, within reasonably short periods. When interactions are considered up front, business plans can be synchronized or staged for maximum benefit. The resulting infrastructure sets the stage for the next set of enterprises. The precise pricing levels for interaction between the different enterprises is a matter of negotiation between entrepreneurs.

The primary changes from our projections in 2006 and 2008 are that the Moon-Mars Constellation program has not advanced, and therefore the prospects have receded, for near-term lunar exploration and resource development implied in the Presidential Vision set out in 2004 of using resources developed in going to the Moon for permanent bases, to go on to Mars. Instead, however, rapid progress has occurred towards the difficult on-orbit servicing technologies needed for refueling, repair and orbit transfers, and these capabilities can now be included in business development calculations. All-out commercial growth must still await the generation of resources beyond Earth, and here the first resources are still projected to be space-generated electric power, and lunar-generated oxygen, though which will come first is now once again in doubt.

CONCLUSIONS

1. A sequence of techno-business developments is postulated, leading towards a full-fledged Space economy.
2. The list of initial enterprises is laid out and refined based on developments over the past decade.
3. Interactions between enterprises has orders of magntitude effects on the viability of space-based enterprises.
4. Despite the uncertainties evident in national space programs, technological advancement is enabling a fairly steady progression along the lines projected.
5. The results to-date reinforce the notion that logical prediction of the progression towards a space economy is possible.

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