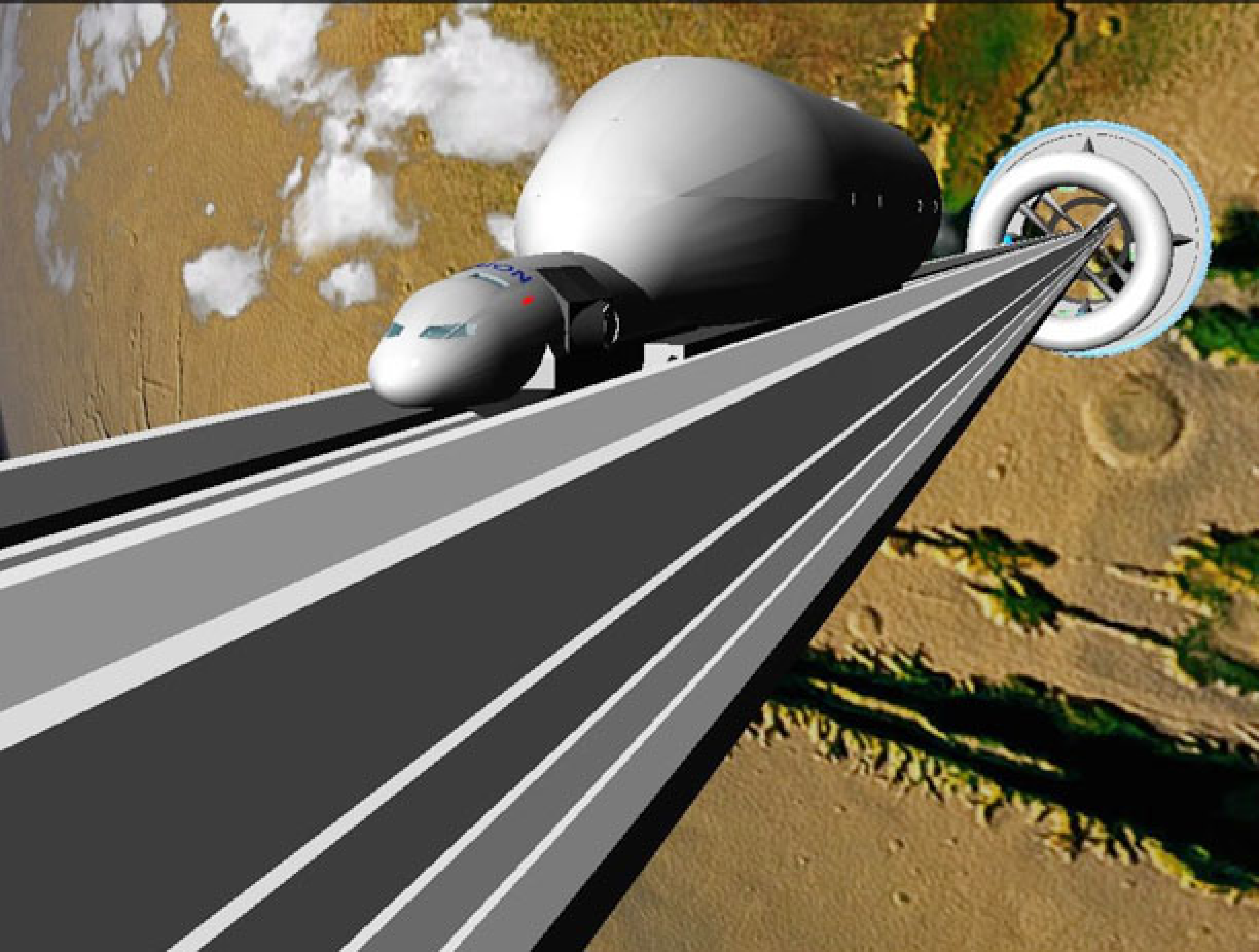
Exploratory Engineering

Ethen Ivy



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Introduction

Exploratory engineering is a term coined by K. Eric Drexler to describe the process of designing and analyzing detailed hypothetical models of systems that are not feasible with current technologies or methods, but do seem to be clearly within the bounds of what science considers to be possible within the narrowly defined scope of operation of the hypothetical system model. It usually results in paper or video prototypes, or (more likely nowadays) computer models that are as convincing as possible to those that know the relevant science, given the lack of experimental confirmation. By analogy with protoscience, it might be considered a form of **protoengineering**.

Usage

Due to the difficulty and necessity of anticipating results in such areas as genetic modification, climate change, molecular engineering, and megascale engineering, parallel fields such as bioethics, climate engineering and hypothetical molecular nanotechnology sometimes emerge to develop and examine hypotheses, define limits, and express potential solutions to the anticipated technological problems. Proponents of exploratory engineering contend that it is an appropriate initial approach to such problems.

Engineering is concerned with the design of a solution to a practical problem. A scientist may ask "why?" and proceed to research the answer to the question. By contrast, engineers want to know how to solve a problem, and how to implement that solution. Exploratory engineering often posits that a highly detailed solution exists, and explores the putative characteristics of such a solution, while holding in abeyance the question of how to implement that solution. If a point can be reached where the attempted implementation of the solution is addressed using the principles of engineering science, the activity transitions from protoengineering to actual engineering, and results in success or failure to implement the design.

Requirements

Unlike the scientific method which relies on peer reviewed experiments which attempt to prove or disprove a falsifiable hypothesis, exploratory engineering relies on peer review, simulation and other methods employed by scientists, but applies them to some hypothetical artifact, a specific and detailed hypothesized design or process, rather than to an abstract model or theory. Because of the inherent lack of experimental falsifiability in exploratory engineering, its practitioners must take particular care to avoid falling into practices analogous to cargo cult science, pseudoscience, and pathological science.

Criticism

Exploratory engineering has its critics, who dismiss the activity as mere armchair speculation, albeit with computer assist. A boundary which would take exploratory engineering out of the realm of mere speculation and define it as a realistic design activity is often indiscernible to such critics, and at the same time is often inexpressible by the proponents of exploratory engineering. While both critics and proponents often agree that much of the highly detailed simulation effort in the field may never result in a physical device, the dichotomy between the two groups is exemplified by the situation in which proponents of molecular nanotechnology contend that many complicated molecular machinery designs will be realizable after an unspecified "assembler breakthrough" envisioned by K. Eric Drexler, while critics contend that this attitude embodies wishful thinking equivalent to that in the famous Sidney Harris cartoon (ISBN 0-913232-39-4) "And then a miracle occurs" published in the American Scientist magazine. In summary the critics contend that a hypothetical model which is both self-consistent and consistent with the laws of science concerning its operation, in the absence of a path to build the device modeled, provides no evidence that the desired device can be built. Proponents contend that there are so many potential ways to build the desired device that surely at least one of those ways will not display a critical flaw preventing the device from being built.

Chapter- 1

Dyson Sphere

A **Dyson sphere** is a hypothetical megastructure originally described by Freeman Dyson. Such a "sphere" would be a system of orbiting solar power satellites meant to completely encompass a star and capture most or all of its energy output. Dyson speculated that such structures would be the logical consequence of the long-term survival and escalating energy needs of a technological civilization, and proposed that searching for evidence of the existence of such structures might lead to the detection of advanced intelligent extraterrestrial life.

Since then, other variant designs involving building an artificial structure or series of structures to encompass a star have been proposed in exploratory engineering or described in science fiction under the name "Dyson sphere". These later proposals have not been limited to solar power stations. Many involve habitation or industrial elements. Most fictional depictions describe a solid shell of matter enclosing a star, which is considered the least plausible variant of the idea.

Origin of concept

The concept of the Dyson sphere was the result of a thought experiment by physicist and mathematician Freeman Dyson, where he noted that every human technological civilization has constantly increased its demand for energy. He reasoned that if human civilization were to survive long enough, there would come a time when it demanded the *total* energy output of the sun. He proposed a system of orbiting structures (which he referred to initially as a *shell*) designed to intercept and collect all energy produced by the sun. Dyson's proposal did not detail how such a system would be constructed, but focused only on issues of energy collection. Dyson is credited with being the first to formalize the concept of the Dyson sphere in his 1959 paper "Search for Artificial Stellar Sources of Infra-Red Radiation", published in the journal *Science*. However, Dyson was inspired by the mention of the concept in the 1937 science fiction novel *Star Maker*, by Olaf Stapledon, and possibly by the works of J. D. Bernal and Raymond Z. Gallun who seem to have explored similar concepts in their work.

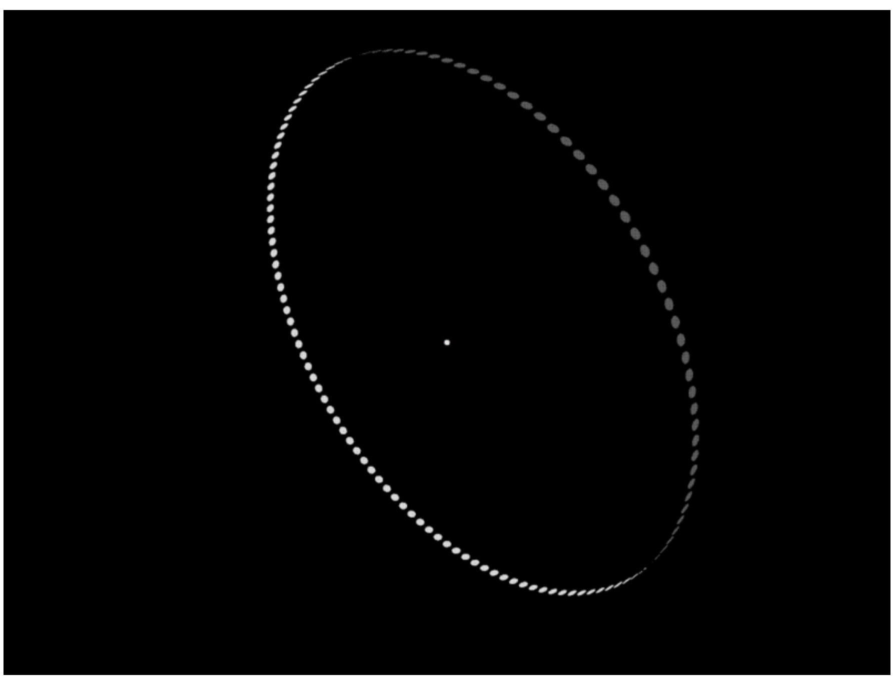
Feasibility

While it is believed that some of the design variants commonly described–specifically those based on the *Dyson shell*–are impractical, design variants of the sphere based on orbiting satellites or solar sails do not require any major theoretical breakthroughs in our basic scientific understanding for their construction. Deployment of spacecraft and satellites using photovoltaics might be seen as the first small steps towards building a *Dyson swarm*. However, creating and deploying energy gathering spacecraft and satellites in the numbers needed to create a solar system sized integrated energy gathering system are well beyond our present-day industrial needs or capabilities. It is also likely that there are unforeseen industrial scaling difficulties in such a construction project, and that our current understanding of industrial automation is insufficient to build the self-maintaining systems needed for the sphere's upkeep.

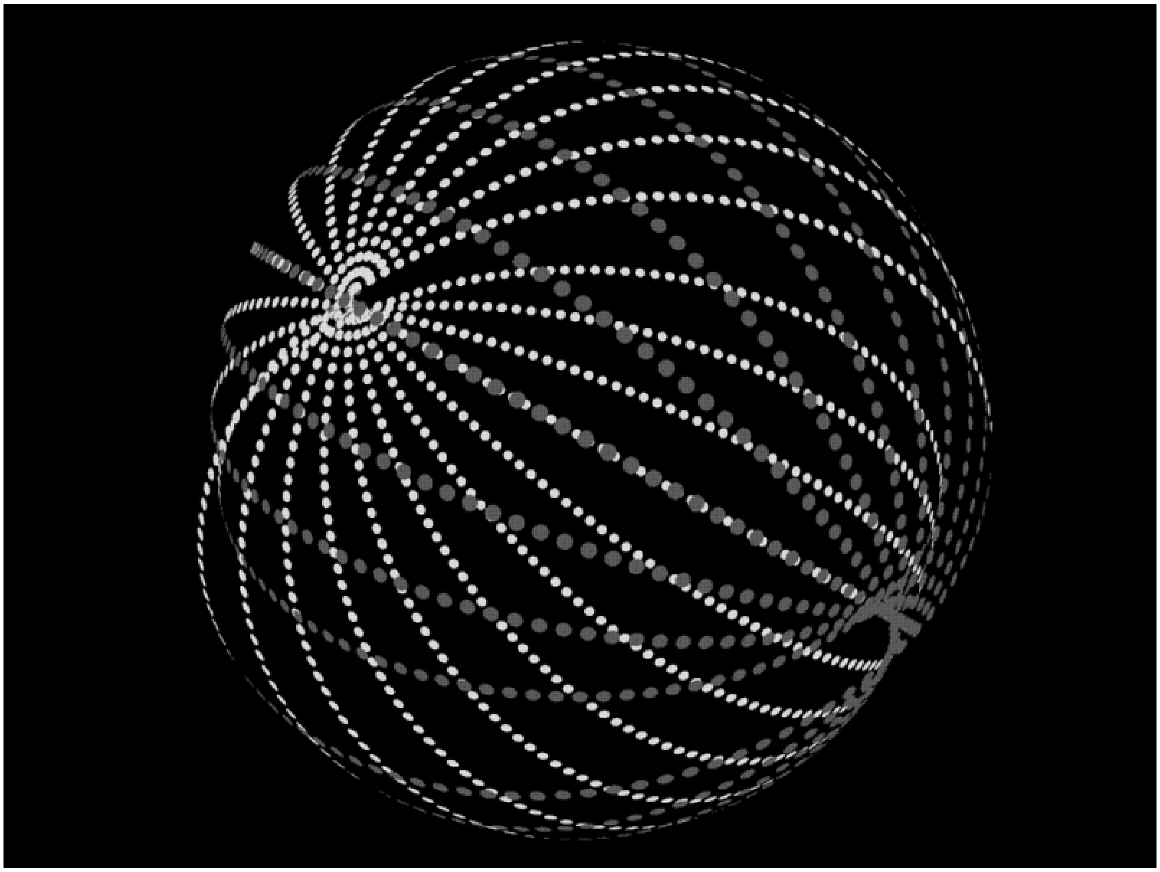
Variants

In fictional accounts, the Dyson sphere concept is often interpreted as an artificial hollow sphere of matter around a star. This perception is a misinterpretation of Dyson's original concept. In response to letters prompted by his original paper, Dyson replied, "A solid shell or ring surrounding a star is mechanically impossible. The form of 'biosphere' which I envisaged consists of a loose collection or swarm of objects traveling on independent orbits around the star."

Dyson swarm



A **Dyson Ring** — the simplest form of the Dyson Swarm — to scale. Orbit is 1 AU in radius, collectors are 1.0×10^7 km in diameter (~25× the Earth–Moon distance), spaced 3 degrees from center to center around the orbital circle.



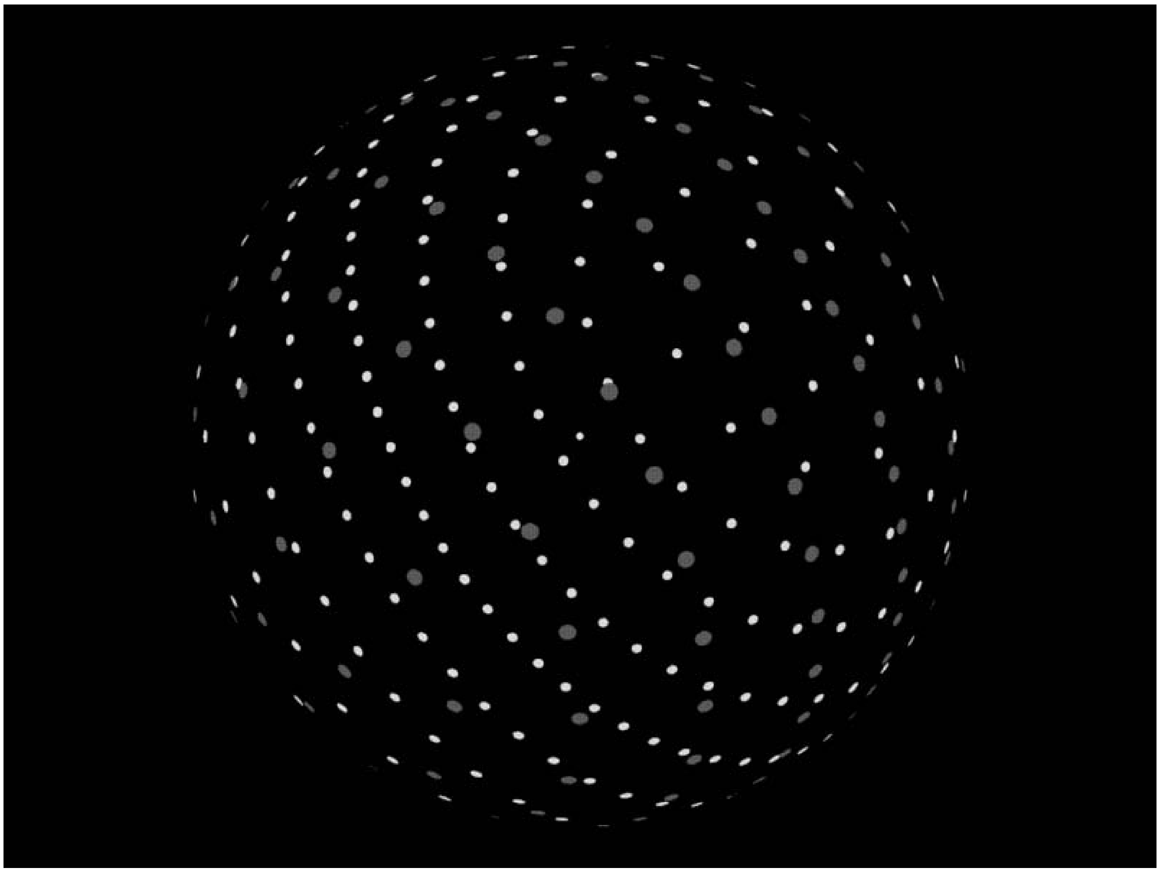
A relatively simple arrangement of multiple Dyson Rings of the type pictured above, to form a more complex Dyson Swarm. Rings' orbital radii are spaced 1.5×10^7 km with regards to one another, but average orbital radius is still 1 AU. Rings are rotated 15 degrees relative to one another, around a common axis of rotation.

The variant closest to Dyson's original conception is the "Dyson swarm". It consists of a large number of independent constructs (usually solar power satellites and space habitats) orbiting in a dense formation around the star. This approach to the construction of a Dyson sphere has several advantages: the components making it up could range widely in individual size and design, and such a sphere could be constructed incrementally over a long period. Various forms of wireless energy transfer could be used in order to transfer energy between constructs.

Such a swarm is not without drawbacks. The nature of orbital mechanics would make the arrangement of the orbits of the swarm extremely complex. The simplest such arrangement is the *Dyson ring* in which all such structures share the same orbit. More complex patterns with more rings would intercept more of the star's output, but would result in some constructs eclipsing others periodically when their orbits overlap. Another potential problem is the increasing loss of orbital stability as adding more orbiting constructs increases the probability of orbital perturbations of other constructs.

As noted below, such a cloud of collectors would alter the light emitted by the star system, but as can be seen here, it is unlikely that such an alteration would be complete, and some of the star's natural light would still be present in the system's emitted spectrum.

Dyson bubble



A **Dyson Bubble**: an arrangement of statites around a star, in a non-orbital pattern. As long as a statite has an unobstructed line-of-sight to its star, it can hover at any point in space near its star. This relatively simple arrangement is only one of an infinite number of possible statite configurations, and is meant as a contrast for a Dyson Swarm only. Statites are pictured as the same size as the collectors pictured above, and arranged at a uniform 1 AU distance from the star.

A second type of Dyson sphere is the "Dyson bubble". It would be similar to a Dyson swarm, composed of many independent constructs (usually solar power satellites and space habitats) and likewise could be constructed incrementally.

Unlike the Dyson swarm, the constructs making it up are not in orbit around the star, but would be statites—satellites suspended by use of enormous light sails using radiation pressure to counteract the star's pull of gravity. Such constructs would not be in danger of collision or of eclipsing one another; they would be totally stationary with regard to the star, and independent of one another. As the ratio of radiation pressure and the force of gravity from a star are constant regardless of the distance (provided the statite has an unobstructed line-of-sight to the surface of its star), such statites could also vary their distance from their central star.

The practicality of this approach is questionable with modern material science, but cannot yet be ruled out. A statite deployed around our own sun would have to have an overall density of 0.78 grams per square meter of sail. To illustrate the low mass of the required materials, consider that the total mass of a bubble of such material 1 AU in radius would be about 2.17×10^{20} kg, which is about the same mass as the asteroid Pallas.

Such a material is currently beyond our ability to produce; the lightest carbon-fiber light sail material currently produced has a density – without payload – of 3 g/m², or about four times as heavy as would be needed to construct a solar statite.

However, there has been some speculation about the creation of ultra light carbon nanotube meshes through molecular manufacturing techniques whose density would be below 0.1 g/m². If production of such materials on an industrial scale is feasible, and such materials could be used in light sails, the average sail density with rigging might be kept to 0.3 g/m² (a "spin stabilized" light sail requires minimal additional mass in rigging). If such a sail could be constructed at this areal density, a space habitat the size of the L5 Society's proposed O'Neill cylinder – 500 km², with room for over 1 million inhabitants, massing 3×10^{6} tons – could be supported by a circular light sail 3,000 km in diameter, with a combined sail/habitat mass of 5.4×10^{9} kg. For comparison, this is just slightly smaller than the diameter of Jupiter's moon Europa (although the sail is a flat disc, not a sphere), or the distance between San Francisco and Kansas City. Such a structure would, however, have a mass quite a lot less than many asteroids. While the construction of such a massive inhabitable statite would be a gigantic undertaking, and the required material science behind it is as yet uncertain, its technical challenges are negligible compared to other engineering feats and required materials proposed in other Dyson sphere variants.

In theory, if enough statites were created and deployed around their star, they would compose a non-rigid version of the Dyson shell mentioned below. Such a shell would not suffer from the drawbacks of massive compressive pressure, nor are the mass requirements of such a shell as high as the rigid form. Such a shell would, however, have the same optical and thermal properties as the rigid form, and would be detected by searchers in a similar fashion.

Dyson shell

The variant of the Dyson sphere most often depicted in fiction is the "Dyson shell": a uniform solid shell of matter around the star. Such a structure would completely alter the emissions of the central star, and would intercept 100% of the star's energy output. Such a structure would also provide an immense surface which many envision being used for habitation, if the surface could be made habitable.

A spherical shell Dyson sphere in our solar system with a radius of one astronomical unit, so that the interior surface would receive the same amount of sunlight as Earth does per solid angle, would have a surface area of at least 272 quadrillion km^2, or about 550 million times the surface area of the Earth. This would intercept the full 400 yotta-watts (4.0×10^{26} watts) of the Sun's output; other variant designs would intercept less, but the shell variant represents the maximum possible energy captured for our solar system at this point of the Sun's evolution. This is approximately 33 trillion times the power consumption of humanity in 1998, which was 12 terawatts.

There are several serious theoretical difficulties with the solid shell variant of the Dyson sphere:

Such a shell would have no net gravitational interaction with its englobed sun, and could drift in relation to the central star. If such movements went uncorrected, they could eventually result in a collision between the sphere and the star—most likely with disastrous results. Such structures would need either some form of propulsion to counteract any drift, or some way to repel the surface of the sphere away from the star.

For the same reason, such a shell would have no net gravitational interaction with anything else inside it. The contents of any biosphere placed on the inner surface of a Dyson shell would not be attracted to the sphere's surface and would simply fall into the star. It has been proposed that a biosphere could be contained between two concentric spheres, placed on the interior of a rotating sphere (in which case, the force of artificial "gravity" is perpendicular to the axis of rotation, causing all matter placed on the interior of the sphere to pool around the equator, effectively rendering the sphere a Niven ring for purposes of habitation, but still fully effective as a radiant energy collector) or placed on the outside of the sphere where it would be held in place by the star's gravity. In such cases, some form of illumination would have to be devised, or the sphere made at least partly transparent, as the star's light would otherwise be completely hidden.

If assuming a radius of one AU, then the compressive strength of the material forming the sphere would have to be immense. Any arbitrarily selected point on the surface of the sphere can be viewed as being under the pressure of the base of a dome *1 AU in height* under the Sun's gravity at that distance. Indeed it can be viewed as being at the base of an infinite number of arbitrarily selected domes, but as much of the force from any one arbitrary dome is counteracted by those of another, the net force on that point is immense, but finite. No known or theorized material is strong enough to withstand this pressure, and form a rigid, static sphere around a star. It has been proposed by Paul Birch (in relation to smaller "Supra-Jupiter" constructions around a large planet rather than a star) that it may be possible to support a Dyson shell by dynamic means similar to those used in a space fountain. Masses traveling in circular tracks on the inside of the sphere, at velocities significantly greater than orbital velocity, would press outwards due to centripetal force. For a Dyson shell of 1 AU radius around a star with the same mass as the Sun, mass traveling ten times orbital velocity (297.9 km/s) would support 99 ($a=v^2/r$) times its own mass in additional shell structure. The arrangement of such tracks suffers from the same difficulties as arranging the orbits of a Dyson swarm, and it is unclear how much energy would be consumed ensuring the velocity of the masses was maintained.

Also if assuming a radius of one AU, then there may not be sufficient building material in the Solar system to construct a Dyson shell. Anders Sandberg estimates that there is 1.82×10^{26} kg of easily usable building material in the Solar system, enough for a 1 AU shell with a mass of 600 kg/m²—about 8–20 cm thick, depending on the density of the material. This includes the hard-to-access cores of the gas giants; the inner planets alone provide only 11.79×10^{24} kg, enough for a 1 AU shell with a mass of just 42 kg/m².

The shell would be vulnerable to impacts from interstellar bodies, such as comets, meteoroids, and material in interstellar space that is currently being deflected by the Sun's bow shock. The heliosphere, and any protection it theoretically provides, would cease to exist.

Other types

Another possibility is the "Dyson net", a web of cables strung about the star which could have power or heat collection units strung between the cables. The Dyson net reduces to a special case of Dyson shell or bubble, however, depending on how the cables are supported against the sun's gravity.

A bubbleworld is an artificial construct that consists of a shell of living space around a sphere of hydrogen gas. The shell contains air, people, houses, furniture, etc. It was invented to answer the question "what is the largest space colony that can be built". However, most of the volume is not habitable and there is no power source.

Theoretically, any gas giant could be enclosed in a solid shell; at a certain radius the surface gravity would be terrestrial, and energy could be provided by tapping the thermal energy of the planet. This concept is explored peripherally in the novel *Accelerando* (and the short story *Curator* which is incorporated into the novel as a chapter) by Charles Stross when Saturn is converted into a human habitable world.

Stellar engines are a class of hypothetical megastructures, whose purpose is to extract useful energy from a star, sometimes for specific purposes. For example, Matrioshka brains extract energy for purposes of computation; Shkadov thrusters extract energy for purposes of propulsion. Some of the proposed stellar engine designs are based on the Dyson sphere.

A black hole could be the power source instead of a star in order to increase energy-to-matter conversion efficiency. A black hole would also be smaller than a star. This would decrease communication distances which would be important for computer-based societies as those described above.

Search for extra-terrestrial intelligence

In Dyson's original paper, he speculated that sufficiently advanced extraterrestrial civilizations would likely follow a similar power consumption pattern as humans, and would eventually build their own sphere of collectors. Constructing such a system would make such a civilization a Type II Kardashev civilization.

The existence of such a system of collectors would alter the light emitted from the star system. Collectors would absorb and reradiate energy from the star. The wavelength(s) of radiation emitted by the collectors would be determined by the emission spectra of the substances making them up, and the temperature of the collectors. Since it seems most likely that these collectors would be made up of heavy elements not normally found in the emission spectra of their central star–or at least not radiating light at such relatively "low" energies as compared to that which they would be emitting as energetic free nuclei in the stellar atmosphere–there would be atypical wavelengths of light for the star's spectral type in the light spectrum emitted by the star system. If the percentage of the star's output thus filtered or transformed by this absorption and reradiation was significant, it could be detected at interstellar distances.

Given the amount of energy available per square meter at a distance of 1 AU from the Sun, it is possible to calculate that most known substances would be reradiating energy in the infrared part of the electromagnetic spectrum. Thus, a Dyson Sphere, constructed by life forms not dissimilar to humans, who dwelled in proximity to a Sun-like star, made with materials similar to those available to humans, would most likely cause an increase in the amount of infrared radiation in the star system's emitted spectrum. Hence, Dyson selected the title "Search for Artificial Stellar Sources of Infrared Radiation" for his published paper.

SETI has adopted these assumptions in their search, looking for such "infrared heavy" spectra from solar analogs. As of 2005 Fermilab has an ongoing survey for such spectra by analyzing data from the Infrared Astronomical Satellite (IRAS).

Chapter- 2

Matrioshka Brain and Megascale Engineering

Matrioshka brain

A **matrioshka brain** is a hypothetical megastructure proposed by **Robert Bradbury**, based on the Dyson sphere, of immense computational capacity. It is an example of a *Class B stellar engine*, employing the entire energy output of a star to drive computer systems. This concept derives its name from Russian Matrioshka dolls.

Concept

The term matrioshka brain was invented by Robert Bradbury as an alternative to the Jupiter brain—a concept similar to the matrioshka brain, but on a smaller planetary scale and optimized for minimum signal propagation delay. A matrioshka brain design is concentrated on sheer capacity and the maximum amount of energy extracted from its source the star, while a Jupiter brain more on computational speed.

Such a structure would be composed of two or more (typically more) Dyson spheres built around a star, and nested one inside another. A significant percentage of the shells would be composed of nanoscale computers. These computers would be at least partly powered by the *energy* exchange between the star and interstellar space. A shell (or component, should a Dyson swarm be the design model used) would absorb energy radiated onto its inner surface, utilize that energy to power its computer systems, and re-radiate the energy outwards. The nanoscale computers of each shell would be designed to run at different temperatures; shells or components at the core could be nearly as hot as the central star, while the outer layer of the matrioshka brain could be almost as cool as interstellar space.

The ideal mechanism for extracting usable energy as it passes "through" a shell or component, the number of shells (or orbital levels) that could be supported in such a manner, the ideal size of the shells to be constructed, and other details, are all issues of speculation.

The idea of the matrioshka brain violates none of the currently known laws of physics, although the engineering details of building such a structure would be staggering, as such a project would require the "disassembly" of significant portions (if not all) of the planetary system of the star for construction materials.

Possible uses

The possible uses of such an immense computational resource tax the imagination. One idea suggested by Charles Stross, in his novel *Accelerando*, would be to use it to run perfect simulations or uploads of human minds into virtual reality spaces supported by the Matrioshka brain. Stross even went so far as to suggest that a sufficiently puissant species utilizing enough raw processing power could launch attacks upon, and manipulate, the structure of the universe itself. In *Godplayers* (2005), Damien Broderick surmises that a matrioshka brain would allow simulating entire alternate universes. The futurist and transhumanist author Anders Sandberg wrote an essay speculating on implications of computing on the massive scale of machines such as the Matrioshka brain, published by the Institute for Ethics and Emerging Technologies.

Commentary

The concept was deployed by its inventor, Robert Bradbury, in the anthology *Year Million: Science at the Far Edge of Knowledge*, and attracted interest from reviewers in the *Los Angeles Times* and the *Wall Street Journal*.

The idea of immensely powerful computing devices was discussed in an essay by Nick Bostrom in *The Philosophical Quarterly*. Bostrom speculates that if humans deliberately evolved to a post-human stage the species would run massive computer simulations before each stage using machines such as the Matrioshka brain. Going further, Bostrom speculates that humans may in fact be actors in a massive computer simulation. Raymond Kurzweil mentions the concept several times in his book *The Singularity Is Near* (2005), following a similar train of thought. He makes the point that existence within a computer simulation could be as "real" as within the conventional biosphere - if indeed the distinction can be made. An article in the April 2003 journal of the British Interplanetary Society also discussed the concept.

Jupiter brain

A Jupiter brain is a theoretical computing megastructure the size of a planet. Unlike a Matrioshka brain, a Jupiter brain is optimized for minimum signal propagation delay, and so has a compact structure. Power generation and heat dissipation are formidable concerns for a Jupiter brain implementation.

While a rigid solid object the size and mass of a rocky planet or gas giant could not be built using any currently known material, such a structure could be built as a low-density lattice with a mass comparable to a large moon or a small rocky planet but a far larger volume, or as a solid but non-rigid structure with the mass and density of a planet (as long as the internal heat gradient is carefully controlled to prevent convection).

Megascale engineering

Megascale engineering (or **macro-engineering**) is a form of exploratory engineering concerned with the construction of structures on an enormous scale. Typically these structures are at least 1,000 kilometers in length—in other words, at least 1 megameter, hence the name. Such large-scale structures are termed megastructures.

In addition to large-scale structures, megascale engineering is also defined as including the transformation of entire planets into a human-habitable environment, a process known as terraforming or planetary engineering. This might also include transformation of the surface conditions, changes in the planetary orbit, and structures in orbit intended to modify the energy balance.

Astroengineering is the extension of *megascale engineering* to megastructures on a stellar scale or larger, such as Dyson spheres, Ringworlds, and Alderson disks.

Megascale engineering often plays a major part in the plot of science fiction movies and books. The micro-gravity environment of outer space provides several potential benefits for the engineering of these structures. These including minimizing the loads on the structure, the availability of large quantities of raw materials in the form of asteroids, and an ample supply of energy from the Sun. The capabilities to employ these advantages are not yet available, however, so they provide material for science fiction themes.

Quite a few megastructures have been designed on paper as exploratory engineering. However, the list of existing and planned megastructures is complicated by the fact that there are no universally agreed-upon criteria for a structure to be called a megastructure. By the most strict definitions, no megastructures currently exist (with the space elevator being the only such project under serious consideration). By more lenient definitions, the Great Wall of China (6.7 Mm) counts as a megastructure.

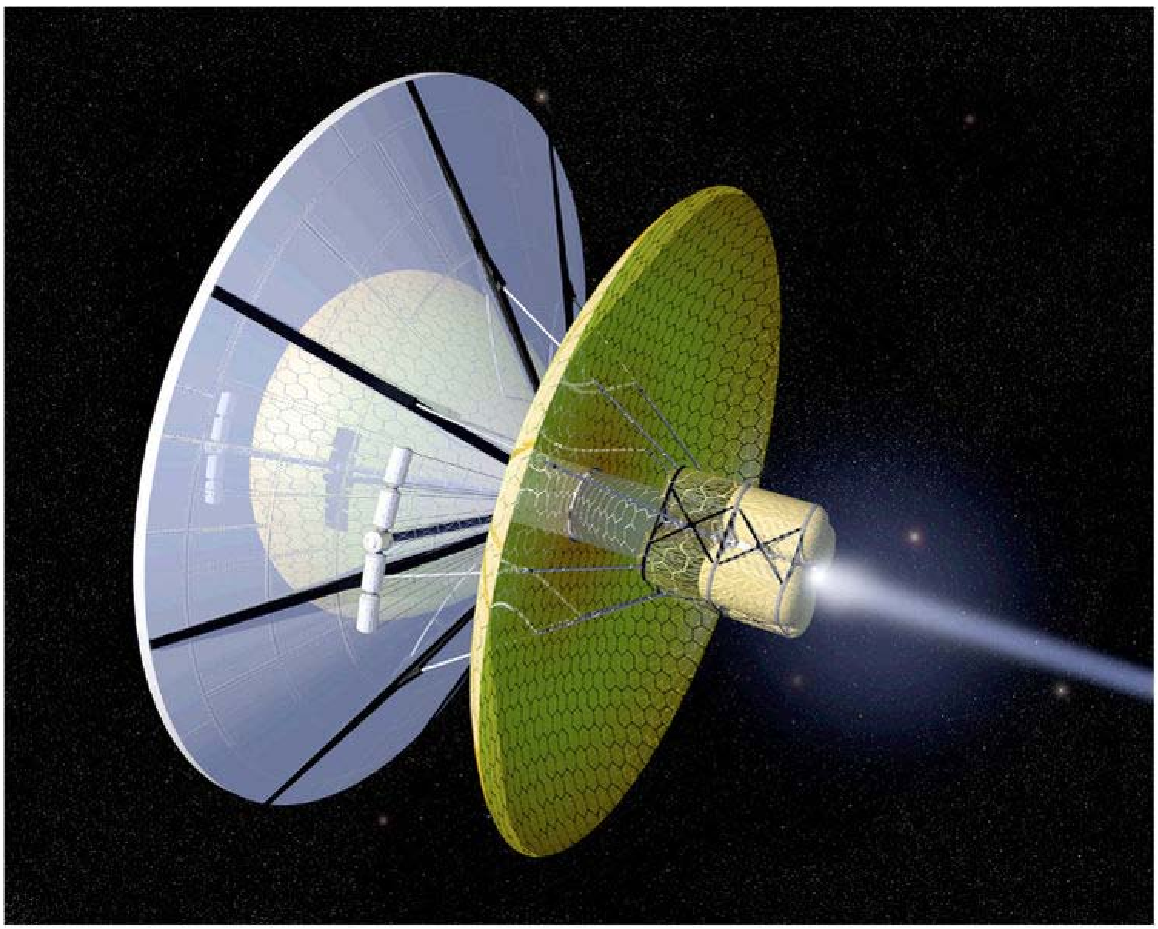
A more complete list of conceptual and existing megastructures, along with a discussion of megastructure criteria, is found under megastructure.

Of all the proposed megastructures, only the orbital elevator, the launch loop, and Martian or lunar space elevator concepts could be built using conventional engineering techniques, and are within the grasp of current material science. Carbon nanotubes may have the requisite tensile strength for the more technologically challenging Earth-based space elevator, but creation of nanotubes of the required length is a laboratory exercise, and adequate cable-scale technology has not yet been shown at all.

The assembly of structures *more* massive than a space elevator would likely involve a combination of new engineering techniques, new materials, and new technologies. Such massive construction projects might require the use of self-replicating machines to provide a suitably large "construction crew". The use of nanotechnology might provide both the self-replicating assemblers, and the specialized materials needed for such a project. Nanotechnology is, however, another area of speculative exploratory engineering at this time.

Chapter- 3

Bussard Ramjet



Artist's conception of a Bussard ramjet. The heart of an actual ramjet—a miles-wide electromagnetic field—is invisible.

The **Bussard ramjet** is a theoretical method of spacecraft propulsion proposed in 1960 by the physicist Robert W. Bussard, popularized by Larry Niven in his Known Space series of books, and referred to by Carl Sagan in the television series and book *Cosmos*.

Bussard proposed a ramjet variant of a fusion rocket capable of fast interstellar spaceflight, using enormous electro-magnetic fields (ranging from kilometers to many thousands of kilometers in diameter) as a ram scoop to collect and compress hydrogen from the interstellar medium. High speeds force the reactive mass into a progressively constricted magnetic field, compressing it until thermonuclear fusion occurs. The magnetic field then directs the energy as rocket exhaust opposite to the intended direction of travel, thereby accelerating the vessel.

Design discussion

A major problem with using rocket propulsion to reach the velocities required for interstellar flight is the enormous amounts of fuel required. Since that fuel must itself be accelerated, this results in an approximately exponential increase in mass as a function of velocity change at non-relativistic speeds, asymptotically tending to infinity as it approaches the speed of light. In principle, the Bussard ramjet avoids this problem by not carrying fuel with it. An ideal ramjet design could in principle accelerate indefinitely until its mechanism failed. Ignoring drag, a ship driven by such an engine could theoretically accelerate arbitrarily close to the speed of light, and would be a very effective interstellar spacecraft. In practice, since the force of drag produced by collecting the interstellar medium increases approximately as its speed squared at non-relativistic speeds and asymptotically tends to infinity as it approaches the speed of light (taking all measurements from the ship's perspective), any such ramjet would have a limiting speed where the drag equals thrust. To produce positive thrust, the fusion reactor must be capable of producing fusion while still giving the incident ions a net rearward acceleration (relative to the ship).

An object's velocity can be calculated by summing over time the acceleration supplied (ignoring the effects of special relativity, which would quickly become significant at useful interstellar accelerations). If a ramjet could accelerate at 10 m/s^2, slightly more than one Earth gravity, it would attain 77% of light velocity within a year. However, if the ramjet has an average acceleration of 0.1 m/s^2, then it needs 100 years to go as fast, and so on.

The top speed of a ramjet-driven spaceship depends on five things:

1. The rate at which mass is collected from space by the ion scoop.
2. The ramjet's exhaust velocity, and the net thrust level obtained from the exhaust jet. The generated thrust can be calculated as the mass of ions expelled per second multiplied by the ramjet exhaust velocity (V_e), adjusted for relativistic effects.
3. The drag produced by collecting the interstellar medium, which will be a function of velocity.
4. The thrust to mass ratio of the ramjet, which is: A = thrust divided mass (N/kg = m/s^2) adjusted for relativistic effects.
5. How long the ramjet is actually able to remain under thrust before it breaks down.

The collected propellant can be used as reaction mass in a plasma rocket engine, ion rocket engine, or even in an antimatter-matter annihilation powered rocket engine. Interstellar space contains an average of 10^{-21} kg of mass per cubic meter of space, primarily in the form of non-ionized and ionized hydrogen, with smaller amounts of helium, and no significant amounts of other gasses. This means that the ramjet scoop must sweep 10^{18} cubic meters of space to collect one gram of hydrogen.

A large energy source adds more mass to the ramjet system, and this makes it harder to accelerate. Therefore, the specific power, (A) of the ramjet's energy source is crucial. The specific power A is the number of joules of energy the starship's reactor generates per kilogram of its mass. This depends on the ramjet fuel's energy density, and on the specific design of the ramjet's nuclear power reactors.

The obvious fuel source, the one proposed by Bussard, is fusion of hydrogen, the most common component of interstellar gas. Unfortunately, the proton-proton fusion rate is close to zero for this purpose: protons in the Sun on average survive for a billion years or more before reacting. Accordingly, an interstellar ramjet would have to be powered by other nuclear reactions, but the required isotopes are rare in the interstellar medium. A fusion reactor used to power a ramjet starship might be a steady state magnetic fusion reactor based on the following nuclear fusion reactions. $^2H + ^2H \rightarrow ^3He + ^1n^0 + 4$ MeV, or $^2H + ^3H \rightarrow ^4He + ^1n^0 + 17.8$ MeV.

This problem was solved, in principle, according to Dr. Bussard by use of the stellar CNO cycle in which carbon is used as a catalyst to burn hydrogen via the strong nuclear reaction. This cycle occurs in the sun (<4%) and is dominant in higher mass stars. The power improvement over the slow PPI chain is by a factor of 10^{16}.

Bussard ramjet designs that use the collected hydrogen only as reaction mass are sometimes referred to as *ram-augmented* interplanetary or interstellar rockets (RAIR) to distinguish them from the designs that use the collected hydrogen as fuel.

The mass of the ion ram scoop must be minimized on an interstellar ramjet. The size of the scoop is large enough that the scoop cannot be solid. This is best accomplished by using an electromagnetic field, or alternatively using an electrostatic field to build the ion ram scoop. Such an ion scoop will use electromagnetic funnels, or electrostatic fields to collect ionized hydrogen gas from space for use as propellant by ramjet propulsion systems (since much of the hydrogen is not ionized, some versions of a scoop propose ionizing the hydrogen, perhaps with a laser, ahead of the ship.) An electric field can electrostatically attract the positive ions, and thus draw them inside a ramjet engine. The electromagnetic funnel would bend the ions into helical spirals around the magnetic field lines to scoop up the ions via the starship's motion through space. Ionized particles moving in spirals produce an energy loss, and hence drag; the scoop must be designed to both minimize the circular motion of the particles and simultaneously maximize the collection. Likewise, if the hydrogen is heated during collection, thermal radiation will represent an energy loss, and hence also drag; so an effective scoop must collect and compress the hydrogen without significant heating. A magnetohydrodynamic generator drawing power from the exhaust could power the scoop.

The collection-radius of such an ionic ramscoop is the distance from the ramjet at which the ramscoop's electric field is greater than the galactic electric field of 1.6×10^{-19} V/m, or the ramscoop's electromagnetic field is greater than the natural galactic magnetic field of 0.1 nanotesla (1×10^{-6} gauss). The strength of the ramscoop collection field would decline proportionately to $1/d^3$ in distance from the ramscoop generator.

Discussions of feasibility

Since the time of Bussard's original proposal, it has been discovered that the region surrounding the sun has a much lower density of interstellar hydrogen than was believed at that time. T.A. Heppenheimer analysed Bussard's original suggestion of fusing protons, but found the bremsstrahlung losses from compressing protons to fusion densities was greater than the power that could be produced by a factor of about 1 billion, thus indicating that the proposed version of the Bussard ramjet was infeasible. However Daniel P. Whitmire's 1975 analysis indicates that a ramjet may achieve net power via the CNO cycle, which produces fusion at a much higher rate ($\sim10^{16}$ times higher) than the proton-proton chain.

Robert Zubrin and Dana Andrews analyzed one hypothetical version of the Bussard ramscoop and ramjet design in 1985. They determined that their version of the ramjet would be unable to accelerate into the solar wind. However, in their calculations they assumed that:

1. The exhaust velocity of their interplanetary ion propulsion ramjet could not exceed 100,000 m/s (100 km/s);
2. The largest available energy source could be a 500 kilowatt nuclear fission reactor.

In the Zubrin/Andrews interplanetary ramjet design, they calculated that the drag force $d/dt(mv_1)$ equals the mass of the scooped ions collected per second multiplied by the velocity of the scooped ions within the solar system relative to the ramscoop. The velocity of the (scooped) collected ions from the solar wind was assumed to be 500,000 m/s.

The exhaust velocity of the ions when expelled by the ramjet was assumed not to exceed 100,000 m/s. The thrust of the ramjet $d/dt(mv_2)$ was equal to the mass of ions expelled per second multiplied by 100,000 meters per second. In the Zubrin/Andrews design of 1985, this resulted in the condition that $d/dt(mv_1) > d/dt(mv_2)$. This condition resulted in the drag force exceeding the thrust of the hypothetical ramjet in the Zubrin/Andrews version of the design.

Consider also the case of a vessel leaving a star system, or heading to the outer planets. In this case, the force produced by the solar wind is beneficial. Since the values for drag are based on relative velocity, using the scoop as a form of electromagnetic sail will provide additional thrust as long as the vessel is travelling at less than 500,000 m/s away from a star. While interstellar matter is relatively scarce, this abundance of high-energy ions in the neighborhood of stars has potential for initial acceleration and braking on arrival.

The key condition that determines whether or not an interstellar ramjet will accelerate forward in the direction of its thrust is that the thrust of the ramjet must exceed drag that results from scooping up ions from space. Or, as discussed above, the condition $d/dt(mv_2) > d/dt(mv_1)$ must be true.

- $d/dt(mv_1)$ is the drag force experienced by the ramjet during its actual operation; $d/dt(mv_1)$ is the mass of collected propellant per unit time times the velocity of the scooped ions relative to the ramjet starship.
- $d/dt(mv_2)$ is the thrust produced by the ramjet; $d/dt(mv_2)$ is the mass of the collected ramjet propellant per unit time multiplied by the exhaust velocity at which it is expelled from the Ramjet engine to generate thrust.

Example

For example, a ramjet might collect 1 gram of incoming ions per second from interstellar space beyond the heliopause, at a velocity of 50 km/s relative to the ramjet driven spacecraft. In this case $d/dt(mv_1)$ is (0.001 kg/s) (50,000 m/s), yielding a drag force of 50 newtons.

If the gram of ions is then accelerated to 500,000 m/s then $d/dt(mv_2)$ is (0.001 kg/s) (500,000 m/s) = 500 N.

Therefore, -50 newtons + 500 newtons yields a net force forward of 450 newtons.

The typical velocity of the solar wind within the solar system is 500 km/s. The typical velocity of the interstellar wind is 50 km/s beyond the heliopause. In the solar system, if the exhaust velocity of the ramjet exceeds 500 km/s there will be a net thrust that will accelerate the ramjet. Figures here assume the spacecraft is travelling towards the sun (since the solar wind is directional), under the worst conditions for thrust.

If the example were set in the solar system, the drag force, $d/dt(mv_1)$, would be about (0.001 kg/s) (500,000 m/s), or 500 newton.

If the exhaust velocity of the ramjet were 1,000,000 m/s then $d/dt(mv_2)$ = (0.001 kg/s) (1,000,000 m/s) = 1000 N of thrust, and -500 newtons + 1000 newtons = net thrust of 500 newtons to accelerate the ramjet forward.

If the Zubrin/Andrews assumption were correct then $d/dt(mv_1)$ = 500 N, and $d/dt(mv_2)$ = 100 N, and the drag forces would exceed the thrust of the ramjet. Under those conditions, the ramjet would likely only function along vectors perpendicular to the solar wind.

Related inventions

Magnetic sail

The calculations (by Robert Zubrin and an associate) inspired the idea of a magnetic parachute or sail. This could be important for interstellar travel because it means that deceleration at the destination can be performed with a magnetic parachute rather than a rocket.

Electrostatic ion scoop

One possible modification of the ramjet design is to use an electrostatic ion scoop, instead of an electromagnetic ion scoop to achieve the ion collection from space. In an electrostatic scoop a negative electric field on a forward grid electrostatically attracts the positive charged ions present in interstellar space and thus draws them into the ramjet engines. This can be a 100% electrostatic scoop in which an electromagnetic field is not used at all. There will be no converging electromagnetic field lines that can potentially generate drag effects by scooping the ions from interstellar space if this pure electrostatic approach is used. The scooped ions will however have an electric field-induced velocity when they are drawn inside of the ion ramjet engine. So long as the velocity of the ramjet engine exhaust jet is greater than the electric field-induced velocity of the incoming scooped ions there can be a net force in the direction of the ramjet's flight that will accelerate the spacecraft.

Furthermore, the net potential difference of the galactic electric field in interstellar space is only 1.6×10^{-19} volt. The effective ion collection radius of an electrostatic ion ram scoop will be the range at which the ramscoop electric field has a greater potential difference from the galactic electric field. This potential difference declines proportionately to $1/d^2$ for distance d from the source of the ram scoop electric field.

Pre-seeded trajectory

Several of the obvious technical difficulties with the Bussard Ramjet can be overcome by prelaunching fuel along the spacecraft's trajectory using something like a magnetic rail-gun.

The advantages of this system include

- Pre-launching only ionized fusion fuel so that either magnetic or electrostatic scoops can more easily funnel the fuel into the engine. The drawback is this will cause the fuel to disperse due to electrostatic repulsion.
- Pre-launching the fuel on a trajectory so that the fuel velocity vector will closely match the expected velocity vector of the spacecraft at that point in its trajectory. This will minimize the "drag" forces generated by the collection of fuel.
- Pre-launching optimized isotope ratios for the fusion engines on the spacecraft. A conventional Bussard ramjet will mostly collect hydrogen with an atomic weight

of 1. This isotope is harder to fuse than either the Deuterium or Tritium isotopes of hydrogen. By launching the ideal ratio of hydrogen isotopes for the fusion engine in the spacecraft you can optimize the performance of the fusion engine.

- Although the pre-launching fuel for the ramjet negates one advantage of the Bussard design (collection of fuel as it moves through the interstellar medium) it retains the advantage of not having to accelerate the mass of the fuel and the mass of the rocket at the same time.
- The prelaunched fuel would provide some visibility into the interstellar medium - thus alerting the trailing spacecraft of unseen hazards (e.g. brown dwarf stars).

The major disadvantages of this system include:

- The spacecraft could not deviate from the precalculated trajectory unless it was critical to do so. Any such deviation would separate the spacecraft from its fuel supply and leave it with only a minimal ability to return to its original trajectory.
- Pre-launched fuel for deceleration at the destination star would not be available unless launched many decades in advance of the spacecraft launch. However, other systems (such as the Magnetic sails) could be used for this purpose.
- It would be very difficult to perform a round-trip with this system unless materials and time are allocated to building another fuel launch mechanism at the destination star.

Chapter- 4

Self-replicating Spacecraft and Sea Dragon (rocket)

Self-replicating spacecraft

The idea of **self-replicating spacecraft** has been applied — in theory — to several distinct "tasks". The particular variant of this idea applied to the idea of space exploration is known as a **von Neumann probe**. Other variants include the Berserker and an automated seeder ship.

Theory

In theory, a self-replicating spacecraft could be sent to a neighbouring star-system, where it would seek out raw materials (extracted from asteroids, moons, gas giants, etc.) to create replicas of itself. These replicas would then be sent out to other star systems. The original "parent" probe could then pursue its primary purpose within the star system. This mission varies widely depending on the variant of self-replicating starship proposed.

Given this pattern, and its similarity to the reproduction patterns of bacteria, it has been pointed out that von Neumann machines might be considered a form of life. In his short story, "Lungfish", David Brin touches on this idea, pointing out that self-replicating machines launched by different species might actually compete with one another (in a Darwinistic fashion) for raw material, or even have conflicting missions. Given enough variety of "species" they might even form a type of ecology, or — should they also have a form of artificial intelligence — a society. They may even mutate with untold thousands of "generations".

The first quantitative engineering analysis of such a spacecraft was published in 1980 by Robert Freitas, in which the non-replicating Project Daedalus design was modified to include all subsystems necessary for self-replication. The design's strategy was to use the probe to deliver a "seed" factory with a mass of about 443 tons to a distant site, have the seed factory replicate many copies of itself there to increase its total manufacturing capacity, over a 500 year period, and then use the resulting automated industrial complex to construct more probes with a single seed factory on board each.

It has been theorized that a self-replicating starship utilizing relatively conventional theoretical methods of interstellar travel (i.e. no exotic faster-than-light propulsion such as "warp drive", and speeds limited to an "average cruising speed" of 0.1**c**.) could spread throughout a galaxy the size of the Milky Way in as little as half a million years.

Implications for Fermi's paradox

In 1981, Frank Tipler put forth an argument that extraterrestrial intelligences do not exist, based on the *absence* of von Neumann probes. Given even a moderate rate of replication and the history of the galaxy, such probes should already be common throughout space and thus, we should have already encountered them. Because we have not, this shows that extraterrestrial intelligences do not exist. This is thus a resolution to the Fermi paradox—that is, the question of why we have not *already* encountered extraterrestrial intelligence if it is common throughout the universe.

A response came from Carl Sagan and William Newman. Now known as *Sagan's Response*, it pointed out that in fact Tipler had underestimated the rate of replication, and that von Neumann probes should have already started to consume most of the mass in the galaxy. Any intelligent race would therefore, Sagan and Newman reasoned, not design von Neumann probes in the first place, and would try to destroy any von Neumann probes found as soon as they were detected. As Robert Freitas has pointed out the assumed capacity of von Neumann probes described by both sides of the debate are unlikely in reality, and more modestly reproducing systems are unlikely to be observable in their effects on our Solar System and the rest of the Galaxy.

Another objection to the prevalence of von Neumann probes is that civilizations of the type that could potentially create such devices may have inherently short lifetimes, and self-destruct before so advanced a stage is reached, through such events as biological or nuclear warfare, nanoterrorism, resource exhaustion, ecological catastrophe, pandemics due to antibiotic resistance, *etc.*

A simple workaround exists to avoid the over-replication scenario. Radio transmitters, or other means of wireless communication, could be used by probes programmed not to replicate beyond a certain density (such as five probes per cubic parsec) or arbitrary limit (such as ten million within one century). One problem with this defence against uncontrolled replication is that it would only require a single probe to malfunction and begin unrestricted reproduction for the entire approach to fail — essentially a technological cancer — unless each probe also has the ability to detect such malfunction in its neighbours and implements a seek and destroy protocol.

Applications for self-replicating spacecraft

The details of the mission of self-replicating starships can vary widely from proposal to proposal, and the only common trait is the self-replicating nature.

Von Neumann probes

A von Neumann probe is a self-replicating spacecraft designed to investigate its target system and transmit information about it back to its system of origin. The concept is named after Hungarian American mathematician and physicist John von Neumann, who rigorously studied the concept of self-replicating machines that he called "Universal Assemblers" and which are often referred to as "von Neumann machines". While von Neumann never applied his work to the idea of spacecraft, theoreticians since then have done so.

If a self-replicating probe finds evidence of primitive life (or a primitive, low level culture) it might be programmed to lie dormant, silently observe, attempt to make contact (this variant is known as a Bracewell probe), or even interfere with or guide the evolution of life in some way.

Physicist Paul Davies of Arizona State University has even raised the possibility of a probe resting on our own Moon, having arrived at some point in Earth's ancient prehistory and remained to monitor Earth.

A variant idea on the interstellar von Neumann probe idea is that of the "Astrochicken", proposed by Freeman Dyson. While it has the common traits of self-replication, exploration, and communication with its "home base", Dyson conceived the Astrochicken to explore and operate within our own planetary system, and not explore interstellar space.

Oxford-based philosopher Nick Bostrom discusses the idea that future powerful superintelligences will create efficient cost-effective space travel and interstellar Von Neumann probes.

Autonomous synthetic life

Similar to a von Neumann probe, the only intelligent beings capable of traveling the huge distances of space are synthetic and self replicating life forms. These life forms are not single probes, but groups of life forms who are teaming together to achieve their goals in space.

Berserkers

A variant of the self-replicating starship is the **Berserker**. Unlike the benign probe concept, Berserkers are programmed to seek out and exterminate lifeforms and life-bearing exoplanets whenever they are encountered.

The name is derived from a series of novels by Fred Saberhagen which feature an ongoing war between humanity and such machines (see: *Berserker*). Saberhagen points out (through one of his characters) that the Berserker warships in his novels are not von Neumann machines themselves, but the larger complex of Berserker machines — including automated shipyards — *do* constitute a von Neumann machine. This again brings up the concept of an ecology of von Neumann machines, or even a von Neumann hive entity.

It is speculated that Berserkers could be created and launched by a xenophobic civilization or could theoretically "mutate" from a more benign probe. For instance, a von Neumann ship designed for terraforming processes — mining a planet's surface and adjusting its atmosphere to more human-friendly conditions — might malfunction and attack inhabited planets, killing their inhabitants in the process of changing the planetary environment, and then self-replicating and dispatching more ships to attack other planets.

Replicating "seeder" ships

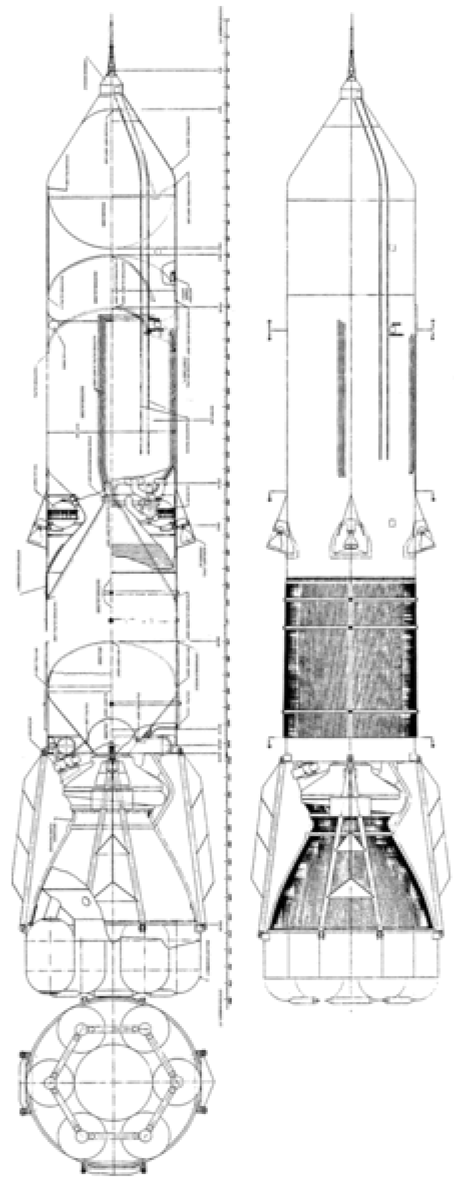
Yet another variant on the idea of the self-replicating starship is that of the "seeder" ship. Such starships might store the genetic patterns of lifeforms from their home world, perhaps even of the species which created it. Upon finding a habitable exoplanet, or even one that might be terraformed, it would try to replicate such lifeforms — either from stored embryos (see: embryo space colonization) or from stored information using molecular nanotechnology to "build" zygotes with varying genetic information from local raw materials.

Such ships might be terraforming vessels, preparing colony worlds for later colonization by other vessels, or — should they be programmed to recreate, raise, and educate individuals of the species that created it — self-replicating colonizers themselves.

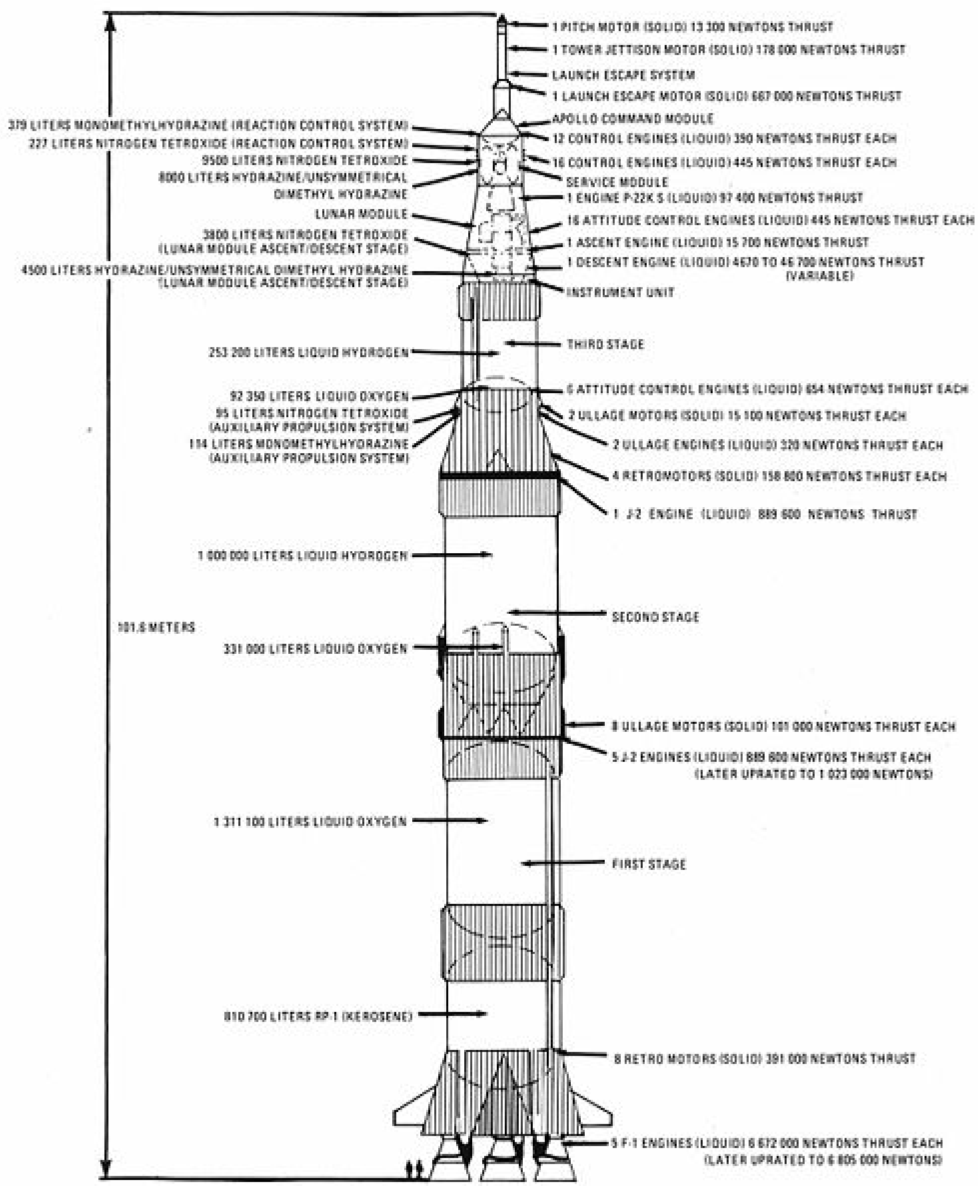
As a side note, this pattern of terraforming and colonization need not be "automated". Manned interstellar colony ships could follow a similar pattern — and might be considered a sort of a combined von Neumann probe/seeder ship in which replication can be performed by the living inhabitants.

Some proponents of space habitats suggest that planets would be entirely unnecessary to a civilization using this approach. Taken to its extreme, this concept could combine self-replicating habitat ships with technologies such as virtual reality, envatted brains and tissue regeneration to efficiently transform cosmic resources into meaningful subjective lives free from suffering.

Sea Dragon



Sea Dragon internal and external views. Both show the ballast tank attached to the first stage engine bell. An Apollo CSM-like spacecraft is mounted on top.



Saturn V to a similar scale. Its second stage would fit inside the first stage engine and nozzle of the Sea Dragon.

The **Sea Dragon** was a 1962 design study for a fully reusable two-stage sea-launched rocket. The project was led by Robert Truax while working at Aerojet, one of a number of designs he created that were to be launched by floating the rocket in the ocean. Although there was some interest at both NASA and Todd Shipyards, nothing ever came of the design as NASA's Future Projects Branch was shut down in the mid-60s. At 150 m long and 23 m in diameter, Sea Dragon would have been the largest rocket ever built.

Truax's basic idea was to produce a low-cost heavy launcher, a concept now called "big dumb booster". To lower the cost of operation, the rocket itself was launched from the ocean, requiring little in the way of support systems. A large ballast tank system attached to the bottom of the first-stage engine bell was used to "hoist" the rocket vertical for launch. In this orientation the cargo at the top of the second stage was just above the waterline, making it easy to access. Truax had already experimented with this basic system in the Sea Bee and Sea Horse designs. To lower the cost of the rocket itself, he intended it to be built of inexpensive materials, specifically 8 mm steel sheeting. The rocket would be built at a sea-side shipbuilder and towed to sea for launch.

The first stage was to be powered by a single enormous 80,000,000 pounds-force (360 MN) thrust engine burning RP-1 and liquid oxygen. The fuels were pushed into the engine by an external source of nitrogen gas, which provided a pressure of 32 atm for the RP-1 and 17 atm for the LOX, providing a total pressure in the engine of 20 atm (~300 psi) at takeoff. As the vehicle climbed the pressures dropped off, eventually burning out after 81 seconds. By this point the vehicle was 25 miles up and 20 miles downrange (40 km x 33 km), traveling at a speed of 4,000 mph (1.8 km/s). The normal mission profile expended the stage in a high-speed splashdown some 180 miles (290 km) downrange. Plans for stage recovery were studied as well.

The second stage was also equipped with a single very large engine, in this case a 6 million kgf thrust engine burning liquid hydrogen and LOX. Although also pressure-fed, in this case the nitrogen kept the system running at a constant lower pressure of 7 atm throughout the entire 260 second burn, at which point it was 230 km up and 940 km downrange. To improve performance, the engine featured an expanding engine bell, changing from 7:1 to 27:1 expansion as it climbed. The overall height of the rocket was shortened somewhat by making the "nose" of the first stage pointed, lying inside the second stage engine bell.

A typical launch sequence would start with the rocket being refurbished and mated to its cargo and ballast tanks on shore. The RP-1 and nitrogen would also be loaded at this point. The rocket would then be towed to a launch site, where the LOX and LH2 would be generated on-site using electrolysis; Truax suggested using a nuclear-powered aircraft carrier as a power supply during this phase. The ballast tanks, which also served as a cap and protection for the first stage engine bell, would then be filled with water, raising the rocket to vertical. Last minute checks could then be carried out, and the rocket launched.

The rocket would have been able to carry a payload of up to 550 metric tons into low earth orbit. Payload costs were estimated to be between $59 to $600 per kg, which is much less than today's launch costs. TRW conducted a program review and validated the design and its expected costs, apparently a surprise to NASA. However, budget pressures led to the closing of the Future Projects Branch, ending work on the super-heavy launchers they had proposed for a manned mission to Mars.

Chapter- 5

Megastructure

A **megastructure** is a built structure typically at least 1,000 kilometers in length—in other words, at least 1 megameter, hence the name. The definition is often informal and varies from source to source. By extension, some people apply the term to any especially large or tall building.

Most megastructure designs could not be constructed with today's level of industrial technology. This makes their design examples of speculative (or exploratory) engineering. Those that could be constructed easily qualify as megaprojects.

Some sources define a megastructure as an enormous self-supporting artificial construct. Other criteria such as rigidity or contiguousness are sometimes also applied, so large clusters of associated smaller structures may or may not qualify. The products of megascale engineering or astroengineering are megastructures.

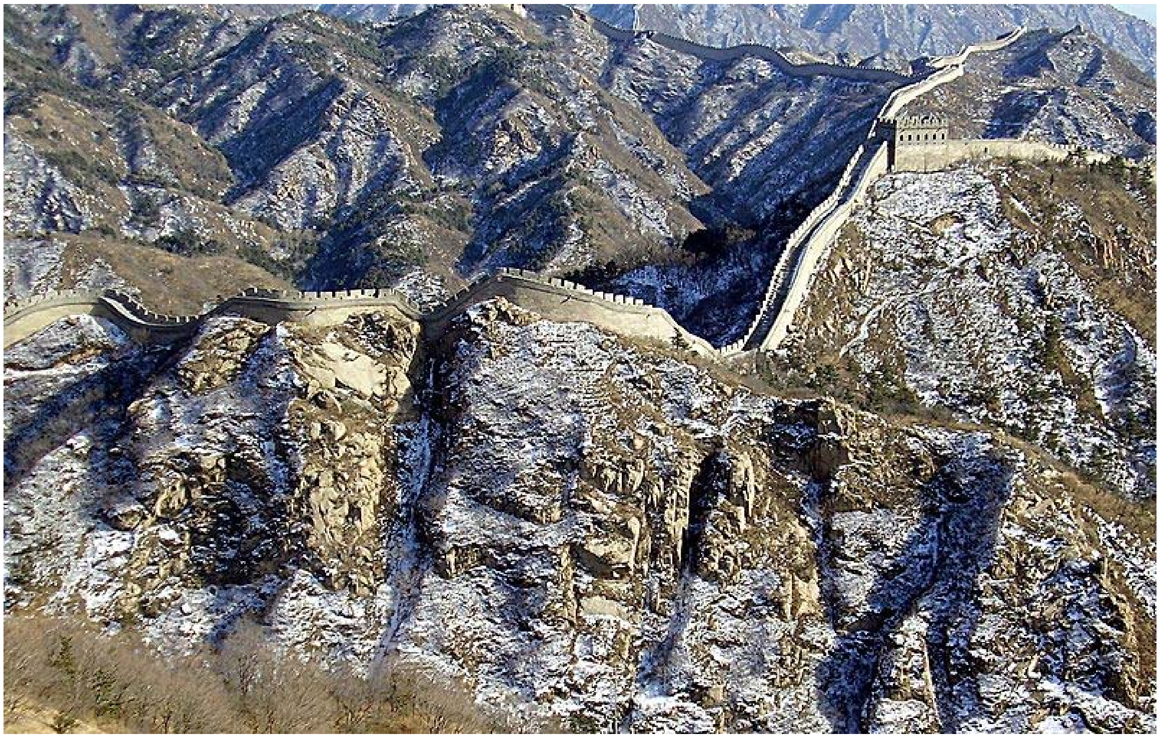
Megastructures are also an architectural concept popularized in the 1960s where a city could be encased in a single building, or a relatively small number of buildings interconnected. Such arcology concepts are popular in science fiction.

Megastructures often play a part in the plot or setting of science fiction movies and books, such as *Rendezvous with Rama* by Arthur C. Clarke.

In 1968, Ralph Wilcoxon defined a megastructure as any structural framework into which rooms, houses, or other small buildings can later be installed, uninstalled, and replaced; and which is capable of "unlimited" extension. Many architects have designed such megastructures. Some of the more notable such architects and architectural groups include the Metabolist Movement, Archigram, Cedric Price, Frei Otto, Constant Nieuwenhuys, Yona Friedman, and Buckminster Fuller. This type of framework allows the structure to adapt to the individual wishes of its residents, even as those wishes change with time.

Other sources define a megastructure as "any development in which residential densities are able to support services and facilities essential for the development to become a self-contained community".

Existing megastructures



The Great Wall of China is an example of a megastructure. This picture was taken near Beijing in winter.

There are structures on Earth that may be considered megastructures, such as

- The Great Wall of China is a human-built megastructure, a few meters wide and 3,947 miles (6,352 km) in length, about 4,975,318 square yards (4,160,000 m^2)

- The Rice Terraces of the Philippine Cordilleras, a 10,360 square kilometer (4,000 square mile) sprawling agricultural landscape carved in the mountains by free tribesmen of Ifugao some 6,000 to 2,000 years ago.

- Skyscrapers represent our current state-of-the-art in large structure engineering.

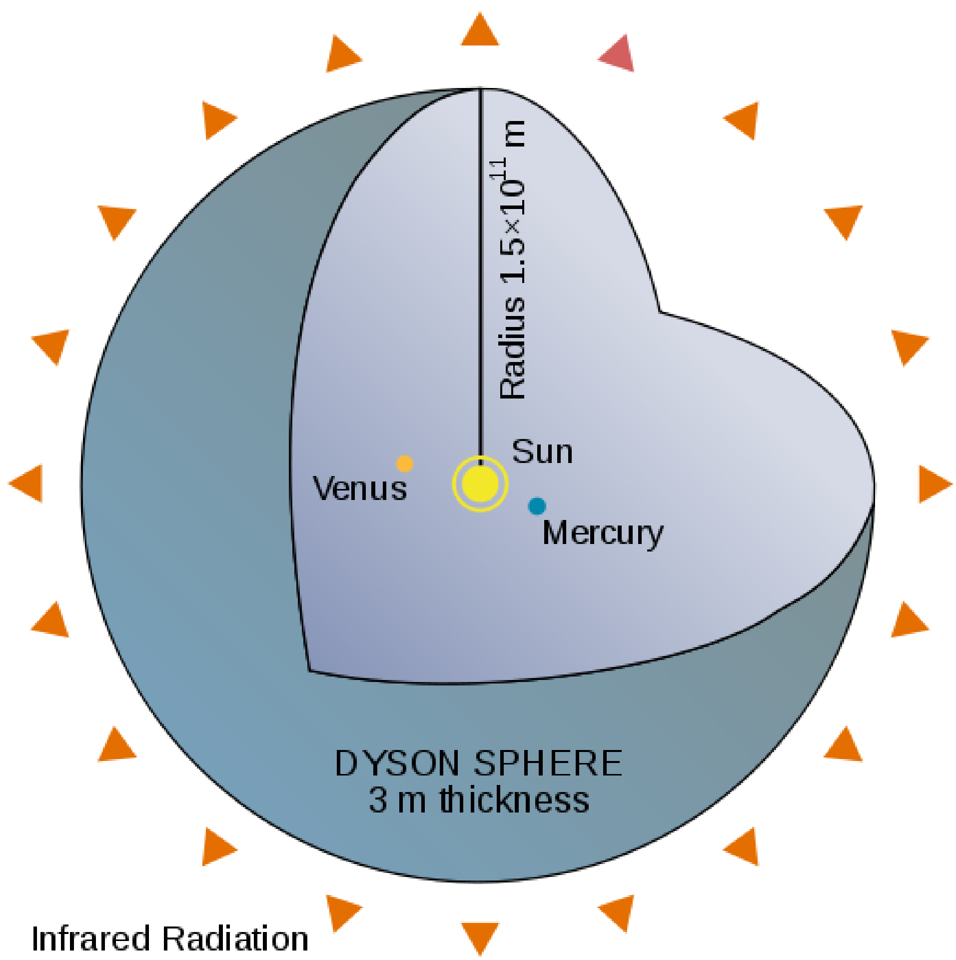
Networks of roads or railways, and collections of buildings (cities and associated suburbs), are usually not considered megastructures, despite frequently qualifying based on size. However, an ecumenopolis might qualify.

Proposed megastructures

- Atlantropa, a hydroelectric dam to be built across the Strait of Gibraltar, and the lowering of the surface of the Mediterranean Sea by as much as 200 metres.

Theoretical megastructures

Stellar scale



A cut-away diagram of an idealized Dyson shell—a variant on Dyson's original concept—1 AU in radius.

Most stellar scale Megastructure proposals are designs to make use of the energy from a sun-like star while possibly still providing gravity or other attributes that would make it attractive for an advanced civilization.

- The Alderson disk is a theoretical structure in the shape of a disk, where the outer radius is equivalent to the orbit of Mars or Jupiter and the thickness is several thousand miles. A civilization could live on either side, held by the gravity of the disk and still receive sunlight from a star bobbing up and down in the middle of the disk.

- A Dyson sphere (also known as a Dyson Shell) refers to a structure or mass of orbiting objects that completely surrounds a star to make full use of its solar energy.
- Larry Niven's Ringworld is an artificial ring with a radius roughly equal to the radius of the Earth's orbit (1 AU). A star is present in the center and the ring spins to provide artificial gravity.
- A Matrioshka brain is a collection of multiple Concentric Dyson Spheres which make use of different wavelengths of light.
- A Stellar engine either uses the temperature difference between a star and interstellar space to extract energy or serves as a Shkadov thruster.
- A Shkadov thruster accelerates an entire star through space by selectively reflecting or absorbing light on one side of it.
- Topopolis (also known as Cosmic Spaghetti) is a large tube that rotates to provide artificial gravity.

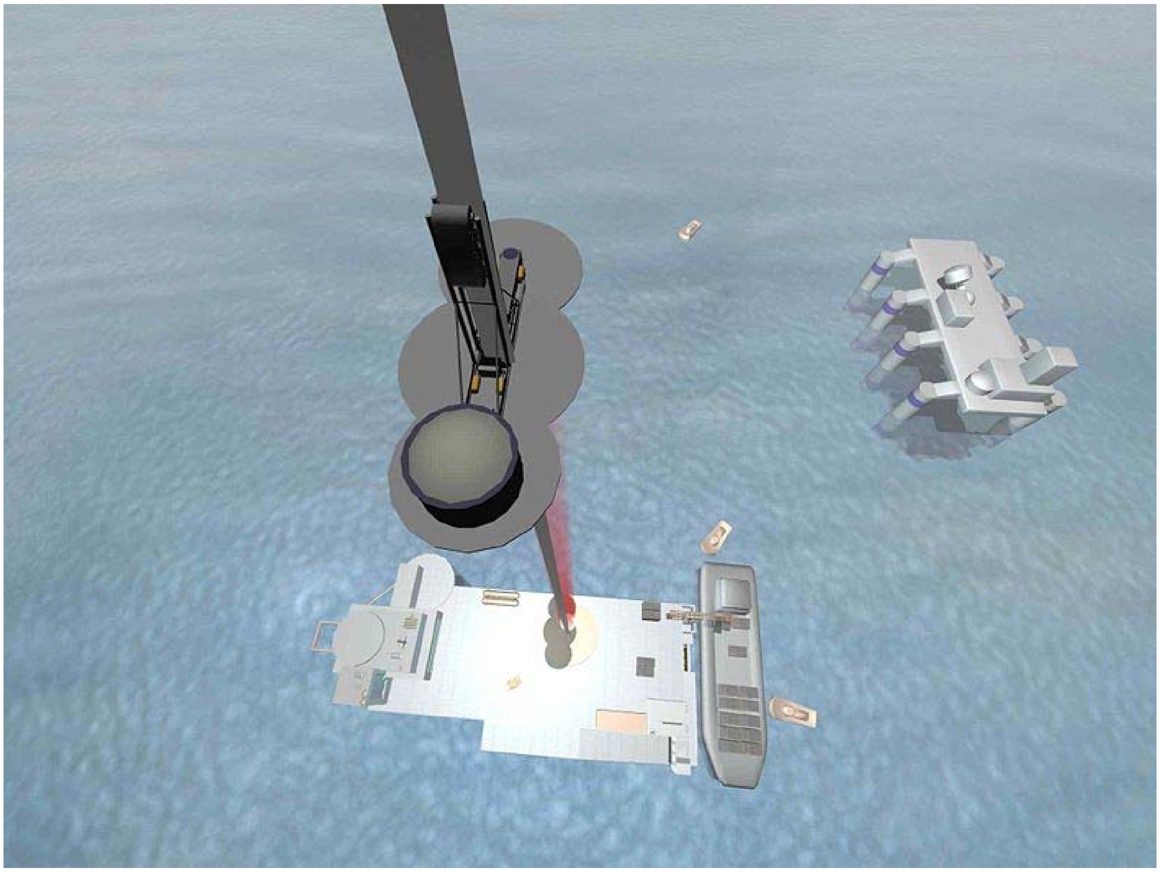
Planetary scale

- An Orbital is a space habitat similar to but much smaller than a Niven Ring. Instead of being centered around a star, it is orbiting a star, thus its diameter is typically on the order of magnitude of a planet. By giving a tilt to its orbit, there's a convenient day and night experience on its surface.
- Globus Cassus is a hypothetical proposed project for the transformation of Planet Earth into a much bigger, hollow, artificial world with the ecosphere on its inner surface. This model serves as a tool to understand the World's real functioning processes.

Orbital structures

- Orbital ring is an enclosed loop slightly larger than the circumference of the Earth so that it can maintain low earth orbit.
- The Bernal sphere is a proposal for a space colony with a maximum diameter of 1.6 kilometers.
- The Stanford torus is a different design with a diameter just under 1.7 kilometers.
- The O'Neill cylinder is yet another space colony proposal.

Trans-orbital structures



One concept for the space elevator has it tethered to a mobile seagoing platform.

- A Skyhook is a very tall structure that hangs down from orbit.
- A Space elevator is a skyhook that is fixed to the ground
- A Space fountain is held up by the momentum of masses which are shot up to the top at high speeds from the ground.
- A Lofstrom loop ("Launch loop") is a 2000 km long iron loop that projects up in an arc to 80 km that is ridden by maglev cars while achieving orbital velocity.
- Rotovator proposals call for a large tether to transfer momentum between spacecraft in transit.

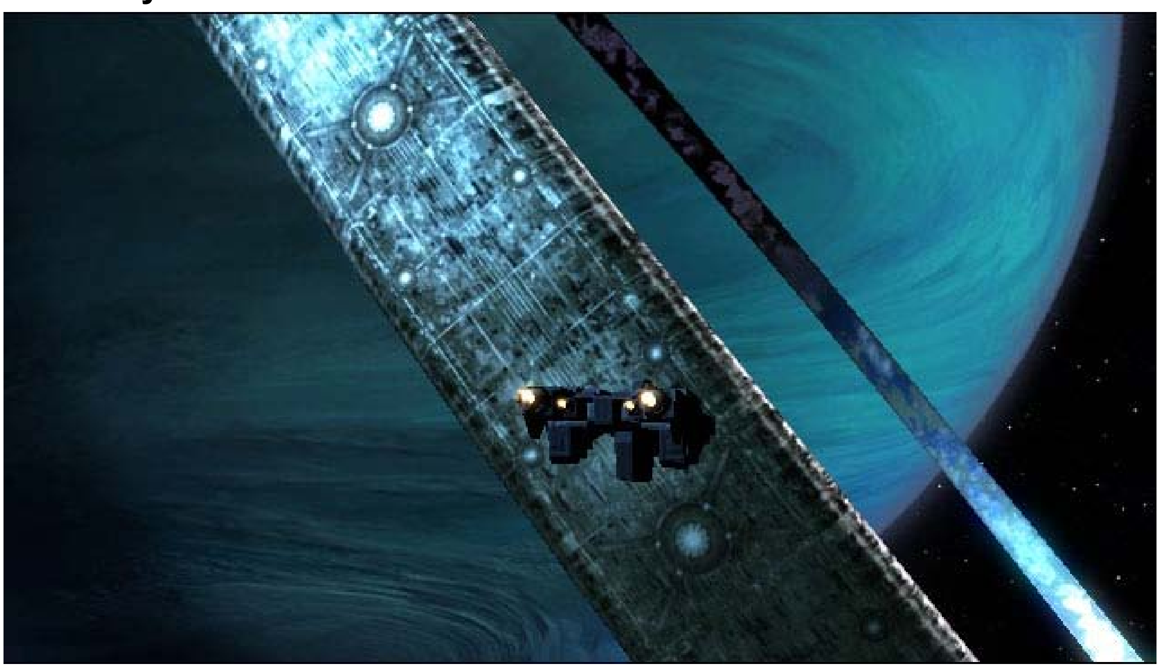
Fictional megastructures

Stellar scale

- The Dyson shell (including its variation, the Ringworld) has appeared in many works of fiction, including the *Star Trek* universe.
- Larry Niven's series of novels about his *Ringworld* centered around, and originated the concept of the Ringworld, or Niven ring.
- In the manga *Blame!* the Megastructure is a vast and chaotic complex of metal, concrete, stone, etc., that covers the Earth and assimilates the Moon.

- In *White Light* by William Barton and Michael Capobianco, a Topopolis is presented as taking over the entire universe.
- In the Heechee books by Frederik Pohl the race of pure energy beings called The Foe have constructed the Kugelblitz, a black hole made of energy and not matter.
- In the Xeelee series of books by Stephen Baxter, the eponymous alien race constructed the Ring, a megastructure made of cosmic strings, spanning over 10 million light years.
- In the game *Airforce Delta Strike* a large Space Elevator called the Chiron Lift is used to send supplies out into outer space. Later in the game it is destroyed by an artificially enhanced human named Pierre who fights for the Orbital Citizens Community (OCC).
- The Ark from the *Halo* universe which served as the last place of safety for the Forerunners from the flood, with the ability to rebuild destroyed Halos.Also in the games, orbital elevators on earth and other colonies are seen and mentioned.
- In *Freelancer*, The Dom'Kavosh's Dyson shell that is inhabited by a drone race created by the Dom'Kavosh, Nomads. This is reached via a hyper gate, created by the same creators as the Dyson sphere.
- The Saga of Cuckoo series novel *Wall Around A Star* mentions a proposal to build a super dyson sphere, completely enclosing the Galactic Center.

Planetary scale



Delta Halo, One of the 7 Halos from the Halo universe

- Death Star from *Star Wars*
- Borg Transwarp Hub and Unicomplexes, Federation Starbases and Fleet Yards
- Buster Machine III from *Gunbuster*.
- Culture Orbital

- Trantor, the capital of an interstellar empire in Isaac Asimov's Foundation series, is a planet entirely covered in one huge metal clad building, with only one small green space: the Emperor's palace grounds
- Coruscant, capital city in the *Star Wars* universe, entirely covers its host planet. It serves as capital of first the Republic and then later the First Galactic Empire.
- The Ori Supergate seen in a number of episodes of *Stargate SG1* could be classed as a megastructure
- In *The Hitchhiker's Guide to the Galaxy* series, Earth, as well as other planets, were artificial megastructures. Earth was intended to function as a gigantic computer, and was built by a race of beings who made their living by manufacturing other planets.
- The Star Forge from Knights of the Old Republic
- Despite being sentient, the Transformers universes Unicron's 'metal planet' form is comparable to a megastructure.
- Mata-Nui in the BIONICLE franchise is classifiable as a megastructre. In the story he is a massive robot as tall as a planet, and inside his body, every inhabitant of the BIONICLE Universe (Matoran, Toa, etc.) all live, unaware that they live inside a massive, space-traveling entity.
- Cybertron itself is a megastructure, comparable to Trantor or Coruscant on a smaller scale.
- The seven Halos from the *Halo* universe are 10,000 km wide rings.
- In the Robotech Sentinels novels, Haydon IV is an artificially constructed cyber-planet with android citizens.
- In the Invader Zim episode "Planet Jackers", two aliens surround the Earth with a fake sky in order to throw it into their sun.
- Nightmare's fortress from Kirby: Right Back at Ya! can be classified as a megastructure because it's the size of a small planet.
- In several works, Arthur C. Clarke writes about a colossal hollow tube, first described in "Rendezvous with Rama" (1973), and inhabited by different races.
- Onyx in the Halo universe is basically a planet made entirely out of forerunner sentinels

Megascale structures

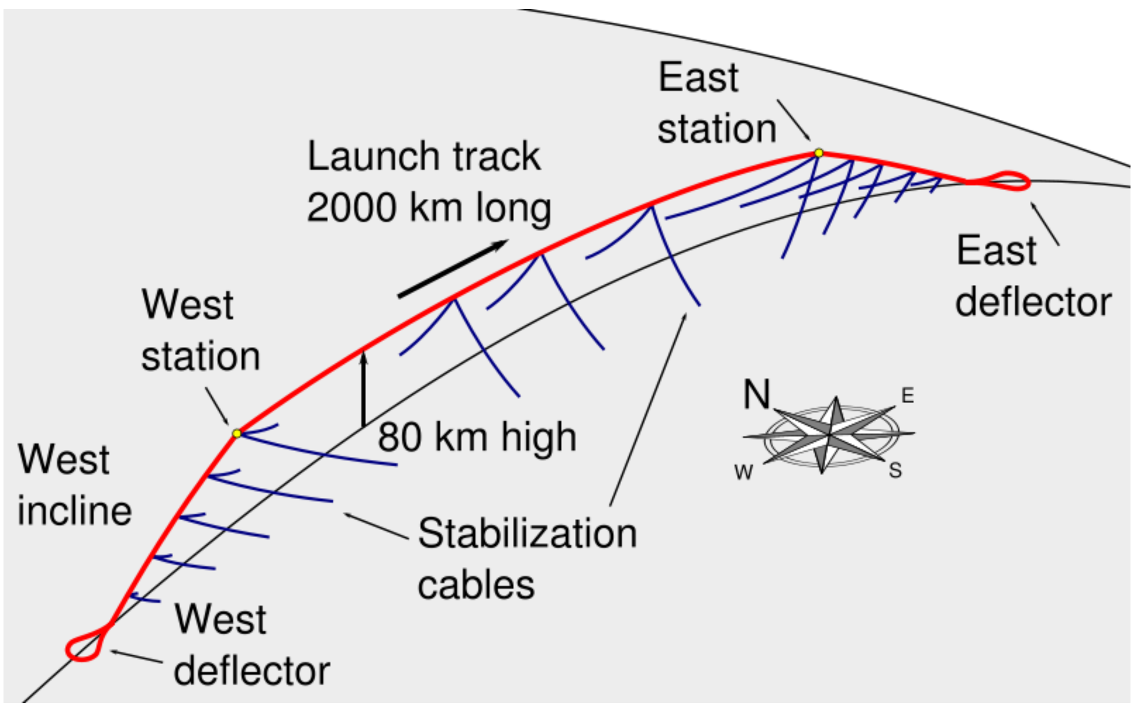
Structures that might not be classified as "*Megastructures*" because they do not meet the requirements, but are indeed "*Mega*" sized structures/constructions.

Stellar scale

- Dyson Bubble - Collection of separate constructions.
- Dyson Swarm - Collection of separate constructions.

Chapter- 6

Launch Loop



Launch loop. (Not to scale). The red marked line is the moving loop itself, blue lines are stationary cables.

A **launch loop** or **Lofstrom loop** is a published design for an active structure maglev cable transport system intended for orbital launch that would be around 2,000 km (1,240 mi) long and maintained at an altitude of up to 80 km (50 mi). A launch loop would be held up at this altitude by momentum of the belt as it circulates around the structure. This circulation, in effect, transfers the weight of the structure onto a pair of magnetic bearings, one at each end, which support it.

Launch loops are intended to achieve non-rocket spacelaunch of vehicles weighing 5 metric tons by electromagnetically accelerating them so that they are projected into Earth orbit or even beyond. This would be achieved by the flat part of the cable which forms an acceleration track above the atmosphere.

The published cost estimates for a working launch loop are significantly lower than a space elevator and additionally the proposed system has a greater launch capacity, lower payload costs and similar or greater payload masses. Unlike the space elevator, no new materials need to be developed.

The system is designed to be suitable for launching humans for space tourism, space exploration and space colonization, and provides a relatively low 3*g* acceleration.

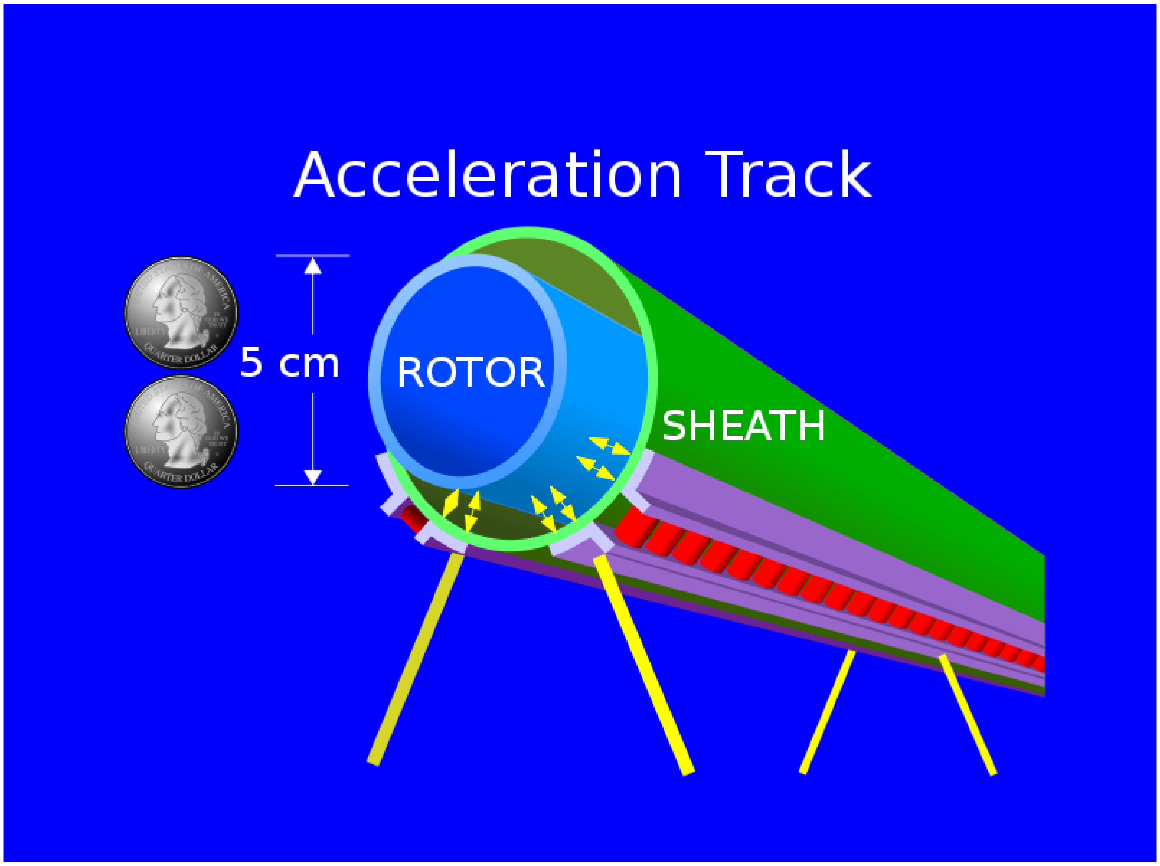
History

Launch loops were described by Keith Lofstrom in November 1981 Reader's Forum of the American Astronautical Society News Letter, and in the August 1982 L5 News.

In 1982 Paul Birch published a series of papers in *Journal of the British Interplanetary Society* which described orbital rings and described a form which he called Partial Orbital Ring System (PORS).

The launch loop idea was worked on in more detail around 1983–1985 by Lofstrom. It is a fleshed-out version of PORS specifically arranged to form a mag-lev acceleration track suitable for launching humans into space; but whereas the orbital ring used superconducting magnetic levitation, launch loops use Electromagnetic suspension (EMS).

Description



Launch loop accelerator section (return cable not shown)

A launch loop is proposed to be a structure around 2,000 km long and 80 km high. The loop runs along at 80 km above the earth for 2000 km then descends to earth before looping back on itself rising back to 80 km above the earth to follow the reverse path then looping back to the starting point. The loop would be in the form of a tube, known as the *sheath*. Floating within the sheath is another continuous tube, known as the *rotor* which is a sort of belt or chain. The rotor is an iron tube approximately 5 cm (2 inches) in diameter, moving around the loop at 14 km/s (31 000 miles per hour).

Although the overall loop is very long, at around 4,000 km circumference, the rotor itself would be thin, around 5 cm diameter and the sheath is not much bigger.

Ability to stay aloft

When at rest, the loop is at ground level. The rotor is then accelerated up to speed. As the rotor speed increases, it curves to form an arc. The sheath forces it to follow a curve steeper than the rotor's natural ballistic curve, which, in turn, exerts a reactive centrifugal force on the sheath, holding it aloft. The loop would be anchored to the ground to remain at a fixed height.

Once raised, the structure requires continuous power to overcome the energy dissipated. Additional energy would be needed to power any vehicles that are launched.

Launching payloads

To launch, vehicles are raised up on an 'elevator' cable that hangs down from the West station loading dock at 80 km, and placed on the track. The payload applies a magnetic field which generates eddy currents in the fast-moving rotor. This both lifts the payload away from the cable, as well as pulls the payload along with 3*g* (30 m/s²) acceleration. The payload then rides the rotor until it reaches the required orbital velocity, and leaves the track.

If a stable or circular orbit is needed, once the payload reaches the highest part of its trajectory then an on-board rocket engine ("kick motor") or other means is needed to circularize the trajectory to the appropriate Earth orbit.

The eddy current technique is compact, lightweight and powerful, but inefficient. With each launch the rotor temperature increases by 80 kelvins due to power dissipation. If launches are spaced too close together, the rotor temperature can approach 770 °C (1043 K), at which point the iron rotor loses its ferromagnetic properties and rotor containment is lost.

Capacity and capabilities

Closed orbits with a perigee of 80 km quite quickly decay and re-enter, but in addition to such orbits, a launch loop by itself would also be capable of directly injecting payloads into escape orbits, gravity assist trajectories past the Moon, and other non closed orbits such as close to the Trojan points.

To access circular orbits using a launch loop a relatively small 'kick motor' would need to be launched with the payload which would fire at apogee and would circularise the orbit. For GEO insertion this would need to provide a delta-v of about 1.6 km/s, for LEO to circularise at 500 km would require a delta-v of just 120 m/s. Conventional rockets require delta-vs of roughly 10 and 14 km/s to reach LEO and GEO respectively.

Launch loops in Lofstrom's design are placed close to the equator and can only directly access equatorial orbits. However other orbital planes might be reached via high altitude plane changes, lunar perturbations or aerodynamic techniques.

Launch rate capacity of a launch loop is ultimately limited by the temperature and cooling rate of the rotor to 80 per hour, but that would require a 17 GW power station; a more modest 500 MW power station is sufficient for 35 launches per day.

Economics

For a launch loop to be economically viable it would require customers with sufficiently large payload launch requirements.

Lofstrom estimates that an initial loop costing roughly $10 billion with a one-year payback could launch 40,000 metric tons per year, and cut launch costs to $300/kg, or for $30 billion, with a larger power generation capacity, the loop would be capable of launching 6 million metric tons per year, and given a five-year payback period, the costs for accessing space with a launch loop could be as low as $3/kg.

Comparisons

Advantages of launch loops

Lofstrom's launch loops are expected to launch at high rates (many launches per hour, independent of weather), and are not inherently polluting. Rockets create pollution such as nitrates in their exhausts due to high exhaust temperature, and can create greenhouse gases depending on propellant choices. Launch loops as a form of electric propulsion can be clean, and can be run on geothermal, nuclear, wind, solar or any other power source, even intermittent ones, as the system has huge built-in power storage capacity.

Unlike space elevators which would have to travel through the Van Allen belts over several days, launch loop passengers can be launched to low earth orbit, which is below the belts, or through them in a few hours. This would be a similar situation to that faced by the Apollo astronauts, who had radiation doses 200 times lower than the space elevator would give.

Unlike space elevators which are subjected to the risks of space debris and meteorites along their whole length, launch loops are to be situated at an altitude where orbits are unstable due to air drag. Since debris does not persist, it only has one chance to impact the structure. Whereas the collapse period of space elevators is expected to be of the order of years, damage or collapse of loops in this way is expected to be rare. In addition, launch loops themselves are not a significant source of space debris, even in an accident. All debris generated has a perigee that intersects the atmosphere or is at escape velocity.

Launch loops are intended for human transportation, to give a safe 3*g* acceleration which the vast majority of people would be capable of tolerating well, and would be a much faster way of reaching space than space elevators.

Launch loops would be quiet in operation, and would not cause any sound pollution, unlike rockets.

Finally, their low payload costs are compatible with large-scale commercial space tourism and even space colonisation.

Difficulties of launch loops

A running loop would have an extremely large amount of energy in the form of linear momentum. While the magnetic suspension system would be highly redundant, with failures of small sections having essentially no effect at all, if a major failure did occur the energy in the loop (1.5×10^{15} joules or 1.5 petajoules) would be approaching the same total *energy* release as a nuclear bomb explosion (350 kilotons of TNT equivalent), although not emitting nuclear radiation.

While this is a large amount of energy, it is unlikely that this would destroy very much of the structure due to its very large size, and because most of the energy would be deliberately dumped at preselected places when the failure is detected. Steps might need to be taken to lower the cable down from 80 km altitude with minimal damage, such as parachutes.

Therefore for safety and astrodynamic reasons, launch loops are intended to be installed over an ocean near the equator, well away from habitation.

The published design of a launch loop requires electronic control of the magnetic levitation to minimise power dissipation and to stabilise the otherwise under-damped cable.

The instabilities are primarily in the turnaround sections as well as the cable.

The turnaround sections are potentially unstable, since movement of the rotor away from the magnets gives reduced magnetic attraction, whereas movements closer gives increased attraction. In either case instability occurs. This problem is routinely solved with existing servocontrol systems that vary the strength of the magnets. Although servo reliability is a potential issue, at the high speed of the rotor, very many consecutive sections would need to fail for the rotor containment to be lost.

The cable sections also share this potential issue, although the forces are much lower. However, an additional instability is present in that the cable/sheath/rotor may undergo meandering modes (similar to a Lariat chain) that grow in amplitude without limit. Lofstrom believes that this instability also can be controlled in real time by servomechanisms, although this has never been attempted.

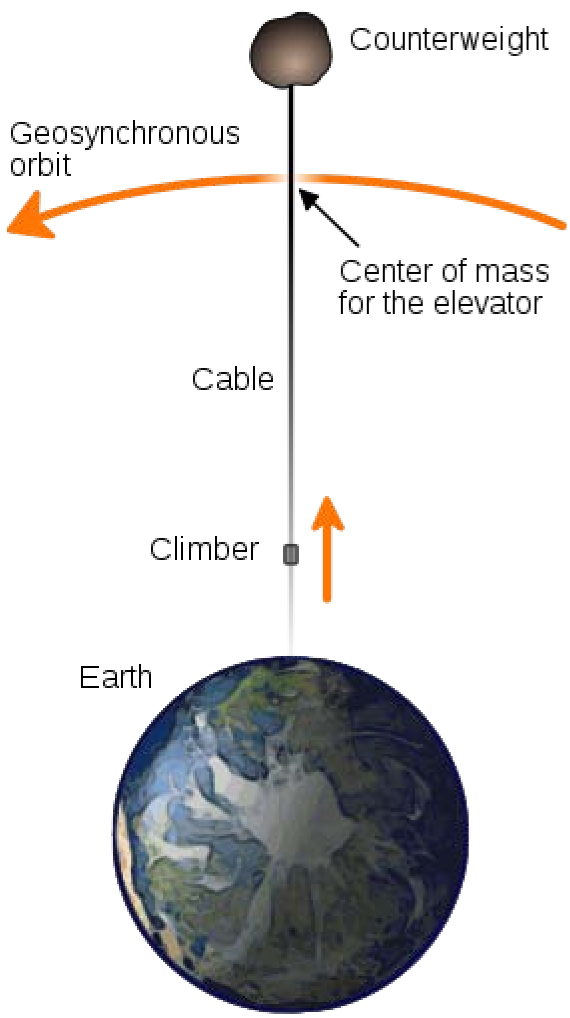
Competing and similar designs

In works by Alexander Bolonkin it is suggested that Lofstrom's project has many non-solved problems and that it is very far from a current technology. For example, the Lofstrom project has expansion joints between 1.5 meter iron plates. Their speeds (under gravitation, friction) can be different and Bolonkin claims that they could wedge in the tube; and the force and friction in the ground 28 km diameter turnaround sections are gigantic. In 2008 Bolonkin proposed a simple rotated close-loop cable to launch the space apparatus in a way suitable for current technology.

Another project, the **space cable**, is a smaller design by John Knapman that is intended for launch assist for conventional rockets, and suborbital tourism. The space cable design uses electrodynamic levitation rather than electromagnetic levitation and discrete 'bolt's rather than a continuous rotor as with the launch loop architecture. John Knapman has also mathematically shown that the meander instability can be tamed.

Chapter- 7

Space Elevator



A space elevator for Earth would consist of a cable anchored to the Earth's surface, reaching into space. By attaching a counterweight at the end (or by further extending the cable for the same purpose), inertia ensures that the cable remains stretched taut, countering the gravitational pull on the lower sections, thus allowing the elevator to remain

in geosynchronous orbit. Once beyond the gravitational midpoint, carriages would be accelerated further by the planet's rotation. (Diagram is not to scale.)

A **space elevator** is a proposed non-rocket spacelaunch structure (a structure designed to transport material from a celestial body's surface into space). Many elevator variants have been suggested, all of which involve travelling along a fixed structure instead of using rocket powered space launch, most often a cable that reaches from the surface of the Earth on or near the Equator to geostationary orbit (GSO) and a counter-mass outside of the geostationary orbit.

Discussion of a space elevator dates back to 1895 when Konstantin Tsiolkovsky proposed a free-standing "Tsiolkovsky" tower reaching from the surface of Earth to geostationary orbit. Most recent discussions focus on tensile structures (specifically, a space tether) reaching from beyond geostationary orbit to the ground. This structure would be held in tension between Earth and the counterweight in space like a guitar string held taut. Space elevators have also sometimes been referred to as *beanstalks*, *space bridges*, *space lifts*, *space ladders*, *skyhooks*, *orbital towers*, or *orbital elevators*.

While some variants of the space elevator concept are technologically feasible, current technology is not capable of manufacturing practical engineering materials that are sufficiently strong and light to build an Earth-based space elevator of the geostationary orbital tether type. Recent conceptualizations for a space elevator are notable in their plans to use carbon nanotube or boron nitride nanotube based materials as the tensile element in the tether design, since the measured strength of nanoscopic carbon nanotubes appears great enough to make this possible. Technology as of 1978 could produce elevators for locations in the solar system with weaker gravitational fields, such as the Moon or Mars.

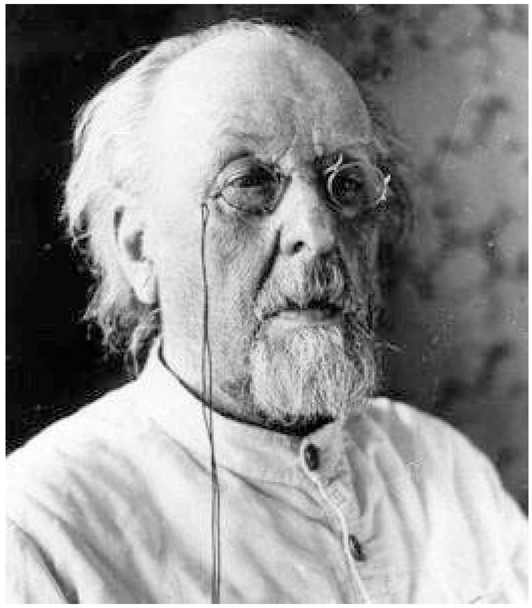
A further issue is that for human riders on an Earth-based elevator, space radiation due to the Van Allen belts would, if unshielded, give a dose well above permitted levels. This would not be an issue for non-living cargo, however.

Geostationary orbital tethers

This concept, also called an **orbital space elevator**, **geostationary orbital tether**, or a **beanstalk**, is a subset of the skyhook concept, and is what people normally think of when the phrase 'space elevator' is used (although there are variants).

Construction would be a large project: the minimum length of an Earth-based space elevator is well over 38,000 km (24,000 mi) long. The tether would have to be built of a material that could endure tremendous stress while also being light-weight, cost-effective, and manufacturable in great quantities. Materials currently available do not meet these requirements, although carbon nanotube technology shows great promise. As with all leading-edge engineering projects, other novel engineering problems would also have to be solved to make a space elevator practical, and there are problems regarding feasibility that have yet to be addressed.

History



Konstantin Tsiolkovsky

Early concepts

The key concept of the space elevator appeared in 1895 when Russian scientist Konstantin Tsiolkovsky was inspired by the Eiffel Tower in Paris to consider a tower that reached all the way into space, built from the ground up to an altitude of 35,790 kilometers (22,238 mi) above sea level (geostationary orbit). He noted that a "celestial castle" at the top of such a spindle-shaped cable would have the "castle" orbiting Earth in a geostationary orbit (i.e. the castle would remain over the same spot on Earth's surface).

Since the elevator would attain orbital velocity as it rode up the cable, an object released at the tower's top would also have the orbital velocity necessary to remain in geostationary orbit. Unlike more recent concepts for space elevators, Tsiolkovsky's (conceptual) tower was a compression structure, rather than a tension (or "tether") structure.

Twentieth century

Building a compression structure from the ground up proved an unrealistic task as there was no material in existence with enough compressive strength to support its own weight under such conditions. In 1959 another Russian scientist, Yuri N. Artsutanov, suggested a more feasible proposal. Artsutanov suggested using a geostationary satellite as the base from which to deploy the structure downward. By using a counterweight, a cable would be lowered from geostationary orbit to the surface of Earth, while the counterweight was extended from the satellite away from Earth, keeping the center of gravity of the cable motionless relative to Earth. Artsutanov's idea was introduced to the Russian-speaking public in an interview published in the Sunday supplement of *Komsomolskaya Pravda* in

1960, but was not available in English until much later. He also proposed tapering the cable thickness so that the stress in the cable was constant—this gives a thin cable at ground level, thickening up towards GSO.

Both the tower and cable ideas were proposed in the quasi-humorous *Ariadne* column in *New Scientist*, 24 December 1964.

Making a cable over 35,000 kilometers (22,000 miles) long is a difficult task. In 1966, Isaacs, Vine, Bradner and Bachus, four American engineers, reinvented the concept, naming it a "Sky-Hook," and published their analysis in the journal *Science*. They decided to determine what type of material would be required to build a space elevator, assuming it would be a straight cable with no variations in its cross section, and found that the strength required would be twice that of any existing material including graphite, quartz, and diamond.

In 1975 an American scientist, Jerome Pearson, reinvented the concept yet again, publishing his analysis in the journal Acta Astronautica. He designed a tapered cross section that would be better suited to building the elevator. The completed cable would be thickest at the geostationary orbit, where the tension was greatest, and would be narrowest at the tips to reduce the amount of weight per unit area of cross section that any point on the cable would have to bear. He suggested using a counterweight that would be slowly extended out to 144,000 kilometers (90,000 miles, almost half the distance to the Moon) as the lower section of the elevator was built. Without a large counterweight, the upper portion of the cable would have to be longer than the lower due to the way gravitational and centrifugal forces change with distance from Earth. His analysis included disturbances such as the gravitation of the Moon, wind and moving payloads up and down the cable. The weight of the material needed to build the elevator would have required thousands of Space Shuttle trips, although part of the material could be transported up the elevator when a minimum strength strand reached the ground or be manufactured in space from asteroidal or lunar ore.

In 1977, Hans Moravec published an article called "A Non-Synchronous Orbital Skyhook", in which he proposed an alternative space elevator concept, using a rotating cable, in which the rotation speed exactly matches the orbital speed in such a way that the instantaneous velocity at the point where the cable was at the closest point to the Earth was zero. This concept is an early version of a space tether transportation system.

In 1979, space elevators were introduced to a broader audience with the simultaneous publication of Arthur C. Clarke's novel, *The Fountains of Paradise*, in which engineers construct a space elevator on top of a mountain peak in the fictional island country of *Taprobane* (loosely based on Sri Lanka, albeit moved south to the Equator), and Charles Sheffield's first novel, *The Web Between the Worlds*, also featuring the building of a space elevator. Three years later, in Robert A. Heinlein's 1982 novel *Friday* the principal character makes use of the "Nairobi Beanstalk" in the course of her travels. In Kim Stanley Robinson's 1993 novel *Red Mars*, colonists build a space elevator on Mars that allows both for more colonists to arrive and also for natural resources mined there to be able to leave for Earth.

21st century

After the development of carbon nanotubes in the 1990s, engineer David Smitherman of NASA/Marshall's Advanced Projects Office realized that the high strength of these materials might make the concept of an orbital skyhook feasible, and put together a workshop at the Marshall Space Flight Center, inviting many scientists and engineers to discuss concepts and compile plans for an elevator to turn the concept into a reality. The publication he edited, compiling information from the workshop, "Space Elevators: An Advanced Earth-Space Infrastructure for the New Millennium", provides an introduction to the state of the technology at the time, and summarizes the findings.

Another American scientist, Bradley C. Edwards, suggested creating a 100,000 km (62,000 mi) long paper-thin ribbon using a carbon nanotube composite material. He chose a ribbon type structure rather than a cable because that structure might stand a greater chance of surviving impacts by meteoroids. Supported by the NASA Institute for Advanced Concepts, Edwards' work was expanded to cover the deployment scenario, climber design, power delivery system, orbital debris avoidance, anchor system, surviving atomic oxygen, avoiding lightning and hurricanes by locating the anchor in the western equatorial Pacific, construction costs, construction schedule, and environmental hazards. The largest holdup to Edwards' proposed design is the technological limit of the tether material. His calculations call for a fiber composed of epoxy-bonded carbon nanotubes with a minimal tensile strength of 130 GPa (19 million psi) (including a safety factor of 2); however, tests in 2000 of individual single-walled carbon nanotubes (SWCNTs), which should be notably stronger than an epoxy-bonded rope, indicated the strongest measured as 52 GPa (7.5 million psi). Multi-walled carbon nanotubes have been measured with tensile strengths up to 63 GPa (9 million psi).

To speed space elevator development, proponents are planning several competitions, similar to the Ansari X Prize, for relevant technologies. Among them are Elevator:2010, which will organize annual competitions for climbers, ribbons and power-beaming systems, the Robolympics Space Elevator Ribbon Climbing competition, as well as NASA's Centennial Challenges program, which, in March 2005, announced a partnership with the Spaceward Foundation (the operator of Elevator:2010), raising the total value of prizes to US$400,000.

In 2005, "the LiftPort Group of space elevator companies announced that it will be building a carbon nanotube manufacturing plant in Millville, New Jersey, to supply various glass, plastic and metal companies with these strong materials. Although LiftPort hopes to eventually use carbon nanotubes in the construction of a 100,000 km (62,000 mile) space elevator, this move will allow it to make money in the short term and conduct research and development into new production methods. The goal was a space elevator launch in 2010." On February 13, 2006 the LiftPort Group announced that, earlier the same month, they had tested a mile of "space-elevator tether" made of carbon-fiber composite strings and fiberglass tape measuring 5 cm (2 in) wide and 1 mm (approx. 6 sheets of paper) thick, lifted with balloons.

In 2007, Elevator:2010 held the 2007 Space Elevator games, which featured US$500,000 awards for each of the two competitions, (US$1,000,000 total) as well as an additional US$4,000,000 to be awarded over the next five years for space elevator related technologies. No teams won the competition, but a team from MIT entered the first 2-gram (0.07 oz), 100% carbon nanotube entry into the competition. Japan held an international conference in November 2008 to draw up a timetable for building the elevator.

In 2008 the book "Leaving the Planet by Space Elevator", by Dr. Brad Edwards and Philip Ragan, was published in Japanese and entered the Japanese best seller list. This has led to a Japanese announcement of intent to build a Space Elevator at a projected price tag of £5 billion. In a report by Leo Lewis, Tokyo correspondent of The Times newspaper in England, plans by Shuichi Ono, chairman of the Japan Space Elevator Association, are unveiled. Lewis says: "Japan is increasingly confident that its sprawling academic and industrial base can solve those [construction] issues, and has even put the astonishingly low price tag of a trillion yen (£5 billion/ $8 billion) on building the elevator. Japan is renowned as a global leader in the precision engineering and high-quality material production without which the idea could never be possible."

Physics of space elevators

Apparent gravitational field

The space elevator cable rotates along with the rotation of the Earth. Objects fastened to the cable will experience upward centrifugal force that opposes some, all, or more than the downward gravitational force at that point. Along the length of the cable, the *actual* (downward) gravity minus the (upward) centrifugal force is called the *apparent* gravitational field.

The apparent gravitational field can be computed this way:

$g = -G \cdot M/r^2 + \omega^2 \cdot r$, where
g is the acceleration along the radius (m s^{-2}),
G is the gravitational constant (m^3 s^{-2} kg^{-1})
M is the mass of the Earth (kg)
r is the distance from that point to Earth's center (m),
ω is Earth's rotation speed (radians/s).

Near the earth's surface the acceleration g_0 at radius r_0 is given by:

$g_0 = G \cdot M/r_0^2$(the other term is negligible), so that:

$G \cdot M = g_0 \cdot r_0^2$, which gives the $G \cdot M$ constant given the ground acceleration and planet radius.

At some point r_1 above the equator line, the two terms (gravity and centrifugal force) equal each other, the tether then carries no weight. This occurs at the level of the stationary orbit:

$r_1 = (g_0 \cdot r_0^2/\omega^2)^{1/3}$ which is to say $G \cdot M/r_1^2 = \omega^2 \cdot r_1$, which gives the value of r_1.

The same holds true for any planet or satellite.

Seen from a geosynchronous station, any object dropped off the tether from a point closer to Earth will initially accelerate downward. If dropped from any point above a geosynchronous station, the object would initially accelerate up toward space. If a long cable is dropped "down" (toward Earth), it must be properly balanced by balancing mass being dropped "up" (away from Earth) for the whole system to remain on the geosynchronous orbit. Some designs imagine the balancing mass being another cable (with counterweight) extending upward, other designs elevate the spool itself as the main cable is payed out. When the lower end of the cable is so long as to reach the Earth, it can be anchored at some place. Once anchored, if more mass is added at the remote end, it will add a tension to the whole cable, which can then be used as an elevator cable.

Cable section

The main technical problem is the long cable's own weight. The cable material combined with its design must be strong enough to hold up 35000 km (22,000 mi) of itself. The primary design factor other than the material is the taper ratio, that is, the ratio and taper rate of the cross sectional area of the cable as it goes from GEO to ground level. The solution is to build it in such a way that at any given point, its cross section area is proportional to the force it has to withstand, that is, the section must follow the following differential equation:

$\sigma \cdot dS = g \cdot \rho \cdot S \cdot dr$, where
g is the acceleration along the radius (m·s^{-2}),
S is the cross-area of the cable at any given point r, (m^2) and dS its variation (m^2 as well),
ρ is the density of the material used for the cable (kg·m^{-3}).
σ is the stress a given area can bear without splitting (N·m^{-2}=kg·m^{-1}·s^{-2}), its elastic limit

The value of *g* is given by the first equation, which yields:

$$\Delta\left[\ln(S)\right]_{r1}^{r0} = \rho/\sigma \cdot \Delta\left[G \cdot M/r + w^2 \cdot r^2/2\right]_{r1}^{r0},$$

the variation being taken between r_1 (geostationary) and r_0 (ground).

It turns out that between these two points, this quantity can be expressed simply as: $\Delta\left[\ln(S)\right] = \rho/\sigma \cdot g_0 \cdot r_0 \cdot (1 + x/2 - 3/2 \cdot x^{1/3})$, or

$$S_0 = S_1 . e^{\rho/\sigma \cdot g_0 \cdot r_0 \cdot (1 + x/2 - 3/2 \cdot x^{1/3})}$$

where $x = \omega^2 \cdot r_0/g_0$ is the ratio between the centrifugal force on the equator and the gravitational force.

Thus, the factor with the main influence is $g_0\ r_0$, the combination of the planet's radius and its surface gravity. The rotational speed is slightly influential, but only as a corrective factor. For Earth, it reduces the strength needed by about one third.

Cable material

The second technical problem is that the $g_0\ r_0$ factor is quite large. Since its influence on the maximal cross-section is exponential, one needs to find materials where σ will be large enough to cancel our gravity. On Earth, we have:

$g_0 \cdot r_0 = 62.5 \cdot 10^6\ m^2 s^{-2}$ (or Joules per kg)
$\rho \approx 3 \cdot 10^3\ kg\ m^{-3}$ for most solid materials, so that σ needs to be:
$\sigma \approx 300 \cdot 10^9\ kg\ m^{-1} s^{-2}$

This corresponds to a cable capable of sustaining 30 tons with a cross-section of one square millimeter, under Earth's gravity.

The *free breaking length* can be used to compare materials: it is the length of a cylindrical cable at which it will split under its own weight (under constant gravity). For a given material, that length is $\sigma/\rho/g_0$. The free breaking length needed is given by the equation

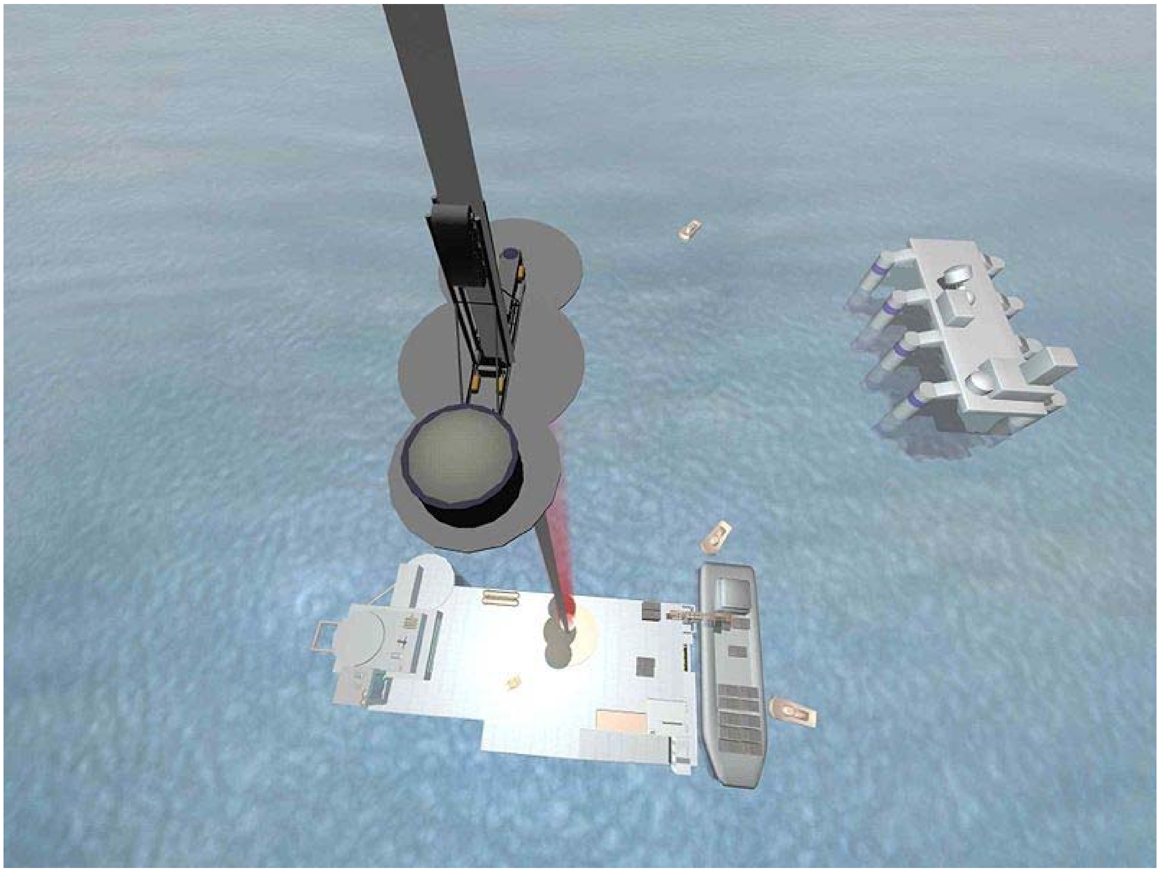
$\Delta\left[\ln(S)\right] = \rho/\sigma \cdot g_0 \cdot r_0 \cdot (1 + x/2 - 3/2 \cdot x^{1/3})$, where
$x = w^2 \cdot r_0/g_0$

If one does not take into account the x factor (which reduces the strength needed by about 30%), this equation also says that the section ratio equals e (exponential one) when:

$$\sigma = \rho \cdot r_0 \cdot g_0$$

In other words, the free breaking length is approximately equal to the planet's radius under its own gravity. Since the section ratio varies exponentially, the free breaking length must be at least of that order of magnitude. If the material is only ten times less resilient, the section needed at a geosynchronous orbit will be e^{10} times the ground section, which is more than a hundredfold in diameter, which is practically impossible.

Structure



One concept for the space elevator has it tethered to a mobile seagoing platform.

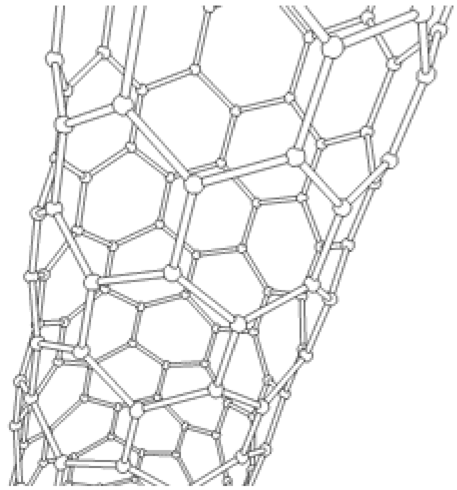
The centrifugal force of earth's rotation is the main principle behind the elevator. As the earth rotates, the centrifugal force tends to align the nanotube in a stretched manner. There are a variety of tether designs. Almost every design includes a base station, a cable, climbers, and a counterweight.

Base station

The base station designs typically fall into two categories—mobile and stationary. Mobile stations are typically large oceangoing vessels. Stationary platforms would generally be located in high-altitude locations, such as on top of mountains, or even potentially on high towers.

Mobile platforms have the advantage of being able to maneuver to avoid high winds, storms, and space debris. While stationary platforms don't have these advantages, they typically would have access to cheaper and more reliable power sources, and require a shorter cable. While the decrease in cable length may seem minimal (no more than a few kilometers), the cable thickness could be reduced over its entire length, significantly reducing the total weight.

Cable



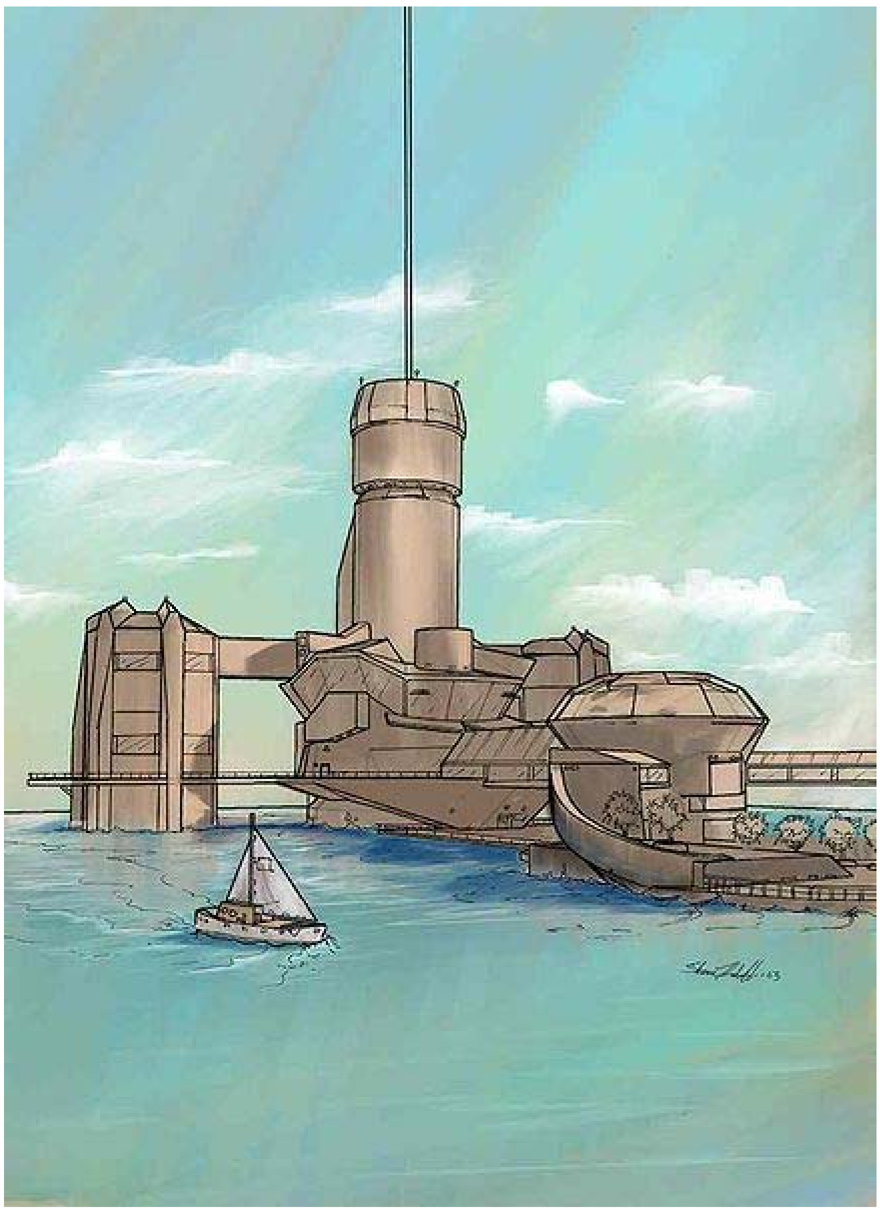
Carbon nanotubes are one of the candidates for a cable material

A space elevator cable must carry its own weight as well as the (smaller) weight of climbers. The required strength of the cable will vary along its length, since at various points it has to carry the weight of the cable below, or provide a centripetal force to retain the cable and counterweight above. In a 1998 report, NASA researchers noted that "maximum stress [*sic*] [on a space elevator cable] is at geosynchronous altitude so the cable must be thickest there and taper exponentially as it approaches Earth. Any potential material may be characterized by the taper factor – the ratio between the cable's radius at geosynchronous altitude and at the Earth's surface."

The cable must be made of a material with a large tensile strength/mass ratio. For example, the Edwards space elevator design assumes a cable material with a specific strength of at least 100,000 kN/(kg/m). This value takes into consideration the entire weight of the space elevator. A space elevator would need a material capable of sustaining a length of 4,960 kilometers (3082 mi) of its own weight *at sea level* to reach a geostationary altitude of 36,000 km (22,300 mi) without tapering and without breaking. Therefore, a material with very high strength and lightness is needed.

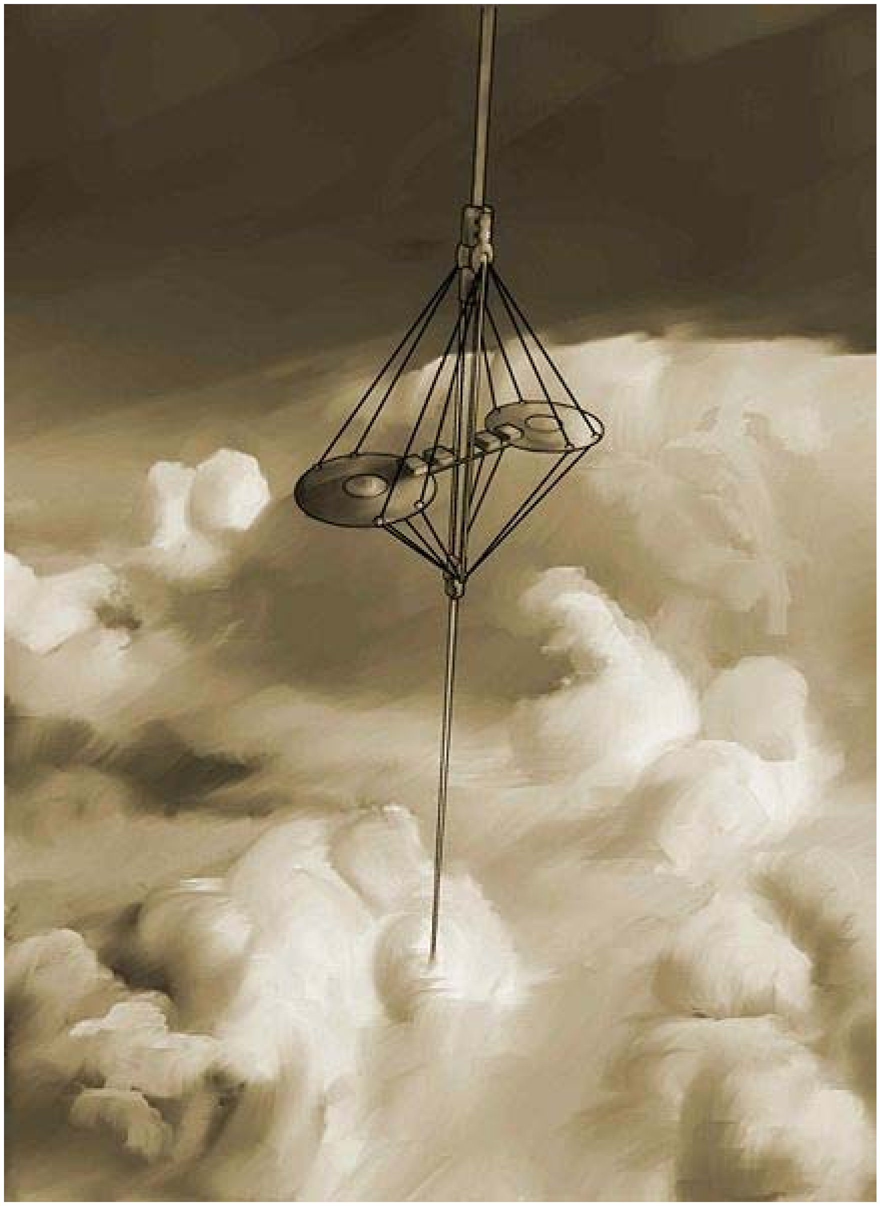
For comparison, metals like titanium, steel or aluminium alloys have breaking lengths of only 20–30 km. Modern fibre materials (which tend to achieve greater strength because the microscopic or crystal structure is aligned with the axis of the material and has fewer defects) such as kevlar, fibreglass and carbon/graphite fibre have breaking lengths of 100–400 km. Quartz fibers have an advantage that they can be drawn to a length of hundreds of kilometers even with the present-day technology. Nanoengineered materials such as carbon nanotubes and, more recently discovered, graphene ribbons (perfect twodimensional sheets of carbon) are expected to have breaking lengths of 5000–6000 km at sea level, and also are able to conduct electrical power.

Carbon is such a good candidate material (for high specific strength) because, as only the 6th element in the periodic table, it has very few of the nucleons which contribute most of the dead weight of any material (whereas most of the interatomic bonding forces are contributed by only the outer few electrons); the challenge now remains to extend to macroscopic sizes the production of such material that are still perfect on the microscopic scale (as microscopic defects are most responsible for material weakness). The current (2009) carbon nanotube technology allows growing tubes up to a few tens of centimeters only.



A seagoing anchor station would incidentally act as a deep-water seaport.

Climbers

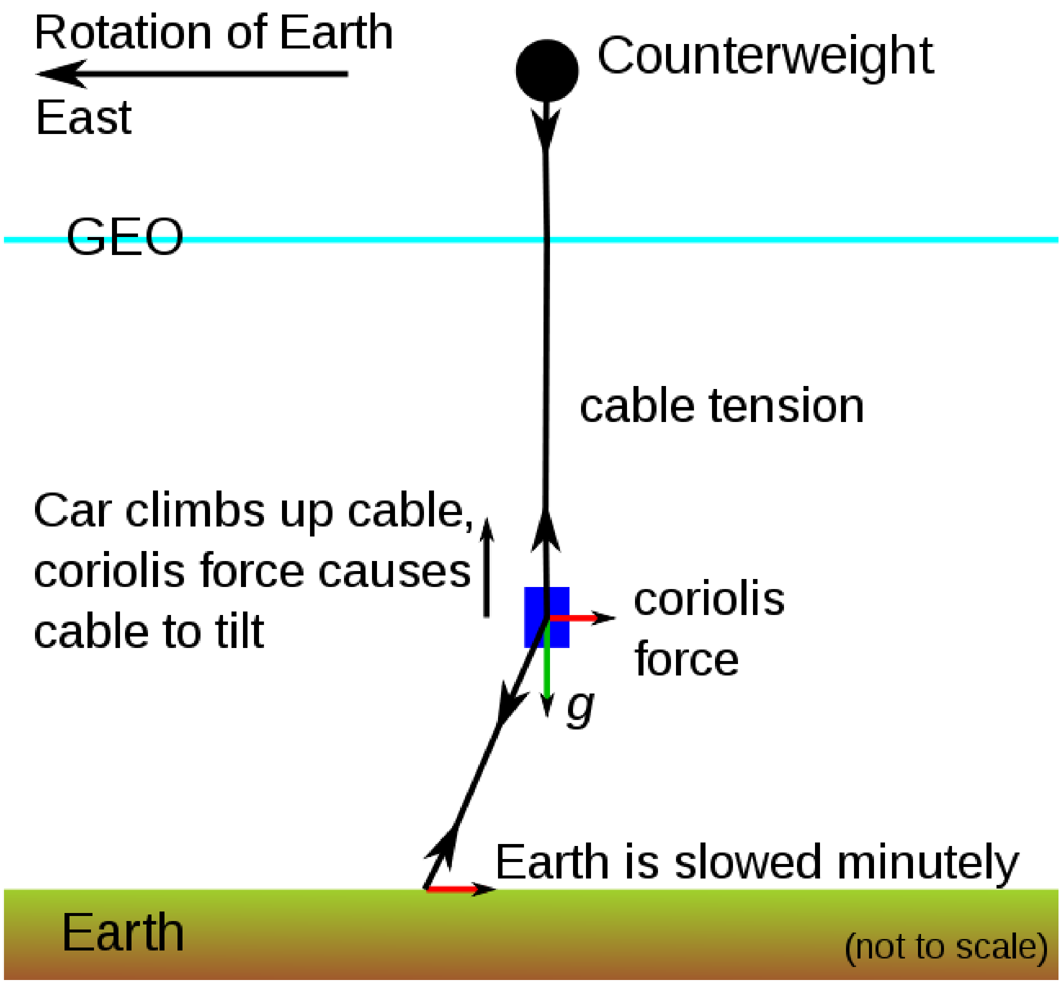


A conceptual drawing of a space elevator climbing through the clouds.

A space elevator cannot be an elevator in the typical sense (with moving cables) due to the need for the cable to be significantly wider at the center than the tips. While various designs employing moving cables have been proposed, most cable designs call for the "elevator" to climb up a stationary cable.

Climbers cover a wide range of designs. On elevator designs whose cables are planar ribbons, most propose to use pairs of rollers to hold the cable with friction.

Climbers must be paced at optimal timings so as to minimize cable stress and oscillations and to maximize throughput. Lighter climbers can be sent up more often, with several going up at the same time. This increases throughput somewhat, but lowers the mass of each individual payload.



As the car climbs, the elevator takes on a 1 degree lean, due to the top of the elevator traveling faster than the bottom around the Earth (Coriolis force). This diagram is not to scale.

The horizontal speed of each part of the cable increases with altitude, proportional to distance from the center of the Earth, reaching orbital velocity at geostationary orbit. Therefore as a payload is lifted up a space elevator, it needs to gain not only altitude but angular momentum (horizontal speed) as well. This angular momentum is taken from the Earth's own rotation. As the climber ascends it is initially moving slightly more slowly than the cable that it moves onto (Coriolis force) and thus the climber "drags" on the cable.

The overall effect of the centrifugal force acting on the cable causes it to constantly try to return to the energetically favourable vertical orientation, so after an object has been lifted on the cable the counterweight will swing back towards the vertical like an inverted pendulum. Provided that the space elevator is designed so that the center of weight always stays above geostationary orbit for the maximum climb speed of the climbers, the elevator cannot fall over. Lift and descent operations must be carefully planned so as to keep the pendulum-like motion of the counterweight around the tether point under control.

By the time the payload has reached GEO the angular momentum (horizontal speed) is enough that the payload is in orbit.

The opposite process would occur for payloads descending the elevator, tilting the cable eastwards and insignificantly increasing Earth's rotation speed.

It has also been proposed to use a second cable attached to a platform to lift payload up the main cable, since the lifting device would not have to deal with its own weight against Earth's gravity. Out of the many proposed theories, powering any lifting device also continues to present a challenge.

Another design constraint will be the ascending speed of the climber. As geosynchronous orbit is at 35,786 km (22,236 mi). Assuming the climber can reach the speed of a very fast car or train of 300 km/h (180 mph) it will take 5 days to climb to geosynchronous orbit.

Powering climbers

Both power and energy are significant issues for climbers—the climbers need to gain a large amount of potential energy as quickly as possible to clear the cable for the next payload.

All proposals to get that energy to the climber fall into 3 categories:

- transfer the energy to the climber through wireless energy transfer while it is climbing
- transfer the energy to the climber through some material structure while it is climbing
- store the energy in the climber before it starts—this requires an extremely high specific energy. Nuclear energy and solar power have been proposed, but generating enough energy to reach the top of the elevator in any reasonable time without weighing too much is not feasible.

The proposed method is laser power beaming, using megawatt powered free electron or solid state lasers in combination with adaptive mirrors approximately 10 m (33 ft) wide and a photovoltaic array on the climber tuned to the laser frequency for efficiency. A major obstacle for any climber design is the dissipation of the substantial amount of waste heat generated due to the less than perfect efficiency of any of the power methods.

Yoshio Aoki, a professor of precision machinery engineering at Nihon University and director of the Japan Space Elevator Association, suggested including a second cable and using the conductivity of carbon nanotubes to provide power.

Various mechanical means of applying power have also been proposed; such as moving, looped or vibrating cables.

Counterweight

Several solutions have been proposed to act as a counterweight:

1. a heavy, captured asteroid;
2. a space dock, space station or spaceport positioned past geostationary orbit; or
3. an extension of the cable itself far beyond geostationary orbit.

The third idea has gained more support in recent years due to the relative simplicity of the task and the fact that a payload that went to the end of the counterweight-cable would acquire considerable velocity relative to the Earth, allowing it to be launched into interplanetary space.

Additionally, Brad Edwards has proposed that initially elevators would be up-only, and that the elevator cars that are used to thicken the cable could simply be parked at the top of the cable and act as a counterweight.

Alternative concepts

The original concept envisioned by Tsiolkovsky was a compression structure, a concept similar to an aerial mast. While such structures might reach the agreed altitude for space (100 km—62 mi), they are unlikely to reach geostationary orbit (35,786 km—22,236 mi). The concept of a Tsiolkovsky tower combined with a classic space elevator cable has been suggested.

A mini version of the Space Elevator to access near-space altitudes of 20 km (12 mi) has been proposed by Canadian researchers. The structure would be pneumatically supported and free standing with control systems guiding the structure's center of gravity. Proposed uses include tourism and commerce, communications, wind generation and low-cost space launch.

Other alternatives to a space elevator include an orbital ring, a pneumatic space tower, a space fountain, a launch loop, a Skyhook, a space tether, and a space hoist.

Launching into deep space

The velocities that might be attained at the end of Pearson's 144,000 km (90,000 mi) cable can be determined. The tangential velocity is 10.93 kilometers per second (6.79 mi/s), which is more than enough to escape Earth's gravitational field and send probes at least as far out as Jupiter. Once at Jupiter, a gravitational assist maneuver permits solar escape velocity to be reached.

Extraterrestrial elevators

A space elevator could also be constructed on other planets, asteroids and moons.

A Martian tether could be much shorter than one on Earth. Mars' surface gravity is 38% of Earth's, while it rotates around its axis in about the same time as Earth. Because of this, Martian areostationary orbit is much closer to the surface, and hence the elevator would be much shorter. Current materials are already sufficiently strong to construct such an elevator. However, building a Martian elevator would be complicated by the Martian moon Phobos, which is in a low orbit and intersects the Equator regularly (twice every orbital period of 11 h 6 min).

A lunar space elevator can possibly be built with currently available technology about 50,000 kilometers (31,000 miles) long extending through the Earth-Moon L1 point from an anchor point near the center of the visible part of Earth's moon.

On the far side of the moon, a lunar space elevator would need to be very long (more than twice the length of an Earth elevator) but due to the low gravity of the Moon, can be made of existing engineering materials.

Rapidly spinning asteroids or moons could use cables to eject materials to convenient points, such as Earth orbits; or conversely, to eject materials to send the bulk of the mass of the asteroid or moon to Earth orbit or a Lagrangian point. Freeman Dyson, a physicist and mathematician, has suggested using such smaller systems as power generators at points distant from the Sun where solar power is uneconomical. For the purpose of mass ejection, it is not necessary to rely on the asteroid or moon to be rapidly spinning. Instead of attaching the tether to the equator of a rotating body, it can be attached to a rotating hub on the surface. This was suggested in 1980 as a "Rotary Rocket" by Pearson and described very succinctly on the Island One website as a "Tapered Sling".

Construction

The construction of a space elevator would be a vast project requiring advances in engineering, manufacturing, and physical technology.

Safety issues and construction challenges

Radiation exposure to passengers traveling through the Van Allen radiation belts, if unshielded, would give a total exposure above levels considered safe. Adequate shielding would be required for manned transits.

A space elevator would present a navigational hazard, both to aircraft and spacecraft. Aircraft could be diverted by air-traffic control restrictions. All objects in stable orbits that have perigee below the maximum altitude of the cable that are not synchronous with the cable will impact the cable eventually, unless avoiding action is taken. For spacecraft one potential solution proposed by Edwards is to use a movable anchor (a sea anchor) to allow the tether to "dodge" any space debris large enough to track.

Impacts by space objects such as meteoroids, micrometeorites and orbiting man-made debris, pose a more difficult problem, because the potential of a strand break to cause a failure cascade is, according to Tom Nugent, the Research Director of LiftPort Inc., "A potential show-stopper for construction of the space elevator [that] has not yet been adequately addressed.".

Economics

With a space elevator, materials might be sent into orbit at a fraction of the current cost. As of 2000, conventional rocket designs cost about $11,000 per pound ($25,000 per kilogram) for transfer to geostationary orbit. Current proposals envision payload prices starting as low as $100 per pound ($220 per kilogram), similar to the $5–$300/kg estimates of the Launch loop, although nowhere near the $310/ton to 500 km orbit quoted to Dr. Jerry Pournelle for an orbital airship system.

Philip Ragan, co-author of the book "Leaving the Planet by Space Elevator", states that "The first country to deploy a space elevator will have a 95 percent cost advantage and could potentially control all space activities."

Chapter- 8

Star Lifting, Generation Ship and Project Daedalus

Star lifting

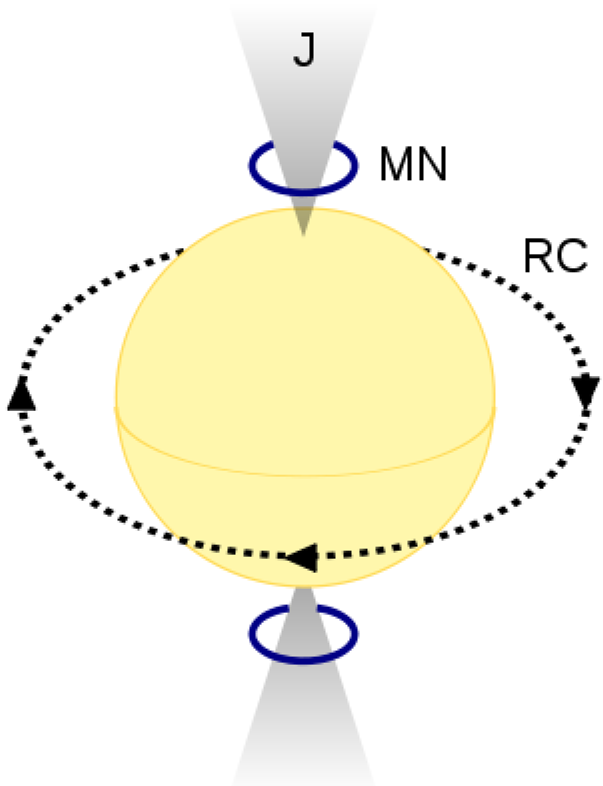
Star lifting is any of several hypothetical processes by which a highly advanced civilization (at least Kardashev-II) could remove a substantial portion of a star's matter in a controlled manner for other uses. The term appears to have been coined by David Criswell.

Stars already lose a small flow of mass via solar wind, coronal mass ejections, and other natural processes. Over the course of a star's life on the main sequence this loss is usually negligible compared to the star's total mass; only at the end of a star's life when it becomes a red giant or a supernova is a large amount of material ejected. The star lifting techniques that have been proposed would operate by increasing this natural plasma flow and manipulating it with magnetic fields.

Stars have deep gravity wells, so the energy required for such operations is large. For example, lifting solar material from the surface of the Sun to infinity requires 2.1×10^{11} J/kg. This energy could be supplied by the star itself, collected by a Dyson sphere; using only 10% of the Sun's total power output would allow 5.9×10^{21} kilograms of matter to be lifted per year (0.0000003% of the Sun's total mass). The Dyson sphere would need to be designed to allow the lifted material to egress through it.

Methods for lifting material

Thermal-driven outflow



A mechanism for "harvesting" solar wind (RC = ring current, MN = magnetic nozzles, J = plasma jet).

The simplest system for star lifting would increase the rate of solar wind outflow by directly heating small regions of the star's atmosphere, using any of a number of different means to deliver energy such as microwave beams, lasers, or particle beams – whatever proved to be most efficient for the engineers of the system. This would produce a large and sustained eruption similar to a solar flare at the target location, feeding the solar wind.

The resulting outflow would be collected by using a ring current around the star's equator to generate a powerful toroidal magnetic field with its dipoles over the star's rotational poles. This would deflect the star's solar wind into a pair of jets aligned along its rotational axis passing through a pair of magnetic rocket nozzles. The magnetic nozzles would convert some of the plasma's thermal energy into outward velocity, helping to cool the outflow. The ring current required to generate this magnetic field would be generated by a ring of particle accelerator space stations in close orbit around the star's equator. These accelerators would be physically separate from each other but would exchange two counterdirected beams of oppositely charged ions with their neighbor on each side, forming a complete circuit around the star.

"Huff-n-Puff"

Criswell proposed a modification to the polar jet system in which the magnetic field could be used to increase solar wind outflow directly, without requiring additional heating of the star's surface. He dubbed it the "Huff-n-Puff" method, inspired from the Big Bad Wolf's threats in the fairy tale of *Three Little Pigs*.

In this system the ring of particle accelerators would not be in orbit, instead depending on the outward force of the magnetic field itself for support against the star's gravity. To inject energy into the star's atmosphere the ring current would first be temporarily shut down, allowing the particle accelerator stations to begin falling freely toward the star's surface. Once the stations had developed sufficient inward velocity the ring current would be reactivated and the resulting magnetic field would be used to reverse the stations' fall. This would "squeeze" the star, propelling stellar atmosphere through the polar magnetic nozzles. The ring current would be shut down again before the ring stations achieved enough outward velocity to throw them too far away from the star, and the star's gravity would be allowed to pull them back inward to repeat the cycle.

A single set of ring stations would result in a very intermittent flow. It is possible to smooth this flow out by using multiple sets of ring stations, with each set operating in a different stage of the Huff-n-Puff cycle at any given moment so that there is always one ring "squeezing". This would also smooth out the power requirements of the system over time.

Centrifugal acceleration

An alternative to the Huff-n-Puff method for using the toroidal magnetic field to increase solar wind outflow involves placing the ring stations in a polar orbit rather than an equatorial one. The two magnetic nozzles would then be located on the star's equator. To increase the rate of outflow through these two equatorial jets, the ring system would be rotated around the star at a rate significantly faster than the star's natural rotation. This would cause the stellar atmosphere swept up by the magnetic field to be flung outward.

This method suffers from a number of significant complications compared to the others. Rotating the ring in this manner would require the ring stations to use powerful rocket thrust, requiring both large rocket systems and a large amount of reaction mass. This reaction mass can be "recycled" by directing the rockets' exhausts so that it impacts the star's surface, but harvesting fresh reaction mass from the star's outflow and delivering it to the ring stations in sufficient quantity adds still more complexity to the system. Finally, the resulting jets would spiral outward from the star's equator rather than emerging straight from the poles; this could complicate harvesting it, as well as the arrangement of the Dyson sphere powering the system.

Harvesting lifted mass

The material lifted from a star will emerge in the form of plasma jets hundreds or thousands of astronomical units long, primarily composed of hydrogen and helium and highly diffuse by current engineering standards. The details of extracting useful materials from this stream and storing the vast quantities that would result have not been extensively explored. One possible approach is to purify useful elements from the jets using extremely large-scale mass spectrometry, cool them by laser cooling, and condense them on particles of dust for collection. Small artificial gas giant planets could be constructed from excess hydrogen and helium to store it for future use.

Stellar husbandry

The lifespan of a star is determined by the size of its supply of nuclear "fuel" and the rate at which it uses up that fuel in fusion reactions in its core. Larger stars have a larger supply of fuel, but the increased core pressure resulting from that additional mass increases the reaction rate even more; large stars have a significantly shorter lifespan than small ones. Current theories of stellar dynamics also suggest that there is very little mixing between the bulk of a star's atmosphere and the material of its core, where fusion takes place, so most of a large star's fuel will never be used naturally.

As a star's mass is reduced by star lifting its rate of nuclear fusion will decrease, reducing the amount of energy available to the star lifting process but also reducing the gravity that needs to be overcome. Theoretically, it would be possible to remove an arbitrarily large portion of a star's total mass given sufficient time. In this manner a civilization could control the rate at which its star uses fuel, optimizing the star's power output and lifespan to its needs. The hydrogen and helium extracted in the process could also be used as fusion reactor fuel. Current fusion generators (and fusion bombs) use deuterium and tritium. Most of a star’s mass consists of light hydrogen and helium. A technologically advanced civilization may develop fusion reactors capable of using ordinary hydrogen by currently unknown means. Alternatively, the material could be assembled into additional smaller stars, to improve the efficiency of its use. Theoretically all the energy of the matter lifted from a star could be harvested if it is made into small black holes, via the mechanism of Hawking Radiation.

Generation ship

A **generation ship** is a hypothetical type of interstellar ark starship that travels across great distances between stars at a speed much slower than that of light. Since such a ship might take from decades, to hundreds, to thousands of years to reach nearby stars, the original occupants of a generation ship grow old and die, leaving their descendants to continue traveling, depending on the life span of its inhabitants and relativistic effects of time dilation.

Obstacles

Biosphere

Such a ship would have to be almost entirely self-sustaining, providing energy, food, air, and water for everyone on board. It must also have extraordinarily reliable systems that could be maintained by the ship's inhabitants over long periods of time. Large, self-sustaining space habitats would be needed. For gaining experience before sending generation ships to the stars, such a habitat could be effectively isolated from the rest of humanity for a century or more, but remain close enough to Earth for help. This would test whether thousands of humans can survive on their own before sending them beyond the reach of help. Small artificial closed ecosystems, including Biosphere 2, have been built in an attempt to work out the engineering difficulties in such a system, with mixed results.

Some have compared planets with life (in particular Earth) to generation ships. This idea is usually called "Spaceship Earth".

Biology and society

Generation ships would also have to solve major biological, social and moral problems, and would also need to deal with complex matters of self-worth and purpose for the various crews involved. As an example, a moral quandary might exist regarding how intermediate generations (for example, those destined to be born, reproduce, and die in transit, without actually seeing tangible results of their efforts) might feel about their forced existence on such a ship.

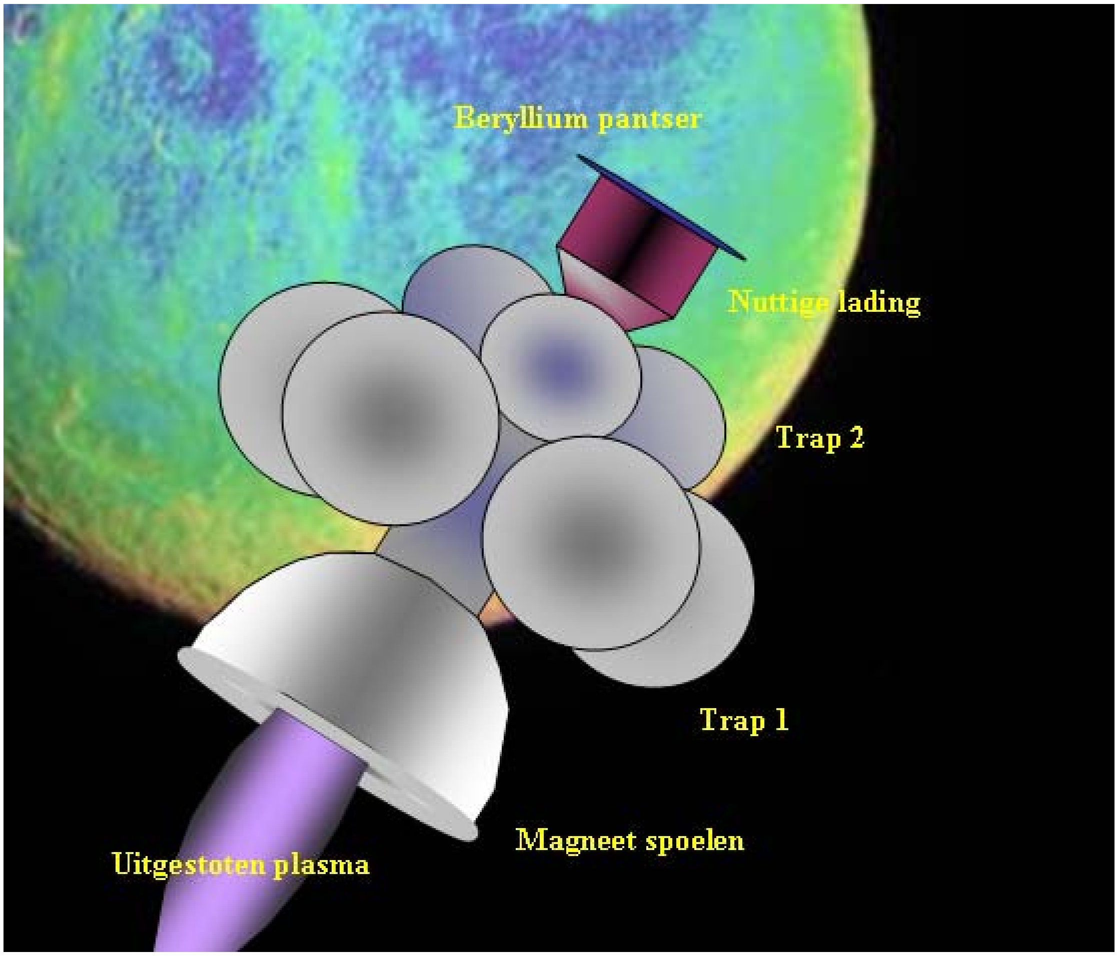
Estimates of the minimum viable population vary. The results of a 2005 study from Rutgers University theorized that the native population of the Americas are the descendants of only 70 individuals who crossed the land bridge between Asia and North America. However, anthropologist Dr. John Moore estimated in 2002 that a population of 150 to 180 would allow normal reproduction for 60 to 80 generations, equivalent to 2000 years. Careful genetic screening and use of a sperm bank from Earth would also allow a smaller starting base with negligible inbreeding.

Generation ships are based on the human life span not changing dramatically. Even though people are living longer and longer it would take a lifespan extension beyond anyone's forecasts for any one individual to live throughout the entire trip.

Cosmic rays

The radiation environment of deep space is very different from that on the Earth's surface or in low earth orbit, due to the much larger flux of high-energy galactic cosmic rays (GCRs), along with radiation from solar proton events and the radiation belts. Like other ionizing radiation, high-energy cosmic rays can damage DNA, increasing the risk of cancer, cataracts, neurological disorders, and non-cancer mortality risks. There are no known practical solutions to this problem.

Project Daedalus



Drawing of the Project Daedalus spaceship

Project Daedalus was a study conducted between 1973 and 1978 by the British Interplanetary Society to design a plausible interstellar unmanned spacecraft. Intended mainly as a scientific probe, the design criteria specified that the spacecraft had to use current or near-future technology and had to be able to reach its destination within a human lifetime. Alan Bond led a team of scientists and engineers who proposed using a fusion rocket to reach Barnard's Star, only 5.9 light years away. The trip was estimated to take 50 years, but the design was required to be flexible enough that it could be sent to any of a number of other target stars.

Concept

Daedalus would be constructed in Earth orbit and have an initial mass of 54,000 tonnes, including 50,000 tonnes of fuel and 500 tonnes of scientific payload. Daedalus was to be a two-stage spacecraft. The first stage would operate for two years, taking the spacecraft to 7.1% of light speed (0.071 *c*), and then after it was jettisoned the second stage would fire for 1.8 years, bringing the spacecraft up to about 12% of light speed (0.12 *c*) before being shut down for a 46-year cruise period. Due to the extreme temperature range of operation required (from near absolute zero to 1,600 K) the engine bells and support structure would be made of molybdenum TZM alloy, which retains strength even at cryogenic temperatures. A major stimulus for the project was Friedwardt Winterberg's inertial confinement fusion drive concept for which he received the Hermann Oberth gold medal award.

This velocity is well beyond the capabilities of chemical rockets, or even the type of nuclear pulse propulsion studied during Project Orion. Instead, Daedalus would be propelled by a fusion rocket using pellets of deuterium/helium-3 mix that would be ignited in the reaction chamber by inertial confinement using electron beams. The electron beam system would be powered by a set of induction coils tapping energy from the plasma exhaust stream. 250 pellets would be detonated per second, and the resulting plasma would be directed by a magnetic nozzle. The computed burn-up fraction for the fusion fuels was 0.175 and 0.133 for the First & Second stages, producing exhaust velocities of 10,600 km/s and 9,210 km/s, respectively. Due to the scarcity of helium-3 it was to be mined from the atmosphere of Jupiter via large hot-air balloon supported robotic factories over a 20 year period.

The second stage would have two 5-meter optical telescopes and two 20-meter radio telescopes. About 25 years after launch these telescopes would begin examining the area around Barnard's Star to learn more about any accompanying planets. This information would be sent back to Earth, using the 40-meter diameter second stage engine bell as a communications dish, and targets of interest would be selected. Since the spacecraft would not decelerate upon reaching Barnard's Star, Daedalus would carry 18 autonomous sub-probes that would be launched between 7.2 and 1.8 years before the main craft entered the target system. These sub-probes would be propelled by nuclear-powered ion drives and carry cameras, spectrometers, and other sensory equipment. They would fly past their targets, still travelling at 12% of the speed of light, and transmit their findings back to the Daedalus second stage mothership for relay back to Earth.

The ship's payload bay containing its sub-probes, telescopes, and other equipment would be protected from the interstellar medium during transit by a beryllium disk up to 7 mm thick and weighing up to 50 tonnes. This erosion shield would be made from beryllium due to its lightness and high latent heat of vaporisation. Larger obstacles that might be encountered while passing through the target system would be dispersed by an artificially generated cloud of particles, ejected by support vehicles called dust bugs, some 200 km ahead of the vehicle. The spacecraft would carry a number of robot "wardens" capable of autonomously repairing damage or malfunctions.

Specifications

- Overall length: 190 metres
- Propellant mass first stage: 46,000 tonnes
- Propellant mass second stage: 4,000 tonnes
- First stage empty mass at staging: 1,690 tonnes
- Second stage mass at cruise speed: 980 tonnes
- Engine burn time first stage: 2.05 years
- Engine burn time second stage: 1.76 years
- Thrust first stage: 7,540,000 newtons
- Thrust second stage: 663,000 newtons
- Engine exhaust velocity: 10,600,000 m/s & 9,210,000 m/s
- Payload mass: 450 tonnes

Variants

A quantitative engineering analysis of a self-replicating variation on Project Daedalus was published in 1980 by Robert Freitas. The non-replicating design was modified to include all subsystems necessary for self-replication, using the probe to deliver a "seed" factory with a mass of about 443 metric tons to a distant site, having the seed factory replicate many copies of itself there to increase its total manufacturing capacity, and then using the resulting automated industrial complex to construct more probes with a single seed factory on board each over a 1,000 year period. Each REPRO would mass over 10 million tons, mostly fuel needed to decelerate from 12% of lightspeed.

Chapter- 9

Lunar Space Elevator and Orbital Ring

Lunar space elevator

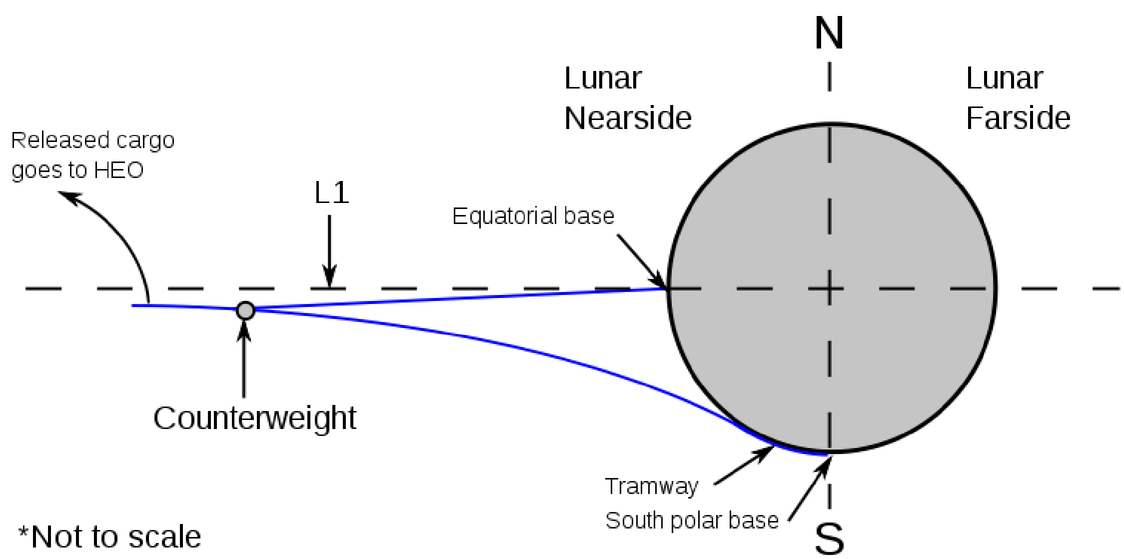


Diagram showing equatorial and polar Lunar space elevators running to L_1. An L_2 elevator would mirror this arrangement on the Lunar far side, and cargo dropped from its end would be flung outward into the solar system.

A **lunar space elevator** is a proposed cable running from the surface of the Moon into space.

It is similar in concept to the better known Earth space elevator idea (a cable suspended above Earth, with its center of gravity slightly above geostationary orbit). It would instead be constructed with its center of gravity in a stationary position above the surface of the Moon, providing a controlled means to transport people and/or materials between the surface and lunar orbit.

A lunar elevator could significantly reduce the costs and improve reliability of soft-landing equipment on the lunar surface. For example, it would permit the use of mass-efficient (high specific impulse), low thrust drives such as Ion drives which otherwise cannot land on the Moon. Since the cable would possess a microgravity point, these and other drives can reach the cable from low Earth orbit (LEO) with very minimal launched fuel from Earth. With conventional rockets, the fuel needed to reach the lunar surface from LEO is many times the landed mass, thus the elevator can slash launch costs for payloads bound for the lunar surface by a similar factor.

Location

There are two lunar-synchronous points where an elevator could be placed that would be stable: the libration points L_1 and L_2. L_1 on the Earth side of the Moon is 56,000 km up from the surface, and L_2 on the far side is 67,000 km up. In these positions, the forces of gravity and centrifugal force are equal, and as long as the system remained balanced (L_1 and L_2 are in unstable equilibrium along the line between Earth and Moon), it would remain stationary.

Both of these positions are substantially farther up than the 36,000 km from Earth to geostationary orbit. Furthermore, the weight of the limb of the cable system extending down to the Moon would have to be balanced by the cable extending further up, and the Moon's slow rotation means the upper limb would have to be much longer than for an Earth-based system. To suspend a kilogram of cable or payload just above the surface of the Moon would require 1,000 kg of counterweight, 26,000 km beyond L_1. (A smaller counterweight on a longer cable, e.g., 100 kg at a distance of 230,000 km — more than halfway to Earth — would have the same balancing effect.) Without the Earth's gravity to attract it, an L_2 cable's lowest kilogram would require 1,000 kg of counterweight at a distance of 120,000 km from the Moon.

The anchor point of a space elevator is normally considered to be at the equator. However, there are several possible cases to be made for locating a lunar base at one of the Moon's poles; a base on a peak of eternal light could take advantage of continuous solar power, for example, or small quantities of water and other volatiles may be trapped in permanently shaded crater bottoms. A space elevator could be anchored near a lunar pole, though not directly at it. A tramway could be used to bring the cable the rest of the way to the pole, with the Moon's low gravity allowing much taller support towers and wider spans between them than would be possible on Earth.

Fabrication

Because of the Moon's lower gravity and lack of atmosphere, a lunar elevator would have less stringent requirements for the tensile strength of the material making up its cable than an Earth-tethered cable. An Earth-based elevator would require high strength-to-weight materials that are theoretically possible, but not yet fabricated in practice (e.g., carbon nanotubes). Whereas, a lunar elevator could be constructed using high-strength commercially available materials such as Kevlar or Spectra.

Compared to Earth, there would be fewer geographic and political restrictions on the location of the surface connection. The connection point of a lunar elevator would not necessarily have to be directly under its center of gravity, and could even be near the poles, where evidence suggests there might be frozen water in deep craters that never see sunlight; if so, this might be collected and converted into rocket fuel.

Jerome Pearson has proposed a cable design using M5 fiber that would have a mass of 6,100 tonnes including a massive counterweight, that would be capable of lifting or depositing loads of 2,000 newtons (450 lbf, or at lunar surface gravity, masses of 1233 kg / 2700 lbm) at the base. The counterweight could potentially be lifted from the lunar surface.

History

The idea of space elevators has been around since 1960 when Yuri Artsutanov wrote a Sunday supplement to *Pravda* on how to build such a structure and the utility of geosynchronous orbit. His article however, was not known in the West. Then in 1966, John Isaacs, a leader of a group of American Oceanographers at Scripps Institute, published an article in *Science* about the concept of using thin wires hanging from a geostationary satellite. In that concept, the wires were to be thin (thin wires/tethers are now understood to be more susceptible to micrometeoroid damage). Like Artsutanov, Isaacs' article also wasn't well known to the aerospace community. In 1975, Jerome Pearson independently came up with the concept and published it in *Acta Astronautica*. That made the aerospace community at large aware of the space elevator for the first time. His article inspired Sir Arthur Clarke to write the novel *The Fountains of Paradise*. Later, Pearson extended his theory to the moon and changed to using the Lagrangian points instead of having it in geostationary orbit.

Materials

Unlike earth-anchored space elevators, the materials for lunar space elevators won't require a lot of strength. Lunar elevators can be made with materials available today. Carbon nanotubes aren't required to build the structure. This would make it possible to build the elevator much sooner, since available carbon nanotube materials in sufficient quantities are still years away.

One material that has great potential is M5 fiber. This is a synthetic fiber that is lighter than Kevlar or Spectra. According to Pearson, Levin, Oldson, and Wykes in their article The Lunar Space Elevator, an M5 ribbon 30 mm wide and 0.023 mm thick, would be able to support 2000 kg on the lunar surface (2005). It would also be able to hold 100 cargo vehicles, each with a mass of 580 kg, evenly spaced along the length of the elevator. Other materials that could be used are T1000G carbon fiber, Spectra 200, or Zylon. All of these materials have breaking lengths of several hundred kilometers under 1*g*.

Potential lunar elevator materials

Material	**Density** ρ **kg/m^3**	**Stress Limit** σ **GPa**	**Breaking height** **($h = \sigma/\rho g$, km)**
Single-wall carbon nanotubes (laboratory measurements)	2266	50	2200
Toray Carbon fiber (T1000G)	1810	6.4	361
Aramid, Ltd. polybenzoxazole fiber (Zylon PBO)	1560	5.8	379
Honeywell extended chain polyethylene fiber (Spectra 2000)	970	3.0	316
Magellan honeycomb polymer M5 (with planned values)	1700	5.7(9.5)	342(570)
DuPont Aramid fiber (Kevlar 49)	1440	3.6	255
Glass fibre (Ref Specific strength)	2600	3.4	133

The materials will be used to build the ribbons which will connect from the L_1 and L_2 balance points to the surface of the moon. The ribbons would be used by the robotic climbing vehicle to get from the surface into orbit. The vehicles would be slow, compared to chemical rockets, but it is a good speed for transferring cargo.

The ribbons are going to be prone to damage by micrometeoroids from space so one way to improve their survivability is to make a multi-ribbon system instead of one. They will have interconnections at regular intervals, so that if one section is damaged, the parallel sections would carry the load until robotic vehicles can come and replace the missing ribbon. The interconnections would be spaced about 100 km apart, which is small enough to allow a robotic climber to carry the mass of the replacement 100 km of ribbon.

Climbing vehicles

One method of getting materials needed from the moon into orbit would be the use of robotic climbing vehicles. These vehicles would consist of two large wheels pressing against the ribbons of the elevator to provide enough friction for lift. The climbers could be set for horizontal or vertical ribbons.

The wheels would be driven by electric motors, which would obtain their power from solar energy or beamed energy. The power required to climb the ribbon would depend upon the lunar gravity field, which drops off the first few percent of the distance to L_1. The power that a climber would require to traverse the ribbon drops in proportion to proximity to the L_1 point. If a 540 kg climber traveled at a velocity of fifteen meters per second, by the time it was seven percent of the way to the L_1 point, the required power would drop to less than a hundred watts, versus 10 kilowatts at the surface.

One problem with using a solar powered vehicle is the lack of sunlight during some parts of the trip. For half of every month, the solar arrays on the lower part of the ribbon would be in the shade. One way to fix this problem would be to launch the vehicle at the base with a certain velocity then at the peak of the trajectory, attach it to the ribbon.

Possible uses

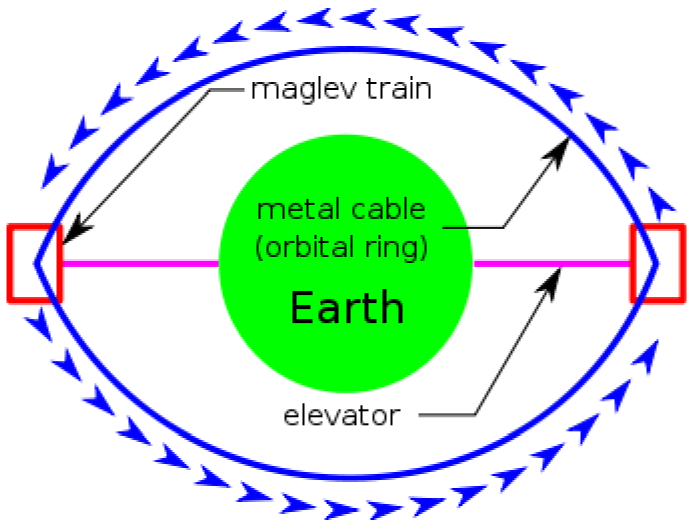
Materials from Earth may be sent into orbit and then down to the Moon to be used by lunar bases and installations.

Former U.S. President George W. Bush, addressing his Vision for Space Exploration, noted that the Moon may serve as a cost-effective construction, launching and fueling site for future space exploration missions. As President Bush announced, *"Its soil contains raw materials that might be harvested and processed into rocket fuel or breathable air."* For example, future Ares V missions could cost-effectively deliver raw materials from Earth for future spacecraft and missions to a Moon-based space dock positioned as a counterweight to a lunar space elevator, while fuel and breathable air could be shipped up from the Moon's surface to the same Moon-based dock along the same lunar space elevator. As well, the total energy needed for transit between the Moon and Mars is actually much less than between the Moon and Earth, so lunar base activity could make a large impact on building a Mars base. Since millions of tonnes of water ice have been found on the moon's poles, there is a much more accessible form of water than the regolith. The proximity of the polar base on the lunar space elevator to the water ice could make mining the ice far more efficient.

The lunar elevator could also be used to transport supplies and materials from the surface of the moon into the Earth’s orbit and vice versa. According to Jerome Pearson, there are plenty of resources on the moon that would be easier to gather and send into Earth orbit rather than launch from Earth. He claims that one such material which would be very valuable is lunar regolith, also known as moon dirt. One particular use for the regolith would be for massive material to shield space stations or crewed deep space missions against solar flares, Van Allen trapped or cosmic radiation. Other materials such as metals and minerals could be mined and sent up for construction. Silicon for solar cells, as would be needed for the construction of massive satellite solar power stations, seems particularly promising.

One disadvantage of the lunar elevator is that it may not be able to carry human passengers. The rate at which cargo is transferred would be too slow, normally taking weeks to reach its destination. Humans would be able to get there faster by using rockets to and from the moon.

Orbital ring



An **Orbital Ring** is a concept for a space elevator that consists of a ring in low earth orbit that rotates at above orbital speed, that has fixed tethers hanging down to the ground.

The structure is intended to be used for space launch.

The original orbital ring concept is related to the space fountain and launch loop and was explored in detail by Paul Birch and published in three parts in the Journal of the British Interplanetary Society in 1982.

History

Arthur C. Clarke published a book called The Fountains of Paradise about space elevators, but which in an appendix referred to an idea to launch things off the Earth using a structure based on mass drivers. The idea apparently did not work, but this inspired further research.

Paul Birch publishes a series of articles in JBIS in 1982.

Yunitsky, Anatoly E. also published a similar idea in 1982.

Birch's model

In the simplest design of an orbital ring system, a rotating cable is placed in a low Earth orbit above the equator, rotating at faster than orbital speed. Not in orbit, but riding on this ring, supported electromagnetically on superconducting magnets, are ring stations that stay in one place above some designated point on Earth. Hanging down from these ring stations are short space elevators made from cables with high tensile strength to mass ratio materials.

Although this simple model would work best above the equator, Paul Birch found that since the ring station can be used to accelerate the orbital ring eastwards as well as hold the tether, it is therefore possible to deliberately cause the orbital ring to precess around the Earth instead of staying fixed in space while the Earth rotates beneath it. By precessing the ring once every 24 hours, the Orbital Ring will hover above any meridian selected on the surface of the Earth. The cables which dangle from the ring are now geostationary without having to reach geostationary altitude or without having to be placed into the equatorial plane. This means that using the Orbital Ring concept, one or many pairs of Stations can be positioned above *any* points on Earth desired or can be moved everywhere on the globe. Thus, any point on Earth can be served by a space elevator. Also a whole network of orbital rings can be built, which, by crossing over the poles, could cover the whole planet and capable of taking over most of freight and passenger transport. By an array of elevators and several geostationary ring stations, asteroid or Moon material can be received and gently put down where land fills are needed. The electric energy generated in the process would pay for the system expansion and ultimately could pave the way for a solar-system-wide terraforming- and astroengineering-activity on a sound economical basis.

If built by launching the necessary materials from Earth, the estimated cost for the system in 1980s money was around $31 trillion if launched using Shuttle-derived hardware, whereas it could fall to $15 billion with bootstrapping, assuming a large orbital manufacturing facility is available to provide the initial 18,000 tonnes of steel, aluminium, and slag at a low cost, and even lower with orbital rings around the moon. The system's cost per kilogram to place payloads in orbit would be around $0.05.

Types of orbital rings

The simplest type would be a circular orbital ring in LEO.

Two other types were also defined by Paul Birch:

- Eccentric orbital ring systems - these are rings that are in the form of a closed shape with varying altitude
- Partial orbital ring systems- this is essentially a Launch loop

In addition, he proposed the concept of "supramundane worlds" such as **supra-jovian** and **supra-stellar** "planets". These are artificial planets that would be supported by a grid of orbital rings that would be positioned above a planet, supergiant or even a star.

Chapter- 10

Tether Propulsion

Artist's conception of satellite with a tether

Tether propulsion systems are proposals to use long, very strong cables (known as tethers) to change the velocity of spacecraft and payloads. The tethers may be used to initiate launch, complete launch, or alter the orbit of a spacecraft. Spaceflight using this form of spacecraft propulsion may be significantly less expensive than spaceflight using rocket engines.

Tethers are kept straight by either rotating end for end, with very high tips speeds (several km/s), or by the difference in the strength of gravity over their length (tidal stabilisation). Tethers require strong, light materials. Some current tether designs use crystalline plastics such as ultra high molecular weight polyethylene, aramid or carbon fiber. A possible future material would be carbon nanotubes, which have an estimated tensile strength between 140 and 177 GPa (20.3-25.6 million psi), and a proven tensile strength in the range 50-60 GPa.

A **momentum exchange tether** is a rotating tether that would grab a spacecraft and then release it at later time. Doing this can transfer momentum and energy from the tether to and from the spacecraft with very little loss; this can be used for orbital manoeuvring. A rotating momentum exchange tether is known as a **bolo**.

Another type of tether is an **electrodynamic tether**, this is a conductive tether that carries a current that can generate thrust or drag from a planetary magnetic field, in much the same way as an electric motor.

History of tether propulsion

Some of the earliest writings on space tethers can be found in the work of Tsiolkovsky. He proposed a tower so tall that it reached into space, held there by the rotation of the Earth. However, there was no realistic way to build it.

Later, another Russian, Yuri Artsutanov, wrote in greater detail about a tensile cable to be deployed from a geosynchronous satellite in Komsomolskaya Pravda (July 31, 1960); downwards towards the ground, and upwards away; keeping the cable balanced.

Jerome Pearson explored synchronous tethers further, and in particular analysed the lunar elevator that can go through the L1 and L2 points.

Hans Moravec and Robert L. Forward investigated the physics of synchronous and non synchronous tethers, including space elevators and performed detailed simulations of tapered tethers that could pick objects off and place objects onto the Moon, Mars and other planets, with little, or even a net gain of energy.

More recently Brad Edwards has done a very great deal to popularise the subject again in the scientific community, and it is now an area of active research.

Construction

To achieve maximum performance and low cost, tethers need to be made of materials with the combination of high tensile strength and low density. Depending on the type of tether, the design equations describe the material by one of three typical quantities.

Space elevator equations typically use a ‘characteristic length’ (L_c). L_c is also known as its 'self-support length' and is the length of untapered cable it can support in a constant 1*g* gravity field. $\mathbf{L_c=\sigma/\rho g}$, where σ is the stress limit (in pressure units) and ρ is the density of the material.

Hypersonic skyhook equations use the material’s ‘specific velocity’ which is equal to the maximum tangential velocity a spinning hoop can attain without breaking. $\mathbf{V_s=\sqrt{(\sigma/\rho)}}$.

Finally, for rotating tethers (rotovators) the value used is the material’s ‘characteristic velocity’ which is the maximum tip velocity a rotating untapered cable can attain without breaking. $\mathbf{V_c=\sqrt{(2\sigma/\rho)}}$. The characteristic velocity equals the specific velocity multiplied by the square root of two.

These values are used in equations similar to the rocket equation and are analogous to specific impulse or exhaust velocity. The higher these values are, the more efficient and lighter the tether can be in relation to the payloads that they can carry. Eventually however, the mass of the tether propulsion system will be limited at the low end by other factors such as momentum storage.

Building materials

Materials proposed include Kevlar, ultra high molecular weight polyethylene, carbon nanotubes, M5 fiber, and diamond.

One material that has great potential is M5 fiber. This is a synthetic fiber that is lighter than Kevlar or Spectra. According to Pearson, Levin, Oldson, and Wykes in their article "The Lunar Space Elevator," an M5 ribbon 30 mm wide and 0.023 mm thick, would be able to support 2000 kg on the lunar surface (2005). It would also be able to hold 100 cargo vehicles, each with a mass of 580 kg, evenly spaced along the length of the elevator. Other materials that could be used are T1000G carbon fiber, Spectra 2000, or Zylon. All of these materials have breaking lengths of several hundred kilometers under 1*g* (10 m/s²).

Potential tether/elevator materials

Material	Density ρ (kg/m³)	Stress Limit σ (GPa)	Char. Length $L_c=\sigma/\rho g$, (km)	Specific Velocity $V_s=\sqrt{(\sigma/\rho)}$, (km/s)	Char. Velocity $V_c=\sqrt{(2\sigma/\rho)}$, (km/s)
Single-wall carbon nanotubes (laboratory measurements)	2266	50	2200	4.7	6.6
Aramid, Polybenzoxazole (PBO) fiber ("Zylon")	1340	5.9	450	2.1	3.0
Toray carbon fiber (T1000G)	1810	6.4	360	1.9	2.7
Magellan honeycomb polymer M5 (planned values)	1700	9.5	570	2.4	3.3
Magellan honeycomb polymer M5 (existing)	1700	5.7	340	1.8	2.6
Honeywell extended chain polyethylene fiber (Spectra 2000)	970	3.0	316	1.8	2.5
DuPont Aramid fiber (Kevlar 49)	1440	3.6	255	1.6	2.2
Specialty materials e.g. silicon carbide	3000	5.9	199	1.4	2.0

Aluminium (6061 T6)	2700	0.276	10.	0.32	0.45

Shape

To exceed the self-support length the tether material can be tapered so that the cross-sectional area varies with the total load at each point along the length of the cable. Correct tapering ensures that the tensile stress at every point in the cable is exactly the same. For very demanding applications, such as an Earth Space Elevator, the tapering can result in excessive ratios of cable weight to payload weight.

In addition the cable must be constructed to withstand micrometeorites and space junk. This can be achieved with the use of redundant cables, such as the Hoytether; redundancy can ensure that it is very unlikely that multiple redundant cables would be damaged near the same point on the cable, and hence a very large amount of total damage can occur over different parts of the cable before failure occurs.

Defining the *characteristic velocity* u of a material in terms of the characteristic length as:

$$L = \frac{u^2}{g}$$

For a rotating tether the thickness A is given as a function of r (the distance from the centre) we get.

$$A(r) = \frac{Mv^2}{TR} e^{(1-\frac{r^2}{R^2})\frac{v^2}{2u^2}}$$

where R is the radius of tether, v is the velocity with respect to the centre, M is the tip mass and T is the design tensile strength (Young's modulus divided by safety factor).

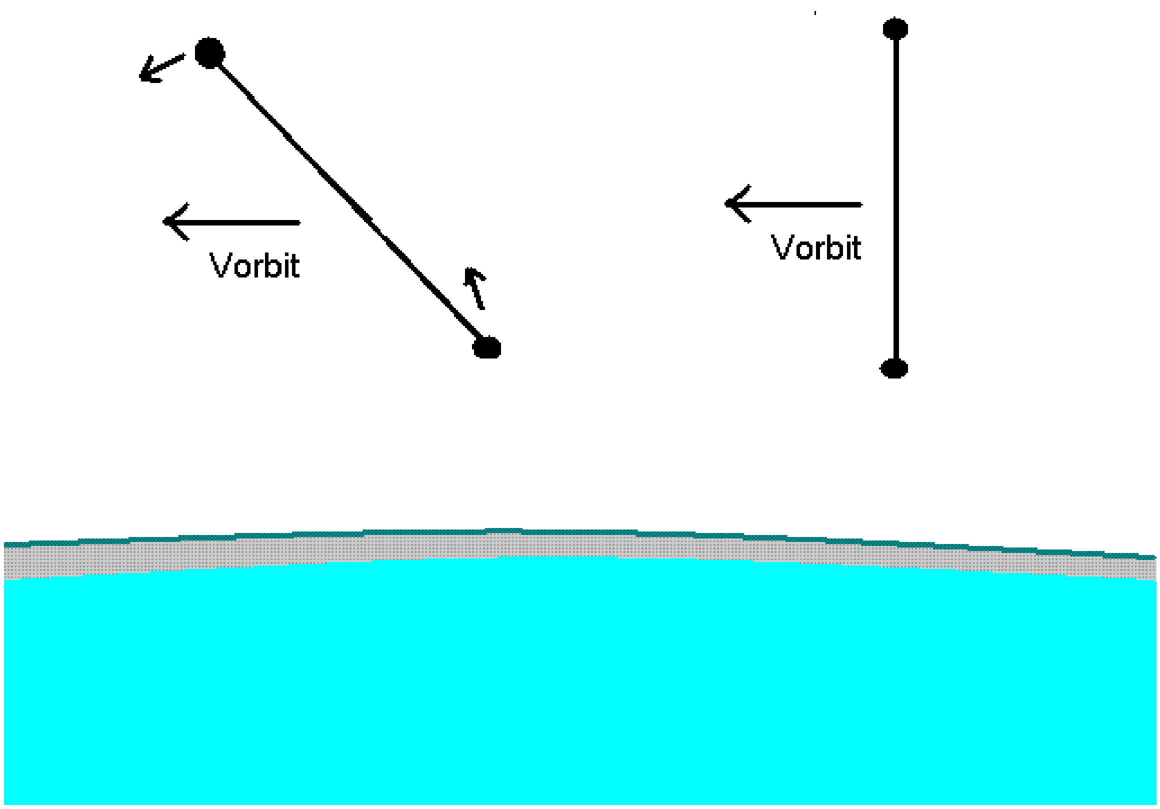
Integrating this gives a payload mass/tether mass ratio of:

$$\frac{M}{m} = 2.51\frac{V}{u} e^{(\frac{V^2}{2u^2})} erf(\frac{V}{1.41u})$$

where erf is the error function associated with the normal probability error function and varies from 0.68 for V/u=1 to 1.0 for V/u > 3

Tether systems

Tidal stabilization

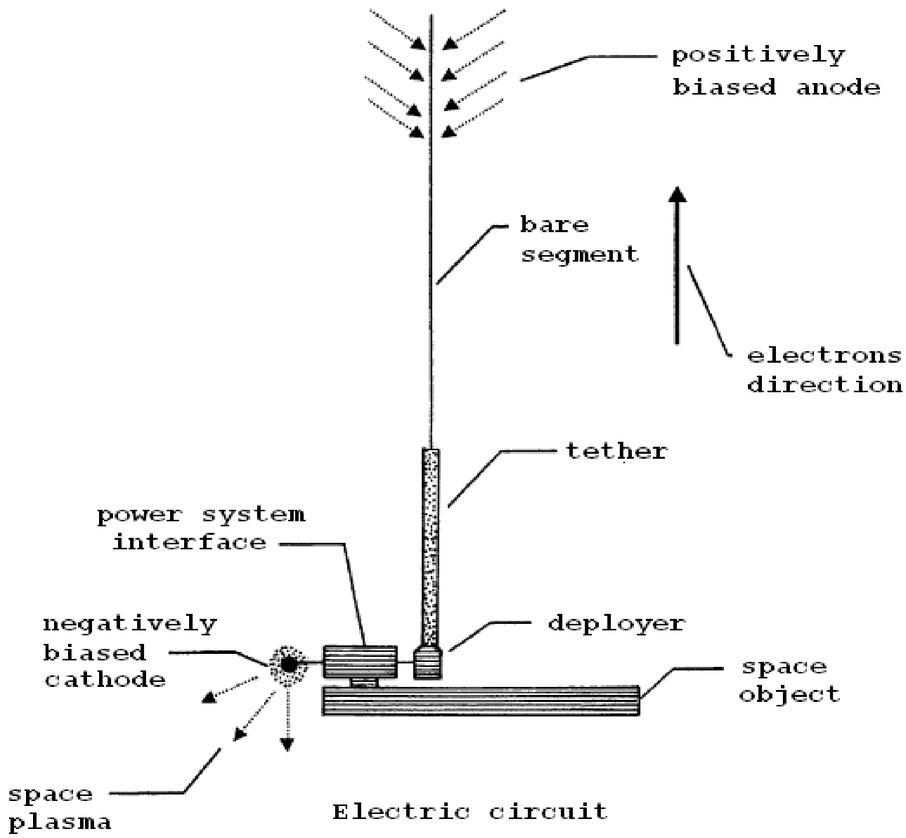


A rotating tether and a tidally stabilised tether in orbit

Gravity-gradient stabilization, also called "gravity stabilization" and "tidal stabilization", is cheap and reliable. It uses no electronics, rockets or fuel.

An attitude control tether has a small mass on one end, and a satellite on the other. Tidal forces stretch the tether between the two masses. There are two ways of explaining tidal forces: In one, the upper part of an object goes faster than its natural orbital speed, so centrifugal force stretches the object upwards. The lower part moves slower than the orbital speed, so it pulls down. Another way to explain tidal force is that the top of a tall object weighs less than the bottom, so they are pulled by different amounts. The "extra" pull on the "bottom" of the object stretches it out. On Earth, these are small effects, but in space, nothing opposes them.

The resulting tidal forces stabilize the satellite so that its long dimension points towards the planet it is orbiting. Simple satellites have often been stabilized this way, with tethers or mass distribution. A small bottle of fluid may be mounted in the spacecraft to damp pendulum vibrations with viscous friction of the fluid motion.



Electrons flow through the conductive structure of the tether to the power system interface, where it supplies power to an associated load, not shown.

Electrodynamic tethers

In a strong planetary magnetic field such as around the Earth or Saturn, a conducting rotovator can be configured as an electrodynamic tether. This can either be used as a dynamo, which slows the tether and changes the angular momentum whilst generating electrical power, or alternatively, its orbital speed and/or angular momentum can be increased electrically from solar or nuclear power by running current through a wire that goes the length of the tether. Thus the tether can be used either to accelerate or brake an orbiting spacecraft.

In both cases the tether pushes against the planet, and thus the momentum gained or lost ultimately comes from the planet.

One complication to these techniques is that if the tether rotates, the direction of current must reverse (such as is the case in alternating currents).

Bolo

A rotating tether, or "bolo," is a high speed rotating tether, spinning so that the tips have a significant speed (~1–3 km/s).

The maximum speed is limited by stress tolerance and safety factor of the tether but the speed can be greatly increased if it is of thicker cross-section in the middle and tapers and is lighter, thinner at the tips.

A spacecraft could rendezvous with one end of the tether, latch to it, and be accelerated by the tether's rotation. The tether and spacecraft would then separate at a later point when the spacecraft's velocity has been changed by the rotovator.

The momentum imparted to the spacecraft is not free. The tether's momentum and angular momentum is changed, and this costs energy that must be recouped. The idea is that the recharge could be done with some form of energy (for instance solar panels generating current for electromagnetic propulsion) that is far cheaper than multi-stage-rocket fuel.

Rotating tethers can also be used to slow down incoming spacecraft, thus increasing the rotational momentum. If the average momentum gained from inward traffic equals that imparted to outward traffic, there is no net energy cost, and thus nothing to recoup.

Rotovators

If the orbital velocity and the tether rotation rate are synchronized, in the rotovator concept the tether tip moves in a cycloid, and at the lowest point is momentarily stationary with respect to the ground.

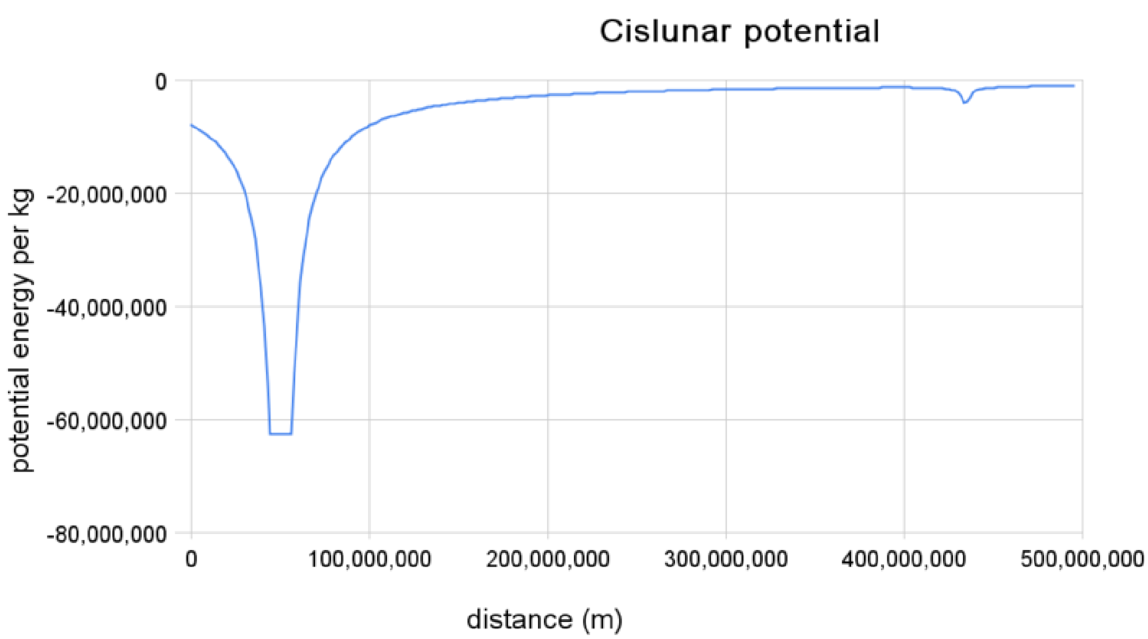
The word rotovator is a portmanteau derived from the words *rotor* and *elevator*. Rotovators would be momentum exchange tethers, with a retrograde motion of the tip closest to their parent body relative to the center of the tether.

Because the tips have a significant speed (typically 1–3 km/s), it can be possible in some cases to cancel the orbital speed such that the tips are stationary at their lowest point with respect to a planetary surface or lunar body. As described by Moravec, this is "a satellite that rotates like a wheel." The tip of the tether moves in approximately a cycloid, in which it is momentarily stationary with respect to the ground. In this case, a payload that is "grabbed" by a capture mechanism on the rotating tether during the moment when it is stationary would be picked up and lifted into orbit; and potentially could be released at the top of the rotation, at which point it is moving with a speed significantly greater than the escape velocity and thus could be released onto an interplanetary trajectory. (As with the bolo, discussed above, the momentum and energy given to the payload must be made up, either with a high-performance rocket engine, or with momentum gathered from payload moving the other direction.)

On bodies with an atmosphere, such as the Earth, the tether tip must stay above the dense atmosphere. On bodies with reasonably low orbital speed (such as the Moon and possibly Mars), a rotovator in low orbit can potentially touch the ground, thereby providing cheap surface transport as well as launching materials into cislunar space.

Cislunar transportation system

Although it might be thought that this requires constant energy input, it can in fact be shown to be energetically favourable to lift cargo off the surface of the Moon and drop it into a lower Earth orbit, and thus it can be achieved without any significant use of propellant, since the moon's surface is in a comparatively higher potential energy state.



Potential energy in the Earth Moon system. Because the moon has higher potential energy, tethers can work together to pick objects off the moon (the tiny dimple on the right), and place it closer to the Earth in LEO, taking essentially no propellant and even generating energy while doing so.

Rotovators can thus be charged by momentum exchange. Momentum charging uses the rotovator to move mass from a place that is "higher" in a gravity field to a place that is "lower". The technique to do this uses the Oberth effect, where releasing the payload when the tether is moving with higher linear speed, lower in a gravitational potential gives more specific energy, and ultimately more speed than the energy lost picking up the payload at a higher gravitational potential, even if the rotation rate is the same. For example, it is possible to use a system of two or three rotovators to implement trade between the Moon and Earth. The rotovators are charged by lunar mass (dirt, if exports are not available) dumped on or near the Earth, and can use the momentum so gained to boost Earth goods to the Moon. The momentum and energy exchange can be balanced with equal flows in either direction, or can increase over time.

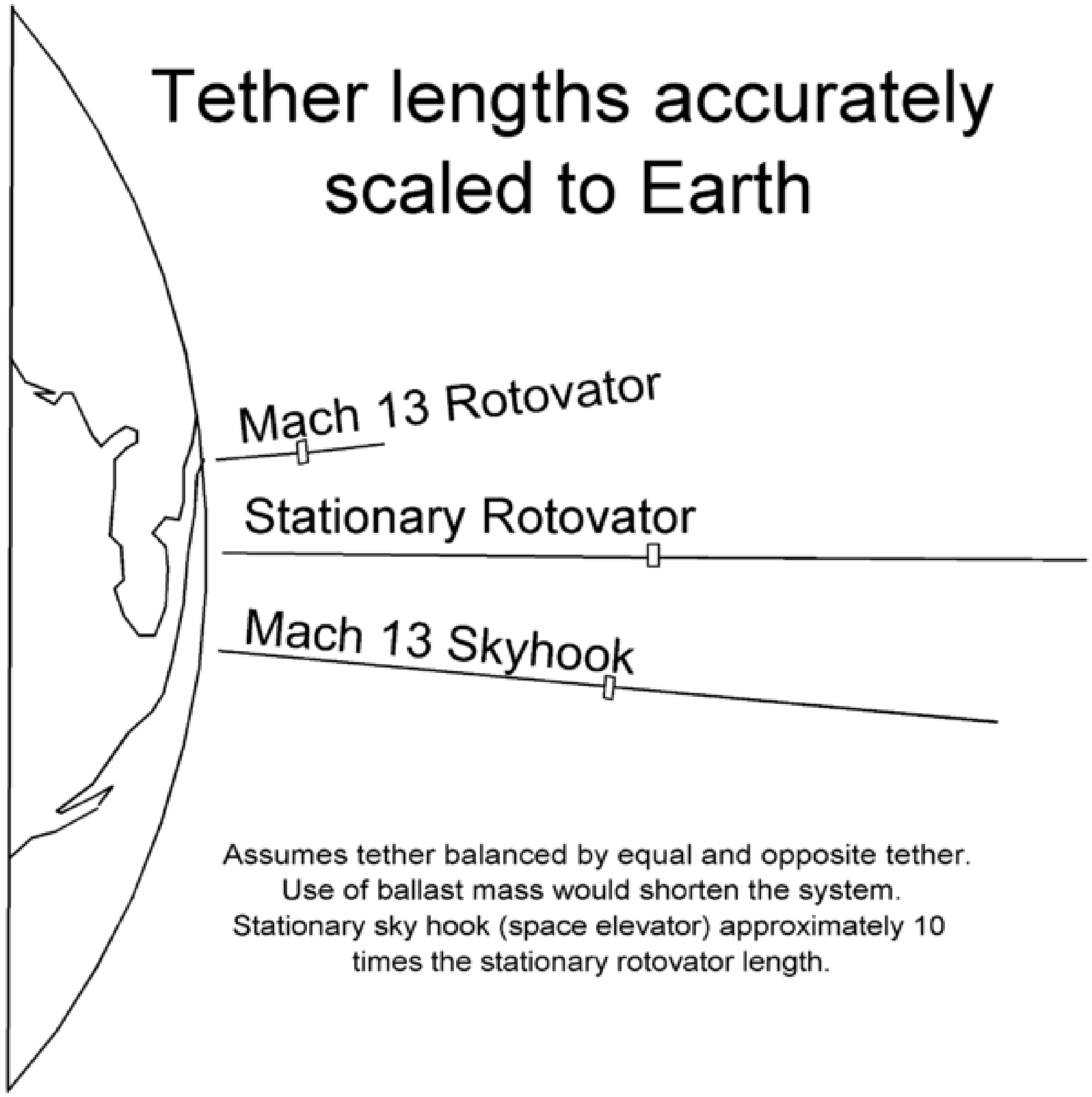
Similar systems of rotovators could theoretically open up inexpensive transportation throughout the solar system.

HASTOL — Earth launch assist rotovator

Unfortunately an Earth-to-orbit rotovator cannot be built from currently available materials since the thickness and tether mass to handle the loads on the rotovator would be uneconomically large. A "watered down" rotovator with two-thirds the rotational speed, however, would halve the centripetal acceleration stresses.

Therefore another trick to achieve lower stresses is that rather than picking up a cargo from the ground at zero velocity, a rotovator could pick up a moving vehicle and sling it into orbit. For example, a rotovator could pick up a Mach-12 aircraft from the upper atmosphere of the Earth and move it into orbit without using rockets, and could likewise catch such a vehicle and lower it into atmospheric flight. It is easier for a rocket to achieve the lower tip speed, so "Single Stage To Tether" has been proposed. One such is called the Hypersonic Airplane Space Tether Orbital Launch (HASTOL). Either air breathing or rocket to tether could save a great deal of fuel per flight, and would permit for both a simpler vehicle and more cargo.

Skyhooks



Orbital tether lengths compared.

A tidal stabilized tether is called a "skyhook" since it appears to be "hooked onto the sky". This term was introduced relating to satellites and orbital mechanics by the Italian scientist Giuseppe Colombo. Skyhooks rotate precisely once per orbit and hence are always oriented the same way to the parent body.

Some are called "hypersonic skyhooks" because the tip nearest the earth travels about Mach-12 to 16 in typical designs. Longer tethers would travel more slowly. At the limit of zero ground speed, it would be re-classified as a *space elevator* or *beanstalk*.

An aircraft or sub-orbital vehicle transports cargo to one end of the skyhook.

Skyhook designs typically require climbers to transport the cargo to the other end (like a beanstalk).

Robert Raymond Boyd and Dimitri David Thomas (with Lockheed Martin Corporation) patented the Skyhook idea in 2000 in a patent titled "Space elevator".

The company Tethers Unlimited Inc (founded by Dr. Robert Forward and Dr. Robert P. Hoyt) has called this approach "Tether Launch Assist".

Space elevator (beanstalk)

A beanstalk (a type of space elevator) is a skyhook that is attached to planetary body. For example, on Earth, a beanstalk would go from the equator to geosynchronous orbit.

A beanstalk does not need to be powered as a rotovator does, because it gets any required angular momentum from the planetary body. The disadvantage is that it is much longer, and for many planets a beanstalk cannot be constructed from known materials. A beanstalk on Earth would require material strengths outside current technological limits (2007). Martian and Lunar beanstalks could be built with modern-day materials however. A space elevator on Phobos has also been proposed.

Beanstalks also have much larger amounts of potential energy than a rotovator, and if heavy parts should fail they might cause multiple impact events as objects hit the earth at near orbital speeds. Most anticipated cable designs would burn up before hitting the ground.

Tether cable catapult system

A tether cable catapult system is a system where two or more long conducting tethers are held rigidly in a straight line, attached to a heavy mass. Power is applied to the tethers and is picked up by a vehicle that has linear magnet motors on it, which it uses to push itself along the length of the cable. Near the end of the cable the vehicle releases a payload and slows and stops itself and the payload carries on at very high velocity. The calculated maximum speed for this system is extremely high, more than 30 times the speed of sound in the cable; and velocities of more than 30 km/s seem to be possible.

Challenges and other problems

Atomic oxygen

Objects in low earth orbit are subjected to noticeable erosion from monomolecular oxygen, due to the high orbital speed with which the molecules strike as well as their high reactivity.

Micrometeorites and space junk

Simple tethers are quickly cut by micrometeoroids and space junk. The lifetime of a simple, one-strand tether in space is on the order of five hours for a length of ten kilometers. This was originally a show stopper for the use of tethers.

Several systems have since been proposed to improve this. The US Naval Research Laboratory has successfully flown a long term tether that used very fluffy yarn. This is reported to remain uncut several years after deployment. Another proposal is to use a tape or cloth. Dr. Robert P. Hoyt patented an engineered circular net, such that a cut strand's strains would be redistributed automatically around the severed strand. This is called a Hoytether. Hoytethers have theoretical lifetimes of tens of years.

Large pieces of junk would cut most tethers, but these are currently tracked on radar and have predictable orbits. A tether could be wiggled to dodge known pieces of junk, or thrusters used to change the orbit, avoiding a collision.

Material strength

Beanstalks and rotovators are currently limited by the strengths of available materials. Although ultra-high strength plastic fibers (Kevlar and Spectra) permit rotovators to pluck masses from the surface of the Moon and Mars, a rotovator from these materials cannot lift from the surface of the Earth. In theory, high flying, supersonic (or hypersonic) aircraft could deliver a payload to a rotovator that dipped into Earth's upper atmosphere briefly at predictable locations throughout the tropic (and temperate) zone of Earth.

Vibrations

Computer models frequently show tethers can snap due to vibration.

Mechanical tether-handling equipment is often surprisingly heavy, with complex controls to damp vibrations. The one ton climber proposed by Dr. Brad Edwards for his Space Elevator may detect and suppress most vibrations by changing speed and direction. The climber can also repair or augment a tether by spinning more strands.

The vibration modes that may be a problem include skipping rope, transverse, longitudinal, and pendulum.

Tethers are nearly always tapered, and this can greatly amplify the movement at the thinnest tip in whip like ways.

Cargo capture

Cargo capture for rotovators is nontrivial, and failure to capture can cause problems. Several systems have been proposed, such as shooting nets at the cargo, but all add weight, complexity, and another failure mode.

Life Expectancy

Currently, the strongest materials in tension are plastics that require a coating for protection from UV radiation and (depending on the orbit) erosion by atomic oxygen. Disposal of waste heat is difficult in a vacuum, so over-heating may cause tether failures or damage.

Control and modelling issues

A tether is not a spherical object, and has significant extent. This means that, as an extended object, it is not directly modellable as a point source, and this means that the center of mass and center of gravity are not usually colocated, and the inverse square law does not apply except at large distances, to the overall behaviour of a tether. Hence the orbits are not completely Keplerian. This makes prediction and modelling extremely complex.

Real Missions

Gemini 11

In 1966, Gemini 11 deployed a 30m (100 foot) tether which was stabilized by a rotation which gave 0.00015 g.

SEDS I

In 1993, NASA launched the "Small Expendable Deployer System" experiments (SEDS-I), which deployed a 20 km tether attached to a spent Delta second stage. This was the first fully successful orbital flight test of a long tether system. The tether swung to the vertical and was cut 1 orbit after the start of deployment. This slung the payload and tether onto a reentry trajectory accurate enough that a pre-positioned observer was able to videotape the payload re-entry and burnup. In this experiments, not only were tether models verified, the test successfully showed that a reentry vehicle can be dropped into a reentry orbit using a tether.

SEDS II

SEDS-2 was a simple tether experiment launched March 9, 1994; and was successfully deployed, and met the mission objectives including having minimal swing and good deployment length. A feedback braking limited the swing after deployment to 4°. It was expected to last almost two weeks, but in fact was cut after 3.7 days and the lower end quickly experienced atmospheric entry.

A follow-on experiment using the SEDS deployer, PMG (Plasma Motor Generator) deployed a 500 m tether to demonstrate electrodynamic tether operation.

MAST

The MAST tether experiment was launched aboard a Dnepr rocket in April 2007. Unfortunately, the tether did not deploy successfully.

TSS-1 (NASA)

NASA deployed an electromagnetic tether from the Space Shuttle in the experiment "Tethered Satellite System 1" (TSS-1), flown on the mission STS-46 in June 1992. Unfortunately, a late-stage modification of the deployment reel system resulted in a protruding bolt jamming the deployment mechanism, and the tether was deployed only to a length of 260 meters. The experiment was reflown in the experiment TSS-1R, flown in February 1996 on the mission STS-75. While this tether successfully deployed to 19 kilometers, it burned through due to excessive current flow.

TiPS

The Tether Physics and Survivability Experiment (TiPS) was launched in 1996 as a project of the US Naval Research Laboratory, and was successfully deployed to a tether length of four kilometers. The tether broke finally in July 2006, in line with debris models published by J. Carroll.

YES2

The YES2 satellite was launched September 14, 2007 from Baikonur. The Young Engineers' Satellite 2 (YES2) was a 36 kg student-built tether satellite part of ESA's Foton-M3 microgravity mission. The YES2 satellite employed a 30 km long tether to deorbit a small re-entry capsule.

STARS

The STARS mission, developed by the Kagawa Satellite Development Project at Kagawa University, was launched 23 January 2009 as a secondary payload aboard H-IIA flight 15, which also launched GOSAT.