Space Exploration with ISS, Reel-Tether, and Oxygen Tanks

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This paper describes a new space exploration architecture that uses the International Space Station initially. Tethers on reels are added to the Station to provide some transportation velocity increments, both getting to the Station and leaving for exploration destinations. A depot of tanks of oxygen is also included near the Station. Later, a system of bases with tethers is placed in equatorial orbit to provide even more efficient transportation. When completed, the tether transportation system can be used to place solar power satellites in orbit.

I. Introduction

The United States government has indicated the willingness to spend considerable amounts of money to develop a capability to do human space exploration beyond low Earth orbit (LEO). A large expendable launch vehicle, called Space Launch System (SLS), has been one of the key considerations. Most architectures use more than one launch of SLS, rendezvous in LEO, and departure to a destination such as an asteroid or the moon. There is a good possibility that other nations would support such an adventure, much as the International Space Station (ISS) has been and continues to be supported by several nations.

While a human mission to an asteroid would be interesting, most architectures do not clearly lead to a sustained development of space assets. This paper will show an approach that leads to several useful future capabilities.

One important future capability is the solar power satellite (SPS), a concept to place solar collectors in space and beam power to Earth. SPS has also been called space-based solar power and several similar names. Although several concepts have been studied, the most popular would place the collectors in large arrays in geosynchronous Earth orbit (GEO) and beam the power to a collector on Earth that is connected to the electric grid. The concept has been studied since early work by Peter Glaser in the 1970's. Several multimillion-dollar studies have shown that the concept might be feasible. There are, however, some serious problems that have kept the concept from development. First, the cost of launch to GEO is currently so expensive that the resulting power costs would be far beyond current market prices. Second, development of the technology and prototype system would require significant expense before the economics of the system would be well understood. Finally, several competing concepts must be considered sufficiently, possibly including experiments in space, to evaluate their relative merits. Figure 1 shows two artist's concepts for SPS.

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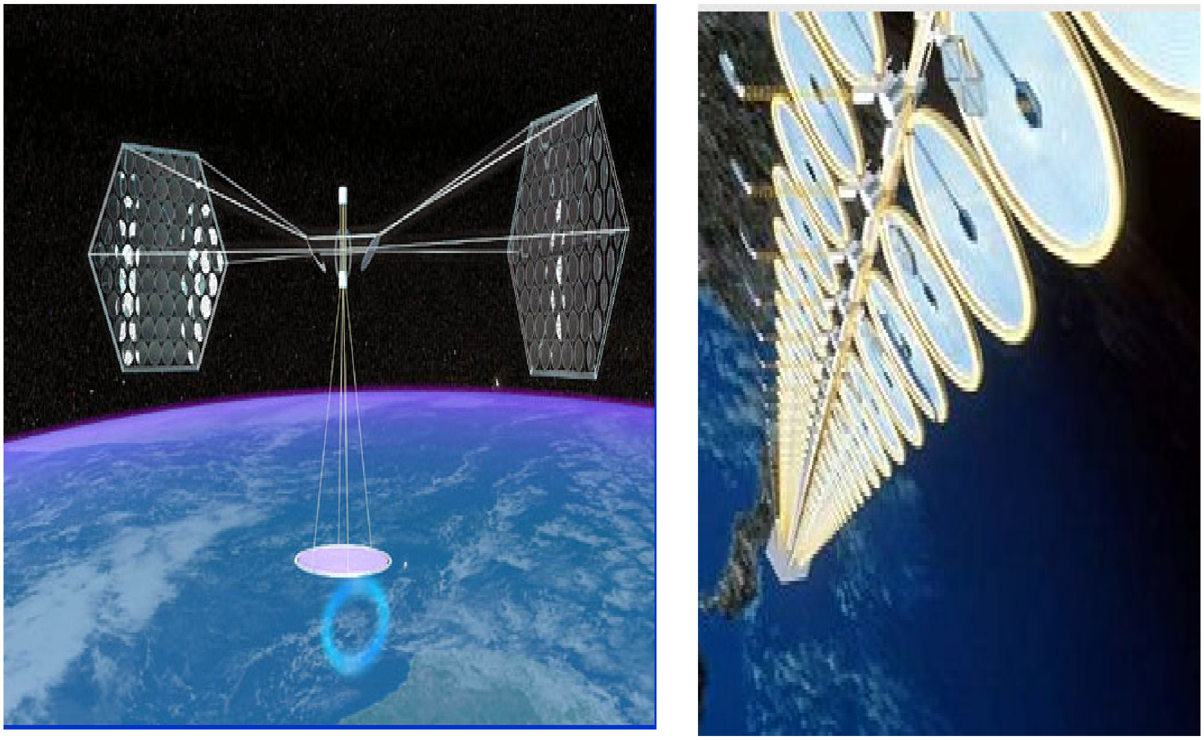


Figure 1. Solar power satellite designs.

The space elevator is also a concept that has been studied for decades. It has also been called gravity ladder and beanstalk. The most common concept would have a part of the system in GEO, with arms extending into space and toward Earth. The arm away from Earth usually ends in a counterweight. The arm extending toward Earth usually ends at a point on the equator. Figure 2 shows some design concepts. As with the SPS, there are some problems with the space elevator concept. The most serious is that there is no existing material that has a sufficient strength-to-density ratio. Where the space elevator passes through the atmosphere, there could be serious interactions. Debris and satellites, especially in low Earth orbit (LEO), could sever the space elevator.

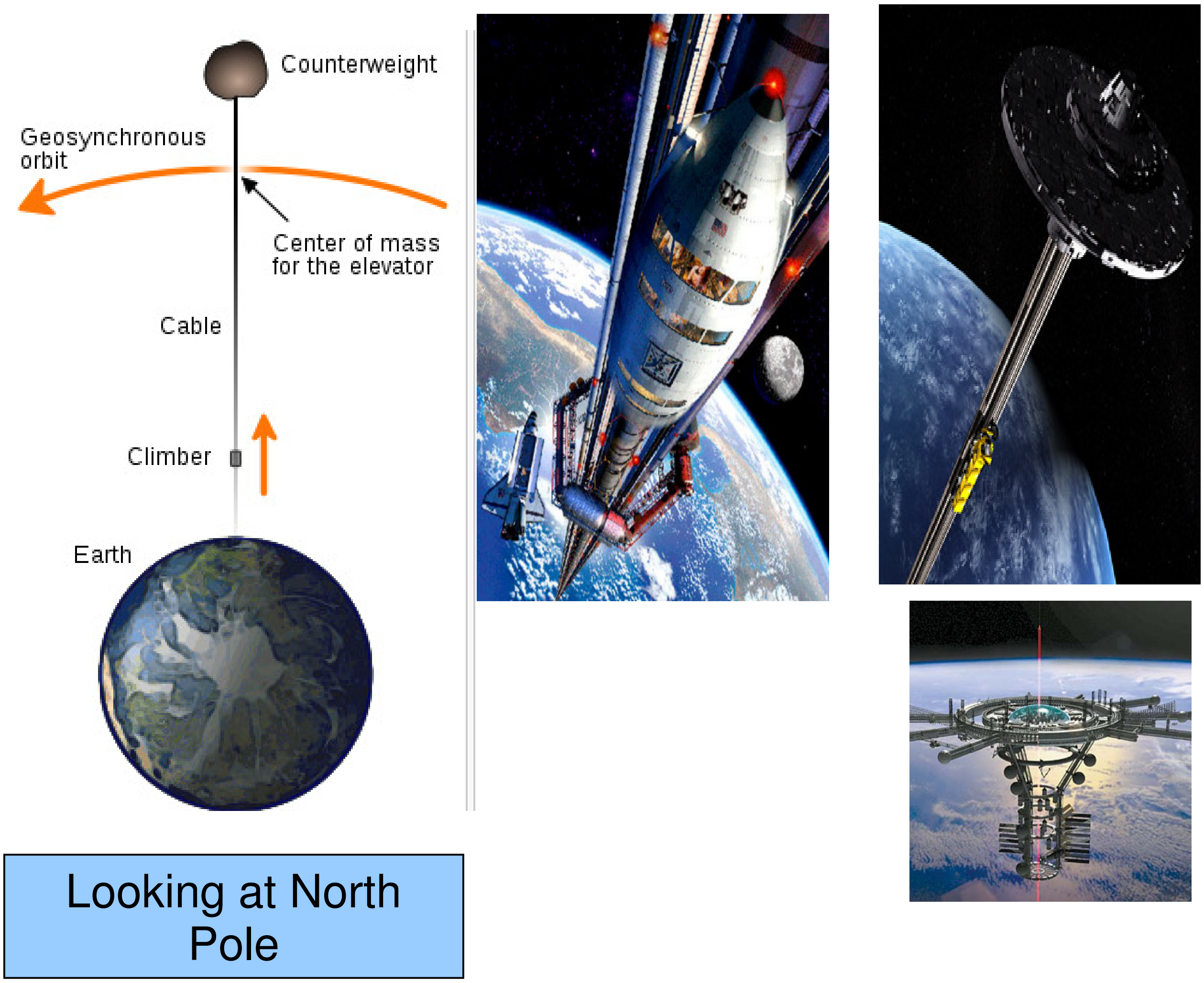


Figure 2. Space elevator designs.

Reusable launch vehicles (RLVs) have long been studied; many believe they are the future path to lower-cost access to space. They could also provide increased safety, reliability, and rapid response as needs arise. Some concepts are shown in Figure 3. As with the SPS and space elevator, the RLV has some difficulties that have led to delays in its development. The primary problem is that the economics are reasonable only for high traffic rates. At the same time, those markets that would provide high traffic rates, such as SPS and tourism, will only develop after launch costs are reduced--the classic chicken-and-egg problem. One way to alleviate this problem is to develop partly reusable vehicles. The Space Shuttle is the one vehicle that has been developed that has partial re-usability. While its degree of success has been argued, it has provided launch of people and cargo that is unmatched by expendable systems. An important aspect of launch vehicles is reducing the velocity requirement to LEO. This paper will address this aspect of launch vehicles but will not consider launch vehicle designs.

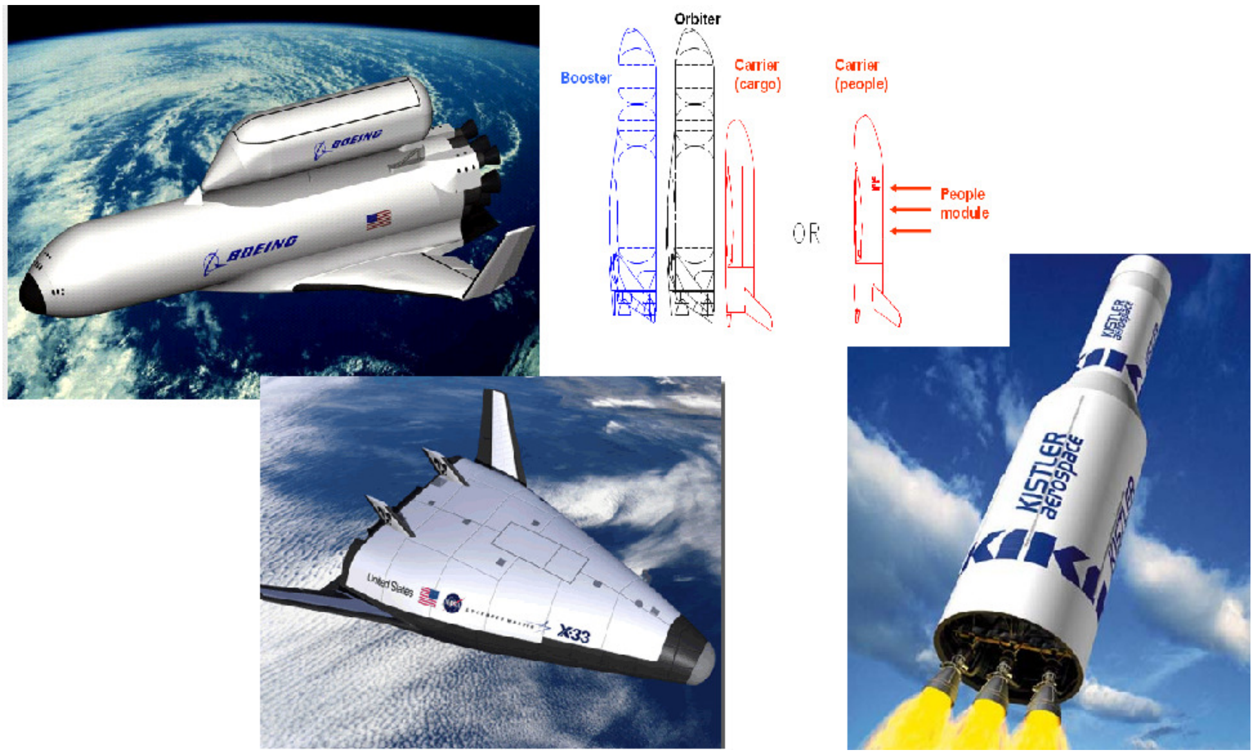


Figure 3. Reusable Launch Vehicle Designs.

One concept that avoids some of the most serious problems of the space elevator is the partial space elevator. Consider first the typical space elevator design, in which the bottom of the space elevator reaches the surface of Earth.

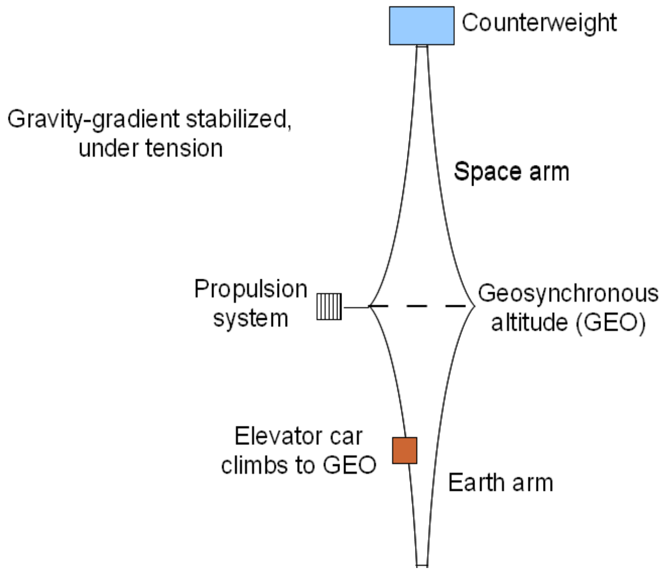


Figure 4. Typical Space Elevator.

The typical space elevator design, as shown in Figure 4, has a central section in orbit at GEO. The Earth arm is at lower altitude and would need to be moving faster to be in orbit; therefore, it wants to fall and needs to be held in place by the upper parts. The space arm is at higher altitude and would need to be moving slower to be in orbit; therefore, it wants to fly off into space and needs to be held by the lower parts. As a result, the space elevator is in tension and is gravity-gradient stabilized. The space arm could be quite long, but an additional mass is used to provide the lift to allow it to end at a reasonable distance. As the elevator car climbs up the space elevator, it gains potential energy and would tend to pull the space elevator downward. It also gains rotational kinetic energy, as its speed around the Earth must increase to keep the rotation at one revolution per day at higher altitudes. The energy must be supplied to the space elevator by a propulsion system. A solar electric or solar sail system could be used. Some energy is returned to the elevator when the car goes down for the next payload or carries a payload down, and a balancing of several cars could be used to minimize the propulsion needs. The propulsion system could be at the counterweight or several locations; the sketches show it at GEO, but a trade study would be needed.

The bottom of the space elevator must have enough area for strength to hold the elevator car and payload. Each section above the bottom must have enough area to hold the elevator car, the payload, and the section below it. When the equations are integrated, the shape is an exponential, as shown in Ref. 1. Similarly, beyond GEO, the shape is a decreasing exponential.

A space elevator between Earth and GEO requires a material with a very high strength-to-density ratio. No current material has a high enough ratio. There is some hope that carbon nanotubes will have an acceptable ratio and make the space elevator feasible from Earth to GEO.

The space elevator does not need to extend all the way from GEO to Earth. In References 1 and 2, a space elevator that extends only part of the way to the surface of Earth was considered. The primary advantage of the partial space elevator is that it allows designs appropriate for existing materials.

Another concept, proposed in Ref. 3, is a depot in LEO with tanks of liquid oxygen (LOX). Figures 5 and 6 illustrate the concept. Commercial launch could be used to lift the LOX tanks to the depot, where they would be held until needed. When an exploration or other mission needed them, the vehicle would be launched to the depot, the tanks would be added, and it would continue the mission. The lift to the depot from the exploration vehicle would be reduced about half using this concept.

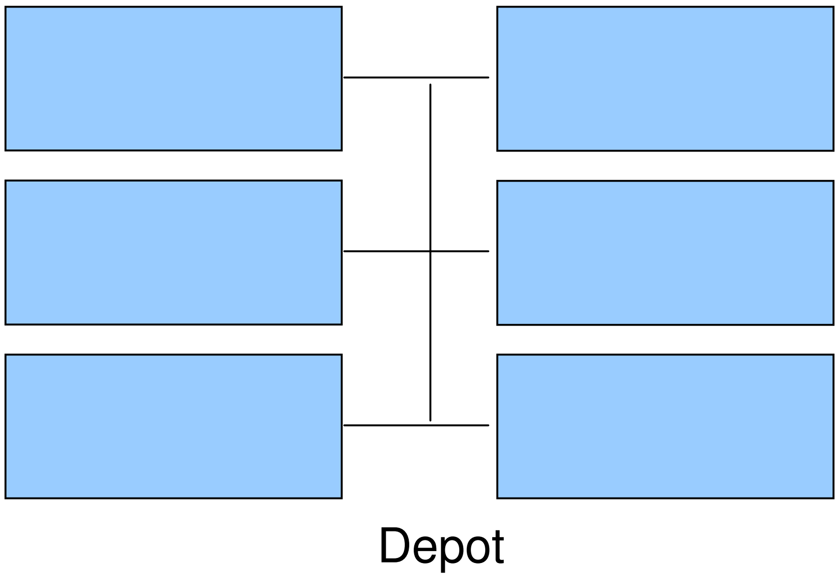


Figure 5. LOX tanks organized into a depot.

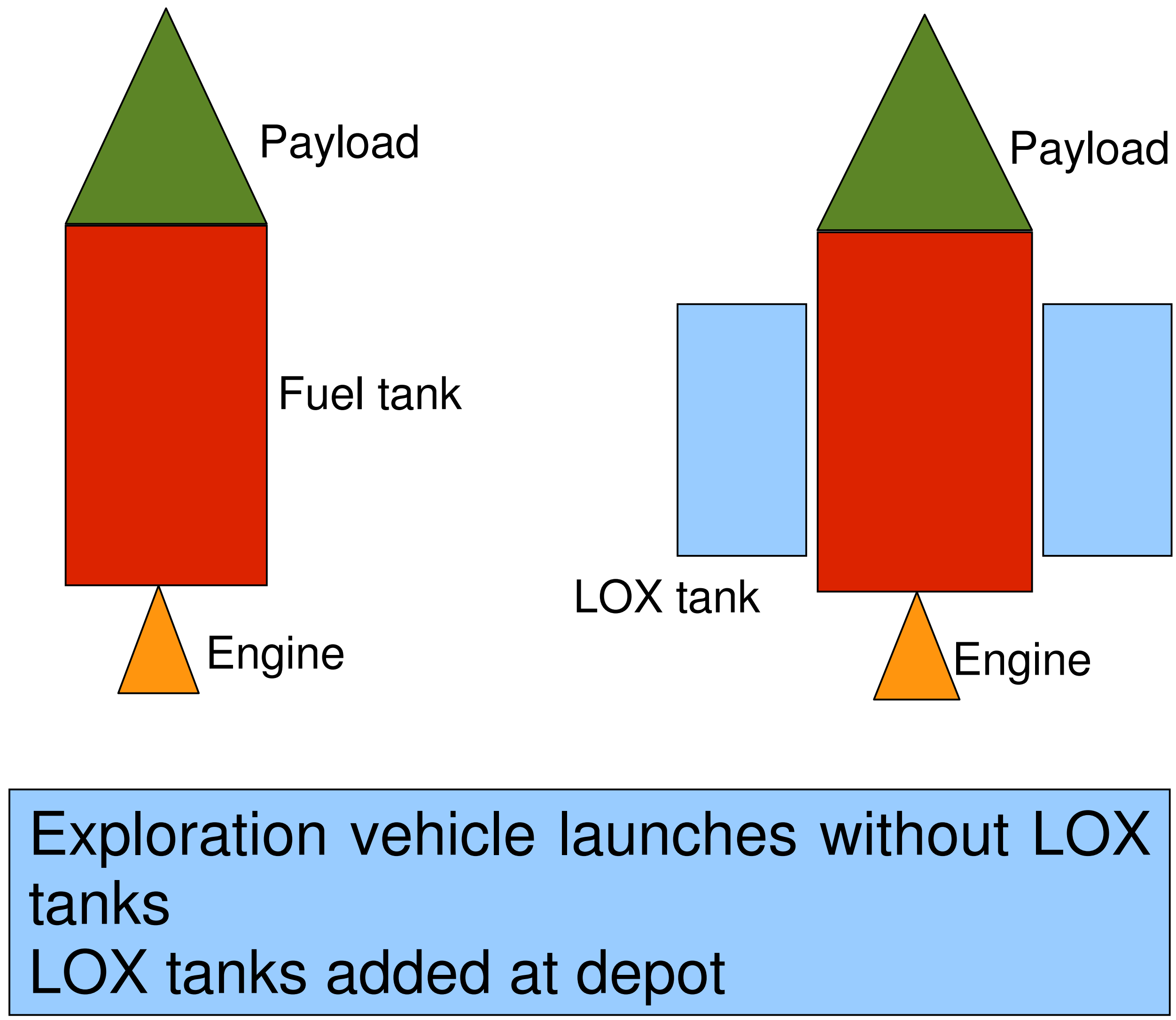


Figure 6. Illustration of LOX tanks added to exploration vehicle at LOX depot.

A final piece of the puzzle comes from a recent paper by Andrews and Woodcock (Ref. 4). Instead of a static tether hanging from the center of gravity, as in the classic space elevator, they proposed a tether that is kept on a drum and reeled out for use. This concept, which will be called the reel-tether here, has some advantages over the static tether for some uses. First, the potential for damage from collisions with debris and other satellites is greatly reduced because the time the tether is extended is minimized. The heating at the bottom, which would be deeper in the atmosphere, would be reduced except for short intervals. The problem of developing a climber or elevator car and a system to provide power to the climber is eliminated. With this concept, the tether cross-section might be wide and not so thick, like tape, to improve reeling and debris resistance. It might look like 8 mm movie film on a reel. With this design, the reel guides the tether to smoothly reel into a single width of tether.

II. Proposed Phased Approach: ISS

The proposed exploration architecture starts with the addition of a reel-tether to the International Space Station (ISS). This ISS tether will improve transportation efficiency to ISS. Figure 7 illustrates the parts. A reel is attached to ISS below the center of gravity. The tether is rolled up or down as the reel rotates. An electric motor, powered by ISS, provides the energy to raise the tether. When the tether is dropped, the motor acts as a generator and returns energy to ISS.

The tether descends from the reel toward Earth. The length of the ISS tether will not be provided in this paper; a detailed trade study will be needed to determine a reasonable length. The length could be 100 to over 400 km. One possibility is to increase the average altitude of ISS, reducing drag and allowing a longer tether.

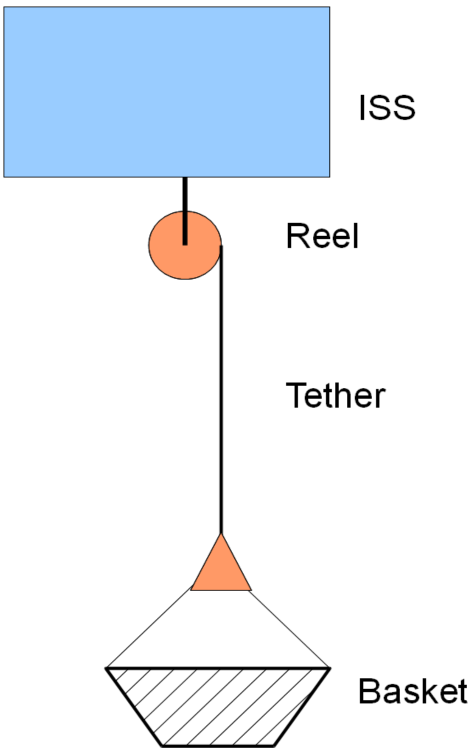


Figure 7. Illustration of ISS tether.

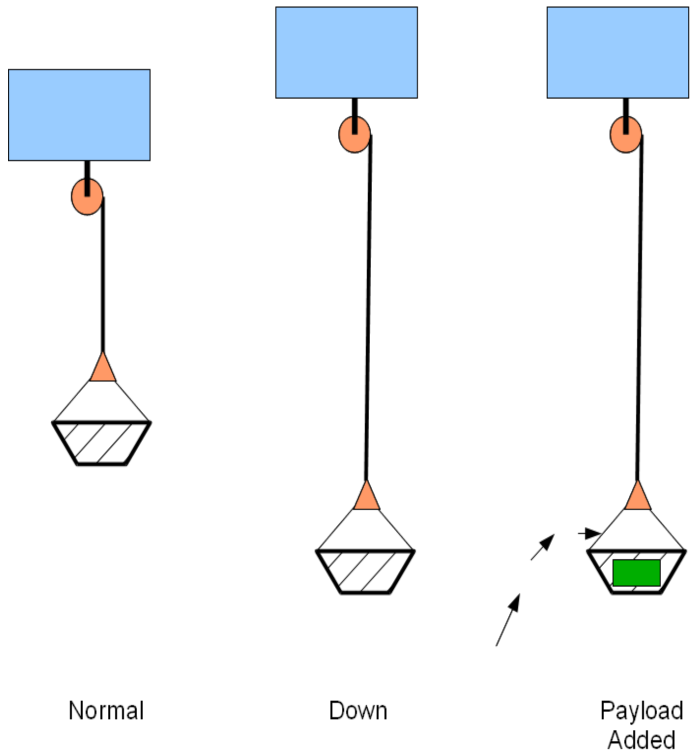


Figure 8. Operation of ISS tether.

At the bottom of the tether is a connection mechanism. A net basket is one possibility, as shown, but other options should be considered in a detailed study. The basket is shown connected to the tether with a harness to several points, possibly four corners.

Figure 8 shows operations with the ISS tether. The normal position would be with the tether rolled up so that the basket is near ISS. This position minimizes any problems with collisions with debris or other satellites. When a payload is coming to ISS, unrolling the tether from the reel would lower the tether and basket, just as a cable is removed from a drum. Note that the ISS would move upward when the tether moves down to preserve the altitude of the center of gravity of the system. Also note that the length of the tether would be relatively much longer than is shown. The payload would then enter the basket, as indicated by the arrows, landing on the netting at the bottom. Once in the basket, the payload is held in place by gravity. The tether is then rolled back up to near ISS, where the manipulator arm or the payload propulsion could complete the mission. Because the payload needs to only reach the bottom of the tether, and because the bottom of the tether is moving slower than orbital speed, the velocity needed to reach the bottom of the tether can be significantly less than normally needed to reach ISS. This velocity reduction can allow more massive payloads to be delivered to ISS or the same payloads on smaller or safer launch vehicles.

When a container of trash is to be discarded from ISS, such as the Progress supply capsule, it can be placed in the basket and lowered. The basket could have a dump mechanism to release the capsule such that it enters and burns. When a payload is to be returned to Earth, such as the Soyuz capsule, it can also be released from the basket at the bottom of the tether for entry and landing. Using the tether for entry of capsules returns energy to ISS and reduces the need for propulsion on the capsules.

One issue that needs to be considered for the ISS tether is electrical energy for the reel motor. When the tether lifts a payload to ISS, some energy must be provided. Some of the energy is returned when payloads are lowed for entry. There is likely to be a net loss, however, and that energy must be provided. The solar cells on ISS could provide the energy, but they might need to be enhanced for frequent use of the tether.

Another issue that must be considered is angular momentum. When payloads are lifted to ISS, they must increase their angular momentum. The basket and payload will tend to trail ISS while it is being lifted. As payloads are lowered with the tether, some angular momentum is recovered. The basket and payload will tend to lead ISS. There will likely be a net loss in angular momentum for the ISS and tether system. The ISS altitude could also be reduced by using the tether. That net loss must be made up with propulsion. Using the existing ISS propulsion would require increased propellant supply. One possibility is to add an electric thruster to ISS. Another is to use the tether for propulsion.

Funding for the ISS tether could come from the NASA budgets for ISS or Space Exploration. Other ISS partners could provide all or part of it. Another possibility is that another country, such as China, which is not currently an ISS partner, could provide the ISS tether as the price of admission to the ISS program.

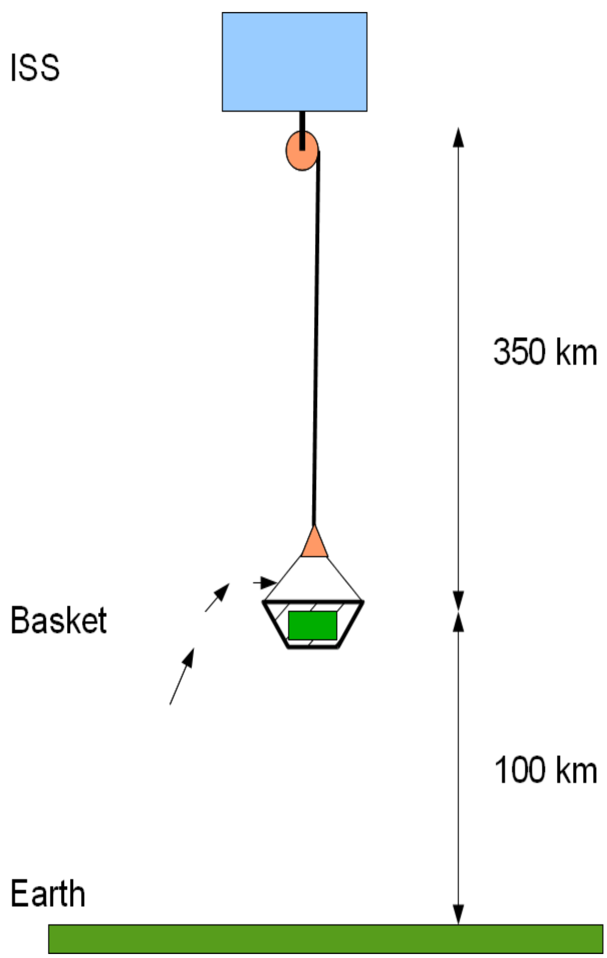


Figure 9. Illustration of ISS tether calculation altitudes.

A calculation was conducted for the ISS at an altitude of 450 km, which is near the top of the normal operating range, as shown in Fig. 9. A tether was assumed to extend to an altitude of 100 km, below which heating may be a problem. The reduction in velocity requirement for transportation from Earth to ISS was reduced by 800 m/s.

A calculation has also been completed for the ISS tether mass. Based on the mass of the Soyuz capsule, a payload mass of 20,000 kg was used. A Dyneema SK-75 fiber with a strength of 2.4 Gpa and a specific gravity of 0.97 was used. Dyneema is an ultra-high molecular weight polyethylene in production since 1990, and it is UV resistant. The calculations show that the tether can be 0.5 mm thick and 46 mm wide. The total mass of the 350 km tether would be about 7850 kg. The reel radius would be about 7.5 m.

The performance benefits of the ISS tether may not be enough to completely justify the investment costs. The rest of the value comes because the ISS tether provides experience with reel-tether transportation, which leads to the next step.

The next step will be addition of an exploration tether that extends from ISS to higher altitudes. It will also be a reel-tether. It will improve transportation from ISS to exploration destinations. The length of the exploration tether will also not be decided in this paper. The exploration tether would likely be much longer than the ISS tether, on the order of thousands of km.

Figure 10 shows the ISS with the exploration tether added. While the drawing shows the reel as the same size as the ISS tether, it could be considerably larger because of the longer tether length. A basket is not shown; most of the transportation uses of the exploration tether would involve connecting the item to the upper end of the tether at ISS, and a basket may not be the preferred mechanism.

There are both benefits and losses associated with using ISS for exploration. The primary loss is that the ISS inclination is too high for most exploration missions, which increases the launch velocity and the velocity from LEO. The ISS tether and the exploration tether should more than compensate for those losses. One advantage of using ISS for exploration is that the exploration astronauts could go to ISS using the same systems as the ISS astronauts. Those systems should provide maximum safety, and the increased flight rate would provide cost reductions and other improvements. Another advantage of using ISS for exploration is that the ISS habitation capabilities would be available for delays in the missions and would allow flexibility in the flight planning. Also, the ISS manipulator arm would be available to help with joining parts of the exploration vehicle

The final step at ISS will be addition of a LOX-tank depot. The ISS tether will help bring LOX tanks to the depot, the exploration vehicle will add the tanks of LOX at the depot, and the exploration tether will help the final vehicle leave Earth for its destination. The depot could be attached to ISS, but a more likely option is to have it follow ISS and rendezvous when needed to add or remove tanks. Another option is to store the depot at the top of the exploration tether at a safe distance above ISS, then reel it to ISS to add or remove tanks. Delivery of LOX tanks to the depot could use the ISS tether. As discussed in Ref. 3, commercial delivery of LOX tanks would provide a business case for development of commercial launch, possibly including partly reusable launch vehicles.

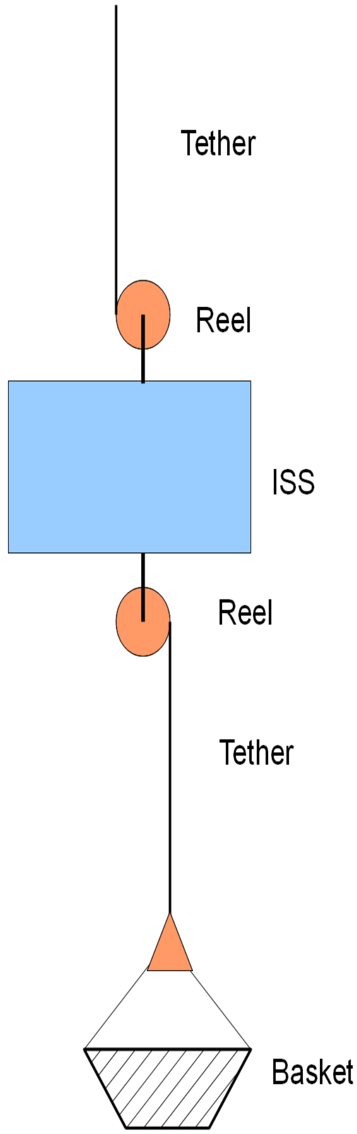
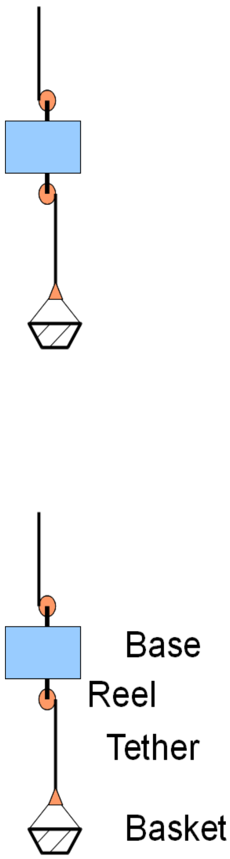


Figure 10. Illustration of exploration tether.

III. Proposed Phased Approach: Equatorial



The next step will be development of a system of reel-tethers in orbit at zero degrees inclination, illustrated in Figs. 11 and 12. This system of reel-tethers will provide most of the propulsion required to reach geosynchronous equatorial orbit (GEO) or to start a mission beyond GEO. Each bottom tether will catch the payload in the basket, then reel it up to the base. It will then be attached to the upper tether and reeled up for release. Figure 12 shows a payload released from the top of the upper tether at Base 1 moving up to the basket at Base 2. With the upper tether at Base 1 reeled out, the payload is moving faster than orbital speed when it is released and therefore moves upward to the reeled-out lower tether at Base 2. The payloads must be able to control themselves during free-flight segments between tethers, and some propulsion might be needed to reach the next tether. The highest base will be at GEO, allowing payloads to exit the system at GEO if that is the final destination.

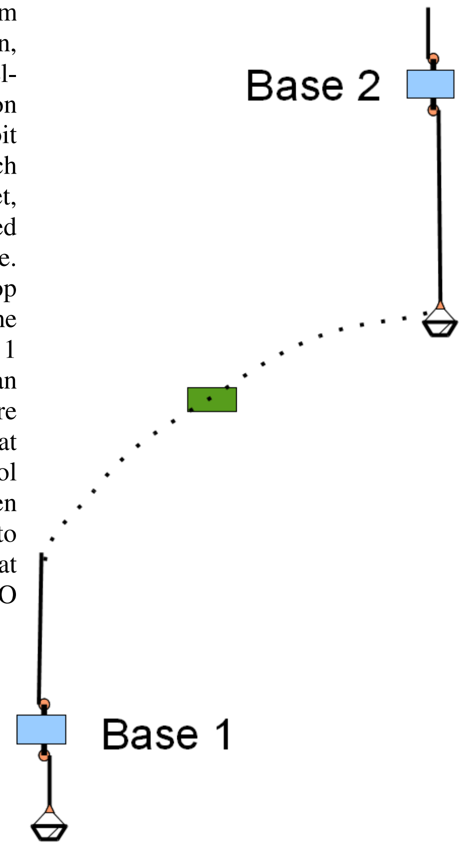


Figure 11. Illustration of equatorial tether system.

Figure 12. Operation of equatorial tether system.

This paper will not attempt to calculate the best number of tether systems, the length of the tethers, or the propulsion needed between tethers. These parameters will depend on the materials available, the mass of the payloads to be lifted, etc. Each base will need solar cells to provide energy to operate the reel motors and propulsion to make up for energy and momentum losses during lifts. Electric thrusters are the likely choice for propulsion. This paper will also not determine if the bases should be manned. Some capability for people to stay at a base may be useful during construction and maintenance, but the bases could be located in a radiation belt that is not a good place for people to stay. As with the exploration tether, a basket may be added to the upper tether at each base but may not be needed for payloads being lifted.

When the equatorial tether system is in place, the reduced transportation costs will allow many new uses of space. The SPS may be one of the most important. Colonies and in-situ resource utilization (ISRU) will also be enhanced.

IV. Concluding Remarks

The proposed phased construction of reel tethers and LOX tank depots will improve the options for development of space. At the conclusion of the developments, space will be accessible, abundant clean power will be available, and a transportation system will be waiting for humanity to explore far beyond Earth.

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