Getting to Space on a Thread …

Space Elevator as Alternative Access to Space

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Abstract

The space elevator is a concept where a tether is used to lift cargo and personnel into space. This tether reaches from the surface of the Earth to a point some 62,000 miles into orbit. Vehicles traveling on this tether will be able to cheaply move heavy loads into orbit. From there, the cargo can be positioned in any desired position, with the major destination being geosynchronous orbit 22,240 miles up. The new technology which makes the space elevator possible is the carbon nano-tube (CNT), a material that is theoretically one hundred or more times stronger and ten times lighter than steel. The USAF, as the DoD Executive Agent for Space, can lead the U.S. in developing and deploying this alternate means of accessing space in support of DoD missions. In doing so, the USAF will be able to better meet its current needs for satellites on orbit along with rapid and extremely economical replenishment. The space elevator allows current missions to expand and new missions to be tackled thanks to its low cost and heavy lift capability and could be built in ten to fifteen years. A thread reaching down all the way from orbit to the surface of the Earth on which laser powered trucks carry huge loads into space for a very low price, this is the space elevator. A space elevator can serve as an alternate means to chemical-powered launch systems for the USAF to access space – a critical part in maintaining superiority of the ultimate high ground.

Contents

"There are no great limits to growth because there are no limits of human intelligence, imagination, and wonder."

- Ronald Reagan

"The first entity to build a space elevator will own space…"1

- Dr. Brad Edwards

Introduction

Should the U.S. Air Force pursue construction of a space elevator as an alternate means for accessing space? This question is critical considering the importance of space assets to the U.S. military and the nation. Today, the military relies on satellite communications, reconnaissance, surveillance, weather, and global positioning systems in orbit to perform even the most basic of missions.[2] The systems U.S. forces uses are not limited to government assets. Commercial and allied communications and imaging systems are routinely used to bolster bandwidth and coverage areas.[3] Unfortunately, these crown jewels of the military and commercial world are becoming increasingly vulnerable to enemy actions.

Jamming[4], direct attack using high powered lasers[5] or kinetic kill weapons[6], as well as attacks on ground sites[7] are but a few of the dangers faced by space assets used by the U.S. military. What happens when an adversary is able to deny U.S. forces of its eyes, ears, timing, and maps (no e-mail!?) provided by satellites? The current method of replacing an orbital asset requires months if not years of lead time and is extremely costly. In the mean-time, the loss of even a single satellite in orbit can greatly impact U.S. air, land, and sea operations. There are neither rockets standing on call to launch nor many replacement satellites in the barn ready for a ride to orbit. It is imperative that the U.S. be prepared to maintain the readiness of its space forces. Launch on demand merely provides a stop-gap means to maintain those capabilities already in place should they fail or be attacked. In order to maintain its superior position in space and to ensure the orbital assets it requires are available at all times, the U.S. must look beyond conventional capabilities to provide cheap, easy, quick, and assured access to space. This method is the space elevator.

> Slamming the last crate into the cargo pod of the lifter, the loadmaster stepped back to admire his work. Ten dull gray packing crates crowded the pod. Each one bore the emblem of the United States Air Force.[8]
>
> - Thread to the Stars

Thesis

The construction of a space elevator by the U.S. would fundamentally alter how the USAF thinks about, plans for, and utilizes space. Space elevator technology could provide a viable alternate means for accessing space for scientific, commercial, and military purposes.[9]

Today, the cost of getting to orbit is the primary limitation on any system or mission wishing to make use of the space environment.[10] The space elevator is the means for the USAF to lead a revolution in space-borne platforms and missions by providing the means to leap beyond current launch capabilities. Cheap access to space would facilitate the expansion of current missions and widen the launch window for entirely new mission arenas.

> The lift-pilot gave the loadmaster a thumbs-up.
>
> The loadmaster returned the gesture and stepped back from the vehicle. He let his gaze rise above the ungainly lifter to the silver thread stretching straight up as far as his eyes could see. Over the net, the loader could hear the pilot check in with the controller and report that his treads were engaged. A second later, the lifter began its long climb into the sky accompanied only by the hum of its electric motors.
>
> - Thread to the Stars

Building the Case

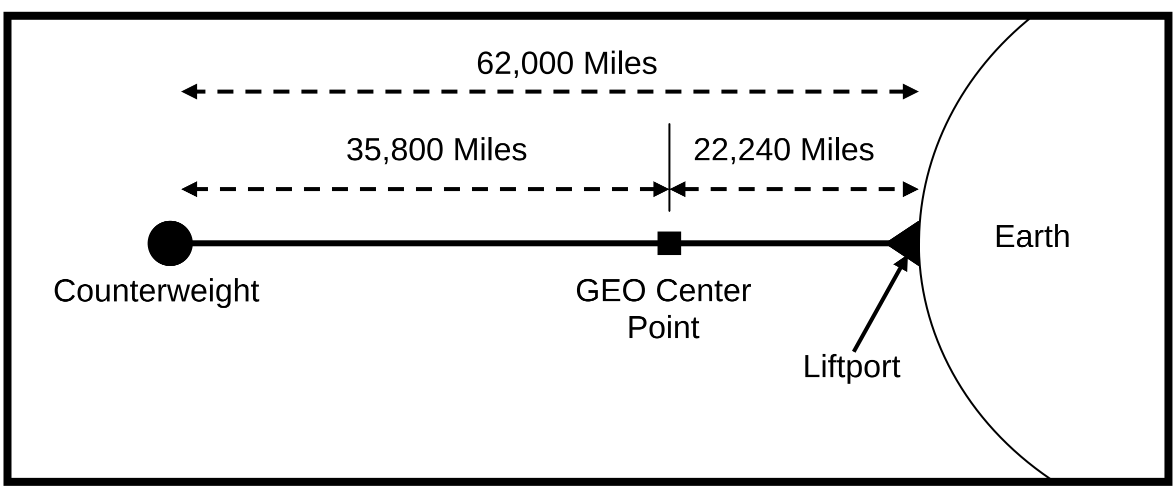
This paper will arm you with the facts necessary to understand a space elevator could be constructed in the near-term with today's technology or technology currently far along in development. The paper starts with an overview of space elevator basics. This brief explanation of the elevator layout and use is followed by a look at the specific technologies required for a space elevator including those available today and those still requiring a little work. The next section is dedicated to the uses of a space elevator by the USAF followed by a discussion of construction techniques and operational requirements. A look at possible future scenarios in space lift will illustrate how the space elevator fits into the future. Finally, this paper will summarize the need for a space elevator and the dangers of allowing another nation or entity to be the first to construct a thread to the stars.

> "This is a trillion-dollar moneymaker for a ten-billion dollar investment." [11]
>
> Brad Edwards, PhD

Space Elevator Basics

In order for the space elevator concept to make sense, it is worth taking a few moments to describe the basics. The space elevator discussed in this paper is a 1-meter wide tether stretching from the surface of the earth out to a point some 62,000 miles in orbit. The base of the ribbon is attached to a platform on the surface (floating at sea) while the space end of the tether extends past geosynchronous orbit to a counter weight. Lifters (or climbers, depending on one's preference) would clamp onto the tether and, using a series of rollers powered by lasers, ascend and descend in order to carry people, material, and cargo to and from orbit. Movement of satellites or larger constructs to appropriate positions in orbit or beyond would be accomplished using a new space logistics system built to handle the cargo brought up by a space elevator.[12] It may be hard to imagine a thread rising straight up into space. The weird part is you need to flip your earth-centric perspective and realize it is hanging down from orbit, not standing up. Easier to imagine? Here is what is happening…

There are two words anyone interested in space elevators must be familiar with: centrifugal force. Basically, centrifugal force is the apparent force on a body "directed away from the center of rotation".[13] As a mass rotates about a point, it experiences forces exerted upon it. A simple way to envision this concept is to think of a ball swinging about your head at the end of a string.[14] The string is kept taut due to the force exerted on it by the mass of the ball flying around in a circle and trying to fly away. Now expand this out to the scale of a space elevator. Your hand holding that yarn and ball are turning about your head (the Earth) at a fixed distance (geosynchronous orbit). The yarn is the CNT tether and the ball is the counterweight revolving about the Earth fast enough to stay directly above the elevator center point at GEO. Now, replace your hand, which is keeping the yarn and ball in place, with the rest of the tether dangling 22,240 miles to the surface of the Earth. The gravitational pull on the lower portion of the tether is perfectly balanced with the upper tether and the counterweight. Thus, your center point does not move even though it is being pulled both out into space and toward the Earth.



Space Elevator Basic Layout

A space elevator of the type described here is estimated to cost $6B in development and construction plus another $4B for regulatory, political, and legal costs. A second thread to space would be much cheaper, about $3B since the research and development and support infrastructure would already be established and the first elevator could be used to lift the necessary elevator material into orbit.[15] For the initial $10B investment the cost for putting 'stuff' into space would drop from $20,000/kg to $250/kg[16] with costs eventually dropping as low as $10/kg[17]. With a single shuttle mission costing $500M[18] and the estimate for trip to Mars hovering around $1T (yes, 'T' for Trillion), even if a space elevator cost twice as much as estimated, it is still a good deal.[19]

A thread reaching down all the way from orbit to the surface of the Earth on which laser powered trucks carry huge loads into space for a very low price, this is the space elevator. With the basics in mind, it is now time to look at the important technologies to be invested in and their uses.

> "Space capabilities contribute to situational awareness; highly accurate, all-weather weapon system employment; rapid operational tempo; information superiority; increased survivability; and more efficient military operations."
>
> AFDD 2-2 Space Operations

Space Elevator Technologies

There are several technologies which will need further development in order to see a space elevator become reality. The four most important technologies are the materials for the tether, lifter systems, power beaming, and orbital logistics. Other technologies which will be touched upon include floating structures for the ground structure, debris tracking and debris avoidance protocols. All of these technologies must be harnessed or matured before the space elevator can be built and utilized to its full extent.

The key component of the type of space elevator proposed here is the tether linking the Earth's surface to GEO. The only materials in development which theoretically possess the required yield strength for the tether called for in a space elevator are called carbon nano-tubes

(CNTs). These CNTs would possess the needed yield strength of 47 GPa[20] without allowing the tether to deform under the immense stresses it would encounter. [21] By comparison, steel has a yield tensile strength of a little less than 1 GPa. The next closest contenders are some titanium alloys and Kevlar with yield strengths a little greater than 1 GPa and 4 GPa respectively. Obviously, none of these materials meets the needs of a space tether. Lab tests on small samples of CNTs have shown yield strengths as high as 65 GPa with conservative estimates for the strength of future CNT structures to be 100-150 GPa. Even going with the lower prediction, CNT material would have a tensile strength 100 times that of steel and be ten times lighter.[22]

These CNTs are "molecules of carbon linked together in a shape that resembles a Chinese finger trap".[23] A paper thin tether just one meter wide made of CNT material could serve as the backbone for earth's first highway into space.[24] This tether would be composed of "thousands of 20-micron-diameter fibers made of carbon nanotubes in a composite matrix" which will be "cross-linked with polyester tape at roughly three-foot intervals".[25] In other words, the CNTs would be embedded within long fibers to aid their cohesiveness and manageability. These fibers would then be linked together to form the tether.

The idea of a space elevator has been around for some time, starting in 1960 with the Russian engineer Yuri Artsutanov[26], but one man managed to make the concept famous. Arthur C. Clarke hit close to the final solution to building a space tower in his book "The Fountains of Paradise" back in 1978. Morgan, the main character in the story uses "continuous pseudo-one-dimensional diamond crystal".[27] Swap Clarke's diamonds (made of carbon) for the more resilient carbon nano-tubes and you have the structure suggested for use in today's space elevator. Clarke's diamond thread would have been made in orbit where extremely pure, weightless conditions could be found. We are a bit luckier as a CNT tether can be constructed on earth where manufacturing capabilities are easier to build and control (at least for the present!). Science fiction has become a very possible science reality.

Lifters are the vehicles which will travel on the tether of the space elevator. The configuration advocated by Dr. Brad Edwards would limit lifters to about 20 tons due to the tensile strength of the structure. Of these 20 tons, about thirteen tons would be pure cargo, an amazing 65% of the total weight compared to about 5% for current launch vehicles. Using rollers which would clamp onto the tether, a lifter would climb the tether at up to 125 mi/hr delivering its payload to GEO in about seven days.[28] Lasers would be used to power the lifters from the ground station.[29] Ground-based tests have shown that current laser technology could deliver the 2.4 megawatts of power needed by each lifter.[30] Adaptive optics could be used to reduce the potential danger to animals, airplanes and the human eye by removing 96 percent of the effect of the laser.[31] The lifters will have to be optimized to provide rigidity in the atmosphere (still far below requirements for rocket borne assets) but light enough to allow maximum cargo carrying capability. Choosing a ribbon shape for the space elevator ribbon "simplifies the design of the tread system for moving the elevator car up and down the cable"[32]. The drive systems will need to be able to track along an extremely thin and relatively narrow tether while moving at high speeds. While technically challenging, none of these lifter issues is insurmountable.

The power laser located at the base of the elevator, or perhaps at some other convenient location with clear weather with in line of sight of the tether[33], would have to be strong enough to reach along the entire length of the space elevator while penetrating the earth's atmosphere and remaining focused to provide the energy needed to power the lifter. The power receiver on the lifter is simply a solar array turned upside down. More efficient battery or fuel cell technology could possible be combined into a hybrid power system allowing a ground based laser to power the lifter through its initial stages of ascent then the on-board power supply to take the vehicle on out along the tether to orbit once the majority of earth's gravitational pull has been left behind. A hybrid system would simplify laser design and allow a single laser to service several lifters in short order instead of focusing on one for the entire seven-day trip out to geosynchronous orbit. For now, battery weight and the power requirements for the lifter make a laser used alone the best option for the first generation of lifter vehicles. The large lifting capabilities of the lifters and cheap, efficient power supplies will carry cargo cheaply and reliably into orbit.

Developing and deploying a space elevator is really only the first step to truly utilizing space to its utmost capacity. With a space elevator in place, 'getting there is half the fun' really no longer applies; it is what you can do once you have attained orbit which really becomes interesting. To enable full use of space and the lift capability of a space elevator, an entirely new industry based on orbital logistics must be developed. Transfer craft to deploy, retrieve, repair, and dispose of space assets will need to be developed. Stations capable of housing workers, visitors, scientists, and maintenance facilities will also be required. Full scale industrial complexes and tourist destinations could eventually be established to take advantage of raw materials and an eager population ready for the space experience as tourists. Finally, with the advent of extremely cheap access to space, there is every reason to believe exploration of the rest of the solar system (and beyond!) will explode. Dr. Brad Edwards asserts a space elevator will not be the end of today's aerospace companies, but will instead be their greatest boon due to the technologies needed to provide and service the massive amount of equipment and machines needed to support the expansion of space missions following the first elevator's construction.[34]

The location of the ground station will be discussed further in a moment. It is sufficient to mention that large sea-going structures of the size needed to support lifter, power, and anchor functions have already been constructed. One needs look no further than the large mobile platforms in use today for oil exploration or rocket launches to see this technology is available. The reason you would want a mobile, ocean-going ground port is the need to move the tether around from time to time in order to avoid orbital debris.[35] Movement of the base station would have to be based on predicting where the ribbon will be at any one time as it will take hours or even days for a small movement of the ground station to translate to movement of the ribbon along its considerable length.

The U.S. does a pretty good job tracking space debris now. An increase in the resolution of space debris tracks will need to be undertaken to ensure threats to the space elevator ribbon and lifters are well understood and thus avoidable. Again, this is not out of the realm of current technology. Combine the mobility of the water borne liftport with the accurate tracking of space debris and you have the components needed to develop avoidance protocols to be used in the daily operation of the space elevator. Whether the operators need to move the ribbon slightly or induce regular oscillations to ensure proper clearance for debris or other operational satellites, the means exist to allow safe operation of a space elevator.

Recapping, the material needed to build the tether itself is the most critical technology needed to create a space elevator. The lifters, their power supply, and the space infrastructure needed to support orbital logistics can all be built using current technology. A floating ground port and orbital tracking systems supporting the space elevator can be based on systems in use today. There is also the consideration of ‘the more you use it the more you learn’. With each lifter traveling up the tether, each new satellite brought into mission, and each new challenge, the builders and operators of the space elevator will learn and adapt. New techniques, equipment, and materials will certainly be developed and brought into everyday use (as if CNTs were not enough). Theoretically, a USAF-led team can build and safely operate a space elevator, but what does it really need one for anyway?

> As the lift-pilot pulled himself through the airlock, he chanced to look out the tunnel window. Several space-suited figures had already cracked open the lifter pods and were busy transferring the cargo to a blue and white USAF transfer craft. "Guess those guys are really excited about whatever I dragged up here."[36]
>
> - Thread to the Stars

Why the USAF should be interested in a space elevator

The USAF will be able to use a space elevator to accomplish and enable current space missions and leverage this new capability for move into new mission areas. Eric Westling, a space elevator consultant says, "It [space elevator] will change the world economy. It's worth what ever it costs to put it up."[37] The space elevator changes everything in space. For the Air Force, space elevators are all about the mission, and it will indeed be worth whatever the cost.

Why should the USAF take the lead in developing a space elevator? Air Force Doctrine Document 1 provides an answer to this question quite well as it sums up the directives from DODD 5100.1. The USAF has the key organizational function to "organize, train, equip, and provide forces for…air and space support…"[38] Furthermore, the USAF is "to provide launch and space support for the Department of Defense."[39] While AFDD 1 lays out the responsibilities of the USAF, the 2001 Quadrennial Defense Review (QDR) tasks the DoD to:

> "Improve responsive space access, satellite operations, and other space enabling capabilities such as the space industrial base, space science and technology efforts and the space professional cadre."[40]

But why the need for the actions mentioned above? The QDR explains:

> "Experience from recent operations, supported by the findings and recommendations in the 2001 QDR and a number of studies and commissions chartered by the Congress and the President – including those on national security, space management, remote sensing, weapons of mass destruction and terrorism – have underscored the increasingly critical role that intelligence capabilities, *including those in space*, play in supporting military operations, policy and planning and acquisition in the Department [DoD]."[41]

The QDR goes on to say:

> "The Department [DoD] will continue to develop responsive space capabilities in order to keep access to space unfettered, reliable and secure. Survivability of space capabilities will be assured by improving space situational awareness and protection, and through other space control measures."[42]

The tasks laid before the USAF are daunting: responsive, unfettered, reliable access to space while supporting the wide range of satellite missions the DoD relies upon for its operations and in support of decision making. The writers of the QDR are asking for a space elevator and didn't even know it! Just how would a space elevator answer all these tasks?

Of the nine principles of war laid out in AFDD 1, three apply directly to the space elevator: mass, maneuver, and security. Mass means to "concentrate the effects of combat power at the most advantageous place and time to achieve decisive results."[43] This means all the tools at the commanders fingertips are applied effectively not simply in overwhelming numbers. A space elevator would enable a commander to easily build up communications, surveillance, and other space assets over his theater for use when and where he deems necessary. Current methods of redistributing space assets are time consuming and drain away the life of those assets as precious fuel is expended to change orbits. Adding to existing capabilities today is also challenging as surplus communications links or additional assets are simply in short supply or not available at all.

Maneuver is simply the "flexible application" of air and space power.[44] Again, with the ability to quickly place satellites into orbit or to have the logistics support in orbit (enabled by an elevator) to move assets around as needed, the space elevator satisfies this basic principle of war. The space elevator provides the flexibility to use space in the precise manner a commander wishes to configure his battlespace. Along with mass and maneuver, one can not forget the principle of security.

Security means "never permit the enemy to acquire unexpected advantage" and "embraces physical and information medium"[45] With a space elevator and the sheer access to space it would provide, no enemy would be able to acquire an unexpected advantage either on the ground, in the air, or especially in orbit. Physical patrol and protection of space-borne assets would be possible while a massive increase in information transfer capabilities could be constructed cheaply meaning he could have all the bandwidth and information he could desire. Assets placed in orbit by the elevator would help a commander no matter where he was located on the globe through increased communications, reconnaissance, surveillance capabilities.

"While the principles of war provide general guidance on the application of military forces, the tenets [of air and space power] provide more specific considerations for air and space forces."[46] A space elevator supports many of these tenets, especially persistence and balance. Persistence as used here can be summed by saying, as "space systems advance and proliferate; they offer the potential for permanent presence over any part of the globe"[47]. The persistence provided by today's systems should be considered at risk, as mentioned earlier. The space elevator would provide greater numbers of more capable, more robust systems and a means to augment and easily replace systems lost to enemy actions. The tenet of balance is to "bring air and space power together to produce a synergistic effect"[48] In other words, finite assets must be used to the best effect. The space elevator allows the placement and servicing of satellites allowing full battlespace awareness and support capabilities which serve as force multipliers.[49]

One of the key operation functions of the USAF is spacelift. "Spacelift delivers satellites, payloads, and material to space. Assured access to space is a key element to US national space policy and a foundation upon which US national security, civil, and commercial space activities depend. The Air Force is the DOD Service responsible to operate U.S. launch facilities."[50] When needed, "spacelift's objective is to deploy new and replenishment assets as necessary to meet U.S. space goals and achieve national security objectives."[51] The great news is that by improving the means to access space, satellites placed in orbit using the space elevator are cheaper due to lower launch costs. Also, the reduction or even elimination of the strict weight limits placed on current systems would be realized using the space elevator. This reduction would simplify designs and allow cheaper but heavier materials to be used in satellite construction.

Spacelift dovetails right into the key USAF operation function of Combat Support which includes "essential capabilities, functions, activities, and tasks necessary to create and sustain air and space forces."[52] Similarly, Agile Combat Support "creates, sustains, and protects all air and space capabilities to accomplish mission objectives across the spectrum of military operations" all the while remaining "responsive and flexible."[53] All of these goals for space forces can be aided or meet using a space elevator.

Besides the spacelift and combat support tenets, the assets placed in orbit and maintained using a space elevator would contribute to other key USAF operation functions such as information operations, command and control, special operations, intelligence thru surveillance and reconnaissance ("essential to national and theater defense and to the security of air, space, subsurface, and surface forces"[54]), combat search and rescue, navigation and positioning used to "provide accurate location and time of reference in support of strategic, operational, and tactical operations"[55], and weather service for both space and atmospheric operating environments[56]. Oddly enough, the one key Air Force operation function not likely to be supported by a space elevator is Counterspace, "those kinetic and nonkinetic operations conducted to attain and maintain a desired degree of space superiority by the destruction, degradation, or disruption of enemy space capability."[57] Although the "main objectives of counterspace operations are to allow friendly forces to exploit space capabilities, while negating the enemy's ability to do the same"[58], using the space elevator for any sort of direct military action of to place overtly military weapons or hardware into orbit would be quite unpalatable to other users and would likely be curtailed with space elevator use policies. Using the space elevator for support missions also helps lower the risk to an elevator in the event of conflict. Pressure exerted by users not involved in the conflict could help keep this structure off target lists. The discussion of weaponizing space, whether with offensive or defensive weapons is an argument that has no good answers at this point.[59] There are plenty of other non-weapon missions to discuss though.

Of all the services within DoD, the Air Force finds itself uniquely positioned to take up the challenge of developing space elevator technologies for missions very much within its realm of responsibility.

"… it's mission … to boldly go where no man has gone before!"
- Gene Roddenberry

The Mission

Okay, so the space elevator won't turn the USAF into the crew of Star Trek's Enterprise, but it will come close. This section will take a little closer look at the current missions improved by a space a elevator and new missions made possible thanks to cheap access to space. The current missions include secure communications, navigation, and constellation replenishment.

Some new missions the USAF could embrace include massive communication arrays, true persistent surveillance from space, orbital solar power stations, and spotlights from space.

The current missions are fairly well understood. Secure communications are key to any military operation. As mentioned earlier, the military has shown an insatiable appetite for bandwidth which is only going to increase as virtual warfighting capabilities, use of unmanned air vehicles, and simply more data is being exchanged between warfighters, coalition partners, rear areas, and support agencies.[60] With weight restrictions basically eliminated thanks to the space elevator, the USAF could orbit massive communications arrays with basically unlimited bandwidth. These systems could include pin-point communication links that would be virtually uninterceptable.[61] Along with communications, all military branches have become dependent on geo-location services provided by the USAF.[62] These services could be easily (and cheaply) serviced thanks to the replenishment rates allowed by a space elevator. Besides the boons described here, a space elevator would aide several other revolutions in the use of space.

With cheap, reliable access to space provided by a space elevator, the USAF stands on the threshold of a new age in space affairs. For instance, persistent intelligence, surveillance, and reconnaissance (ISR) from orbit becomes a reality. Mirrors fifteen meters in diameter could be placed in GEO and "would have the same collecting power as a 2-meter system in a 400 mile orbit but could be positioned for 24/7 observation of any point on Earth."[63] ISR assets could be moved around as needed to meet the needs of the Combatant Commanders. Similarly, ISR assets could easily be stockpiled for contingency response. Other new missions would also become viable.

Building a space elevator suddenly makes many projects feasible which would have direct application to support the U.S. military. Power generation from orbit and on-call nighttime illumination are but two of these missions.[64] Solar power is a free and inexhaustible energy supply. Using a space elevator, massive solar power collection and transmission stations could be constructed in GEO that could relieve and someday replace fossil fuel-based energy production. For the military, such stations could be developed to beam power down to fielded forces relieving these units from the need to bring fuel or generators into an undeveloped area of operations.[65] Similarly, on-call illumination from either mirrors or spotlights in orbit could be built to support military operations or emergency response.[66] These satellites would prove very useful in illuminating targeted areas or exposing enemy positions while leaving friendly forces shielded by darkness. In an emergency response situation, the same orbital illumination could be used to provide light while terrestrial power was restored or response personnel were in action. With a space elevator, legacy missions would grow while new missions are enabled. With these missions in mind, it is time to turn to the actual construction and operation of a space elevator.

> "The major difference between a thing that might go wrong and a thing that cannot possible go wrong is that when a thing that cannot possible go wrong goes wrong it usually turns out to be impossible to get at or repair."
>
> Douglas Adams, *Mostly Harmless*

Space Elevator How To Manual – Operations and Issues

There have been several methods suggested for constructing a space elevator. Some of these methods have included single tethers, multiple tethers, rigid towers and a combination of tower and tether. The simple fact is the state of technology and materials have prohibited the serious consideration of any of these methods until very recently. Building a rigid tower along the lines of a super skyscraper or aerial mast is simply out of the realm of possibility using current construction methods. As mentioned earlier, it was only with the discovery of CNTs that a material which could support the severe stresses placed on a tether-type space elevator seemed on the horizon. Using CNTs, the construction techniques needed to create a space elevator become better defined. No tower is needed, just a ground station, the tether, and a counterweight. Placement of the ground station or liftport is an interesting problem in itself.

Dr. Edwards has completed exhaustive comparisons of possible ground sites around the globe. His study takes into account latitude (distance from the equator), freedom of movement, lightening, storms, shipping lanes and flight routes, military protection, safety and recovery zones, international airport locations, service and staffing, and environmental issues.[67] A tether hanging down from space would not necessarily have to terminate its grounded end exactly on the equator. Edwards argues that by moving the tether away from the equator, many locations open up and the elevator will be out of the way of many LEO satellites that regularly cross the equator, helping to lessen the chance of collision.[68] Since there will be some need to move the tether around to avoid orbital collisions, a floating liftport is envisioned. Large oceangoing structures are routinely used for a variety of purposes around the world and probably pose the least risk for any space elevator plans. Moving the tether around means you need a lot of open ocean to work with.[69] Examination of historical lightening and storm data on the earth's surface rules out many areas of interest for placement of the liftport. Taking into account shipping lanes and flight routes, relatively close location to military protection, good airport, and personnel for staffing needs along with enough open ocean to allow for safety and recovery zones should something fall from the elevator at lower attitudes leaves two basic areas for location of the ground station. These are in the Pacific Ocean west of South America and in the Indian Ocean west of Australia.[70]

In the near future, maneuvering the liftport to keep the tether out of the way of objects in orbit seems to be a viable means of operation. I propose that this is not the manner in which space elevators need to continue into the far future. For one thing, constantly moving the liftport requires outstanding situational awareness of everything in orbit that will ever cross the tether along with accurate computing programs to catalog, predict, and model both the movement of every piece of hardware and junk in orbit along with the location of the tether, predictions of where it will be in space depending on the loads place upon it by winds, cargo, movement of the liftport, solar wind, gravitational pull, vibrations, etc. This mode of operation may be acceptable for the first space elevator as it is essential to its success. There would seem to be better long-term solutions to this problem.

With a space elevator, many of the missions currently performed by spacecraft in orbits lower than GEO can be replicated by more robust systems further away from earth. The example of optical systems mentioned earlier is a case in point. As missions are taken over by structures further out from earth, the lower orbital planes can be cleared as satellites end their useful life span and are de-orbited. There will still be debris and satellites from nations who either choose not to use the space elevator or simply want to retain legacy capabilities. Debris may be cleaned up at some point, but until then, maneuvering the space elevator will be an essential operational task by a mobile ground station. Until the use of lower orbits declines and the debris can be mitigated, land-based, fixed sites will not be feasible as the liftport will need to move around in a collision avoidance dance.

The tether attached to the ground station is the next subject of discussion. The tether envisioned here is a flat ribbon just a meter-wide and paper-thin.[71] Lifter rollers would grip either side of the ribbon and be used to propel the lifters along the ribbon. This technique was recently illustrated at the Space Elevator Games at the 2006 X-Prize in Las Cruces, New Mexico where contestants raced their climber design up a 200-ft long industrial ribbon powered by light beams. A CNT ribbon would be braided in a cris-cross pattern that in theory would be strong enough to allow a 20-ton lifter to climb into space. The tether would stretch out though GEO to a distance of 62,000 miles. At this length, the tether would weigh about 800 tons and require a 600 ton counterweight at the end of the ribbon.[72] The weight of the ribbon is balanced at GEO with earth's gravity pulling the lower half of the ribbon toward the surface with centrifugal force pulling the tether and counterweight outward. As a reminder, the counterweight and length of ribbon beyond GEO are acting like the ball to keep the lower half of the ribbon from falling back to Earth. The question then becomes: How do you get a 62,000 mile tether from a liftport out into GEO?

The simple answer to how you get a 62,000 mile tether from the surface to orbit is: you don't. There is no way lift this 800 ton mass into space all at once. The solution is to start small and build up. Edwards estimates two heavy lift launch vehicles currently available could deliver the first cord of the CNT tether to orbit where it could then be unraveled.[73] Once the tether is within the atmosphere, a high altitude balloon could be used to either bring the tether to the ground station or attach the orbiting tether to a shorter length hanging from the balloon down to the liftport. Either way, once you have a CNT string running from earth to orbit, you have the beginnings of a space elevator.

With the initial thread to space set in place, small climbers powered by lasers would ascend into space, carrying another thin line of CNT which would be bonded to the first line. How this bonding would be accomplished is one of the technical hurdles to be overcome during the design and planning of the space elevator. In Edward's design, braided CNT cables would be bonded by epoxy and strapped together every few feet. This first climber would be followed by up to 280 more climbers until the tether was at design width. All of these climbers would be grouped together at the end of the 62,000 mile tether in order to form the counterweight. Since the counterweight grew with the addition of each line, it would be of sufficient weight to provide the centrifugal force needed to keep the tether balanced at GEO.[74] At this point, all of the components of the space elevator are in place: maneuverable ground station, tether, and counter weight. The first-ever space elevator is ready for business.

Day-to-day business on the space elevator should make access to space routine, even boring. Regularly scheduled lifters would depart the liftport, spaced out so as not to overly stress the tether. If the same tether is used to bring return trips down, these would have to be scheduled around ascents. An easier method would be to have two or more tethers in operation. With four tethers, two could be used for upward traffic, another for return trips, and the fourth could be undergoing maintenance or simply in standby mode. Multiple tethers would simplify operations while ensuring continuity of operations should there be some sort of catastrophic failure or merely unscheduled repair needs. Tracking and avoiding other objects in orbit would be another daily chore. Driving the floating liftport around so as to swing the tether out of the way of debris or active satellites would be a task best left to a computer control system able to accurately model the desired position of the cable. The passengers and cargo customers using the space elevator should barely be aware of the complex choreography going on behind the scenes as the operators manage the systems supporting mankind's new link to outer space.

While the operation of a space elevator will become as routine as running an air freight business, there are some issues which make this shipping company unique. These issues include: world politics, military usage, safety of the elevator, and the destination. Any one of these issues is problematic so a closer look at how they interact together for the operators of a space elevator is warranted.

Politics tops the list of headaches for the operators of a space elevator. There are three sub-issues here worth mentioning. First, the nation which constructs a space elevator will hold the keys to the usage of space due to the extremely low cost to orbit. Forming a semi-private consortium to operate the space elevator will help alleviate some concerns of one nation dominating space access since a corporation would simply sell space to anyone who wishes to use the elevator.[75] Secondly, friction would likely arise when nations who participated in the elevator construction received priority service, per the charter of the consortium. This would simply need to be understood by those using the elevator as a benefit for taking the risks in the first place. Also, some nations may find themselves left out in the cold should their usage of the elevator be blocked due to any number of reasons. This could be due to activities in the international arena. Dealing with such a nation is best left to national governments, not the elevator operators to handle.

Another potential issue is that a successful space elevator would likely put most other launch providers out of business overnight no matter what their nationality. This eventuality could be handled by governments maintaining at least a core capability to back up access to space should the space elevator experience damage or be unusable for any reason. Also, these industries could be focused on space infrastructure and logistics development instead of launch capabilities to keep eager aerospace firms employed. Actually, the construction of a space elevator would be wonderful for all of these industries due to expanded construction of space assets to be lifted by the space elevators and the orbital infrastructure needed to support them.[76] Tied into the politics of operating a space elevator is the use by military services of this valuable asset.

As this paper has pointed out, military services, namely the USAF, would find a space elevator quite useful in carrying out many missions in space. Reconnaissance, communication, geo-location, and weather are but a few of the services which would benefit from the use of a space elevator. Nations not involved in the construction of the space elevator could still have use of the elevator to place non-threatening assets into space. What actually is placed in orbit will likely be dictated by treaties, law, or simply constrained by good faith.

There are many threats facing those operating a space elevator. These threats include: attacks or sabotage, weather, and debris. Since the space elevator provides such a valuable link to orbit for commercial, scientific, as well as military purposes, it immediately becomes a prime target for those opposed to the policies or very nature of the nations operating the elevator. Threats can be mitigated by placement of the liftport in an isolated location, active air, sea, and perhaps space defenses, as well as procedures to ensure the safety of cargo and passengers similar to those employed by airlines today.[77] Weather has been discussed earlier. Again, threats from powerful storms, electrical storms and natural threats like micrometeorites must be mitigated or decreased through design and operation methodology. Man-made debris will also need to be taken into account by operators of the elevator. While active satellites in lower orbits can be easily predicted and avoided by moving the tether, extremely accurate tracking of the 110,000 pieces of debris over 1 cm will need to be carried out. Operators of the space elevator can tie into the tracking networks of debris already in place (NORAD) and perhaps deploy sensors of their own to increase the fidelity of tracking capabilities. Managing the risk of multiple threats as well as the military use and politics involved makes the operation of the space elevator an extremely challenging prospect.

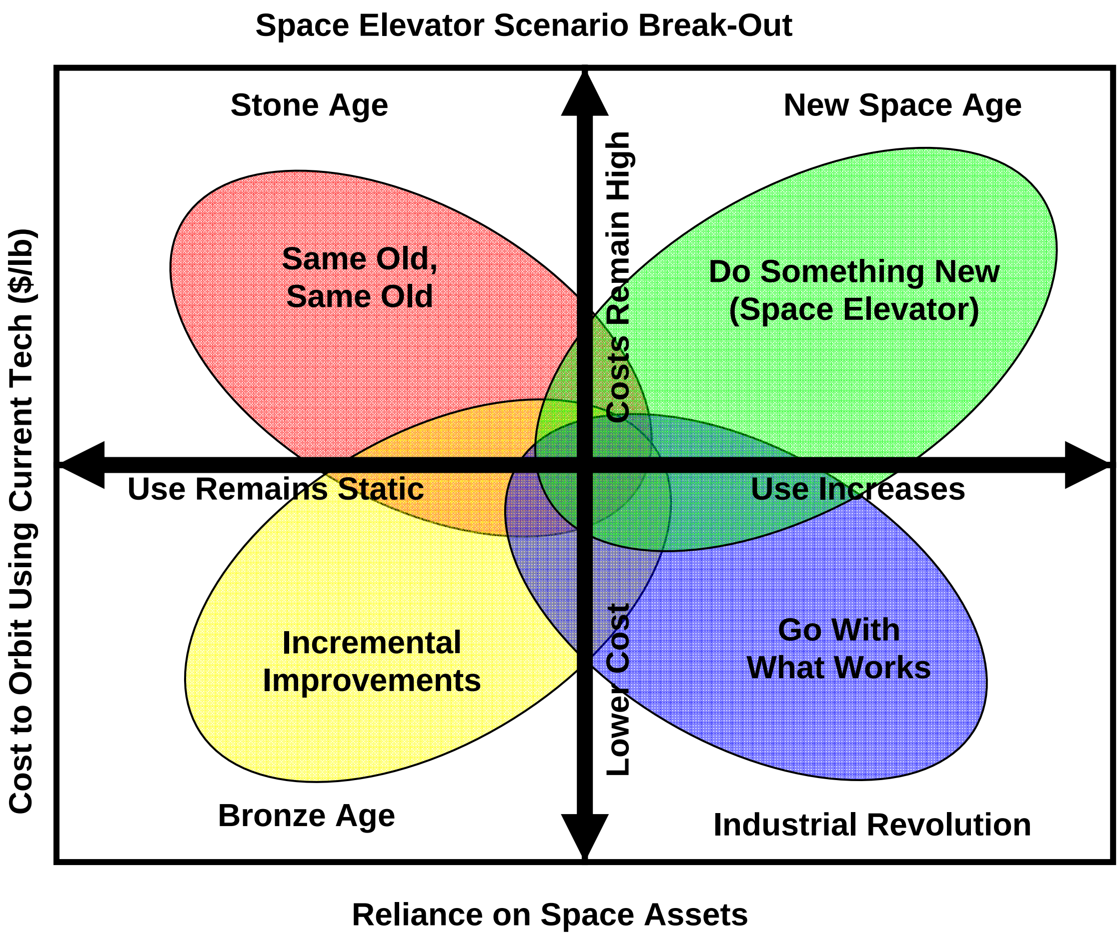
Getting to the 'top-floor' of the space elevator will make any obstacles faced by space elevator operators will worth the energy involved. Of course, cargo and personnel transports must be able to handle the rigors of outer space and be deployable once they arrive at their final destination. Planning will need to be undertaken to receive, store, deploy, and house those people and materials delivered up the tether. The new logistics of space operations made possible by the space elevator will be a massive undertaking in itself. Mastery of space will meet a "turning point" for the better only through "the act of planning and building the initial infrastructure" for space logistics. The rewards from building up the logistics side in space "creates the knowledge, experience, and industrial base necessary to establish economically useful, acceptably safe, and acceptably affordable logistics capabilities within the new frontier."[78]

Space elevator operations, although challenging, will give the USAF the access to space it needs. Preparing for the entire scope of issues facing the future operators will be rewarding thanks to the destination and usefulness of the tools placed in orbit by the space elevator.

> "Two roads diverged in woods, and I – I took the one less traveled by, and that has made all the difference."
>
> Robert Frost, *The Road Not Taken*

Scenario Development

A look at scenario forecasting will help illustrate under what conditions a nation might consider building a space elevator. This paper will briefly examine two spectrums of interest: cost to orbit using current technology and reliance on space assets.



Combining the cost to orbit spectrum with the reliance on space assets spectrum creates four possible scenarios for decision makers. Each scenario can be examined in light of the need for investment in revolutionary technology development such as the space elevator to expand delivery capability to orbit.

The first scenario is called the Stone Age. Here, the number of space assets remains fairly static, say at current levels with a negligible increase each year while cost to orbit remains the same, that is, fairly high.[79] A decision maker in this scenario sees the technology he has on hand is good enough to meet his current needs in space. One might assume satellite numbers in space will remain static since each new payload can carry more and more thus negating the need for more assets. This increase in on-board capabilities due to miniaturization, better materials, and computing power may even keep up with demand (for the short-term at least). Why plow funds into new technology when it won't pay off for a few years anyway? The decision to stay with what works and continue to pay the high cost to orbit for each payload marks the Stone Age decision maker. This leaves the decision maker with more funds to apply to more pressing near-term issues and releases him from the responsibility of developing new technologies.

Another scenario where the reliance on space assets remains fairly static is called the Bronze Age. Here, cost to orbit has been reduced by incremental improvements to launch vehicles. The payload argument arises once more. Improvements to satellites can soak up most of the modest increase in demand and lower launch costs negate the need for new ways to access space. Again, the decision maker would likely decide to stay with what works and not look into revolutionary technologies. Taking a look at the other end of the usage spectrum presents the decision maker with more of a challenge though.

The third scenario is called the Industrial Revolution. Here, cost to orbit has decreased due to increased volume of launches and/or some incremental improvement in manufacturing and launch systems. At the same time, reliance on satellites has greatly increased beyond the ability of existing systems, even though they may have been improved to increase throughput or capabilities. More assets are needed in orbit, explaining the higher volume in launches which would help bring down the cost per launch. Lower costs thanks to small improvements and efficiencies found in a higher launch rate have been realized by industry and government users alike. In the Industrial Revolution, a decision maker may again wish to stay with what works and stick with conventional access methods to space. After all, why rock the boat when everything is humming along so nicely? (One can only hope there is not an accident on the launch pad or in orbit which would grind the launch rate to a halt as has occurred in the past following both manned and unmanned missions failures.) But what happens if the launch costs don't come down?

In the fourth and final scenario, a nation enters the New Space Age. Here, use of satellites increases while costs to orbit remain high. Decision makers must decide whether to continue to pay extremely high launch costs for each and every payload or look for alternative methods to accessing space. Upon looking at the technologies available, a decision maker might decide a space elevator is the way to go. A nation's leaders could easily fund the relatively low cost of this technology which would fundamental change business in space.

Rockets have not changed much in the past fifty years. The fact is the rockets today are very similar to those flown since the beginning of the space age. An example of the lack of change to current launch vehicles one needs look no further than recent studies which show liquid rocket propellant tanks and engine weights have "not changed substantially over time".[80] In other words, you can only go so far with chemical propulsion. Project after project has been unable to fulfill the basic goal of lowering the cost to orbit or making space flight more airline-like. So costs remain high. Similarly, while rockets have been the sole way into space, satellites continue to grow in number and complexity. There is no magic bullet on the horizon to suddenly bring the cost to orbit down and there is no sign the current trend of growing reliance on space assets will level off or decrease. We have entered the New Space Age. The path laid out here to meet the challenges of the New Age is to do something new…investment in a space elevator. The USAF can take the lead in this endeavor

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"640k ought to be enough for anybody."

- Bill Gates, 1981

Parting Words

The future which can be made possible with a space elevator is stunning in its breadth, complexity, and sheer potential. With a concerted effort, the US could skip generations of launch vehicles while continuing to expand missions in space limited only by the imagination. With the rate of technological advancement towards creating materials which could be used for a tether and the availability of technology to support all other aspect of space elevator operations, the USAF really has three choices: continue with current incremental improvements in launch capabilities, allow someone else to build the space elevator, or take the lead in advocating and constructing a space elevator.

Continuing on with current operations and slowly implementing improvements in launch capabilities would be the safest bet for the USAF. After all, it is what has done for the last fifty years. But, growing needs for satellites and high costs dictate something else needs to be done. Doing things the old fashioned would leave the path to space elevator open to other nations, possible a competitor in more ways than one. As has been mentioned, the first to build an elevator will possess such an advantage over every other space-faring nation that those coming in second may never be able to fully recover. Maintaining space superiority demands the US not come in second when it comes to employing this new technology. Taking the lead and mandating a need for a new approach to space access is something the USAF must do. For a relatively small investment over a decade or more, the USAF can partner up with other agencies and nations to ensure the U.S. remains the leader in space access and space superiority.

The need for cheap and easy access to space is very real. For decades, the idea of the space elevator has been overshadowed by the technological gap between the dream and reality.

Today, the technology is real and easily within a dedicated nation's grasp. Building a space elevator is a project the USAF should embrace and see through to the end.

In closing, I present a quote from Arthur C. Clarke, one which I believe to be true, "Whatever technical developments the future brings, I don't believe there will ever be a more efficient, more economical way of reaching space."[81]

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