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In order to support future military operations logistically, the US military must utilize the domain of space for logistical prepositioning. A Space Based Logistics network will be able to support simultaneous operations anywhere in the world with unparalleled responsiveness. This future supporting concept draws from existing and emerging spacefaring technologies and describes the major aspects and challenges of a Space Based Logistics network.

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Executive Summary

<u>Title</u>: Space Based Logistics

<u>Author</u>: Major Timothy F. Riemann, USMC

<u>Thesis</u>: In order to support future military operations logistically, the US military must utilize the domain of space for logistical prepositioning. A Space Based Logistics network will be able to support simultaneous operations anywhere in the world with unparalleled responsiveness. This future supporting concept draws from existing and emerging spacefaring technologies and describes the major aspects and challenges of a Space Based Logistics network.

“The surface of the Earth is the shore of the cosmic ocean. From it we have learned most of what we know. Recently, we have waded a little out to sea, enough to dampen our toes or, at most, wet our ankles. The water seems inviting. The ocean calls.”

—*Dr. Carl Sagan*

"My logisticians are a humorless lot. They know if my campaign fails, they are the ones I will slay."

- *Alexander the Great*

For centuries, military professionals and commanders have attempted to achieve operational freedom while maintaining a logistical tether. The majority of contemporary American military operations use logistical distribution networks centered on expansive fixed infrastructure. Bases are, in many ways, logistical repositories that support military operations. Just as tactics and techniques must evolve in order to maintain relevance on future battlefields, so too must logistics. Enemy anti-access/area denial (A2/AD) systems threaten to turn any "iron mountain" into a molten ruin. Moreover, the *Marine Corps Operating Concept* (MOC) states that the ability to operate and thrive in future environments will depend greatly on the extent to which the Marines "redesigned [their] logistics to support distributable forces across a dynamic and fully contested battlespace."[1] In September 2016, Marine Corps Installations and Logistics Command published the *Marine Corps Hybrid Logistics: A Blend of Old and New* as the conceptual framework for their plan to support the *MOC*. At the end of *Hybrid Logistics*, LtGen M.G. Dana, Deputy Commandant of Installations and Logistic Command challenges every Marine to read, critique, and improve the *Hybrid Logistics* concept. He challenges Marines to be innovative and creative in their critiques of the concept and candidly asks, "Do we have this right? Do you have other innovative ideas to further this most important effort?"[2] The Space Based Logistics supporting concept is a direct answer to LtGen Dana's question.

Space Based Logistics (SBL) is a transformative logistical platform of the future. While SBL has some challenges associated with its implementation, it will offer significant advantages to current logistical infrastructure and practices. First, the future operating environment will likely demand an increase in US military presence caused by humanitarian crisis, political instability, natural disasters, or outright conflict. Though many of these places will not have fixed or operable infrastructure, the US military will face an increasing demand for its assistance in such environments. SBL will be a truly global logistical platform SBL with the capability to support simultaneous operations separated by thousands of miles without relying on terrestrial bases or infrastructure.   Second, SBL will provide unparalleled responsiveness. The speed at which SBL will deliver supplies anywhere on earth, to potentially multiple theaters of operation, will be measured in minutes and hours, not days and weeks.[1] Such responsiveness will provide the necessary freedom of movement for emerging concepts of truly distributed operations. Emerging future operating concepts call for the Marine Corps to assist in defeating anti-access / A2/AD defenses, but their feasibility depends on logistical flexibility. Third, "Multi-Domain Battle" demands integrated maneuver warfare across all five domains; again, however, logistical support is key. From all these standpoints, the need for logistics to facilitate, rather than constrain, future operations will only increase over time, above all in "places without bases."[2]

With these considerations in mind, the following research questions helped frame the supporting concept presented below:

- Is it possible to exploit the physical domain of space as a place for the warfighting function of logistics?
- Is it possible to place, maintain, and deliver logistical supplies from space to any particular place on earth in support of various military operations?
- What current and emerging technologies exist that could support and facilitate prepositioning in space?

[1] SBL estimates that a prepositioned payload could be delivered anywhere on earth in a *maximum* of 114 minutes after detaching from a logistical node. This was calculated by adding time to make one full orbit around earth (90 minutes) and the estimated time it would take an object to fall at terminal velocity to a given position (anywhere from 16-24 minutes).

[2] This idea of operating in "Places Without Bases" was central to the Advanced Studies Program conducted at The Marine Corps Command and Staff College during the FY 16-17 academic year.

The scope of this supporting concept is long term and therefore has the potential to appear divorced from reality, scientifically unrestrained, and all together wishful. It rests nevertheless on a firm base of research into current spacefaring technology, likely and foreseeable advancements in aerospace and space exploration, and forecasts of realistic future operating environment. It is plausible that the US military could start to implement SBL, given several key assumptions, c. 2035.

- Technology will get cheaper, more capable, and will continue to proliferate throughout the globe.
- America's DoD budget will remain constant or grow as a percent of GDP.
- Worldwide interest in Space Tourism, Colonization, Asteroid mining, interplanetary settlement and space exploitation will continue to expand.
- Space treaties and laws will continue to align with our evolving national security objectives.

In understanding the potential future operating environment, one must consider both likely drivers of change and probable continuities. Military professionals and think tank analysts continually try to anticipate what critical factors will create and complicate the military battlegrounds of the future. Many of the current forecasting models offer a bleak depiction of the future operating environment in which the American military will fight. While the key drivers vary depending on which forecast one reads, many of them concur on things like youth population bulges, exploitation of social media, and effects of climate change. all as forces shaping the global future. Two key drivers most relevant to the problem of logistical support, however, are the demand for an American military presence and the availability of key resources.

Demand for American Presence:

In the future, the demand for American leadership, support, aid and capacity will continue to grow and expand. As the world's only remaining superpower, America will remain the country to whom others turn to in times of natural disasters political crisis, or open conflict. Today, the United States has USAID department staff members in over 100 countries. In the past decade, the United States has given more foreign aid and military assistance in the form of Humanitarian Aid and Disaster Relief (HADR) operations than ever before.[3] Budding democracies and nations in extreme poverty will continue to rely heavily on the benevolent values of the United States for security and stability. Longstanding and emerging strategic relationships with other nations will be tested during crisis and the United States' ability to provide the requisite support will be indicative of US commitment to these nations. It will be necessary to respond faster and to more numerous demands than in the past. There is little to suggest that this will change in the coming years ahead.

While the demand for our support will continue to grow, foreign nation's tolerance of permanent American military bases will continue to decline. While the contributing factors for this intolerance is the subject of much debate and analysis, the fact that places where American forces have been long establish are now becoming unwelcome is clear. In November 1992 the United States Navy lowered the flag for the last time over Subic Bay in the Philippines. Similarly, after a failed coup of President Erdogan in Turkey, huge swarms of angry protestors assembled outside the American military base in Incirlik screaming "Yankees Go Home".[4] In early April 2017, a US Navy Sea Bee detachment was ordered to leave the country of Cambodia.[5] Any service member who has visited or been stationed on Camp Schwab, Okinawa can attest to the enormous and vocal crowd that gathers daily to demand a withdraw of American forces from Okinawa.

It may appear contradictory to say that there will be an increased demand for US support while, at the same time, asserting that there is growing demand for American troop withdraw. However, people will continue to rely on American's ability to support them by projecting military and other instruments of national power, but United States will not be able to do so from many of the same pre-established bases that to which it has become accustomed. A contracted American presence via an altered and diminished network of bases, coupled with a growing demand for the fruits of American prosperity will present significant challenges in terms of power projection, area access, and, fundamentally, logistical support.

Competition for Natural Resources:

The demand for natural resources has been perhaps the most common drivers of conflict in human history. A rapidly growing world population, rise in the living standards of millions world wide, and an inconvenient fact that there is a finite amount of resources means that demands and claims to food, water, metals and energy sources are bound to spark conflict. In his book *Earth Wars: the Battle for Global Resources,* Geoff Hiscock highlights the problem ahead with regard to natural resources when he says "The remaining oil is too political, coal's too dirty, nuclear is too dangerous, wind's too fickle, solar's too expensive, hydro's too dislocating, geothermal is too hard to wrangle, and fracked gas is too divisive."[6] If our current sources of power and resources are in question, where will countries turn?

Countries across the world, including resource poor countries like China and Russia, will have to continue to find and exploit new sources of supply, including those beyond earth. In fact, in 2015 the US Congress passed the Space Act, essentially allowing private citizens and corporations the right to claim, explore, and mine asteroids for resources.[7] In 2016, Luxembourg announced plans to invest hundreds of millions in space mining companies and will develop a previously non-existent international legal framework for the potentially lucrative practice. The country's deputy prime minister, Étienne Schneider, said: "Our aim is to open access to a *wealth* of previously unexplored mineral *resources*, on lifeless rocks hurtling through space, without damaging natural habitats.[8] While the competition for natural resources will continue to serve as a catalyst for future conflict, it will also be the genesis of future innovation. Countries who lack the resources will demand the technological capability to tap into these sources of great wealth. From this rapid emergence of cheaper and more capable spacefaring technologies (rockets, space crafts, space hotels…), the concept of Space Based Logistics will become a realistic possibility.

While they imply certain plausible trends, these two drivers – demand for US presence, and availability of resources – nevertheless also constitute key uncertainties. Based on their interaction in both negative and positive directions, one cannot predict *the* future, but one can anticipate *alternative* futures, dependent on how these trends play out over time. The potential interaction of these forces yields several such alternative futures, depicted below.

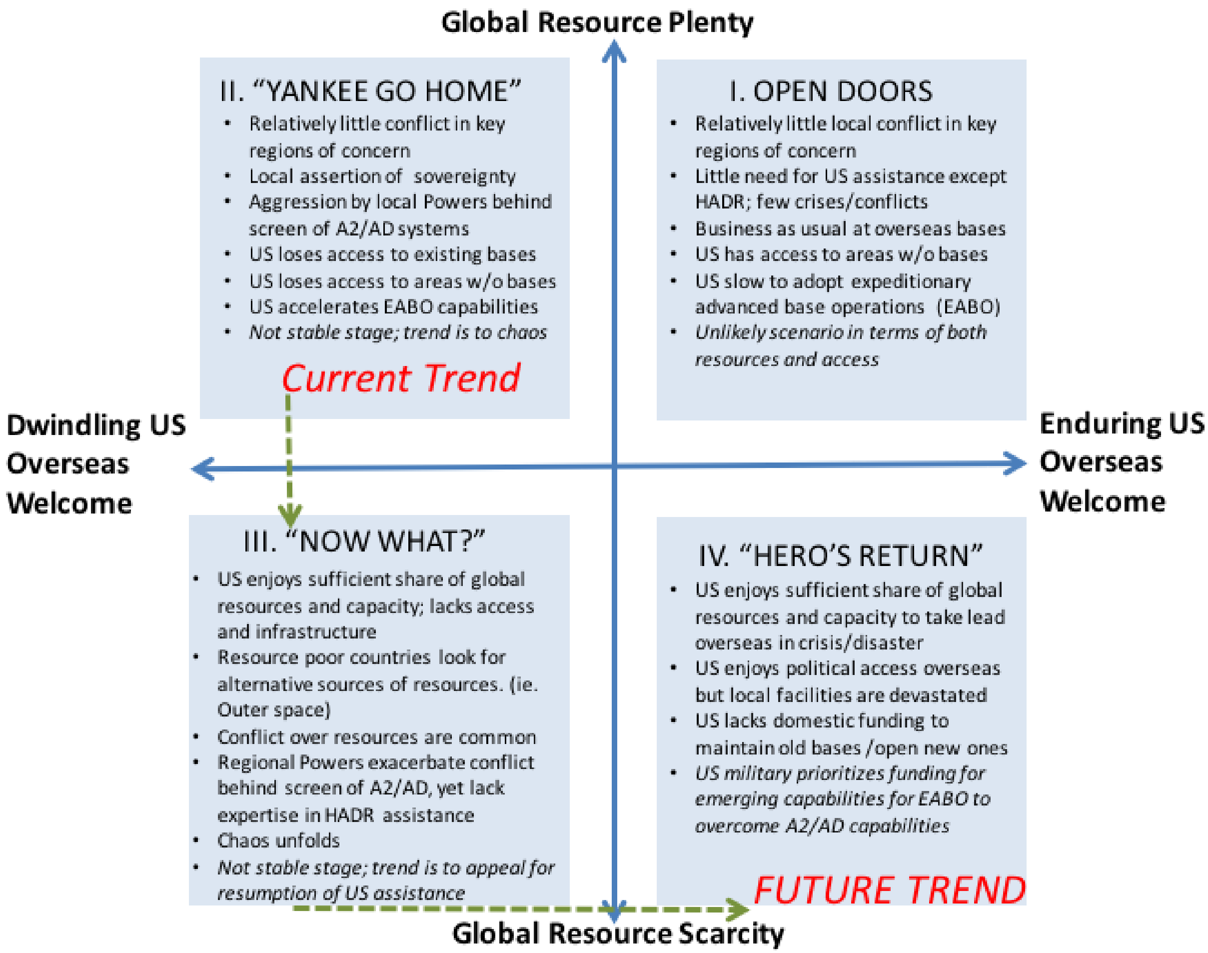

Figure 1

The future operating environment described in Quadrant IV, "Hero's Return", presents many challenges to current US methods of conducting operations and providing logistics. In this environment, pre-established bases and large logistical nodes are no longer available and financial constraints will prevent the US military from establishing new bases.

From these considerations, the central problem in the future operating environment emerges. Maneuver warfare in the future operating environment will require innovation across all six warfighting functions. With regard to logistics, the US does not currently have a logistical platform with the flexibility, world-wide range, and timeliness needed to support future operations in places without fixed infrastructure. Not only current and future global trends, but also official US military doctrine attest to the fact that this capability will be vital to US interest as the sole global superpower.

In the *2012 Capstone Concept for Joint Operations: Joint Force 2020*, the joint chiefs recognized the role that the space domain would play in future conflicts by noting, “Space and cyberspace will play a particularly important role in the years ahead. As these domains figure more prominently in the projection of military power, operations in them will become both a precursor to and integral part of armed combat in the land, maritime, and air domains.”[9] This publication indicates that, in the current military mind, space serves primarily as an enabler for operations on land, sea and in the air. The perception is that space is a domain for satellites, ballistic missiles, and communication equipment, not a realistic place for strategic logistical prepositioning. Moreover, the United States has enjoyed unrivaled and unquestionable access and movement in space for the last several decades. However, technological advancements and interest in space demand a shift in thinking about this domain as no longer a place “up there” for astronauts and satellites.

This freedom to navigate and operate has been and will continue to be a vital element in projecting power and influence across the world. As JP 3-14 *Space Operations* acknowledges, "Space capabilities are vital to overall military mission accomplishment and provide advantages needed for success in all joint operations.” The document goes on to describe the five space mission areas: space situational awareness, space force enhancement, space support, space control, and space force application. [10] In terms of logistical support, JP 3-14 only mentions how satellite communication can help inform logistical planning, but there is no mention of logistical prepositioning. The US role as a military super power, in no small part, has been predicated on the capabilities enabled by unrivaled space assets. In order to maintain this role, the US must look to exploit new opportunities afforded by space technology and utilize space in ways previously impossible or unimagined.

JP 4-0, *Logistics*, mentions "space" multiple times, and provides a graphical depiction of how joint logistics will operate in the future, with space listed as one of the domains. JP 4-0 recognizes that joint logistics will require and take place in the space domain, but it fails to detail how and in what manner. MCDP 4, the Marine Corps foundational logistics doctrine, is equally devoid of any hint or mention of an overlap between the domain of space and the warfighting function of logistics.

In November 2016, the Marine Corps convened a large scale war-game to test their ability to conduct Expeditionary Advanced Based Operations (EABO). One of the many learning points that emerged from the three-day war-game was the logistical challenges associated with conducting EABO. The participants noted that "in order to retain capability…support functions must be conducted in a new way, with a more *complex logistical network supporting the distributed force*."[11] In fact, the two warfighting functions that were highlighted as being the most challenging to conducting EABO were command and control (C2) and logistics. Participants also acknowledged that "survivable, effective theater, and *even global level,* distribution networks will be critical to effectively sustain the force forward" and players recognized "the importance of Phase 0 operations and *prepositioning*." SBL offers potential solutions on multiple fronts of the EABO concept, particularly those highlighted by the war-game participants. The building of a SBL infrastructure would be commensurate with Phase 0 operations, would serve as a diversified form of prepositioning, and would be capable of providing massive amounts of logistical support to any place on earth.

In the *MOC*, Marine Corps leaders describe the way the Marine Corps will evolve, integrate, train, and organize the force in order to operate and fight in the 21st century. The *MOC* contends that a requirement for success in the future is directly predicated on the Marine Corps's ability to develop innovative logistical solutions, "because iron mountains of supply and lakes of liquid fuel are liabilities and not supportive of maneuver warfare."[12] Responding to the MOC, *Hybrid Logistics* details a supporting concept for future logistics in support of the *MOC*. The concept admits that, "today and in the future, Marines will be fighting in five domains – sea, air, land, space, and cyberspace," and that our future enemies "will make the building of mountains of steel ashore problematic."[13] It goes on to mention that on, "future battlefields, [the Corps] will still need to move large amounts of sustainment, but [the Corps] will optimize tactical distribution with unmanned platforms…"[14] Nevertheless, the document fails to mention anything about prepositioning supplies in space. *Hybrid Logistics* and the *MOC* both recognize the importance of the space domain as well as proposes institutional changes not just in the way Marines fight and think but how they are supported logistically as well. However, there is no mention in either of these documents about the potential of developing a space-based logistical platform.

The concept of SBL supports all of these Marine Corps concepts. Nested within current and emerging doctrine, it will offer solutions to the problems identified in the EABO war-game, while remaining consistent to the Marine Air Ground Task Force's (MAGTF) expeditionary nature. In so doing, it maintains the Corps's innovative reputation and institutional ethos of operating in "every clime and place".

To understand the SBL concept in detail, one must consider a spectrum of functions, as depicted below.

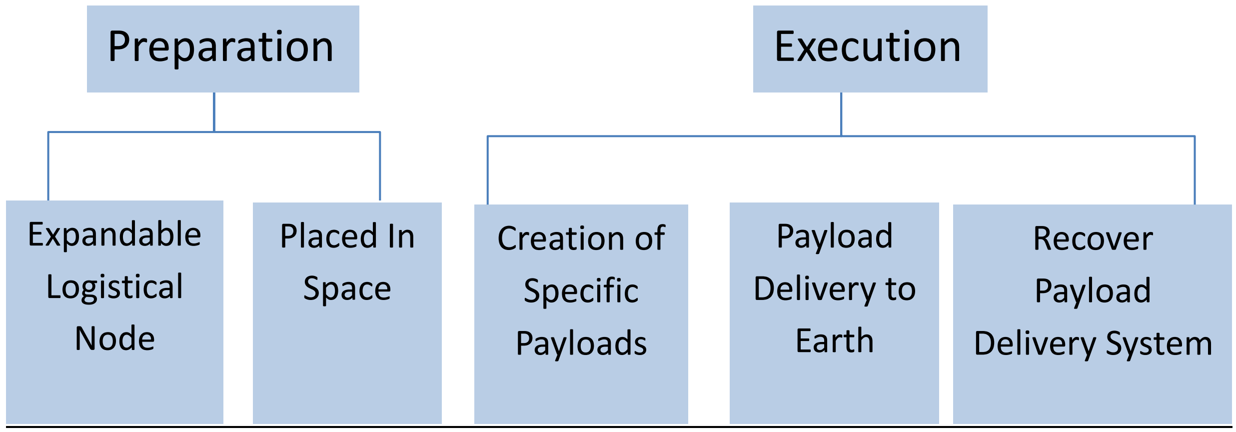

Figure 2

One may thus understand the SBL supporting concept as defined in the following terms: Numerous, expandable, modular logistical nodes are placed in space. When needed, tailor-made logistical payloads will be readied onto reusable spacecraft capsules (RSC), detach from the space logistical nodes, re-enter the Earth's atmosphere, and deliver the logistical payload safely and with the accuracy of contemporary helicopters. Once payload is off loaded, RSC is recovered and prepared for further use. Much of the US military's language articulating operating concepts, both present and future, tends to consist mainly of fuzzy descriptions and catchy slogans. Words matter; one can therefore best understand the SBL concept by examining the components of the concept piece by piece.

"Numerous, expandable, modular logistical nodes"

The idea of developing and placing in space large expandable modules is not new. In fact, America's first two communication satellites were both expandable metallic balloons known as Echo 1 and Echo 2, and they were launched into orbit in 1960 and 1964 respectively. NASA continued to develop prototypes and designs of interstellar, expandable habitats designed with interplanetary travel and colonization in mind. Later, in the 1990s, a team of NASA engineers and architects were tasked with improving previous expandable concepts and building an expandable habitat intended to support a mission to Mars.[15] This task expanded into designing a platform suitable for the International Space Station. Over the course of the next few years, "the innovative engineers soon shaped a revolutionary concept that provided an alternative to a hard aluminum shell architecture."[16] The structure was known as Transit Habitat, or TransHab for short, and was a "hybrid space structure that synthesized a hard central core with an inflatable exterior shell."[17] In 1999, the National Space Society (NSS), fearful of expanding cost of the TransHab project, sent a letter to the House of Representatives recommending that NASA "should not develop under its own auspices an inflatable habitation module for the International Space Station,"[18] but did recommend that the patents and technology be made available to private industry for further development. Where the NSS and American legislative body saw obstacles and cost, a real-estate billionaire turned space enthusiast saw opportunity.

Robert Bigelow made his millions by building a successful chain of extended stay hotels and developing commercial real-estate. In 1999, after the cancellation of the TransHab project, Mr. Bigelow purchased the patents to the expandable technology and founded Bigelow Aerospace Inc. Since that time, Bigelow Aerospace's mission "has been to provide affordable destinations for national space agencies and corporate clients."[19] The company hopes to create quasi-hotels from their developed expandable habits and capitalize on the emerging business of space tourism.[20]

With this vision in mind, in 2006 and 2007 Bigelow Aerospace developed and launched successful expandable platforms called *Genesis I and Genesis II* into Low Earth Orbit (LEO). The success of these early prototypes validated Mr. Bigelow's belief that his company could develop and deploy expandable habitats into space. Capitalizing and learning from their early success, his team of aerospace engineers developed the Bigelow Expandable Activity Module (BEAM). In the spring of 2016, the BEAM was stowed inside a SpaceX Dragon RSC and launched via a SpaceX Falcon Rocket bound for the ISS. When the Dragon docked with the International Space Station, the BEAM was removed and inflated, and on June 6^{th}, astronaut Jeff Williams became the first person to enter a BEAM while in LEO. BEAM will remain docked at ISS and undergo two years of testing, examination and analysis in order to ensure that it meets safety standards for human habitation.[21]

It is Bigelow Aerospace emerging technology and larger habitat that is central to the SBL concept. Recently, United Launch Authority (ULA) announced a partnership with Bigelow Aerospace to launch the next generation of expandable habitat, the B330, into LEO by 2020.[22] The B330 is a space habitat with over 12,000 cu/ft of pressurized, usable space and is designed to hold up to six people and supplies for prolonged sojourns to LEO. It has two universal docking ports on either end that would allow RSCs or other Bigelow products to link up and expand the existing structure with increased capacity. At least conceptually, there is no limit to the number of possible B330 linked together. The B330 is made of durable, state of the art material that offers more than minimal protection from radiation and space debris. Further, its 20-year life span means it can remain in continual orbit for the better part of two decades. The figure below is an example of potential layout of an orbiting B330.

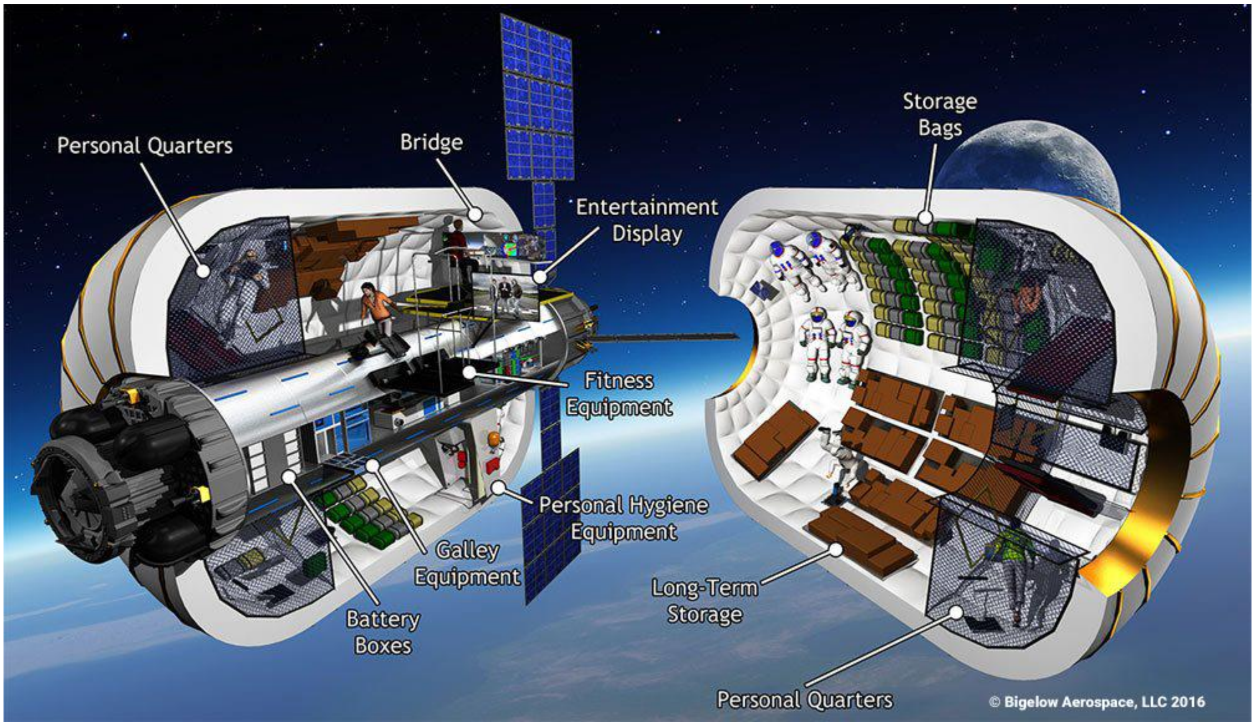

Figure 3

At the company's Nevada headquarters, Bigelow's engineers have successfully constructed a significantly larger expandable habitat than the B330. Bigelow's *Olympus* is an expandable space habitat with over 80,000 cubic feet of pressurized, usable space. This massive habitat has more than twice the capacity of the International Space Station (ISS) and is nearly six times larger than the B330. However, like the B330, it will have NASA Docking Systems (NDS) on both ends and will be capable of independent orbit around the earth for decades. Some technology insiders and space enthusiasts believe that the *Olympus* may be capable of launching into LEO by the time the ISS is set to retire in 2024.[23] Though the company is primarily focused on the success of BEAM aboard the ISS and furthering the B330's mission profile, Mr. Bigelow "keeps the Olympus front and center for inspiration, a symbol of all that's left to be done."[24]

Expandable modules like the ones developed by NASA and Bigelow Aerospace are better suited than fixed structures to support SBL because they are compacted and compartmentalized prior to launch and then inflated upon reaching their space destination. In terms of space saving and efficient stowing, consider by analogy the idea of taking a tent on a camping trip. If you had to keep the tent in its intended shape and full size, it would make for an interesting car ride and the would-be campers would struggle to find space for other items. The fact that you can compress the tent and place it neatly in your car saves space and makes room for other items. The same underlying principle highlights the reason for opting for an expandable habitat rather than a fixed metal space structure. In summary, the SBL concept envisions multiple *Olympus* or similar expandable habitats converted into orbital warehouses filled with military logistical supplies. The next important step in this supporting concept is to figure out a way to place such a large item and associated equipment into space.

"…placed in space …"

The definition of space will vary depending on the agency or organization providing a response. For instance, the Fédération Aéronautique Internationale (FAI) and National Aeronautics and Space Administration (NASA) both utilize the Karman Line to differentiate between outer space and inside earth's atmosphere. Anything that travels beyond 100 kilometers from sea level will pass the nominal Karman Line and into outer space. The Department of Defense, however, does not offer such clarity. Joint Publication (JP) 1-02, *Department of Defense Dictionary of Military and Associated Terms*, does not even provide a definition of what is meant by 'space,' though it provides definitions for 16 space related terms like “space asset”, “space support”, and “space systems.” JP 3-14, *Space Operations*, similarly fails to provide a definition of what constitutes the physical domain of space. For the purposes of this concept, the Karman Line serves as the boundary and de facto definition of the space domain.

The *Olympus* prototype is too large to be transported into LEO via any current launch system. However, there are numerous companies that are currently designing and developing larger and more capable “super heavy lift” launch vehicles that will, in the foreseeable future, be able to deliver hundreds of thousands of pounds of cargo to space, including an *Olympus* expandable habitat. It is important to understand that there are essentially three different types of launch vehicles: reusable launch vehicles (RLV), expendable launch vehicles (ELV) and a hybrid reusable/expendable vehicle (HLV). While SBL can be accomplished by any of the three, they have varying capabilities and limitations. A brief overview will clarify the differences.

The contemporary space program, until very recently, has been dominated by ELVs, with the notable exception being the United States Space Shuttle (capable of Vertical Takeoff, Horizontal Landing (VTHL)). As the name suggests, an ELV is capable of performing only a single launch. After a single launch, its components (boosters, rockets, fairing, etc…) are unusable for a second mission. The physical structure of an ELV accounts for 75-85% of its associated costs, spent on components that can never be utilized again. On the one hand, RLV’s are considerably more expensive to produce due to the durability and reliability requirements of the components. While its initial production costs are higher than those of an ELV, an RLV can close the cost gap substantially with each successive launch and, after enough redeployments, becomes more cost effective.[25] Also, an ELV will jettison many of its forever unusable components upon reaching LEO. Unlike the reusable components on an RLV, many discarded

ELV components add to the growing problem of space debris discussed in depth on page 39. In addition to the initial production cost of an RLV, there is also added weight for thermal protection designed to keep components safe from the tremendous rise in temperature associated with atmospheric reentry. Rockets and boosters require landing systems or a parachute, further adding to the weight and reducing initial payload capacity. This added weight increases the cost to place the RLV into orbit.

For decades, the aerospace community, NASA, and space enthusiast debated which type of launch system was optimal for particular space missions and capabilities. In 2000, the Air Force Scientific Advisory Board addressed the debate between RLVs and and ELVs and concluded that, if the Air Force planned on accomplishing the explicit goal of "controlling and exploiting the full aerospace continuum," RLVs "will be necessary to make routine space operations affordable."[26] The same report goes on to conclude that with regard to RLVs, "probably no other single technology offers such great promise of enabling the future of military space operations and civil space activities."[27] The RLV was always desired, but the science needed to bring one into being seemed always just beyond the aerospace community's grasp.

A much anticipated breakthrough took place on 22 December 2015. After two previously unsuccessful attempts, a private company called Space Exploration Technologies Corporation, better known as SpaceX, successfully landed its Falcon9 RLV at Cape Canaveral, FL after the rocket flew over 120 miles from earth and into sub-orbital flight.[28] SpaceX's founder and CEO, Elon Musk, made it the company's mission to create the first reusable rocket when he founded the pioneering company in 2002. The tech-millionaire turned self-taught rocket scientist agreed that the key to affordable and reliable access to space could only be fully attained once a reusable rocket was developed and proven. Since the company's initial success, they have recovered rockets eight times after initial launch and displayed versatility by landing rockets not just back at the original launch site, but on ocean platforms as well. Further, on March 20, 2017, for the first time, a previously used RLV was used a second time to conduct an orbital launch. Musk commented on the significance of this achievement by saying:

> [This] means you can fly and re-fly an orbital-class booster [RLV], which is the most expensive part of the rocket. This is going to be ... a huge evolution in spaceflight. It's the difference between if you had airplanes that you threw [out] after every flight, versus you could reuse them multiple times.[29]

SpaceX's next ambitious goal is to make a landing-to-relaunch turnaround time of less than 24 hours.[30]

SpaceX and competitors like Blue Origin have made tremendous discoveries, breakthroughs and cost cutting advancements aimed at making manned and unmanned access to space cheaper, better, and more affordable via reusable platforms. These leaps and bounds on the scientific front are allowing larger and larger payloads to reach space for cheaper and cheaper. (Cost will be covered in another section). For example, the Falcon Heavy (FH) is SpaceX's next generation launcher and is currently making its final preparations for its maiden voyage later in 2017. It is classified as a 'super heavy rocket,' meaning that it is both larger and more capable than its Falcon9 predecessors. When launched, it will be able to lift more than twice the payload of the next closest operational launch vehicle, United Launch Alliance's Delta IV Heavy, at one-third the cost. The FH will be able to carry over 140,000 pounds of payload to LEO, nearly three times the capacity of the Falcon9.[31] Though FH's expressed purpose is to reenergize human spaceflight and interplanetary exploration, it could not only launch an *Olympus* into LEO but also take many of the necessary logistical items needed to convert the expandable habitat into a celestial logistical storehouse. If SpaceX's goal of a 24 hour redeployment of an RLV and payload is realized and accomplished, in theory, just shy of a million total pounds of cargo could be placed in LEO in one week. This unrivaled payload lift capacity coupled with increasingly diminishing cost barriers makes the SpaceX FH, or commensurate platform, an ideal component of the SBL concept.

Customized Payloads:

With an established orbital logistics facility, SBL would require the ability to create tailor-made payloads and load them onto a RSC. If these logistical deliveries are going to be in support of varying operations across the ROMO, they will have to be customized in order to sufficiently support that specific military mission. A large scale military operation will require different payloads than a HA/DR situation. In order to facilitate the creating and loading of these customized payloads, one explored possibility is to have each of the *Olympus*-style logistical facilities manned by service members or contractors. This option would require frequent rotation of personnel, further modifications of the logistical facility to accommodate human life, and increase force protection measures to ensure human survivability. For these reasons, the idea of manning these logistical facilities was considered but not recommended.

A solution to the problem of creating and loading specific payloads is solved by the utilization of autonomous mobile robots (AMR). These robots and their associated technology have already proven especially apt at inventory management in warehouses and supply depots for companies like Amazon, the world's largest on-line retailer. By 2015, Amazon had employed over 30,000 ARMs across 13 of their warehouse facilities and saw significant efficiencies achieved by the use of the AMRs. Various companies have developed AMRs that can be programed and uploaded with the inventory and location of millions of items within a given warehouse. Some, like Rethink Robotic's 'Baxter', are extremely capable of picking up items and placing them somewhere else.[32] If SBL incorporated this technology, earth-based persons could remotely create and communicate the requirements of a particular payload to AMRs aboard the logistical facility. These AMRs could then assemble the elements of each payload manifest from the existing stockpiles and load them onto one of the two attached RSC. Each orbiting logistical facility could create two separate and distinct payloads aboard two RSC at the same time. In theory, one payload could be created to support an HA/DR mission in the pacific region while another payload is created simultaneously to support large scale combat operations in South America.

Payload Delivery to Earth

Placing an orbiting warehouse in space and preparing specific earth-bound payloads presents a new and challenging problem: how can these logistical items be delivered quickly to support military operations? Aeronautical engineers and spacecraft designers face numerous challenges and complications when attempting to answer this question. By comparison, getting something into space, while complicated, is substantially easier than bringing something from space back to earth. The following requirements all pertain to an RSC capable of supporting SBL:

- NDS compatible
- Capable of docking with, and receiving payloads from, an *Olympus*-style expandable module

- Capable of surviving the challenges of atmospheric reentry
- Capable of delivering substantial size payload of supplies
- Capable conducting accurate vertical landing
- Capable of being recovered by aircraft
- Capable of being utilized repeatedly

Capable of surviving the challenges of atmospheric reentry with substantial sized payload.

Since the dawn of the American space program, one of the most challenging problems for aeronautical engineers and spacecraft designers has been creating a platform capable of surviving atmospheric reentry. The fatal US Space Shuttle *Columbia* disaster in 2003 and the extensive damage done to the Russian *Soyuz* in 2008 typify the dangers and challenges associated with conducting reentry from space. Any spacecraft attempting to reenter Earth's atmosphere must travel in excess of 17,500 miles per hour within the correct reentry corridor in order to successfully penetrate earth's atmosphere. If a spacecraft comes in too steep, it is possible for it to combust or crush under the cumulative effects of gravity, known as G-forces. If the reentry angle is too shallow or flat, the spacecraft will skip off of Earth's atmosphere like a rock skipped across a placid lake. Further compounding the aerodynamic problem of atmospheric reentry, "there are serious thermodynamic issues with a 17,500-miles-per-hour (mph) plunge through Earth's atmosphere."[33] Traveling at this tremendous speed and encountering the dense air within Earth's atmosphere, the spacecraft causes the air to compress, creates friction, and generates extremely hot temperatures. While exact temperatures associated with reentry are predicated on many variables like size of capsule, speed of reentry, and effectiveness of the heat shield, a returning space craft must be able to withstand temperatures in excess of 1400 degrees. Lastly, in order to fulfill a SBL concept, a craft returning from space must be able to deliver substantially sized payloads to the service members on the ground. While the contents of these payloads are beyond the scope of this supporting concept, the payloads must be large enough to justify and validate the complicated and costly nature of delivering logistics from space.

Must be capable of conducting an accurate vertical landing.

The US Space Program has demonstrated the ability to bring large payloads back from space via the Space Shuttle. Despite demonstrating the ability to bring back to earth payloads in excess of 30,000 lb payloads, this platform does not support or conform to the requirements of SBL. The problem lies with the limitations of its landing abilities. The Space Shuttle and many other spacecraft are only capable of landing horizontally and therefore require safe, secure, and expansive runways in order to facilitate a landing. A SBL concept is designed around delivering logistical supplies across the ROMO, including contested and inhospitable areas where secured access to airports or runways cannot be guaranteed or assumed. For this reason, horizontally landing spacecraft or space planes are not considered as a viable delivery method for SBL.

The ability of a spacecraft to deliver payloads from LEO and land both vertically and accurately is just beyond the grasp of current capabilities. Currently, the Russian spacecraft *Soyuz* has returned both payloads and humans[34] from space in a vertically landing spacecraft, while in 2016, SpaceX's *Dragon* successfully departed from the ISS and conducted a vertical landing into the ocean off the coast of Mexico. In terms of return payload capacity, the *Dragon's* 6000 pound return capacity offers a considerable advantage over the *Soyuz*'s meager 300 pound return capacity[35] The reason that neither of these two platforms support a SBL concept is due to the fact that both rely on parachute deceleration systems as their primary landing method. Both capsules deploy massive parachutes in order to slow the speed of their descent during the final stages atmospheric reentry. In attempting to deliver logistical supplies from space during kinetic or semi-kinetic military operation, these slowly falling payloads would be susceptible to enemy targeting or direct fire weapons. Also, the parachute system does not allow for the level of accuracy of landing required to support a SBL concept. Once the parachute system deploys, the spacecraft is essentially at the mercy of the wind and other weather influences. For this reason, vertical landing platforms still require expansive landing areas to account for this variable. This inability to land accurately would be an extremely limiting if not all together disqualifying planning consideration for support of military operations, and commanders would be understandably disinclined to utilize SBL due to the inherent uncertainty and imprecision of the landing platform.

A solution to this difficulty, however, is in sight. SpaceX's *Dragon v2* was developed as a viable transportation capsule that could safely land humans on Mars.[3] To do so would require a capsule with an alternative to the parachute deceleration system that has existed since the *Friendship 7* delivered John Glenn safely from space in 1962. Deployment of parachutes to slow the descent of a reentry capsule works well on earth, but the system would fail to slow down a capsule sufficiently in and around Mars' atmosphere. Hence the solution was to design the *Dragon v2* with a propulsive landing system capable of producing the correct amount of counter-thrust as the capsule approached its destination in order to facilitate a soft landing on the ground. Not only will this system allow the spacecraft to continue its descent at higher speeds for a

[3] Elon Musk once said said that he "hopes to die on Mars, just not on impact."

longer period of time, but also it will be much more difficult for potential adversaries to target and destroy.

The requirement for liquid fuel to initiate the retro-thrust landing system as well as the need for a permanent landing gear system both added weight to the second generation spacecraft, reducing its return payload capacity. Though it is currently the closest RSC under development that would meet the future needs of a SBL concept, further innovations and technological developments are still required in order to bring down developmental cost and increase payload capacity. Figure 4 shows the traditional parachute deceleration systems next to the propulsive landing system required for SBL.

Figure 4

Recovery of Payload Delivery System

Once the RSC has delivered the intended logistical supplies to its intended recipients, the operating force must still recover it somehow for future use. There are multiple methods, all situationally dependent, that could solve the problem of recovery. One method is concealing the RSC until such time as it can be recovered by ground forces. Short term camouflage could be stored on the RSC and the recipients would be required to place it over the capsule after off-loading its contents. While this method could be utilized for very short durations of time and in extremely permissive environments, this camouflage system would take up precious cargo space and reduce the return payload capacity. Therefore, is not practical or recommended.

Second, a potential stipulation for requesting of SBL resupply could be that the users have to provide a planned method of recovering and safeguarding the capsules and that this plan must be approved prior to deploying the RSC. Planners and commanders would have the ability to tailor their recovery plan to the operational environment, accept risk when necessary, and utilize creative thinking and problem solving in order to achieve the mission of recovering the RSC. This flexibility could come at the expense of planning time or could delay the acquisition of SBL due to misunderstanding, discussions, or demands for further refinement of a desired recovery plan. For this reason, placing the safeguarding and recovery of the RSC in the recipient's hands is feasible but not recommended.

In order for the RSC to be recovered, it must be able to initiate a launch abort system from the grounded position and be capable of climbing several thousand feet above ground level (AGL). As the RSC nears its highest point prior to deceleration back down to earth, a point known as apogee, "recovery would be accomplished by snagging the capsule with an appropriately sized cargo plane (C-17 or C-05)."[36] While it may sound far-fetched or beyond the scope of the technologically feasible, this method of recovery has been demonstrated for decades, though not with space capsules. In fact, in 2009 a group of aerospace scientists and aviation experts showed via modeling the possibility of recovering a RSC via the above method is theoretically possible and realistic, but this technique has yet to be physically demonstrated.[37] A required altitude of several thousand feet could place the RSC safely beyond the threat capabilities of enemy small arms or direct fire weapons. Once the RSC is recovered, it can be returned to the necessary facility for maintenance, repairs, refueling and subsequent redeployment back to space.

<u>Increase in percentage of NASA's operating budget</u>.

In order for the United States to remain dominant in the space domain, NASA's funding must not be allowed to stagnate as it has during recent administrations. NASA is the repository of the majority of the United States' knowledge and talent with regard to the space program and space technologies and they develop America's world-leading aerospace technology. Currently, NASA receives approximately .5% of the US's total annual operating budget, down significantly from the 1960's during the space-race with Russia . Over the next 10 years, NASA budgetary allocation percentage needs to grow slowly but consistently until it reaches 2% of the national budget. With an increased operating budget, NASA will be able to encourage creativity and innovation as they award contracts to private industries like Bigelow Aerosapce, SpaceX, Orbital ATK and many others. Many of these private industries are heavily dependent on NASA funding in order to stay operational and allowing NASA's budget decrease will result correlate directly with decreased space capabilities. With this monetary commitment, NASA will continue to attract some of the brightest and most talented engineers, scientist, and innovators who will all continue to ensure American space superiority.

<u>Increased focus on science, technology, engineering and math (STEM) in the US educational system.</u>

If SBL is ever going to become a reality, the American educational system must place an premium on facilitating STEM based learning and interest. As noted earlier, SBL is a multidecade supporting concept and will be implemented, refined, and executed by children who are currently in elementary and secondary school. Recently, there has been some encouraging news on this front. In February 2017, President Trump signed into law H.R. 321 and H.R 225. Both of these laws promote and protect women entering the STEM fields. Less than a month later, President Trump phoned astronaut Peggy Whitson aboard the ISS where the two discussed, among other things, STEM education for women in America. According to the 2015 Programme for International Student Assessment (PISA), the United States was ranked an unimpressive 38th out of 71 countries in math and 24th out of 71 in science.[38] The US educational system needs to produce graduates who are imbued with a skeptical and scientific mindset that fosters creativity and values evidence.

Space Debris:

Cleaning up the man-made problem of orbital debris, also known as space junk, is one of the most important and imperative issues not just for the realization of SBL, but for any and all current and future spacefaring nations. Space debris takes two forms: natural (meteoroid) and artificial (anything man-made). The realm of LEO was free of artificial debris for the first few billion years of earth's existence but that changed forever in October 1957 when the Russian spacecraft Sputnik 1 successfully entered LEO. Since 1957, LEO has become increasingly congested with more and more debris left behind by previous trips to space, jettisoned boosters and rocket fairings, and nonfunctioning satellites. In less than 70 years, mankind has turned space into a literal junk yard that now threatens to hinder future space-based aspirations.

Today, the Joint Space Operations Center (JSpOC) tracks on a daily basis more than 16,000 objects orbiting Earth. About 5 percent of those being tracked are functioning payloads or satellites, 8 percent are rocket bodies, and about 87 percent are debris or inactive satellites.[39] This does not encapsulate the totality of the space debris problem. It is critical to note here that the debris tracked by JSpOC have to be large enough to detect with ground-based sensors and equipment. JSpOC is only capable of seeing objects 10cm large or more. It is estimated that there are over 170 million pieces of debris that are between 1mm and 9cm but, because of their small size, cannot be tracked or monitored with any regularity.[40] This debris can range from fragmented pieces of destroyed satellites to nuts, bolts and even paint chips. The very small objects that are caught in earth's gravitation field are traveling at tremendous speeds, in excess of 17,000 miles per hour. Over the course of many decades, debris will gradually decelerate and be pulled into earth's atmosphere where it very often is incinerated before it reaches the earth. However, while they are in contained in LEO, they pose a serious risk to any and all objects due to the speed they are traveling.

While floating paint chips or bolts may not seem to be a considerable threat to space operations, consider that a piece of space debris the size of softball, if it collided with a working satellite, would likely cause enough damage to render the satellite unusable. A 1-cm size object would be capable of penetrating the ISS's protective shield and would most likely disable a spacecraft.[41]

The problem of space debris was further exacerbated in very recent history. In January 2007, China fired an anti-satellite (ASAT) weapon at one of its non-functioning weather satellites located in LEO. It is unclear whether China destroyed its own satellite in order to flaunt its ASAT capability to the world's spacefaring nations or if it was telegraphing nefarious intentions towards other nations' space platforms. What is very clear was the result: more than 3000 pieces of cataloged debris with hundreds of thousands of additional pieces of debris too small for detection and tracking.[42] While this destruction of a space-based platform remains the largest recorded creation of space debris in history,[43] there have been other catastrophes that have intensified the space debris problem. The 2009 accidental collision of an operational US Iridium satellite with a non-functioning Russian satellite created nearly 1900 pieces of tracked and cataloged debris in LEO. Together, these two events, both in the last decade, account for 36% of the cataloged debris currently congesting LEO.[44]

Continued and repetitive launches to space, coupled with the incidents described above, have resulted in the growing problem of space debris. The mere presence of more and more debris causes the likelihood of collision between two objects to increase proportionally. In his 1978 work, "Collision Frequency of Artificial Satellites: The Creation of a Debris Belt," NASA scientist Donald Kessler proposed a theory that "satellite collisions will produce a number of fragments, some of which may be capable of fragmenting other satellites upon collision, creating even more fragments."[45] This cascading effect of increasing amounts of orbital debris could result in the destruction of most or all space based platforms and satellites and would leave "a belt of debris around the earth."[46] This reaction, known as the Kessler Effect, could result in long term effects felt by nearly every individual in the developed and developing world: loss of the Global Positioning System (GPS), loss of telecommunication and television infrastructure, loss of satellite imagery, and severe degradation of the US military's ability to conduct basic operations, to name just a few. Further compounding the problem, this "belt of debris" would have to be "cleaned up" prior to replacement of any of the 1100-plus satellites.

A solution to this problem remains elusive. There are basically two schools of thought: mitigation and remedy. Mitigation is focused on preventing further irresponsible creation of space debris via international laws, economic incentives, or the creation of a collective set of regulations.[47] Ideas for mitigation range from requiring a satellite company to pay a "deposit," which is returned when the company successfully removes its satellite from orbit at the end of its lifespan, to the creation of space maintenance facilities that can fix or repair damaged satellites. Remedy is focused on the active removal of a particular piece or pieces of debris. Methods to remove debris in this manner include space netting, lasers, and the Defense Advanced Research Projects Agency (DARPA) project called Catcher's Mitt. This study recommended immediate investment in active removal technology.[48] In February 2017, the Japanese Aerospace Exploration Agency attempted to use an electromagnetic tether to clear LEO of debris, but the platform failed to work as designed.[49]

Noted astrophysicist Neil DeGrasse Tyson said, on the subject of accumulating and expanding problem of space debris, that humans "may be putting so much debris in space as to close ourselves off from space travel because of the dangers it would take to get though our own garbage heap."[50] Given the rapidly increasing possibility of catastrophic orbital collision, failure to address and reduce the ever-growing problem of space debris, whether through means of mitigation or remedy, threatens the success of all future space-based missions. This vast accumulation of debris would not only prevent a successful SBL from materializing but would serve as a hindrance to any space initiative or exploration for generations to come.

Costs

Getting to space is extremely expensive and research and development of space platforms is equally cost prohibitive. Table 1 shows an estimated initial cost projection of one functional SBL platform placed in space for one year.

Item	Cost
Olympus Habitat Rental	1 rental spot =110 cubic meters @ $25 million / 60 days.[51] Capacity of 1 Habitat = 2200 cubic meters (20 rental spots) X $25 million X 6 payments = $3 billion / year
Heavy Lift Rocket	*Olympus* Launch to LEO = 140,000 lbs X $675 / lb =$90 million[52][4] 8 launches to deliver supplies = $720 million[5] 1 launch to deliver RSCs to LEO = $90 million
RSC	25,000,000 X 2 RSC = 50,000,000[6] (attached to either end of the Olympus)
Supplies Procurement	1,000,000 lbs = $10,000,000[7]
Total 1st Year Cost	$3.96 billion

Table 1

While the initial price of placing one SBL can be daunting, this price estimate is just below the FY17 military budget allocated to purchase two Virginia-class attack submarines.[53] Moreover, this is a projected 2040 capability being presented at 2018 pricing. The vast technological innovation and breakthroughs coupled with the price reducing effect of free market competition will substantially reduce this cost. To illustrate this point, consider by analogy the first commercially sold cellular telephone. In 1983, this cell phone weighed 2.5 pounds, was 13

[4] This assumes a 2018 launch price and an *Olympus* expandable habitat on the lowest weight projection. $675 / pound is the result of dividing the projected cost by the habitat's weight.
[5] Cost estimated off of Falcon Heavy cost projections of $90 million to deliver up to 140,000 lbs to LEO. 1 million pounds of supplies / 140,000 lbs per launch= 7.14 launches. Rounded to 8 total launches. Price assumes a 2018 launch price.
[6] Production cost of a future RSC not available.
[7] Weight of logistical supplies to be placed in LEO will be predicated on which type of supplies is designated. Volume will be a much more limiting factor then weight.

inches tall, had a limited call range, could store a maximum of 30 numbers, needed 10 hours of charging for only 30 minutes of talk time and cost $4,000 dollars.[54] Fast forward thirty years and the cellular telephone is globally ubiquitous, is lightweight, fits in the palm of the user's hand and pocket, can call worldwide, can access a world of instant information in seconds, can last for days when fully charged, and costs $40 at a local Wal-Mart. In 30 years, the cellular telephone went from a novelty item for only the extremely wealthy to a commonplace commodity for more than 95% of the adult American population.[55] If today's spacefaring and rocket technology is the equivalent of the 1983 cellular telephone, the idea of SBL becomes a viable and much more realistic. After the demonstrated ability to recover a rocket, Elon Musk commented that he was "highly confident that it's possible to achieve at least 100-fold reduction in the cost of space access."[56] If his prediction comes true and space access experiences the same cost reduction over a 30-year time span as that of the cellular telephone (99% cost reduction, increased capability, etc…) an expansive network of SBL nodes falls squarely into the realm of the possible.

Conclusion:

SBL has the potential to be the transformative logistical platform of the future. Marine Corps leaders and planners continually espouse the need for innovation in order to succeed on future battlefields where traditional logistical assets will have been rendered obsolete. Current and emerging spacefaring technology, if leveraged and employed correctly, will make it possible to preposition supplies and recall them back to earth with unprecedented speed and precision when needed to support military missions. During the interwar period, Marine Corps' innovators and visionaries recognized the potential presented by amphibious warfare and focused a tremendous amount time and effort into transforming this vision into reality. SBL offers the same magnitude of service redefining capability as amphibious warfare did in the 1930s and will require a similar dedication of purpose and innovative spirt by today's Marine Corps leaders in order to meet the challenges of tomorrow's operating environment.

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