Infrastructure Based Exploration – An Affordable Path To Sustainable Space Development

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The Space Paradigm is Shifting

On May 25th 2012, Space Exploration Technology's (SpaceX) successfully berthed its Dragon capsule with the International Space Station, returned it safely to earth for a second time, and ushered in a new era and a new type of space exploration and development. SpaceX was the first private corporation in history to send a liquid fuel rocket to orbit and to return a large space capsule safely from orbit. These accomplishments were the culmination of 6 years of effort, which was a very short time for the development of two new launch vehicles and a large spacecraft capable of safe returning to earth. What was most noteworthy, however, was that several hundred million dollars of private funds were invested to make this a reality and that NASA only paid SpaceX when they achieved their milestones; it was a gamechanger.

Since the dawn of the space age more than 50 years ago, space exploration has been accomplished with systems designed and built for a specific purpose and intended for a single use. Twentieth-century rockets that could only travel to low earth orbit were expended at the end of the mission. The capsules that sent astronauts to orbit and eventually to the moon were all dedicated to a single purpose and a single mission.

Today, we have vastly more capable industries, unprecedented technologies, and sixty years of spacefaring experience. This paper examines ways that we can incorporate new assets into our thinking and formulate new strategies to explore and develop space in a manner better designed to serve the unique needs and opportunities of the 21st Century.

Three new trends have emerged to frame future strategies. The central trend drives the others. All evidence indicates that we will explore space forever. After more than fifty years in space, interest has not waned, and the number and diversity of people and organizations that want to do things in space continues to increase.

The second trend is that space activities will become increasingly heterogeneous, encompassing a changing blend of government and private enterprises with diverse international collaborations.

A third trend arises from the first two and enables them: an infrastructure-based approach to space exploration and development.

In summary, we will go to space more often, for more diverse purposes, with a broader community of suppliers and users, for longer durations and distances, and with no end in sight.

Infrastructure-based exploration and development leverages commercially developed, reusable systems to address the concepts of affordability and sustainability that make this vision not only possible, but also more practical than single purpose missions. This concept is inspired by and synergistic with NASA's multi-destination human space exploration strategy that uses a capability-driven approach[1]. NASA's goal is to foster "a safe, robust, affordable, sustainable, and flexible space program by developing a set of core evolving capabilities instead of specialized, destination-specific hardware. These core capabilities allow NASA the flexibility to conduct increasingly complex missions to a range of destinations over time. By expanding human presence throughout the solar system, we increase our scientific knowledge, enable technological and economic growth, and inspire global collaboration and achievement."

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[1] *Voyages: Charting the Course for Sustainable Human Exploration.* National Aeronautics and Space Administration. June 2012. http://www.nasa.gov/exploration/whyweexplore/voyages-report.html

With NASA as the inspiration, trailblazer, and anchor-tenant, the infrastructure-based exploration and development approach presented in this paper focuses on the synergistic contributions and roles that private industry can offer NASA for sustainable human space exploration.

Taken together, these three trends (sustained exploration and development; diversity of purposes, users and suppliers; and capabilities-driven and infrastructure-based space exploration) can form the foundation of the 21st Century space economy.

Paradigm Partners for Sustainable Exploration and Development of Space: Flexible Path and Infrastructure-Based Exploration

The Obama administration has adopted the "flexible path" model for human exploration that was highlighted by the Augustine Committee[2] in their 2009 report. In *Voyages: Charting the Course for Sustainable Human Exploration,* NASA has articulated capabilities that need to be developed that will enable missions to multiple destinations; the Moon, near earth asteroids, Phobos or Demos and the surface of Mars.

To develop this approach, NASA is also supporting a number of commercial space transportation initiatives for delivery of cargo and eventually crew to the International Space Station (ISS). These include the Commercial Orbital Transportation Services (COTS) program and Commercial Crew Development (CCDev) program[3].

In addition, NASA is supporting several of the Google Lunar X Prize contestants with the $30 million Innovative Lunar Demonstration Data (ILDD) program[4].

NASA also recently completed a set of conceptual studies of orbital propellant storage and transfer that could lead to the development of orbital propellant depots as well as studies of reusable solar electric transfer vehicles[5]. These would benefit lunar, asteroid, and Mars missions and would benefit from lunar and asteroid resource mining.

In the private sector, Bigelow Aerospace has invested hundreds of millions of dollars to develop and demonstrate expandable commercial orbital habitats. Planetary Resources has announced its intention to mine asteroids to supply space resource depots and terrestrial markets.

This paper will examine the infrastructure building blocks and synergies that become possible if these space systems become available later in the decade.

The Apollo Anomaly and Sustainable Space Exploration and Development

One foundational question that has come to the forefront recently is stark in its simplicity but profound in its implications; how long will we explore space? Unless a major catastrophe occurs, all indications support the hypothesis that humanity will continue to explore space for the foreseeable future. If that is true, what are the implications? A look back into history may provide a useful perspective on this topic.

On May 25th, 1961, President John F. Kennedy stood before a joint session of congress and declared, "I believe that this nation should commit itself to achieving the goal, before this decade is out, of landing a man to the moon and returning him safely to earth". This was a truly remarkable goal for the President to articulate considering that the total manned space experience of the United States at that time consisted of Alan Shepard's 15 minute suborbital flight that had occurred only 20 days before and had barely reached a peak altitude of 116 miles. It was a long way from the 250,000 miles it would take to reach the lunar surface.

There have been many volumes written about the motivations behind Kennedy's challenge of

[2] Review of the U.S. Human Space Flight Plans Committee, 2009

[3] http://www.nasa.gov/exploration/commercial/crew/ccicap-announcement.html

[4] http://www.nasa.gov/home/hqnews/2010/oct/HQ_10-259_ILDD_Award.html

[5] http://www.nasa.gov/mission_pages/tdm/cpst/index.html

going to the moon[6]. A review of the literature leads to one clear conclusion: that the moon was a means to an end and not an end in itself. Apollo was a way to demonstrate to the entire world the superiority of American democracy over Soviet communism by achieving an "impossible" dream of humanity through technological prowess and ideological advantage. This is why, even before the first lunar landing was achieved, the NASA budget was being scaled back and the final two flights, for which launch vehicles had been built, were cancelled. After only 13 flights the Saturn 5 launch vehicle was abandoned after an investment of $6.5 billion (almost $50 billion in today's dollars).

The Apollo Program clearly achieved its geopolitical objectives. It was a breathtaking, empowering, and inspiring achievement. Few endeavors did more to inspire and unite humanity. Spinoffs from Apollo technologies have saved lives, generated wealth, and improved the quality of life for billions of people for generations. But it left no useful space infrastructure that could sustain the exploration and development of space. For this reason, no human being has travelled beyond low Earth orbit since the last man left the Moon on December 14, 1972. Because Apollo was so different in scale and priority from all the space programs before or since many people are starting to refer to it as "the Apollo anomaly."

Infrastructure-Based Exploration

Sustainable exploration and development of space requires a flexible infrastructure that provides materials, services, and utilities that support multiple purposes and multiple users at multiple destinations (initially: the moon, near earth asteroids (NEAs) and Mars, rather than building specialty vehicles for each mission/destination. Sustained exploration allows, and likely requires, commercial capabilities and assets to be leveraged to develop, operate and evolve the required infrastructure. The COTS/SpaceX example provides empirical evidence that this kind of approach would speed the development, reduce the cost, and increase the value of multiple-use in-space resources.

[6] John M. Logsdon, John F. Kennedy and the Race to the Moon, Palgrave Macmillian, 2010

In this paper, Infrastructure-Based Exploration (IBE) is the term used to embody the strategy enabled by commercially leveraged in-space assets that support multiple users, purposes, and destinations over indefinite periods of time.

What capabilities do we need to provide and what capabilities do we need to demonstrate to make IBE a reality? Different studies have emphasized different options, but most identify the following as essential to sustainable exploration:

1. Frequent, reliable, and cheap access to low earth orbit (LEO) for people and a wide range of cargo sizes.
2. Vehicles capable of moving payloads and passengers beyond (LEO) to orbits around other planetary bodies.
3. In-space resource extraction and processing systems to provide materials needed to support operations in cis-lunar space (CLS).
4. Resource depots in LEO and out in CLS to support asteroid and Mars missions.
5. Reliable high bandwidth communication and navigation
6. Landers capable of landing people and equipment upon bodies with significant gravitational fields.

Each of these elements will be described and the current status and future plans discussed.

1. Routine and reliable access to low earth orbit (LEO)

Starting in 2006 with the Commercial Orbital Transportation Services (COTS) program and then in 2009 with the Commercial Crew Development (CCDev) program, NASA has committed almost $2 billion to ensure that private industry is capable of delivering cargo and then crew to the ISS.

The COTS program was a non-traditional procurement that utilized a Space Act Agreement (SAA) utilizing NASA's "other transaction authority", instead of a FAR (Federal Acquisition Regulations) based contract, and this type of acquisition strategy is an important element of an IBE strategy.

The use by COTS of an SAA has several important implications.

First, it demonstrates the value of a milestone-based payment plan, where the government pays only upon successful completion of the milestone. Further, in the COTS-SAA, the milestones were set by the proposing industries, not by NASA. This provided the companies with greater freedom for structuring a workable deal, but the government then used this as an evaluation criteria and held them to a stringent acceptance criteria. NASA enforced performance accountability when the Agency deselected Rocketplane-Kistler because it did not meet its own milestone for private funding. This approach is very different from the traditional FAR-based cost-plus contracts where the government provides a tightly written specifications to industry, then the government pays the company for performance corrections and schedule slips.

Second, the COTS-SAA required commercial partners to put their own resources into the development effort, which helped ensure an alignment of business goals.

Finally, because the COTS-SAA structure only pays on delivery, government oversight can be reduced and focused only on critical elements. This has been show to significantly reduce the cost when compared to FAR based, cost-plus contracts.

In late 2006, Space Exploration Technologies (SpaceX) won an open COTS competition that led to the signing of an SAA valued at $278 million. This SAA called for development of a new launch vehicle (the Falcon 9) and a cargo/crew capsule (the Dragon). While development took longer than SpaceX had predicted, on May 25th, 2012, which was the third successful flight of the Falcon 9 and the second successful flight of the Dragon capsule, the Dragon successfully berthed with the ISS. The COTS-SAA was not only a success for NASA, it was a successful paradigm for stimulating this business approach. SpaceX currently has a backlog of more than 40 flights for their Falcon 9 rocket valued at over $3 billion with over 60% of this backlog coming from commercial and international customers.

NASA recently did a cost estimating comparison using its NAFCOM (NASA/Air Force Cost Model) estimating tool and uncovered some startling results. According to the NAFCOM model, if NASA had developed the Falcon 9 using traditional, FAR based, cost plus contracts and the usual oversight processes called for by NASA procedures (NASA 7120.5), the cost would have been almost $4 billion. In comparison, SpaceX's demonstrated expenses for the Falcon1 and Falcon 9 combined were less than $400 million[7].

Why the COTS Approach Worked

The NASA study identified several differences between the two approaches that help to explain the large differences.

1) Acquisition Strategy – In a fixed price/milestone based SAA there is much less government oversight than is required in a FAR based Cost Plus Fee contract. This saves a substantial amount of cost and time and incentivizes both performance and efficiency.
2) Requirements Stability – In the COTS-SAA there were fewer specific design requirements (which tend to change), but more stringent top level requirements (which tend not to change). The overall result was far fewer changes than in the typical cost plus contract and the responsibility and authority for design changes rested within the company.
3) Organization Efficiency – SpaceX is a very vertically integrated company that manufactures over 85% of the Falcon 9 components (by mass and value) in-house. This enables significant efficiencies in time, cost and quality.
4) Lean Management Structure – SpaceX has a very lean organization that currently consists of 2000 personnel at 3 major sites. The company is also privately held with the majority ownership held by the CEO Elon Musk. The organization is very flat with 14 senior functional managers reporting to the CEO.
5) Early Phase Studies/System Engineering – The study found that the early phase studies and system

[7] NASA Figures Show That Commercial Rocket Costs Less Than Half as Much as Government-Run Effort Would, John Matson, Scientific American, September 28, 2011

engineering efforts at SpaceX were significantly more disciplined at SpaceX than at NASA.

6) Funding Commitment – The funding commitment of the COTS-SAA is more fixed than the annual funding variations that plague FAR contracts.

This analysis points to a potential route to sustainability through public/private partnerships modeled after the COTS-SAA. This will be referred to as the Commercial Leverage Model (CLM).

But the Commercial Leverage Model is not applicable in all situations. There are several criteria that should be considered in evaluating the applicability of the CLM for a particular project. These criteria include the level of maturity of the relevant technologies, which must be relatively high; the existence or potential for customers beyond the government; the level of commercial interest in entering into such an agreement; and the ability of the commercial partner to finance their portion of the effort.

In addition to the COTS project for cargo, Space X also won an award on the CCDev program to demonstrate the ability to carry crew to and from the ISS. Their first award was for $75 million and the most recent award was for $440 million, which is intended to carry the development through the design phase to completion of the Critical Design Review (CDR). Boeing and the Sierra Nevada Corporation are also being funded under this phase of the CCDev, with Boeing receiving $460 million and Sierra Nevada receiving $212.5 million if all of their milestones are met.

If all goes well, then by 2016, NASA should have two or more domestic suppliers capable of transporting crew and cargo to and from the ISS. These same suppliers will also be able to sell their services to other customers, which should help reduce the cost to the government while opening space to a new generation of users.

2. **Reusable vehicles capable of moving payloads and passengers beyond (LEO) out into cis-lunar space (CLS)**

The idea of a "space tug" that could take payloads from one orbit to another and even to the moon and beyond has been contemplated since the early planning stages of the Space Shuttle program back in 1969.

The program has gone under a number of different names including: Orbital Maneuvering Vehicle (OMV,1984), Orbital Transfer Vehicle (OTV,1988), and most recently Solar Electric Propulsion (SEP, 2011)[8]

The OMV and the OTV were both chemical rockets that required large amounts of propellant. SEP on the other hand makes use of various types of ion/plasma drives. These drives are much more efficient than a corresponding chemical system and require much less fuel, but they are typically very low thrust systems which require longer trip times. These systems also require a large source of electrical or plasma energy: on the order of tens of kilowatts to megawatts depending on the application.

In late 2011, NASA awarded contracts with at total value of $3 million to five companies for the purpose of studying solar electric propulsion spacecraft. Under the terms of these contracts, each company will deliver a final report to help define a mission concept that would demonstrate the solar electric propulsion technologies, capabilities, and infrastructure required for sustainable, affordable human presence in space[9]. These studies are expected to help identify technology gaps and propose innovative technical solutions for issues currently impeding the use of solar electric propulsion.

In 2012, NASA awarded two contracts for advanced deployable solar array systems. Phase 1, valued at $5-7 million each, includes design, and analysis and test of a scalable solar array system capable of generating more than 30kW of power. Both teams are also required to identify the most critical technological risks of extending their concepts to 250kW or greater power levels[10].

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[8] NASA Studying Solar-Electric Propulsion For "Space Tugboat", Darren Quick, Aero Qizmo, January 31, 2012

[9] http://www.nasa.gov/home/hqnews/2011/sep/HQ_11-299_Solar_Electric.html

[10] http://www.nasa.gov/home/hqnews/2012/aug/HQ_12-270_Solar_Array_Selections.html

Former astronaut Dr. Franklin Chang-Diaz is one person who is very interested in these developments. The company he founded, Ad Astra Rocket Company, is developing an advanced plasma rocket engine called VASIMR® (variable specific impulse magnetoplasma rocket) that has the efficiency of an ion engine but with far higher thrust levels. Although the thrust that the VASIMR® can produce is still far lower than those produced by chemical engines, they can operate for much longer periods of time while requiring much less propellant per unit of thrust. Combining the solar electric arrays that NASA is developing with advance engine concepts such as VASIMR® could enable the development of reusable vehicles that are capable of transporting very large cargo payloads in cis-lunar space[11].

3. Resource extraction and processing systems to provide materials needed to support operations in Cis Lunar Space

The concept of "living off the land" is as old as the human desire to see what lies beyond the next hill. Throughout human history, people learned to make use of what was at hand to survive in new environments. This becomes more important as humankind travels farther into the solar system. In space jargon, living off the land is referred to as in-situ resource utilization (ISRU).

NASA has been developing a payload called RESOLVE (Regolith and Environmental Science and Oxygen and Lunar Volitale Extraction) to extract resources from the lunar regolith(soil). This past summer, NASA and the Canadian Space Agency (CSA) collaborated with the Pacific International Space Center for Exploration Systems (PISCES) and conducted a 9 day field test of the RESOLVE instrument and other key exploration systems on the slopes of Mauna Kea, an extinct volcano on the Big Island of Hawaii. The RESOLVE instrument was combined with the CSA Artemis Jr. rover and drill. RESOLVE is designed to prospect for water ice and other lunar resources. The tests went very well and the goal is to try it out on the Moon in the 2016 timeframe[12].

This ISRU capability has become increasingly important since the confirmation in 2009 by NASA's Lunar Reconnaissance Orbit (LRO) and the Lunar Crater Observation and Sensing Satellite (LCROSS) of large quantities of water ice in the permanently shadowed craters near the lunar poles. There appears to be hundreds of millions of tons of water ice in these craters but what form the ice is in and how difficult it will be to extract is unknown. If RESOLVE can be delivered to in the lunar polar regions, then it can make the measurements required to determine the feasibility and practicality of using lunar ice to supply deep space exploration and development.

The State of Hawaii recently voted $3 million in funding for a ground demonstration of an International Lunar Research Park (ILRP). The ILRP is planned as a three phase program to assemble an international collaboration to design, develop and implement a lunar research and operations facility that will support a wide range of government, scientific and commercial customers and partners. The first phase of this project will be the development of a terrestrial analog of the ILRP on the Big Island of Hawaii. This analog site will allow testing of the interactions and collaboration between the robotic elements planned for Phase 2, which they have called a Robotic Lunar Village (RLV). The Phase 2 concept is for robotic and teleoperated agents to construct human habitats and support systems on the Moon. Phase 3 envisions human occupation, research and development carried out by public and private organizations from many countries.

The ILRP hopes to leverage the development efforts of separate private endeavors, the 26 teams from around the world who are attempting to win the Google Lunar X Prize[13]. Google has offered a $20 million first prize to the first team that can place a robotic lander on the surface of the moon, travel 500m and send back high definition video of what they see.

Planetary Resources Inc. (PRI) was unveiled by its founders Peter Diamandis and Eric Anderson in 2012 to mine near earth asteroids (NEAs)[14]. Their backers include some of the wealthiest individuals on Earth: Google executives Larry

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[11] http://www.adastrarocket.com/aarc/

[12] http://www.nasa.gov/home/hqnews/2012/jul/HQ_12-237_NASA_Hawaii_Missions.html

[13] http://www.googlelunarxprize.org/

[14] http://www.planetaryresources.com/

Page and Eric Schmidt, two time private astronaut Charles Simonyi, an early Microsoft executive, Ross Perot Jr., son of the former electronics executive turned politician and James Cameron who is an advisor on the project. The success of SpaceX and the support of people such as these garners a great deal of interest on the part of the media and others and helps overcome the "giggle factor".

One potential market for PRI is to explore for water in Near Earth Asteroids (NEA). NEAs are not in the main belt between Mars and Jupiter but instead have orbits that come close to or cross the orbit of the earth, making them potentially more accessible. PRI plans to sell propellants made from these extracted materials in earth orbiting depots. Later they plan to mine precious metals and other valuable resources.

As an example, Amun 3554 is a metallic asteroid NEA which is about a mile in diameter. Based on remote observations, it is estimated that the total value of the metals on this asteroid, if they could be brought back to earth would be on the order of $20 trillion at current market prices[15]. Many of these same type of asteroids have crashed into the moon over the last several billion years and similar quantities of valuable resources can be expected to be found at multiple sites on the moon as well.

4. Resource depots for supplies and habitats for people in LEO and out in CLS

Trading posts, where explorers and settlers could get supplies, equipment and information, played an important role in the development of North America. The space equivalent of trading posts are called resource depots. There are currently two precursor resource depots in operation. One is the permanently occupied International Space Station and the other is the man-tended Chinese space station Tisangong. To date the ISS has been used more as a habitat and as a research facility than as a trading post but the potential is there and the use of the ISS as a trading post and deep space staging area is baselined in NASA's *Voyages: Charting the Course for Sustainable Human Space Exploration*[1].

In addition to government sponsored space habitats, there are currently several other private orbital facilities that are in various states of development. The most mature are the expandable modules being developed by Bigelow Aerospace (BA)[16]. Founded in 1999 by real estate developer Bob Bigelow, the company signed a license agreement with NASA for its TransHab technology. TransHab was a concept for an expandable space station module with a diameter of 8.2 meters that was developed by NASA JSC engineers in 1997. Despite significant progress that was made on the concept, Congress eliminated funding for this project in 2000. After reading about the project cancellation Mr. Bigelow contacted NASA and made arrangements to license the technology.

In 2006, Bigelow Aerospace launched their first subscale test habitat utilizing this expandable technology, Genesis 1 followed the next year by Genesis 2. Each module has approximately 11.5 cubic meters of pressurized volume. Both of these unmanned vehicles are still working well on orbit and sending back data on a daily basis. Bigelow is developing the much larger BA 330 habitat, which will be capable of housing 6 occupants and provides 330 cubic meters of habitable volume but this development is dependent on NASA's CCDev program to provide human access to and from orbit[17]. For comparison, the habitable volume of the Destiny module on the International Space Station is approximately 106 cubic meters.

Bigelow Aerospace is currently working with both Boeing and SpaceX regarding access to their habitats and the current plan is to launch the first BA 330 in the 2016 timeframe with at least 2 other modules to quickly follow. This will provide almost 1000 cubic meters of volume for commercial use and be capable of supporting 18 people on orbit. In comparison, the International Space Station has a total habitable volume of approximately 388 cubic meters.

To date, Bigelow has invested almost $200 million of his own money into the BA series of

[15] This $20 Trillion Rock Could Turn a Startup Into Earth's Richest Company, Chris Taylor, Mashable Business, April 26, 2012

[16] http://www.bigelowaerospace.com/

[17] NASA Contracts Benefit North Las Vegas Outfit, Jennifer Robinson, Las Vegas Review-Journal, Aug. 4, 2012

space facilities and is prepared to invest an additional $300 million to make them operational. Bigelow Aerospace recently expanded its Las Vegas production facility from 165,000 sq. ft. up to 350,000 sq. ft. in preparation for future production. Bigelow Aerospace is also looking at placing their facilities at the Earth/Moon Lagrange points (EM L1/2), as well as on the surface of the moon, and eventually on Mars.

One aspect of resource depots that has recently received a great deal of attention is cryogenic propellant storage and transfer, the space equivalent of a gas station. One of the limitations of chemical rocket propulsion is that sending large payloads beyond low earth orbit requires large rockets that can weigh millions of pounds, 85% or more of which is propellant. For example, the Saturn 5, that was used to send the Apollo astronauts to the moon, weighed 6.5 million pounds at liftoff, could lift 260,000 pounds to LEO, and deliver about 35,000 pounds to the lunar surface. However, 5.5 million pounds of the weight was propellant.

But what if you did not need to carry all the propellant mass needed for the mission when it launches from the Earth? What if there was fuel on orbit waiting at the depot to fill up the rockets tanks and only enough propellant was required at launch to get to the depot? This could greatly reduce the size of the launch vehicles that are needed. NASA has designated cryogenic propellant storage and transfer as a high priority research objective and conducted a series of concept studies in 2011-12. NASA hopes to fly a technology demonstration mission in 2016 that will store and transfer hydrogen and possibly oxygen as well. This demonstration would open the way for the development of propellant depots with NASA as an ideal anchor tenant for the resource depot as it was for COTS-CRS transportation services.

5. Reliable, high bandwidth communication and navigation

Instant, world-wide communication is something that we tend to take for granted in the 21st century. We can pick up a phone and call anyplace in the world in a few seconds and for a reasonable (mostly) cost. But communicating to assets in space and receiving data from these assets is much more challenging and expensive. Space communication tends to lag far behind terrestrial communications. Currently the primary communications link between NASA and the ISS is the Tracking and Data Relay Satellite System (TDRSS) which is a suite of government owned and operated satellites in GEO to relay signals transmitted from a ground site in New Mexico to the ISS. Communication with planetary spacecraft is done using a series of three 70 meter antennas around the world that make up the Deep Space Network (DSN) operated by the Jet Propulsion Laboratory (JPL).

To meet the challenges of the 21st century new, higher performance communications must be provided to a broader array of government and commercial customers. Fortunately, there are a number of interesting technology programs that are being carried out in a number of countries. In 2001, the European Space Agency (ESA) conducted the world's first spacecraft-to-spacecraft laser communication demonstration. In 2013 NASA and ESA will transmit laser communications signals between the earth and the moon. This project is part of NASA's Lunar Laser Communication Demonstration (LLCD) project which will use a new optical terminal flying on NASA's Lunar Atmosphere and Dust Environment Explorer (LADEE)[18]. These optical systems should greatly improve the data rates that can be supported while also reducing the mass and power required.

With this kind of communication, capabilities such as telepresence and teleoperation will be possible. Teleoperations in earth orbit and the Earth-Moon Libration Points (EM L1/2) as well as teleoperations on the lunar surface will not only enable more productive government sponsored missions and explorations, it will greatly assist private projects such as the International Lunar Research Park and Planetary Resources Inc.

6. Landers capable of landing people and equipment upon bodies with significant gravitational fields

Landing on the moon is very different from landing on Mars. The moon does not have an atmosphere, while Mars has one that is tenuous but challenging to traverse. Landing on the moon is something we have done previously on

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18 http://www.esa.int/esaMI/Operations/SEMCXUAXH3H_0.html

the Surveyor and Apollo programs but not something we have done for 40 years. The Google Lunar X Prize may provide some relevant near term demonstrations and develop expertise that can be leveraged, but one-shot, throw away landers are not the solution. Ultimately, what is needed are reusable landers and ascent vehicles that can land on the moon or Mars, offload their cargo of people and equipment, be refueled and reloaded, then venture back into space to rendezvous with orbiting assets that will take the cargo and return to earth. Given that there are large quantities of water/ice on both the moon and Mars as well as other substances that would make excellent propellants, these types of reusable vehicles are an important area for near-term development.

Assembling The Pieces

There are a number of projects already underway that could form the nucleus of this new sustainable infrastructure based exploration.

Beyond COTS and CCDev, Elon Musk CEO of SpaceX is talking about developing the transportation systems that would allow humans to travel to Mars within the next 15-20 years. He is talking about ticket prices to Mars being reduced from billions of dollars down to half a million dollars, an extraordinary gamechanging concept of unprecedented scope.

If one starts putting the pieces together, for example combining a Dragon capsule with a BA 330 and adding a space tug and propellant depots, it could open up the entire inner solar system to human exploration and development. With the availability of advanced telecommunications and next generation planetary spacecraft, we could have robot scout missions all over the solar system (this is what many of the Goggle Lunar X Prize companies as well as PRI have in mind). These robotic scouts could conduct scientific research as well as prospect for valuable materials around the solar system.

Once this infrastructure is in place it would enable the development of a wide variety exploration, development, and commercial enterprises. For example a resource depot at EM L1/2 could include a propellant depot and well as a Bigelow habitat and an advanced communication node. A depot at EM L2 on the farside of the moon would allow real time teleoperations on the lunar regions that are hidden from the earth. This could be a precursor to a lunar robotic village which could then lead to a lunar habitat and an ILRP. With solar electric propulsion capabilities it may be possible to move NEAs from their eccentric orbits and nudge them into lunar orbit or EM L1/2 where they can be researched in detail and processed. With the advent of reusable launch systems, the corresponding reduction in cost, and the other infrastructure elements that have been discussed, sustainable human travel to Mars could become a reality.

Governments play a crucial role in this development. Traditionally, governments have been vital in the development of national infrastructure: railroads, bridges, telecommunications, airports, roads, power grids, etc. But the private sector has a vital role to play as well and it is the concept of public/private partnerships, each partner doing what they do best, that holds the greatest promise for the a sustainable space future.