Space-Based Solar Power

(Technological Advancements & Applications)

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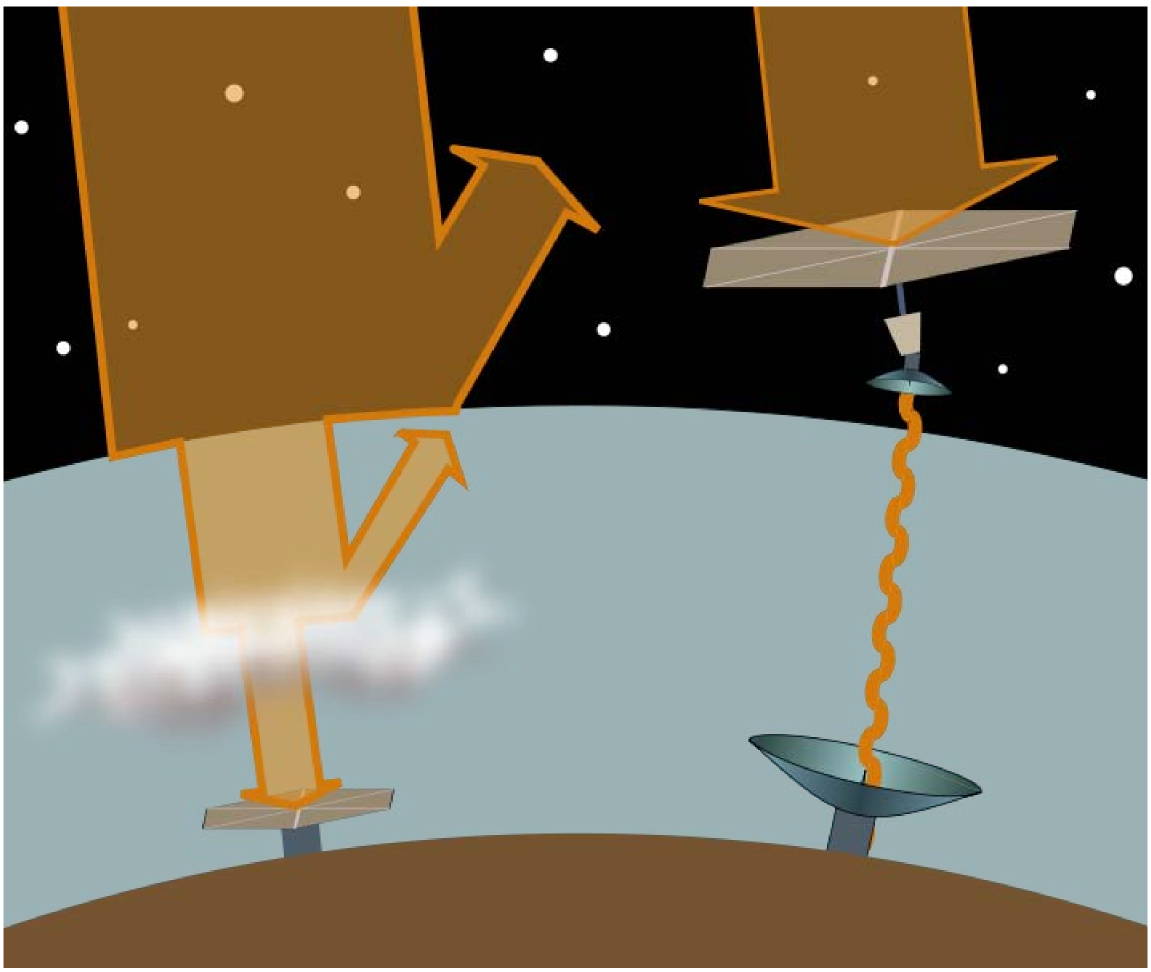
Introduction to Space-based Solar Power



On the left: Part of the solar energy is lost on its way through the atmosphere by the effects of reflection and absorption.
On the right: Space-based solar power systems convert sunlight to microwaves outside the atmosphere, avoiding these losses, and the downtime due to Earth's rotation, experienced by surface installations.

Space-based solar power (SBSP) (or historically **space solar power**- SSP) is a system for the collection of solar power in space, for use on Earth. SBSP differs from the usual method of solar power collection in that the solar panels used to collect the energy would reside on a satellite in orbit, often referred to as a **solar power satellite** (SPS), rather than on Earth's surface. In space, collection of the Sun's energy is unaffected by the various obstructions which reduce efficiency or capacities of Earth surface solar power collection.

The World Radiation Centre's 1985 standard extraterrestrial level for solar irradiance is 1367 W/m^2. The integrated total terrestrial solar irradiance is 950 W/m^2. Extraterrestrial solar irradiance is thus 144% of the maximum terrestrial irradiance, and has a different radiation profile, including wavelengths blocked by the atmosphere. A major interest in SBSP stems from the length of time the solar collection panels can be exposed to a consistently high amount of solar radiation. For most of the year, a satellite-based solar panel can collect power 24 hours per day, whereas a terrestrial station can collect for at most 12 hours per day, if weather permits, and only during peak hours—irradiance under the best of conditions is quite reduced near sunset and sunrise.

Collection of solar energy in space for use on Earth introduces two new problems and can alleviate an existing one. First, installation of the collection satellites, and second transmitting energy from them to the surface for use. The first requires upgrading and extension of existing solar panel technologies. Since wires extending from Earth's surface to an orbiting satellite are neither practical nor currently possible, many SBSP designs have proposed the use of microwave beams for wireless power transmission. The collecting satellite would convert solar energy into electrical energy, powering a microwave emitter oriented toward a collector on the Earth's surface. Dynamic solar thermal power systems on satellites are also being investigated. Since the beam can be steered, it can be directed as needed to accommodate periods of high power use in particular locations (e.g., during the hottest part of the day in summer, or cold spells in winter). As well, one of the current problems of electricity use is long distance transmission from generating sites to usage sites. Because at least one type of receiving antenna, the rectenna, is relatively inexpensive, it may be possible to reduce the need for electricity transmission lines by sensible siting of receiving antennas, potentially reducing costs and grid interconnect failures, such as the blackouts of 1965 and 2003.

Some problems normally associated with terrestrial solar power collection would be entirely avoided by such a design, e.g., dependence on weather conditions, contamination or corrosion, damage by wildlife or plant encroachment, etc. Other problems will likely be encountered, such as more rapid radiation damage or micrometeoroid impacts.

Timeline

- **1968**: Dr. Peter Glaser introduced the idea of a large solar power satellite system with square miles of solar collectors in high geosynchronous orbit (GEO is an orbit 36,000 km above the equator), for collection and conversion of sun's energy into an electromagnetic microwave beam to transmit usable energy to large receiving antennas (rectennas) on Earth for distribution.

- **1973**: Dr. Peter Glaser was granted U.S. patent number 3,781,647 for his method of transmitting power over long distances (e.g., from an SPS to the Earth's surface) using microwaves from a large (on the close order of one square kilometer) antenna on the satellite to a much larger one on the ground, now known as a rectenna.

- **1970s**: DOE and NASA examined the Solar Power Satellite (SPS) concept extensively, publishing the design and feasibility studies.

- **1994**: The United States Air Force conducted the Advanced Photovoltaic Experiment using a satellite launched into low Earth orbit by a Pegasus rocket.

- **1995–1997**: NASA conducted a “Fresh Look” study of space solar power (SSP) concepts and technologies.

- **1998**: Space Solar Power Concept Definition Study (CDS) identified credible commercially viable SSP concepts, identifying technical and programmatic risks.

- **1998**: Japan's space agency starts a program for developing a Space Solar Power System (SSPS), which continues to the present day.

- **1999**: NASA's Space Solar Power Exploratory Research and Technology program program begun.

- **2000**: John Mankins of NASA testified in the U.S. House of Representatives, saying "Large-scale SSP is a very complex integrated system of systems that requires numerous significant advances in current technology and capabilities. A technology roadmap has been developed that lays out potential paths for achieving all needed advances — albeit over several decades.

- **2001**: PowerSat Corporation founded by William Maness.

- **2001**: Dr. Neville Marzwell of NASA stated, "We now have the technology to convert the sun's energy at the rate of 42 to 56 percent... We have made tremendous progress. ...If you can concentrate the sun's rays through the use of large mirrors or lenses you get more for your money because most of the cost is in the PV arrays... There is a risk element but you can reduce it... You can put these small receivers in the desert or in the mountains away from populated areas. ...We believe that in 15 to 25 years we can lower that cost to 7 to 10 cents per kilowatt hour. ...We offer an advantage. You don't need cables, pipes, gas or copper wires. We can send it to you like a cell phone call—where you want it and when you want it, in real time."

- **2001**: NASDA (Japan's national space agency) announced plans to perform additional research and prototyping by launching an experimental satellite with 10 kilowatts and 1 megawatt of power.

- **2007**: The US Pentagon's National Security Space Office (NSSO) issued a report on October 10, 2007 stating they intend to collect solar energy from space for use on Earth to help the United States' ongoing relationship with the Middle East and the battle for oil. The International Space Station may be the first test ground for this new idea, even though it is in a low-earth orbit.

- **2007**: In May 2007 a workshop was held in the USA at MIT to review the current state of the market and technology.

- **2009**: A new company from the US, Space Energy, Inc., announced plans to provide commercial space-based solar power. They say they have developed a "rock-solid business platform" and should be able to provide space-based solar power within a decade.

- **2009**: American company Pacific Gas and Electric (PG&E) announced it is seeking regulatory approval for an agreement with Solaren to buy 200 MW of solar power, starting in 2016, which Solaren has plans to provide via SBSP. PG&E spokesman Jonathan Marshall stated that "We've been very careful not to bear risk in this."

- **2009**: PowerSat Corporation filed a patent application concerning ganging multiple power satellites to form a single coherent microwave beam, and a mechanism to use the solar array to power ion thrusters to lift a power satellite from LEO to GEO.

- **2009**: Japan announced plans to orbit solar power satellites that will transmit energy back to earth via microwaves. They hope to have the first prototype orbiting by 2030.

- **2010**: Europe's largest space company EADS Astrium plans to put a solar-collecting demo satellite in space.

- **2010**: Prof. Andrea Massa and Prof. Giorgio Franceschetti will organize a Special Session on the "Analysis of Electromagnetic Wireless Systems for Solar Power Transmission" at the 2010 IEEE International Symposium on Antennas and Propagation.

History

The SBSP concept, originally known as *Satellite Solar Power System* ("SSPS") was first described in November 1968. In 1973 Peter Glaser was granted U.S. patent number 3,781,647 for his method of transmitting power over long distances (e.g., from an SPS to the Earth's surface) using microwaves from a very large (up to one square kilometer) antenna on the satellite to a much larger one on the ground, now known as a rectenna.

Glaser then worked at Arthur D. Little, Inc., as a vice-president. NASA signed a contract with ADL to lead four other companies in a broader study in 1974. They found that, while the concept had several major problems—chiefly the expense of putting the required materials in orbit and the lack of experience on projects of this scale in space, it showed enough promise to merit further investigation and research.

Between 1978 and 1981 the US Congress authorized DOE and NASA to jointly investigate the concept. They organized the Satellite Power System Concept Development and Evaluation Program. The study remains the most extensive performed to date. Several reports were published investigating the engineering feasibility of such an engineering project. They include:

- Resource Requirements (Critical Materials, Energy, and Land)
- Financial/Management Scenarios
- Public Acceptance
- State and Local Regulations as Applied to Satellite Power System Microwave Receiving Antenna Facilities
- Student Participation
- Potential of Laser for SBSP Power Transmission
- International Agreements
- Centralization/Decentralization
- Mapping of Exclusion Areas For Rectenna Sites
- Economic and Demographic Issues Related to Deployment
- Some Questions and Answers
- Meteorological Effects on Laser Beam Propagation and Direct Solar Pumped Lasers
- Public Outreach Experiment
- Power Transmission and Reception Technical Summary and Assessment
- Space Transportation

The project was not continued with the change in Administrations after the 1980 US Federal elections.

The Office of Technology Assessment concluded

Too little is currently known about the technical, economic, and environmental aspects of SPS to make a sound decision whether to proceed with its development and deployment. In addition, without further research an SPS demonstration or systems-engineering verification program would be a high-risk venture.

More recently, the SBSP concept has again become interesting, due to increased energy demand, increased energy costs, and emission implications, starting in 1997 with the NASA "Fresh Look". In assessing "What has changed" since the DOE study, this study asserts that

Another important change has occurred at the US national policy level. US National Space Policy now calls for NASA to make significant investments in technology (not a particular vehicle) to drive the costs of ETO *[Earth to Orbit]* transportation down dramatically. This is, of course, an absolute requirement of space solar power.

One might take the NASA "Fresh Look" study as encouraging because the main difficulty identified is driving down Earth to Orbit costs. However, Dr. Pete Worden claimed that space-based solar is about five orders of magnitude more expensive than solar power from the Arizona desert. A major factor in this five orders of magnitude is the cost of transporting materials to orbit. Dr. Worden referred to possible solutions as speculative solutions that would not be available for decades at the best, leaving space-based solar power with no business case for the foreseeable future.

SERT

In 1999 NASA's Space Solar Power Exploratory Research and Technology program (SERT) was initiated for the following purpose:

- Perform design studies of selected flight demonstration concepts;
- Evaluate studies of the general feasibility, design, and requirements.
- Create conceptual designs of subsystems that make use of advanced SSP technologies to benefit future space or terrestrial applications.
- Formulate a preliminary plan of action for the U.S. (working with international partners) to undertake an aggressive technology initiative.
- Construct technology development and demonstration roadmaps for critical Space Solar Power (SSP) elements.

It was to develop a solar power satellite (SPS) concept for a future gigawatt space power systems to provide electrical power by converting the Sun's energy and beaming it to the Earth's surface. It was also to provide a developmental path to solutions for current space power architectures. Subject to further study, it proposed an inflatable photovoltaic gossamer structure with concentrator lenses or solar heat engines to convert sunlight into electricity. The program looked at both systems in sun-synchronous orbit and geosynchronous orbit.

Some of SERT's conclusions include the following:

- The increasing global energy demand is likely to continue for many decades resulting in new power plants of all sizes being built.
- The environmental impact of those plants and their impact on world energy supplies and geopolitical relationships can be problematic.
- Renewable energy is a compelling approach, both philosophically and in engineering terms.
- Many renewable energy sources are limited in their ability to affordably provide the base load power required for global industrial development and prosperity, because of inherent land and water requirements.

- Based on their Concept Definition Study, space solar power concepts may be ready to reenter the discussion.
- Solar power satellites should no longer be envisioned as requiring unimaginably large initial investments in fixed infrastructure before the emplacement of productive power plants can begin.
- Space solar power systems appear to possess many significant environmental advantages when compared to alternative approaches.
- The economic viability of space solar power systems depends on many factors and the successful development of various new technologies (not least of which is the availability of much lower cost access to space than has been available), however, the same can be said of many other advanced power technologies options.
- Space solar power may well emerge as a serious candidate among the options for meeting the energy demands of the 21st century.

Program

Model System Categories (MSC's) were defined and ranged from relatively small-scale demonstrations to very large-scale operational SPS systems. In broad terms, each MSC represented an idea of what scale, technology, missions, etc. might be achievable in a particular future timeframe. The technology investment plan uses a time phased methodology to develop hardware and systems starting at 600 volts, followed by 10,000v, and ending with 100,000v to spread development and testing infrastructure costs over the life of the program rather than incur them from the beginning. The 600v technology had immediate application for the Advanced Space Transportation Program (ASTP).

- 2005: ~100 kW, Free-flyer, demo-scale commercial space
- 2010: ~100 kW Planetary Surface System, demo-scale, space exploration
- 2015: ~10 MW Free-flyer, Transportation; Large demo, solar clipper
- 2020: 1 GW Free-flyer, Full-scale solar power satellite commercial space

Solar power generation

Current solar cells were considered too heavy, expensive and hard to deploy. Flexible thin film cells promised one viable future option for low mass, low cost, and high production capability by depositing special materials in very thin (micrometers) layers. Flexibility promotes deposition on lightweight inflatable structures needed for packaging large arrays in launch vehicles. The materials considered (kapton) did not have the high temperature properties needed to allow cell growth deposition so development of a low temperature growth process for thin film solar cells was pursued. In the year 2000 the production of 5% efficient prototype small-area cells was followed by a 10% efficient prototype on kapton.

Very high efficiency photovoltaics

Two longer range investigations into high efficiency solar cells was undertaken. 1) "Rainbow" cells to be tailored to the wavelengths of specific ranges of sunlight focused through a prism. 2) An ensemble of quantum dots in a size range to capture most of the radiation from the solar energy spectrum. The collection would be equivalent to an array of semiconductors individually size tuned for optimal absorption at their bandgaps throughout the solar energy emission spectrum. Theoretical efficiencies were in the range of 50-70%.

High voltage arc mitigation

The arrays for an SSP platform would have to operate at 1000 volt or higher, as compared to the current International Space Station's 160v photovoltaic arrays. Development of design and manufacturing techniques to prevent 1000v self-destructive arcing continued. Several arc mitigation techniques were evaluated. Samples incorporating the most promising techniques were acquired and tested to achieve a non-arcing "rad" hard high voltage (greater than 300v) array. Initial development was performed at 300v to utilize existing facilities and equipment.

Solar dynamics

Solar Dynamic (SD) power systems concentrate sunlight into a receiver where the energy is transferred to a heat engine for conversion to electrical power. Brayton heat engines utilize a turbine, compressor, and rotary alternator to produce power using an inert gas working fluid. Such a system was devised for use on an SSP.

Cost, mass, and technical risk of various Solar Power Generation (SPG) options for a solar dynamic system were studied. For a 10MW SD system, at high power levels this technology was shown to be competitive with projected photovoltaic systems. Testing was performed to determine the characterization of high temperature secondary concentrator refractive materials in an SD environment. A prototype refractive secondary concentrator with a concentration ratio of 10:1 was designed. This, combined with a primary concentrator of 1000:1 would result in a very high 10,000:1 ratio which permits a reasonable pointing accuracy requirement of 0.1°. The performance of the sapphire concentrator was evaluated via an on-sun calorimeter test.

Power management & distribution

Power Management and Distribution (PMAD) covers the entire power system between the source or power generator and the load, which in this case is the transmitter. Studies were being conducted to determine sensible technologies this size and scope. All of the switches, conductors and converters were immense compared to current spacecraft. Questions such as using alternating current vs direct current power distribution, grounding schemes, standard current conductors vs high and/or low temperature superconductors, system voltage level vs environmental arcing mitigation strategies, types of power converters and system protection devices, and high temperature radiation resistant circuit elements. Results were to be published by the Systems Analysis and Technology Working Group (SATWG) at the culmination of FY 98-99 SERT. Meanwhile, technologies were selected, wherever possible, to leverage other government technology investigations:

Superconductors

A contracted study was continued for the implementation of superconductors on the SSP. Initial studies showed that transmission voltages could be reduced to less than 300 Volts, mitigating arcing effects. Superconductor complications included cryogenic cooling systems with armor to protect against micrometeoroid impact and specialized connectors at segment, switch and power converter interfaces. It was shown that the tremendous magnetic repulsion force (on the order of 3.5 MT/meter radially at 1 Megamp) could be used for deployment and to present an extremely rigid structure.

Silicon carbide power electronics

Silicon carbide technologies leading to power devices continued to be pursued. This leveraged work previously funded to develop defect free and thick SiC epitaxial substrates. Although substrates could currently be manufactured with acceptably small numbers of micropipe defects, the next goal was to reduce other defects that can harm the performance of power devices. An objective was to demonstrate the high temperature operation of high-voltage SiC diodes, MOSFETs, and JFETs in a DC-DC power converter and develop models for predicting the influence of defects on device performance.

Milestones/products 1999: Demonstrated a 2 kW SiC thyristor operating at 300C; breadboarded 300 volt switch and 600 volt switch; completed dynamic characterization of SiC thyristors. 2000: Completed converter topology vs device study with a breadboard converter prototype; Tested 600v/100amp solid body fuse.

Ion thrusters

Ion thrusters are an enabling technology for SSP Low Earth Orbit (LEO) to Geostationary Orbit (GEO) orbit transfer and station keeping. Studies showed that advanced electric propulsion can provide a factor of 5 increase in payload for Earth to orbit transfer when compared to storable biprop and cryogenic biprop thrusters; payload mass that normally would be manifested for propellant. Comparisons made to gridded ion thrusters, magnetoplasmadynamic and pulsed inductive thrusters showed that Hall thruster technology provides overall greater benefits, including quicker trip times, good power density, a good contemporary technology base and good flight history, all translating into commercial industry acceptance. Advances such as direct power drive from the solar arrays and single and/or two-stage operation will allow payloads of 13 to 15 metric tons per 20 metric tons to LEO from launch as opposed to only 2 metric tons using chemical propulsion. Trip times from LEO to GEO are also reasonable at 120 to 230 days depending on performance setpoint. The proposed Hall thruster system consisted of four 50 kW krypton Hall thrusters directly driven from a 200 kW solar array. The propulsion system will be included on each SSP segment. Performance required from the Hall thruster units is 2000 to 3500 sec ISP with an overall system efficiency of 52% to 57%. Due to the mass of fuel required to place the entire system into geostationary orbit, propellants besides xenon (normally used), such as krypton and noble gas mixtures were proposed. Additional work on alternative fuels would eventually need to be conducted.

In 2000: tested high power Hall thruster; evaluated 1st generation domestic 50 kW breadboard engine in GRC high power Hall thruster test bed and high current cathode development

Advantages

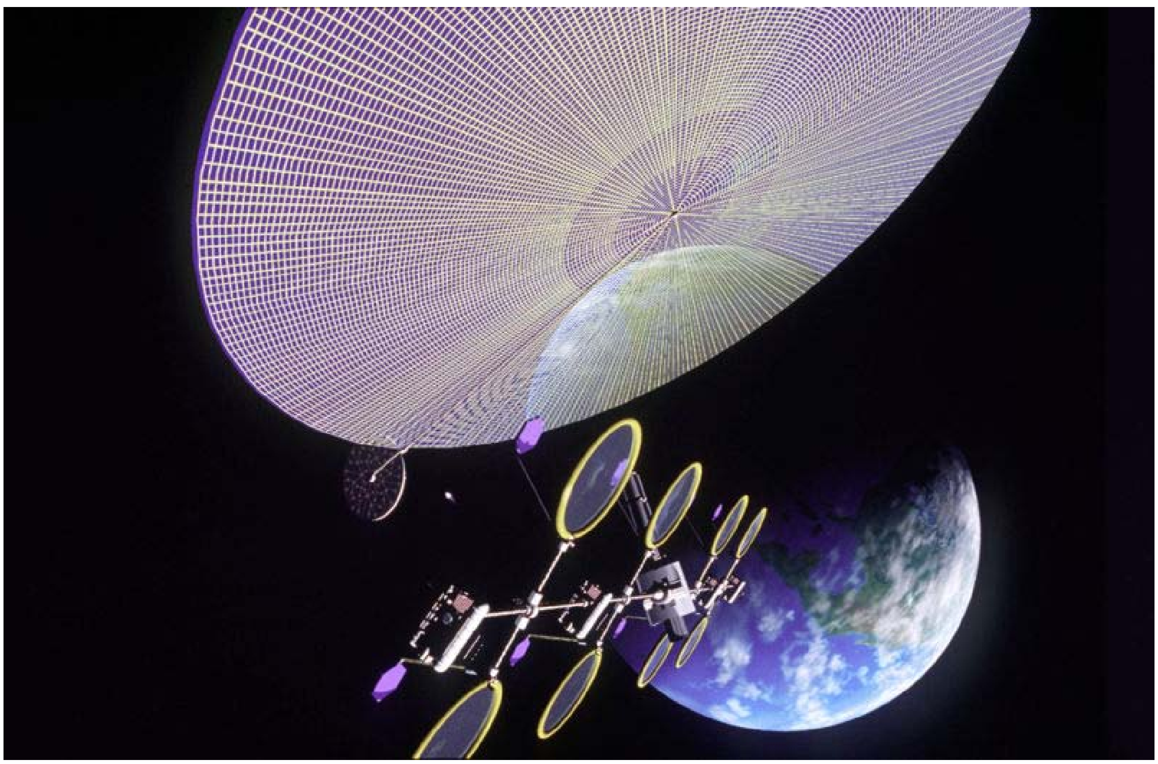
The SBSP concept is attractive because space has several major advantages over the Earth's surface for the collection of solar power. There is no air in space, so the collecting surfaces would receive much more intense sunlight, unaffected by weather. In geostationary orbit, an SPS would be illuminated over 99% of the time; such an SPS would be in Earth's shadow on only a few days at the spring and fall equinoxes; and even then for a maximum of 75 minutes late at night when power demands are at their lowest. This characteristic of SBSP avoids the expense of storage facilities (dams, oil storage tanks, coal dumps) necessary in many Earth-based power generation systems. Additionally, SBSP would have fewer or none of the ecological (or political) consequences of fossil fuel systems.

SBSP would also be applicable on a global scale. Nuclear power raises questions of proliferation and waste disposal, which pose problems everywhere, but especially in undeveloped areas which are less capable of coping with them. SBSP poses no such known potential threat.

This technology can be of value to relief efforts in disaster areas. SBSP could step in at short notice to provide as much power as is necessary both for the relief effort and to provide continuity of energy until ground based transfer methods are restored.

There is a significant military advantage to SBSP in that it would provide the option to have almost instantaneous sustained power nearly anywhere on the globe. It has been estimated that the average price of fuel for the US Army exceeds $5 per gallon. During Operation Iraqi Freedom, there is an estimate that fuel costs in some areas approached $20 per gallon. This is undoubtedly due to the cost of physically moving large quantities of fuel, and the massive security costs in protecting these convoys in a war zone. The estimated costs given above do not include the high cost in the lives of American servicemen and women who are killed or injured during attacks on supply convoys. With a mobile SBSP receiving station, the Army could quickly be provided with megawatts of clean, sustained energy. If a conflict forced a rapid change in the geographic location of Army personnel, the power from SBSP could simply be redirected by altering the position of the SBSP satellites. If SBSP became an established source of power, it could also provide a military benefit in that the supply would inherently be much more secure than traditional energy delivery methods, chances of an energy scarcity based conflict could be much reduced.

Design



Space-based solar power essentially consists of three parts:

1. a means of collecting solar power in space, for example via solar cells or a heat engine
2. a means of transmitting power to earth, for example via microwave or laser
3. a means of receiving power on earth, for example via a microwave antenna (rectenna)

The space-based portion will be in a freefall, vacuum environment and will not need to support itself against gravity other than relatively weak tidal stresses. It needs no protection from terrestrial wind or weather, but will have to cope with space-based hazards such as micrometeors and solar storms.

Solar energy conversion (solar photons to DC current)

Two basic methods of converting sunlight to electricity have been studied: photovoltaic (PV) conversion, and solar dynamic (SD) conversion.

Most analyses of solar power satellites have focused on photovoltaic conversion (commonly known as "solar cells"). Photovoltaic conversion uses semiconductor cells (*e.g.*, silicon or gallium arsenide) to directly convert photons into electrical power via a quantum mechanical mechanism. Photovoltaic cells are not perfect in practice, as material purity and processing issues during production affect performance; each has been progressively improved for some decades. Some new, thin-film approaches are less efficient (about 20% vs 41% for best in class in each case as of late 2009), but are much less expensive and generally lighter.

In an SPS implementation, photovoltaic cells will likely be rather different from the glass-pane protected solar cell panels familiar to many in current terrestrial use, since they will be optimized for weight, and will be designed to be tolerant of the space radiation environment (some thin film silicon solar panels are highly insensitive to ionising radiation), but will not need to be encapsulated against corrosion from environmental exposure or biological deterioration. They do not require the structural support required for terrestrial use, where the considerable gravity and wind loading imposes structural requirements on terrestrial implementations.

Wireless power transmission to the Earth

Wireless power transmission was proposed early on as a means to transfer energy from collection to the Earth's surface. The power could be transmitted as either microwave or laser radiation at a variety of frequencies depending on system design. Whichever choice is made, the transmitting radiation would have to be non-ionizing to avoid potential disturbances either ecologically or biologically. This established an upper limit for the frequency used, as energy per photon (and consequently the ability to cause ionization) increases with frequency. Ionization of biological materials doesn't begin until ultraviolet or higher frequencies, so most radio frequencies would be feasible.

Microwave power transmission

William C. Brown demonstrated in 1964, during Walter Cronkite's CBS News program, a microwave-powered model helicopter that received all the power it needed for flight from a microwave beam. Between 1969 and 1975, Bill Brown was technical director of a JPL Raytheon program that beamed 30 kW of power over a distance of 1 mile at 84% efficiency.

Microwave power transmission of tens of kilowatts has been well proven by existing tests at Goldstone in California (1975) and Grand Bassin on Reunion Island (1997).

More recently, microwave power transmission has been demonstrated, in conjunction with solar energy capture, between a mountain top in Maui and the main island of Hawaii (92 miles away), by a team under John C. Mankins. Technological challenges in terms of array layout, single radiation element design, and overall efficiency, as well as the associated theoretical limits are presently a subject of research, as it is demonstrated by the upcoming Special Session on "Analysis of Electromagnetic Wireless Systems for Solar Power Transmission" to be held in the 2010 IEEE Symposium on Antennas and Propagation.

Laser power beaming experiments

A large-scale demonstration of power beaming is a necessary step to the development of solar power satellites. Laser power beaming was envisioned by some at NASA as a stepping stone to further industrialization of space.

In the 1980s researchers at NASA worked on the potential use of lasers for space-to-space power beaming, focusing primarily on the development of a solar-powered laser. In 1989 it was suggested that power could also be usefully beamed by laser from Earth to space. In 1991 the SELENE project (SpacE Laser ENErgy) was begun, which included the study of laser power beaming for supplying power to a lunar base.

In 1988 the use of an Earth-based laser to power an electric thruster for space propulsion was proposed by Grant Logan, with technical details worked out in 1989. He proposed using diamond solar cells operating at six hundred degrees to convert ultraviolet laser light, a technology that has yet to be demonstrated even in the laboratory. His ideas were adapted to be more practical.

The SELENE program was a two-year research effort, but the cost of taking the concept to operational status was too high, and the official project was ended in 1993, before reaching a space-based demonstration.

Spacecraft sizing

The size of a solar power satellite would be dominated by two factors: the size of the collecting apparatus (e.g. panels and mirrors), and the size of the transmitting antenna. The distance from Earth to geostationary orbit (22,300 miles, 35,700 km), the chosen wavelength of the microwaves, and certain laws of physics (specifically the Rayleigh Criterion or diffraction limit) will all be factors.

It has been suggested that, for best efficiency, the satellite antenna should be circular and about 1 kilometer in diameter or larger; the ground antenna (rectenna) should be elliptical, 10 km wide, and a length that makes the rectenna appear circular from GEO (Geostationary Orbit). (Typically, 14 km at some North American latitudes.) Smaller antennas would result in increased losses to diffraction/sidelobes. For the desired (23 mW/cm²) microwave intensity these antennas could transfer between 5 and 10 gigawatts of power.

According to some research, to collect and convert the target volume of power, the satellite would require between 50 and 100 square kilometers of collector area (if readily available ~14% efficient monocrystalline silicon solar cells were deployed). State of the art multi-junction solar cells with a maximum efficiency of 43% could reduce the necessary collector area by two thirds. In any case, an SPS's structure will necessarily be large (perhaps kilometers across), making it larger than most man-made structures on Earth, and building structures of such size in orbit has never been attempted.

Location

GEO

The main advantage of locating a space power station in geostationary orbit is that the antenna geometry stays constant, and so keeping the antennas lined up is simpler. Another advantage is that nearly continuous power transmission is immediately available as soon as the first space power station is placed in orbit; other space-based power stations have much longer start-up times before they are producing nearly continuous power.

LEO/MEO instead of GEO

A collection of LEO (Low Earth Orbit) space power stations has been proposed as a precursor to GEO (Geostationary Orbit) space-based solar power. There would be both advantages (shorter energy transmission path, lower cost) and disadvantages (frequent changes in antenna geometries, increased debris collisions, more power stations needed to receive power continuously). It might be possible to deploy LEO systems sooner than GEO because the antenna development would take less time, but it may take longer to prepare and launch the number of required satellites.

Moon

People such as David Criswell suggest that the moon is the optimum location for solar power stations, and promote **lunar solar power**.

The main advantages of locating the solar power collector on the moon is that most of its mass could be constructed out of locally available lunar materials, using in-situ resource utilization, significantly reducing the amount of mass and therefore the launch costs required compared to other space-based solar power stations.

Earth-based infrastructure

The Earth-based receiver antenna (or rectenna) is a critical part of the original SPS concept. It would probably consist of many short dipole antennas, connected via diodes. Microwaves broadcast from the SPS will be received in the dipoles with about 85% efficiency. With a conventional microwave antenna, the reception efficiency is still better, but the cost and complexity is also considerably greater, almost certainly prohibitively so. Rectennas would be multiple kilometers across. Crops and farm animals may be raised underneath a rectenna, as the thin wires used for support and for the dipoles will only slightly reduce sunlight, or non arable land could be used, so such a rectenna would not be as expensive in terms of land use as might be supposed.

Dealing with launch costs

One problem for the SBSP concept is the cost of space launches and the amount of material that would need to be launched.

Much of the material launched need not be delivered to its eventual orbit immediately, which raises the possibility that high efficiency (but slower) engines could move SPS material from LEO to GEO at an acceptable cost. Examples include ion thrusters or nuclear propulsion.

Power beaming from geostationary orbit by microwaves carries the difficulty that the required 'optical aperture' sizes are very large. For example, the 1978 NASA SPS study required a 1-km diameter transmitting antenna, and a 10 km diameter receiving rectenna, for a microwave beam at 2.45 GHz. These sizes can be somewhat decreased by using shorter wavelengths, although they have increased atmospheric absorption and even potential beam blockage by rain or water droplets. Because of the thinned array curse, it is not possible to make a narrower beam by combining the beams of several smaller satellites. The large size of the transmitting and receiving antennas means that the minimum practical power level for an SPS will necessarily be high; small SPS systems will be possible, but uneconomic.

To give an idea of the scale of the problem, assuming a solar panel mass of 20 kg per kilowatt (without considering the mass of the supporting structure, antenna, or any significant mass reduction of any focusing mirrors) a 4 GW power station would weigh about 80,000 metric tons, all of which would, in current circumstances, be launched from the Earth. Very lightweight designs could likely achieve 1 kg/kW,, meaning 4,000 metric tons for the solar panels for the same 4 GW capacity station. This would be the equivalent of between 40 and 150 heavy-lift launch vehicle (HLLV) launches to send the material to low earth orbit, where it would likely be converted into subassembly solar arrays, which then could use high-efficiency ion-engine style rockets to (slowly) reach GEO (Geostationary orbit). With an estimated serial launch cost for shuttle-based HLLVs of $500 million to $800 million, and launch costs for alternative HLLVs at $78 million, total launch costs would range between $11 billion (low cost HLLV, low weight panels) and $320 billion ('expensive' HLLV, heavier panels). For comparison, the direct cost of a new coal or nuclear power plant ranges from $1 billion to $1.5 billion dollars per GW (not including the full cost to the environment from CO2 emissions or storage of spent nuclear fuel, respectively); another example is the Apollo missions to the Moon cost a grand total of $24 billion (1970's dollars), taking inflation into account, would cost $140 billion today, more expensive than the construction of the International Space Station.

Building from space

Gerard O'Neill, noting the problem of high launch costs in the early 1970s, proposed building the SPS's in orbit with materials from the Moon. Launch costs from the Moon are potentially much lower than from Earth, due to the lower gravity. This 1970s proposal assumed the then-advertised future launch costing of NASA's space shuttle. This approach would require substantial up front capital investment to establish mass drivers on the Moon.

Nevertheless, on 30 April 1979, the Final Report ("Lunar Resources Utilization for Space Construction") by General Dynamics' Convair Division, under NASA contract NAS9-15560, concluded that use of lunar resources would be cheaper than Earth-based materials for a system of as few as thirty Solar Power Satellites of 10GW capacity each.

In 1980, when it became obvious NASA's launch cost estimates for the space shuttle were grossly optimistic, O'Neill et al. published another route to manufacturing using lunar materials with much lower startup costs. This 1980s SPS concept relied less on human presence in space and more on partially self-replicating systems on the lunar surface under remote control of workers stationed on Earth. This proposal suffers from the current lack of such automated systems. The design and construction of these automated systems and their use to produce a mass driver launching system on the moon from lunar materials is expected to take more than twenty years. The partially self replicating systems would include locally produced power generation, perhaps solar cells or heat engine produced electrical power.

Asteroid mining has also been seriously considered. A NASA design study evaluated a 10,000 ton mining vehicle (to be assembled in orbit) that would return a 500,000 ton asteroid fragment to geostationary orbit. Only about 3,000 tons of the mining ship would be traditional aerospace-grade payload. The rest would be reaction mass for the mass-driver engine, which could be arranged to be the spent rocket stages used to launch the payload. Assuming that 100% of the returned asteroid was useful, and that the asteroid miner itself couldn't be reused, that represents nearly a 95% reduction in launch costs. However, the true merits of such a method would depend on a thorough mineral survey of the candidate asteroids; thus far, we have only estimates of their composition.

Having a relatively cheap per pound source of raw materials from space would lessen the concern for low mass designs and result in a different sort of SPS being built. The low cost per pound of lunar materials in O'neill's vision would be supported by using lunar material to manufacture more facilities in orbit than just solar power satellites.

Non-conventional launch methods

SBSP costs might be reduced if a means of putting the materials into orbit were developed that did not rely on rockets. Some possible technologies include ground launch systems such as mass drivers or Lofstrom loops, which would launch using electrical power, or the geosynchronous orbit space elevator. However, these require technology that is yet to be developed. John Hunter of Quicklaunch is working on commercialising the 'Hydrogen Gun', a new form of mass driver which proposes to deliver unmanned payloads to orbit for around 5% of regular launch costs (or $500 per pound; US$1,000 *per* kilogram) and perform 5 launches per day.

Advanced techniques for launching from the moon may reduce the cost of building a solar power satellite from lunar materials. Some proposed techniques include the lunar mass driver and the lunar space elevator, first described by Jerome Pearson. It would require establishing silicon mining and solar cell manufacturing facilities on the Moon.

Counter arguments

Safety

The use of microwave transmission of power has been the most controversial issue in considering any SPS design.

At the Earth's surface, a suggested microwave beam would have a maximum intensity at its center, of 23 mW/cm^2 (less than 1/4 the solar irradiation constant), and an intensity of less than 1 mW/cm^2 outside of the rectenna fenceline (the receiver's perimeter). These compare with current United States Occupational Safety and Health Act (OSHA) workplace exposure limits for microwaves, which are 10 mW/cm^2, - the limit itself being expressed in voluntary terms and ruled unenforceable for Federal OSHA enforcement purposes. A beam of this intensity is therefore at its center, of a similar magnitude to current safe workplace levels, even for long term or indefinite exposure. Outside the receiver, it is far less than the OSHA long-term levels Over 95% of the beam energy will fall on the rectenna. The remaining microwave energy will be absorbed and dispersed well within standards currently imposed upon microwave emissions around the world. It is important for system efficiency that as much of the microwave radiation as possible be focused on the rectenna. Outside of the rectenna, microwave intensities rapidly decrease, so nearby towns or other human activity should be completely unaffected.

Exposure to the beam is able to be minimized in other ways. On the ground, physical access is controllable (e.g., via fencing), and typical aircraft flying through the beam provide passengers with a protective metal shell (i.e., a Faraday Cage), which will intercept the microwaves. Other aircraft (balloons, ultralight, etc.) can avoid exposure by observing airflight control spaces, as is currently done for military and other controlled airspace.

The microwave beam intensity at ground level in the center of the beam would be designed and physically built into the system; simply, the transmitter would be too far away and too small to be able to increase the intensity to unsafe levels, even in principle.

In addition, a design constraint is that the microwave beam must not be so intense as to injure wildlife, particularly birds. Experiments with deliberate microwave irradiation at reasonable levels have failed to show negative effects even over multiple generations.

Some have suggested locating rectennas offshore, but this presents serious problems, including corrosion, mechanical stresses, and biological contamination.

A commonly proposed approach to ensuring fail-safe beam targeting is to use a retrodirective phased array antenna/rectenna. A "pilot" microwave beam emitted from the center of the rectenna on the ground establishes a phase front at the transmitting antenna. There, circuits in each of the antenna's subarrays compare the pilot beam's phase front with an internal clock phase to control the phase of the outgoing signal. This forces the transmitted beam to be centered precisely on the rectenna and to have a high degree of phase uniformity; if the pilot beam is lost for any reason (if the transmitting antenna is turned away from the rectenna, for example) the phase control value fails and the microwave power beam is automatically defocused. Such a system would be physically incapable of focusing its power beam anywhere that did not have a pilot beam transmitter.

The long-term effects of beaming power through the ionosphere in the form of microwaves has yet to be studied, but nothing has been suggested which might lead to any significant effect.

Atmospheric damage due to launches

When hot rocket exhaust reacts with atmospheric nitrogen, it can form nitrogen compounds. In particular these nitrogen compounds are problematic when they form in the stratosphere, as they can damage the ozone layer. However, the environmental effect of rocket launches is negligible compared to higher volume polluters, such as airplanes and automobiles.

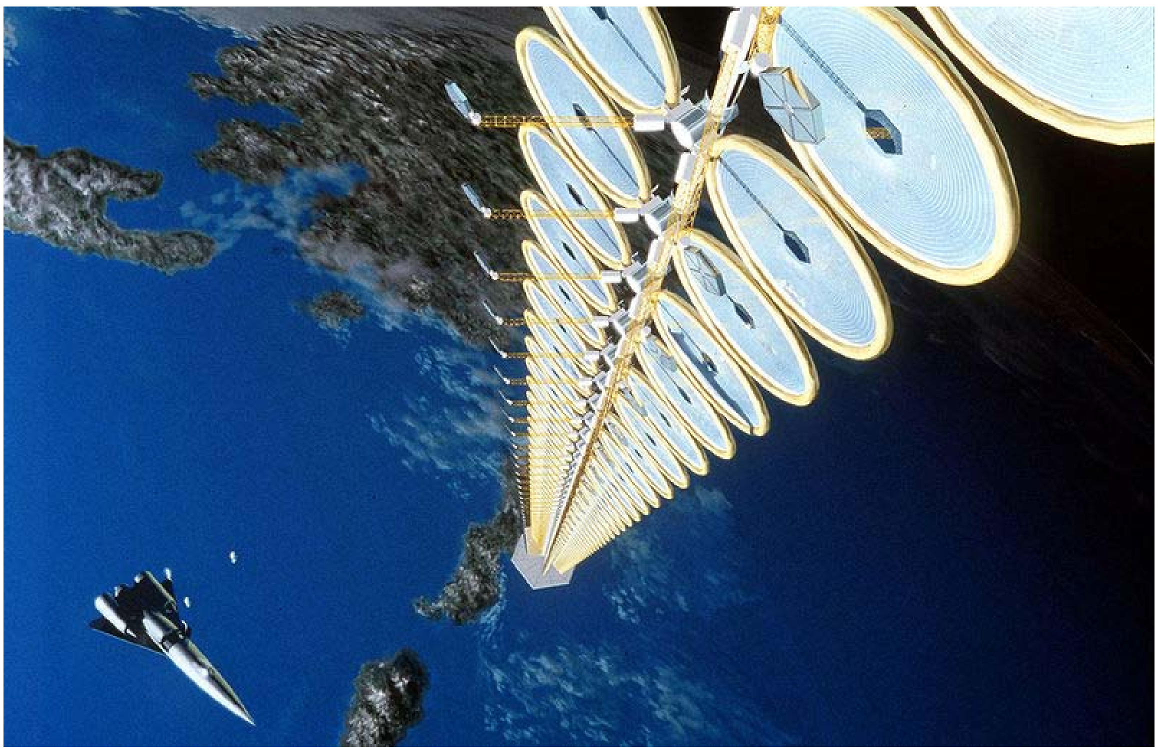
In fiction

- Space stations transmitting solar power have appeared in science-fiction works like Isaac Asimov's *Reason* (1941), that centers around the troubles caused by the robots operating the station. Asimov's short story "The Last Question" also features the use of SBSP to provide limitless energy for use on Earth.
- In the novel "Skyfall" (1976) by Harry Harrison an attempt to launch the core of powersat from Cape Canaveral ends in disaster when the launch vehicle fails trapping the payload in a decaying orbit.
- Solar Power Satellites have also been seen in the work of author Ben Bova's novels "Powersat" and "Colony".

- In Sid Meier's *Alpha Centauri*, an endgame 'building' that fulfills the same function as an SPS is the 'Orbital Power Transmitter' which provides every city that you own with a unit of energy per satellite launched, providing the city has an Aerospace Command building or your faction controls the space elevator. Building multiple Orbital Power Transmitters provides massive bonuses to energy generation and soon pay for themselves many times over.
- In a 1981 storyline from the Iron Man comic book (issues #142-144), a rogue microwave transmission from a secret Solar Power Satellite is responsible for numerous deaths in Allentown, Iowa.
- In the computer games *SimCity 2000* and *3000*, plants that implemented solar satellite technology called microwave powerplants were available in the future. One disaster scenario involved the beam missing the receiver and hitting the city's infrastructure. The plant was discontinued in *SimCity 4* but several fan-made microwave powerplants were available on various *SimCity 4* fan sites.
- In the film *Die Another Day*, a satellite weapon is disguised as a solar power satellite.
- In *Mobile Suit Gundam 00*, a solar power satellite array is constructed around the Earth and is used to harness solar energy for use. They play a critical plot role in the superpowers' power balance.
- In *After War Gundam X*, a solar power station is built on the moon, and is used to supply energy via microwave to various mobile suits, to energize their powerful "Satellite Cannons".

Chapter-2

Wireless Energy Transfer



An artist's depiction of a solar satellite, which could send energy wirelessly to a space vessel or planetary surface.

Wireless energy transfer or *Wireless Power* is the process that takes place in any system where electrical energy is transmitted from a power source to an electrical load without interconnecting wires. Wireless transmission is useful in cases where instantaneous or continuous energy transfer is needed but interconnecting wires are inconvenient, hazardous, or impossible.

Wireless energy transfer is different from wireless transmission of information, such as radio, where the signal-to-noise ratio (SNR) or the percentage of power received becomes critical only if it is too low to adequately recover the signal. With wireless power transmission, efficiency is the more important parameter.

The most common form of wireless power transmission is carried out using induction, followed by electrodynamic induction. Other present-day technologies for wireless power include those based upon microwaves and lasers.

History of wireless energy transfer

- **1820**: André-Marie Ampère develops Ampere's law showing that electric current produces a magnetic field.
- **1831**: Michael Faraday develops Faraday's law of induction describing the electromagnetic force induced in a conductor by a time-varying magnetic flux.
- **1864**: James Clerk Maxwell synthesizes the previous observations, experiments and equations of electricity, magnetism and optics into a consistent theory and mathematically models the behavior of electromagnetic radiation.
- **1888**: Heinrich Rudolf Hertz confirms the existence of electromagnetic radiation. Hertz's "*apparatus for generating electromagnetic waves*" was a VHF or UHF "radio wave" spark gap transmitter.
- **1891**: Nikola Tesla improves Hertz-wave wireless transmitter RF power supply or exciter in his patent No. 454,622, "System of Electric Lighting."
- **1893**: Tesla demonstrates the wireless illumination of phosphorescent lamps of his design at the World's Columbian Exposition in Chicago.
- **1894**: Hutin & LeBlanc, espouse long held view that inductive energy transfer should be possible, they received U.S. Patent # 527,857 describing a system for power transfer at 3 kHz.
- **1894**: Tesla wirelessly lights up phosphorescent and incandescent lamps at the 35 South Fifth Avenue laboratory, and later at the 46 E. Houston Street laboratory in New York City by means of "electro-dynamic induction," that is to say wireless resonant inductive coupling.
- **1894**: Jagdish Chandra Bose ignites gunpowder and rings a bell at a distance using electromagnetic waves, showing that communications signals can be sent without using wires.
- **1895**: Bose transmits signals over a distance of nearly a mile.
- **1896**: Tesla transmits signals over a distance of about 48 kilometres (30 mi).
- **1897**: Guglielmo Marconi uses a radio transmitter to transmit Morse code signals over a distance of about 6 km.
- **1897**: Tesla files the first of his patent applications dealing specifically with wireless transmission.
- **1899**: In Colorado Springs, Tesla writes, "the inferiority of the induction method would appear immense as compared with the *disturbed charge of ground and air method*."
- **1900**: Marconi fails to get a patent for radio in the United States.
- **1901**: Marconi transmits signals across the Atlantic.
- **1902**: Tesla vs. Reginald Fessenden - U.S. Patent Interference No. 21,701, System of Signaling (wireless); selective illumination of incandescent lamps, time and frequency domain spread spectrum telecommunications, electronic logic gates in general.

- **1904**: At the St. Louis World's Fair, a prize is offered for a successful attempt to drive a 0.1 horsepower (75 W) airship motor by energy transmitted through space at a distance of least 100 feet (30 m).
- **1916**: Tesla states, "In my [*disturbed charge of ground and air*] system, you should free yourself of the idea that there is [electromagnetic] radiation, that energy is radiated. It is not radiated; it is conserved."
- **1917**: Tesla's Wardenclyffe tower is demolished.
- **1926**: Shintaro Uda and Hidetsugu Yagi publish their first paper on Uda's *"tuned high-gain directional array"* better known as the Yagi antenna.
- **1961**: William C. Brown publishes an article exploring possibilities of microwave power transmission.
- **1964**: Brown demonstrates on CBS News with Walter Cronkite a model helicopter that received all the power needed for flight from a microwave beam. Between 1969 and 1975, Brown was technical director of a JPL Raytheon program that beamed 30 kW over a distance of 1 mile at 84% efficiency.
- **1968**: Peter Glaser proposes wirelessly transferring solar energy captured in space using "Powerbeaming" technology. This is usually recognized as the first description of a solar power satellite.
- **1971**: Prof. Don Otto develops a small trolley powered by induction at The University of Auckland, in New Zealand.
- **1973**: World first passive RFID system demonstrated at Los-Alamos National Lab.
- **1975**: Goldstone Deep Space Communications Complex does experiments in the tens of kilowatts.
- **1988**: A power electronics group led by Prof. John Boys at The University of Auckland in New Zealand, develops an inverter using novel engineering materials and power electronics and conclude that power transmission by means of electrodynamic induction should be achievable. A first prototype for a contact-less power supply is built. Auckland Uniservices, the commercial company of The University of Auckland, patents the technology.
- **1989**: Daifuku, a Japanese company, engages Auckland Uniservices Ltd. to develop technology for car assembly plants and materials handling providing challenging technical requirements including multiplicity of vehicles.
- **1990**: Prof. John Boys team develops novel technology enabling multiple vehicles to run on the same inductive power loop and provide independent control of each vehicle. Auckland UniServices Patents the technology.
- **1996**: Auckland Uniservices develops an Electric Bus power system using Electrodynamic Induction to charge (30-60 kW) opportunistically commencing implementation in New Zealand. Prof John Boys Team commission 1st commercial IPT Bus in the world at Whakarewarewa, in New Zealand.
- **1998**: RFID tags powered by electrodynamic induction over a few feet
- **1999**: Dr. Herbert L. Becker powers a lamp and a hand held fan from a distance of 30 feet.
- **2001**: Splashpower formed in the UK. Uses coupled resonant coils in a flat "pad" style to transfer tens of watts into a variety of consumer devices, including lamp, phone, PDA, iPod etc.

- **2004**: Electrodynamic Induction used by 90 percent of the US$1 billion clean room industry for materials handling equipment in semiconductor, LCD and plasma screen manufacture.
- **2005**: Prof Boys' team at The University of Auckland, refines 3-phase IPT Highway and pick-up systems allowing transfer of power to moving vehicles in the lab.
- **2007**: Using Electrodynamic Induction a physics research group, led by Prof. Marin Soljačić, at MIT, wirelessly power a 60W light bulb with 40% efficiency at a 2 metres (6.6 ft) distance with two 60 cm-diameter coils.
- **2008**: Bombardier offers new wireless transmission product PRIMOVE, a power system for use on trams and light-rail vehicles.
- **2008**: Industrial designer Thanh Tran, at Brunel University made a wireless lamp incorporating a high efficiency 3W LED.
- **2008**: Intel reproduces Nikola Tesla's original 1894 implementation of Electrodynamic Induction and Prof. John Boys group's 1988 follow-up experiments by wirelessly powering a nearby light bulb with 75% efficiency.
- **2008**: Greg Leyh and Mike Kennan of the Nevada Lightning Laboratory publish a paper on Nikola Tesla's *disturbed charge of ground and air method* of wireless power transmission with circuit simulations and test results showing an efficiency greater than can be obtained using the Electrodynamic Induction method.
- **2009**: A Consortium of interested companies called the Wireless Power Consortium announce they are nearing completion for a new industry standard for low-power Inductive charging
- **2009**: An Ex approved Torch and Charger aimed at the offshore market is introduced. This product is developed by Wireless Power & Communication, a Norway based company.
- **2009**: A simple analytical electrical model of electrodynamic induction power transfer is proposed and applied to a wireless power transfer system for implantable devices.
- **2009**: Lasermotive uses diode laser to win $900k NASA prize in power beaming, breaking several world records in power and distance, by transmitting over a kilowatt more than several hundred meters.
- **2009**: Sony shows a wireless electrodynamic-induction powered TV set, 60 W over 50 cm
- **2010**: Haier Group debuts "the world's first" completely wireless LCD television at CES 2010 based on Prof. Marin Soljačić's follow-up research on Nikola Tesla's electrodynamic induction wireless energy transmission method and the Wireless Home Digital Interface (WHDI).

Near field

Near field is wireless transmission techniques over distances comparable to, or a few times the diameter of the device(s), and up to around a quarter of the wavelengths used. Near field energy itself is non radiative, but some radiative losses will occur. In addition there are usually resistive losses. Near field transfer is usually magnetic (inductive), but electric (capacitive) energy transfer can also occur.

Induction

The action of an electrical transformer is the simplest instance of wireless energy transfer. The primary and secondary circuits of a transformer are not directly connected. The transfer of energy takes place by electromagnetic coupling through a process known as mutual induction. (An added benefit is the capability to step the primary voltage either up or down.) The battery charger of a mobile phone or the transformers on the street are examples of how this principle can be used. Induction cookers and many electric toothbrushes are also powered by this technique.

The main drawback to induction, however, is the short range. The receiver must be very close to the transmitter or induction unit in order to inductively couple with it.

Electrodynamic induction

Resonant energy transfer or **resonant inductive coupling** is the near field wireless transmission of energy between two coils that are highly resonant at the same frequency. The equipment to do this is sometimes called a **resonant or resonance transformer**. While many transformers employ resonance, this type has a high *Q* and is often air cored to avoid 'iron' losses. The coils may be present in a single piece of equipment or in separate pieces of equipment.

Resonant transfer works by making a coil *ring* with an oscillating current. This generates an oscillating magnetic field. Because the coil is highly resonant any energy placed in the coil dies away relatively slowly over very many cycles; but if a second coil is brought near to it, the coil can pick up most of the energy before it is lost, even if it is some distance away. The fields used are predominately non radiative, near field (sometimes called evanescent waves), as all hardware is kept within 1/4 wavelength distance, and thus they radiate little energy from the transmitter to infinity.

One of the applications of the resonant transformer is for the CCFL inverter. Another application of the resonant transformer is to couple between stages of a superheterodyne receiver, where the selectivity of the receiver is provided by tuned transformers in the intermediate-frequency amplifiers. Resonant transformers such as the Tesla coil can generate very high voltages with or without arcing, and are able to provide much higher current than electrostatic high-voltage generation machines such as the Van de Graaff generator. Resonant energy transfer is the operating principle behind proposed short range wireless electricity systems such as WiTricity and systems that have already been deployed, such as some types of RFID tags and contactless smart cards.

These types of systems generate magnetic fields that are unlikely to cause health issues in humans.

Resonant coupling

Non-resonant coupled inductors, such as typical transformers, work on the principle of a primary coil generating a magnetic field and a secondary coil subtending as much as possible of that field so that the power passing though the secondary is as close as possible to that of the primary. This requirement that the field be covered by the secondary results in very short range and usually requires a magnetic core. Over greater distances the non-resonant induction method is highly inefficient and wastes the vast majority of the energy in resistive losses of the primary coil.

Using resonance can help efficiency dramatically. If resonant coupling is used, each coil is capacitively loaded so as to form a tuned LC circuit. If the primary and secondary coils are resonant at a common frequency, it turns out that significant power may be transmitted between the coils over a range of a few times the coil diameters at reasonable efficiency.

Energy transfer and efficiency

The general principle is that if a given amount of energy is placed into a primary coil which is capacitively loaded, the coil will 'ring', and form an oscillating magnetic field. The energy will transfer back and forth between the magnetic field in the inductor and the electric field across the capacitor at the resonant frequency. This oscillation will die away at a rate determined by the *Q* factor, mainly due to resistive and radiative losses. However, provided the secondary coil cuts enough of the field that it absorbs more energy than is lost in each cycle of the primary, then most of the energy can still be transferred.

The primary coil forms a series RLC circuit, and the *Q* factor for such a coil is:

$$Q = \frac{1}{R}\sqrt{\frac{L}{C}},$$

Because the *Q* factor can be very high, (experimentally around a thousand has been demonstrated with air cored coils) only a small percentage of the field has to be coupled from one coil to the other to achieve high efficiency, even though the field dies quickly with distance from a coil, the primary and secondary can be several diameters apart.

Coupling coefficient

The coupling coefficient is the fraction of the flux of the primary that cuts the secondary coil, and is a function of the geometry of the system. The coupling coefficient is between 0 and 1.

Systems are said to be tightly coupled, loosely coupled, critically coupled or overcoupled. Tight coupling is when the coupling coefficient is around 1 as with conventional transformers. Overcoupling is when the secondary coil is close enough that it tends to collapse the primary's field, and critical coupling is when the transfer in the passband is optimal. Loose coupling is when the coils are distant from each other, so that most of the flux misses the secondary, in Tesla coils around 0.2 is used, and at greater distances, for example for wireless power transmission, it may be lower than 0.01.

Power transfer

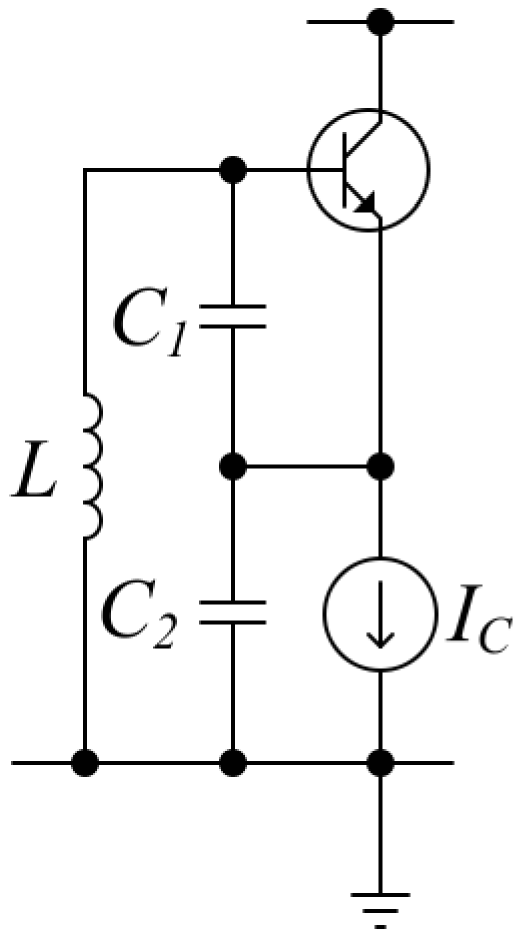
Because the *Q* can be very high, even when low power is fed into the transmitter coil, a relatively intense field builds up over multiple cycles, which increases the power that can be received—at resonance far more power is in the oscillating field than is being fed into the coil, and the receiver coil receives a percentage of that.

Voltage gain

The voltage gain of resonantly coupled coils is proportional to the square root of the ratio of secondary and primary inductances.

Transmitter coils and circuitry

Unlike the multiple-layer secondary of a non-resonant transformer, coils for this purpose are often single layer solenoids (to minimise skin effect and give improved *Q*) in parallel with a suitable capacitor, or they may be other shapes such as wave-wound litz wire. Insulation is either absent, with spacers, or low permittivity, low loss materials such as silk to minimise dielectric losses.

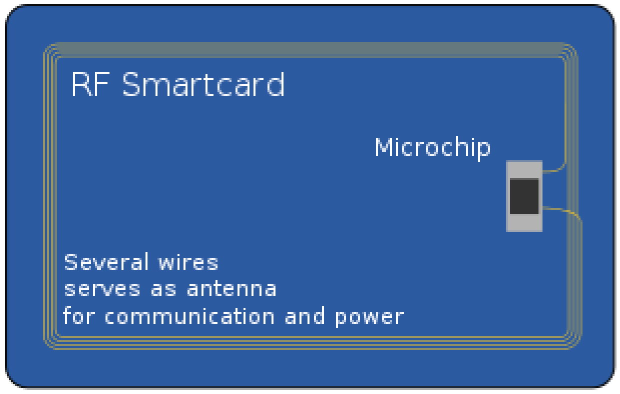


Colpitts oscillator. In resonant energy transfer the inductor would be the transmitter coil and capacitors are used to tune the circuit to a suitable frequency.

To progressively feed energy/power into the primary coil with each cycle, different circuits can be used. One circuit employs a Colpitts oscillator.

In Tesla coils an intermittent switching system, a "circuit controller or "break," is used to inject an impulsive signal into the primary coil; the secondary coil then rings and decays.

Receiver coils and circuitry

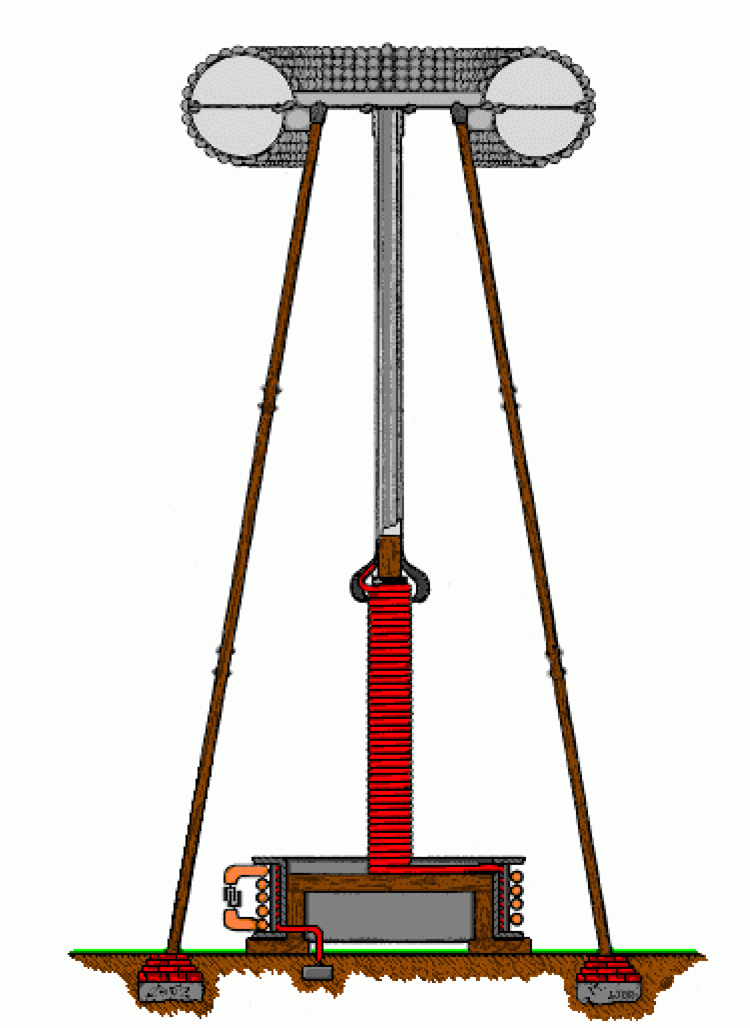


The receiver of a smart card has a coil connected to a chip which provides capacitance to give resonance as well as regulators to provided a suitable voltage

The secondary receiver coils are similar designs to the primary sending coils. Running the secondary at the same resonant frequency as the primary ensures that the secondary has a low impedance at the transmitter's frequency and that the energy is optimally absorbed.

To remove energy from the secondary coil, different methods can be used, the AC can be used directly or rectified and a regulator circuit can be used to generate DC voltage.

History



This advanced Tesla coil was designed to implement wireless energy transfer by means of the *disturbed charge of ground and air method.*

In 1894 Nikola Tesla used resonant inductive coupling, also known as "electro-dynamic induction" to wirelessly light up phosphorescent and incandescent lamps at the 35 South Fifth Avenue laboratory, and later at the 46 E. Houston Street laboratory in New York City.]]. In 1897 he patented a device called the high-voltage, resonance transformer or "Tesla coil." Transferring electrical energy from the primary coil to the secondary coil by resonant induction, a Tesla coil is capable of producing very high voltages at high frequency. The improved design allowed for the safe production and utilization of high-potential electrical currents, "without serioius liability of the destruction of the apparatus itself and danger to persons approaching or handling it."

In the early 1960s resonant inductive wireless energy transfer was used successfully in implantable medical devices including such devices as pacemakers and artificial hearts.

While the early systems used a resonant receiver coil, later systems implemented resonant transmitter coils as well. These medical devices are designed for high efficiency using low power electronics while efficiently accommodating some misalignment and dynamic twisting of the coils. The separation between the coils in implantable applications is commonly less than 20 cm. Today resonant inductive energy transfer is regularly used for providing electric power in many commercially available medical implantable devices.

Wireless electric energy transfer for experimentally powering electric automobiles and buses is a higher power application (>10 kW) of resonant inductive energy transfer. High power levels are required for rapid recharging and high energy transfer efficiency is required both for operational economy and to avoid negative environmental impact of the system. An experimental electrified roadway test track built circa 1990 achieved 80% energy efficiency while recharging the battery of a prototype bus at a specially equipped bus stop. The bus could be outfitted with a retractable receiving coil for greater coil clearance when moving. The gap between the transmit and receive coils was designed to be less than 10 cm when powered. In addition to buses the use of wireless transfer has been investigated for recharging electric automobiles in parking spots and garages as well.

Some of these wireless resonant inductive devices operate at low milliwatt power levels and are battery powered. Others operate at higher kilowatt power levels. Current implantable medical and road electrification device designs achieve more than 75% transfer efficiency at an operating distance between the transmit and receive coils of less than 10 cm.

In 1995, Professor John Boys and Prof Grant Covic, of The University of Auckland in New Zealand, developed systems to transfer large amounts of energy across small air gaps.

In 1998, RFID tags were patented that were powered in this way.

In November 2006, Marin Soljačić and other researchers at the Massachusetts Institute of Technology applied this near field behavior, well known in electromagnetic theory, the wireless power transmission concept based on strongly-coupled resonators. In a theoretical analysis, they demonstrate that, by designing electromagnetic resonators that suffer minimal loss due to radiation and absorption and have a near field with mid-range extent (namely a few times the resonator size), mid-range efficient wireless energy-transfer is possible. The reason is that, if two such resonant circuits tuned to the same frequency are within a fraction of a wavelength, their near fields (consisting of 'evanescent waves') couple by means of evanescent wave coupling (which is related to quantum tunneling). Oscillating waves develop between the inductors, which can allow the energy to transfer from one object to the other within times much shorter than all loss times, which were designed to be long, and thus with the maximum possible energy-transfer efficiency. Since the resonant wavelength is much larger than the resonators, the field can circumvent extraneous objects in the vicinity and thus this mid-range energy-transfer scheme does not require line-of-sight. By utilizing in particular the magnetic field to achieve the coupling, this method can be safe, since magnetic fields interact weakly with living organisms.

Comparison with other technologies

Compared to inductive transfer in conventional transformers, except when the coils are well within a diameter of each other, the efficiency is somewhat lower (around 80% at short range) whereas tightly coupled conventional transformers may achieve greater efficiency (around 90-95%) and for this reason it cannot be used where high energy transfer is required at greater distances.

However, compared to the costs associated with batteries, particularly non-rechargeable batteries, the costs of the batteries are hundreds of times higher. In situations where a source of power is available nearby, it can be a cheaper solution. In addition, whereas batteries need periodic maintenance and replacement, resonant energy transfer could be used instead. Batteries additionally generate pollution during their construction and their disposal which largely would be avoided.

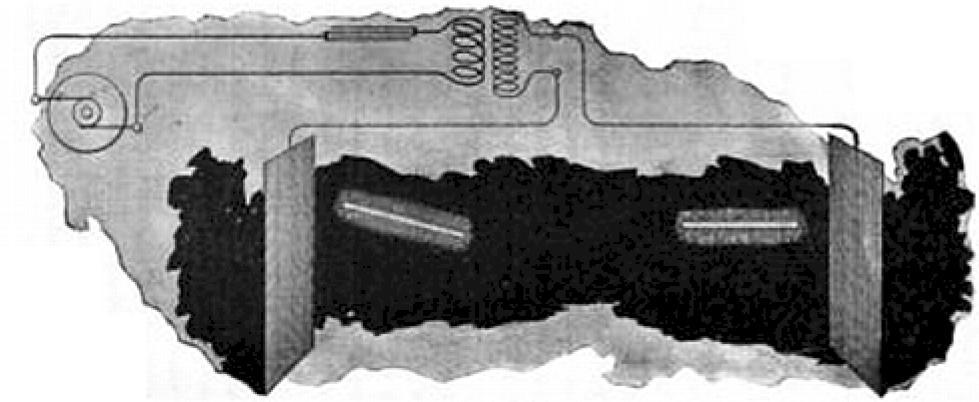
Regulations and safety

Unlike mains-wired equipment, no direct electrical connection is needed and hence equipment can be sealed to minimize the possibility of electric shock.

Because the coupling is achieved using predominantly magnetic fields; the technology may be relatively safe. Safety standards and guidelines do exist in most countries for electromagnetic field exposures (e.g.) Whether the system can meet the guidelines or the less stringent legal requirements depends on the delivered power and range from the transmitter.

Deployed systems already generate magnetic fields, for example induction cookers and contactless smart card readers.

Electrostatic induction



Tesla illuminating two exhausted tubes by means of a powerful, rapidly alternating electrostatic field created between two vertical metal sheets suspended from the ceiling on insulating cords.

The "electrostatic induction effect" or "capacitive coupling" is an electric field gradient or differential capacitance between two elevated electrodes over a conducting ground plane for wireless energy transmission involving high frequency alternating current potential differences transmitted between two plates or nodes. The electrostatic forces through natural media across a conductor situated in the changing magnetic flux can transfer energy to a receiving device (such as Tesla's wireless bulbs). Sometimes called "the Tesla effect" it is the application of a type of electrical displacement, i.e., the passage of electrical energy through space and matter, other than and in addition to the development of a potential across a conductor.

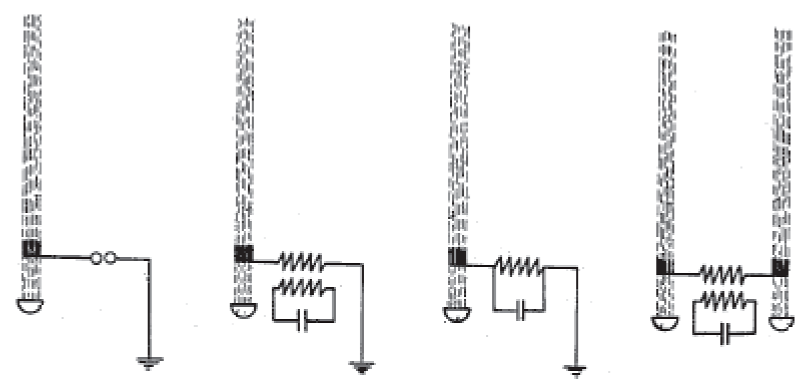
Tesla stated,

"Instead of depending on [electrodynamic] induction at a distance to light the tube . . . [the] ideal way of lighting a hall or room would . . . be to produce such a condition in it that an illuminating device could be moved and put anywhere, and that it is lighted, no matter where it is put and without being electrically connected to anything. I have been able to produce such a condition by creating in the room a powerful, ***rapidly alternating electrostatic field***. For this purpose I suspend a sheet of metal a distance from the ceiling on insulating cords and connect it to one terminal of the induction coil, the other terminal being preferably connected to the ground. Or else I suspend two sheets . . . each sheet being connected with one of the terminals of the coil, and their size being carefully determined. An exhausted tube may then be carried in the hand anywhere between the sheets or placed anywhere, even a certain distance beyond them; it remains always luminous."

and

“In some cases when small amounts of energy are required the high elevation of the terminals, and more particularly of the receiving-terminal D' may not be necessary, since, especially when the frequency of the currents is very high, a sufficient amount of energy may be collected at that terminal by ***electrostatic induction*** from the upper air strata, which are rendered conducting by the active terminal of the transmitter or through which the currents from the same are conveyed."

Far field



Means for long conductors of electricity forming part of an electric circuit and electrically connecting said ionized beam to an electric circuit. Hettinger 1917 -(U.S. Patent 1,309,031)

Far field methods achieve longer ranges, often multiple kilometer ranges, where the distance is much greater than the diameter of the device(s). The main reason for longer ranges with radio wave and optical devices is the fact that electromagnetic radiation in the far-field can be made to match the shape of the receiving area (using high directivity antennas or well-collimated Laser Beam) thereby delivering almost all emitted power at long ranges. The maximum directivity for antennas is physically limited by diffraction.

Beamed power, size, distance, and efficiency

The size of the components may be dictated by the distance from transmitter to receiver, the wavelength and the Rayleigh criterion or diffraction limit, used in standard radio frequency antenna design, which also applies to lasers. In addition to the Rayleigh criterion Airy's diffraction limit is also frequently used to determine an approximate spot size at an arbitrary distance from the aperture.

The Rayleigh criterion dictates that any radio wave, microwave or laser beam will spread and become weaker and diffuse over distance; the larger the transmitter antenna or laser aperture compared to the wavelength of radiation, the tighter the beam and the less it will spread as a function of distance (and vice versa). Smaller antennae also suffer from excessive losses due to side lobes. However, the concept of laser aperture considerably differs from an antenna. Typically, a laser aperture much larger than the wavelength induces multi-moded radiation and mostly collimators are used before emitted radiation couples into a fiber or into space.

Ultimately, beamwidth is physically determined by diffraction due to the dish size in relation to the wavelength of the electromagnetic radiation used to make the beam. Microwave power beaming can be more efficient than lasers, and is less prone to atmospheric attenuation caused by dust or water vapor losing atmosphere to vaporize the water in contact.

Then the power levels are calculated by combining the above parameters together, and adding in the gains and losses due to the antenna characteristics and the transparency and dispersion of the medium through which the radiation passes. That process is known as calculating a link budget.

Radio and microwave

A parabolic antenna for **Erdfunkstelle Raisting**, based in Raisting, Bavaria, Germany.

Microwave power transmission

Microwave power transmission (**MPT**) is the use of microwaves to transmit power through outer space or the atmosphere without the need for wires. It is a sub-type of the more general wireless energy transfer methods.

History

Following World War II, which saw the development of high-power microwave emitters known as cavity magnetrons, the idea of using microwaves to transmit power was researched. In 1964, William C. Brown demonstrated a miniature helicopter equipped with a combination antenna and rectifier device called a rectenna. The rectenna converted microwave power into electricity, allowing the helicopter to fly. In principle, the rectenna is capable of very high conversion efficiencies - over 90% in optimal circumstances.

Most proposed MPT systems now usually include a phased array microwave transmitter. While these have lower efficiency levels they have the advantage of being electrically steered using no moving parts, and are easier to scale to the necessary levels that a practical MPT system requires.

Using microwave power transmission to deliver electricity to communities without having to build cable-based infrastructure is being studied at Grand Bassin on Reunion Island in the Indian Ocean.

Common safety concerns

The common reaction to microwave transmission is one of concern, as microwaves are generally perceived by the public as dangerous forms of radiation - stemming from the fact that they are used in microwave ovens. While high power microwaves can be painful and dangerous as in the United States Military's Active Denial System, MPT systems are generally proposed to have only low intensity at the rectenna.

Though this would be extremely safe as the power levels would be about equal to the leakage from a microwave oven, and only slightly more than a cell phone, the relatively diffuse microwave beam necessitates a large rectenna area for a significant amount of energy to be transmitted.

Research has involved exposing multiple generations of animals to microwave radiation of this or higher intensity, and no health issues have been found.

Proposed uses

MPT is the most commonly proposed method for transferring energy to the surface of the Earth from solar power satellites or other in-orbit power sources. MPT is occasionally proposed for the power supply in beam-powered propulsion for orbital lift space ships.

Although lasers are more commonly proposed, their low efficiency in light generation and reception has led some designers to opt for microwave based systems.

Current status

Wireless Power Transmission (using microwaves) is well proven. Experiments in the tens of kilowatts have been performed at Goldstone in California in 1975 and more recently (1997) at Grand Bassin on Reunion Island. In 2008 a long range transmission experiment successfully transmitted 20 watts 92 miles from a mountain on Maui to the main island of Hawaii.

Microwave radio relay

Heinrich-Hertz-Turm in Germany

Microwave radio relay is a technology for transmitting digital and analog signals, such as long-distance telephone calls and the relay of television programs to transmitters, between two locations on a line of sight radio path. In microwave radio relay, radio waves are transmitted between the two locations with directional antennas, forming a fixed radio connection between the two points. Long daisy-chained series of such links form transcontinental telephone and/or television communication systems.

How microwave radio relay links are formed

Relay towers on Frazier Mountain, Southern California

Because a line of sight radio link is made, the radio frequencies used occupy only a narrow path between stations (with the exception of a certain radius of each station).

Antennas used must have a high directive effect; these antennas are installed in elevated locations such as large radio towers in order to be able to transmit across long distances. Typical types of antenna used in radio relay link installations are parabolic reflectors, shell antennas and horn radiators, which have a diameter of up to 4 meters. Highly directive antennas permit an economical use of the available frequency spectrum, despite long transmission distances.

Danish military radio relay node

Planning considerations

Because of the high frequencies used, a quasi-optical line of sight between the stations is generally required. Additionally, in order to form the line of sight connection between the two stations, the first Fresnel zone must be free from obstacles so the radio waves can propagate across a nearly uninterrupted path. Obstacles in the signal field cause unwanted attenuation, and are as a result only acceptable in exceptional cases. High mountain peak or ridge positions are often ideal: Europe's highest radio relay station, the *Richtfunkstation Jungfraujoch*, is situated atop the *Jungfraujoch* ridge at an altitude of 3,705 meters (12,156 ft) above sea level.

Multiple antennas provide space diversity

Obstacles, the curvature of the Earth, the geography of the area and reception issues arising from the use of nearby land (such as in manufacturing and forestry) are important issues to consider when planning radio links. In the planning process, it is essential that "path profiles" are produced, which provide information about the terrain and Fresnel zones affecting the transmission path. The presence of a water surface, such as a lake or river, in the mid-path region also must be taken into consideration as it can result in a near-perfect reflection (even modulated by wave or tide motions), creating multipath distortion as the two received signals ("wanted" and "unwanted") swing in and out of phase. Multipath fades are usually deep only in a small spot and a narrow frequency band, so space and frequency diversity schemes were usually applied in the third quarter of the 20th century.

The effects of atmospheric stratification cause the radio path to bend downward in a typical situation so a major distance is possible as the earth equivalent curvature increases from 6370 km to about 8500 km (a 4/3 equivalent radius effect). Rare events of temperature, humidity and pressure profile versus height, may produce large deviations and distortion of the propagation and affect transmission quality. High intensity rain and snow must also be considered as an impairment factor, especially at frequencies above 10 GHz. All previous factors, collectively known as path loss, make it necessary to compute suitable power margins, in order to maintain the link operative for a high percentage of time, like the standard 99.99% or 99.999% used in 'carrier class' services of most telecommunication operators.

Portable microwave rig for television news

Over-horizon microwave radio relay

In over-horizon, or tropospheric scatter, microwave radio relay, unlike a standard microwave radio relay link, the sending and receiving antennas do not use a line of sight transmission path. Instead, the stray signal transmission, known as "tropo - scatter" or simply "scatter," from the sent signal is picked up by the receiving station. Signal clarity obtained by this method depends on the weather and other factors, and as a result a high level of technical difficulty is involved in the creation of a reliable over horizon radio relay link. Over horizon radio relay links are therefore only used where standard radio relay links are unsuitable (for example, in providing a microwave link to an island).

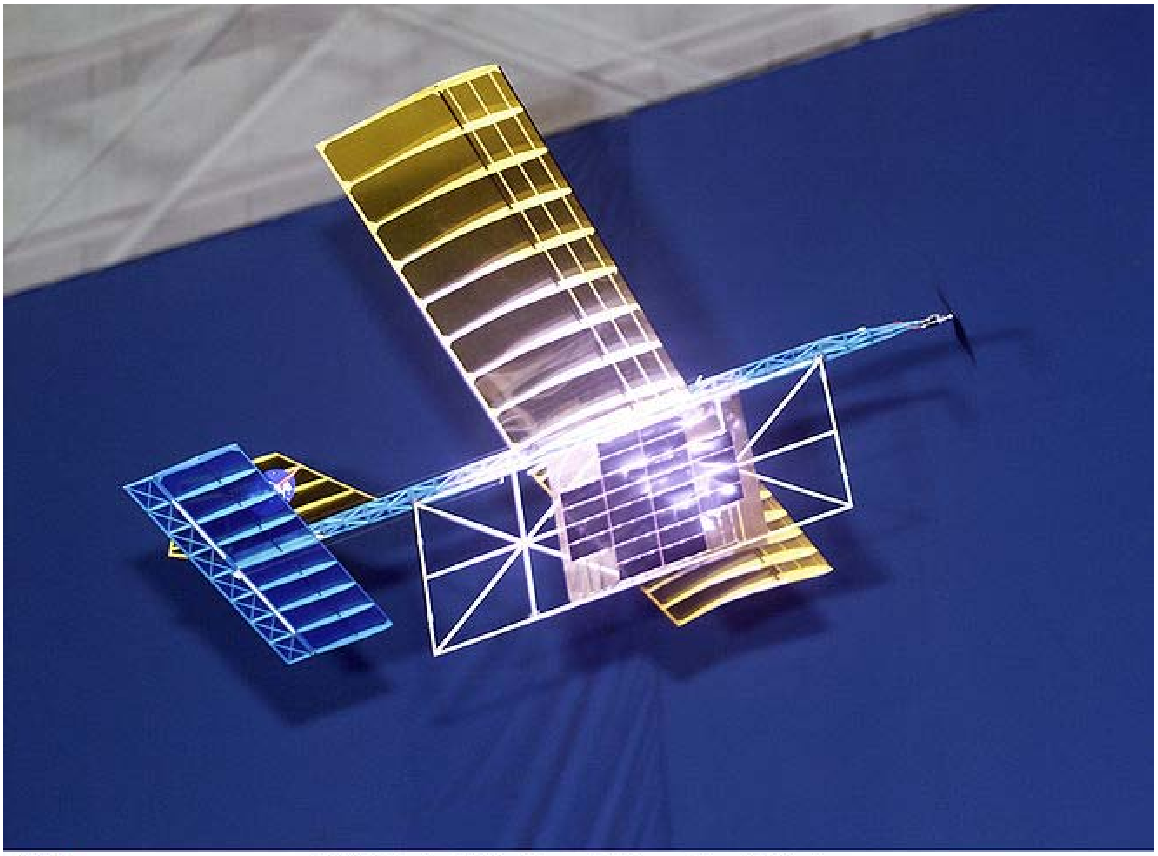
Usage of microwave radio relay systems

During the 1950s the AT&T Communications system of microwave radio grew to carry the majority of US Long Distance telephone traffic, as well as intercontinental television network signals. The prototype was called TDX and was tested with a connection between New York City and Murray Hill, the location of Bell Laboratories in 1946. The TDX system was set up between New York and Boston in 1947. The TDX was improved to the TD2, which still used klystrons, and then later to the TD3 that used solid state electronics. The main motivation in 1946 to use microwave radio instead of cable was that a large capacity could be installed quickly and at less cost. It was expected at that time that the annual operating costs for microwave radio would be greater than for cable. There were two main reasons that a large capacity had to be introduced suddenly: Pent up demand for long distance telephone service, because of the hiatus during the war years, and the new medium of television, which needed more bandwidth than radio.

Similar systems were soon built in many countries, until the 1980s when the technology lost its share of fixed operation to newer technologies such as fiber-optic cable and optical radio relay links, both of which offer larger data capacities at lower cost per bit. Communication satellites, which are also microwave radio relays, better retained their market share, especially for television.

At the turn of the century, microwave radio relay systems are being used increasingly in portable radio applications. The technology is particularly suited to this application because of lower operating costs, a more efficient infrastructure, and provision of direct hardware access to the portable radio operator.

Laser



NASA Dryden Flight Research Center Photo Collection
http://www.dfrc.nasa.gov/Gallery/Photo/index.html
NASA Photo: ED03-0249-18 Date: September 18, 2003 Photo By: Tom Tschida

With a laser beam centered on its panel of photovoltaic cells, a model plane makes the first flight of an aircraft powered by a laser beam inside a building at NASA Marshall.

With a laser beam centered on its panel of photovoltaic cells, a lightweight model plane makes the first flight of an aircraft powered by a laser beam inside a building at NASA Marshall Space Flight Center.

In the case of electromagnetic radiation closer to visible region of spectrum (10s of microns (um) to 10s of nm), power can be transmitted by converting electricity into a laser beam that is then pointed at a solar cell receiver. This mechanism is generally known as "powerbeaming" because the power is beamed at a receiver that can convert it to usable electrical energy.

There are quite a few unique advantages of laser based energy transfer that outweigh the disadvantages.

1. collimated monochromatic wavefront propagation allows narrow beam cross-section area for energy confinement over large ranges.
2. compact size of solid state lasers-photovoltaics semiconductor diodes allows ease of integration into products with small form factors.
3. ability to operate with zero radio-frequency interference to existing communication devices i.e. wi-fi and cell phones.
4. control of Wireless Energy Access, instead of omnidirectional transfer where there can be no authentication before transferring energy.

These allow laser-based wireless energy transfer concept to compete with conventional energy transfer methods.

Its drawbacks are:

1. Conversion to light, such as with a laser, is moderately inefficient (although quantum cascade lasers improve this)
2. Conversion back into electricity is moderately inefficient, with photovoltaic cells achieving 40%-50% efficiency. (Note that conversion efficiency is rather higher with monochromatic light than with insolation of solar panels).
3. Atmospheric absorption causes losses.
4. As with microwave beaming, this method requires a direct line of sight with the target.

The laser "powerbeaming" technology has been mostly explored in military weapons and aerospace applications and is now being developed for commercial and consumer electronics Low-Power applications. Wireless energy transfer system using laser for consumer space has to satisfy Laser safety requirements standardized under IEC 60825.

To develop an understanding of the trade-offs of Laser ("a special type of light wave"-based system):

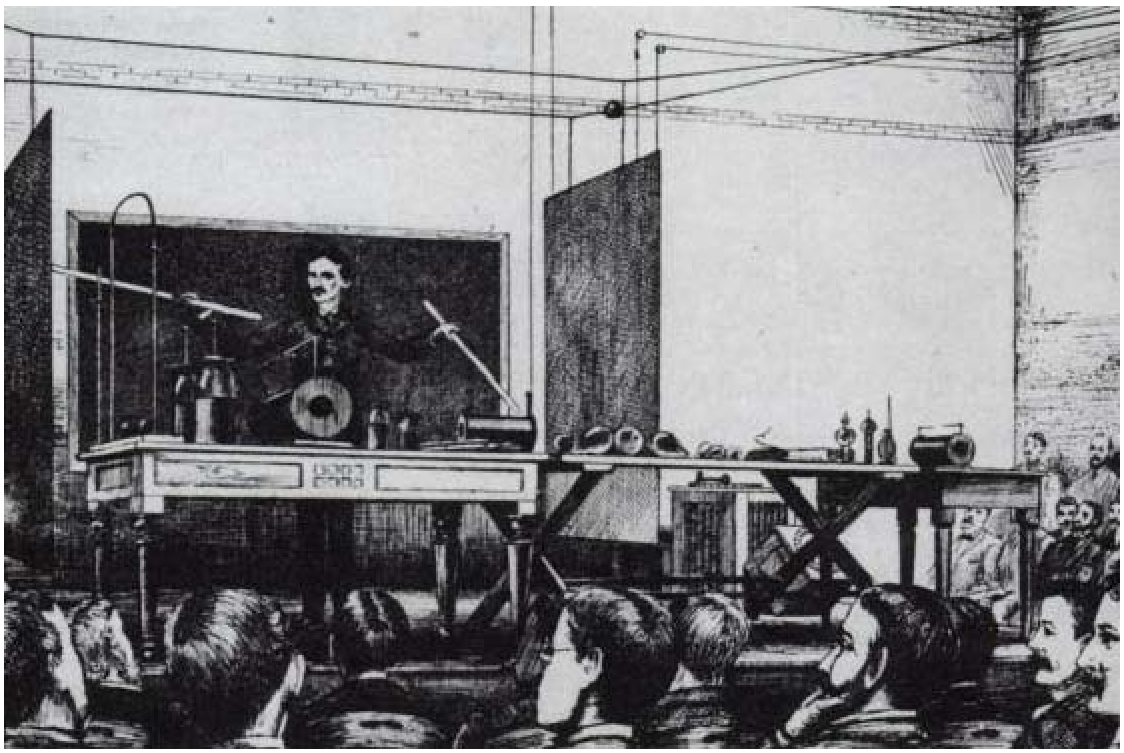
1. Propagation of a laser beam (on how Laser beam propagation is much less affected by diffraction limits)
2. Coherence and the range limitation problem (on how spatial and spectral coherence characteristics of Lasers allows better distance-to-power capabilities)
3. Airy disk (on how wavelength fundamentally dictates the size of a disk with distance)
4. Applications of laser diodes (on how the laser sources are utilized in various industries and their sizes are reducing for better integration)

Geoffrey Landis is one of the pioneers of solar power satellite and laser-based transfer of energy especially for space and lunar missions. The continuously increasing demand for safe and frequent space missions has resulted in serious thoughts on a futuristic space elevator that would be powered by lasers. NASA's space elevator would need wireless power to be beamed to it for it to climb a tether.

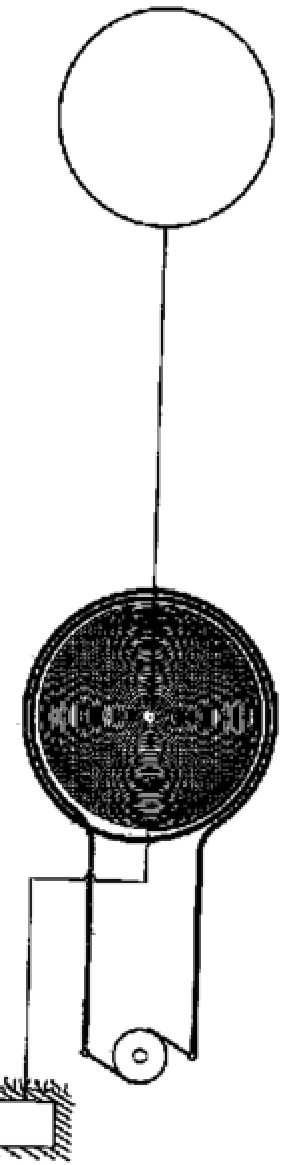
NASA's Dryden Flight Research Center has demonstrated flight of a lightweight unmanned model plane powered by a laser beam. This proof-of-concept demonstrates the feasibility of periodic recharging using the laser beam system and the lack of need to return to ground.

"Lasermotive" demonstrated laser powerbeaming at one kilometer during NASA's 2009 powerbeaming contest. Also "Lighthouse DEV" (a spin off of NASA Power Beaming Team) along with "University of Maryland" is developing an eye safe laser system to power an small UAV. Since 2006, "PowerBeam" which originally invented the eye-safe technology and holds all crucial patents in this technology space, is developing commercially ready units for various consumer and industrial electronic products.

Electrical conduction



Wireless energy transmission demonstration during Tesla's high frequency and potential lecture of 1891.



Tesla coil transformer wound in the form of a flat spiral. This is the transmitter form as described in U.S. Patent 645,576.

Electrical energy can be transmitted by means of electrical currents made to flow through naturally existing conductors, specifically the earth, lakes and oceans, and through the upper atmosphere starting at approximately 35,000 feet (11,000 m) elevation — a natural medium that can be made conducting if the breakdown voltage is exceeded and the constituent gas becomes ionized. For example, when a high voltage is applied across a neon tube the gas becomes ionized and a current passes between the two internal electrodes. In a wireless energy transmission system using this principle, a high-power ultraviolet beam might be used to form vertical ionized channels in the air directly above the transmitter-receiver stations. The same concept is used in virtual lightning rods, the electrolaser electroshock weapon and has been proposed for disabling vehicles. A global system for "the transmission of electrical energy without wires" dependant upon the high electrical conductivity of the earth was proposed by Nikola Tesla as early as 1904.

"The earth is 4,000 miles radius. Around this conducting earth is an atmosphere. The earth is a conductor; the atmosphere above is a conductor, only there is a little stratum between the conducting atmosphere and the conducting earth which is insulating. . . . Now, you realize right away that if you set up differences of potential at one point, say, you will create in the media corresponding fluctuations of potential. But, since the distance from the earth's surface to the conducting atmosphere is minute, as compared with the distance of the receiver at 4,000 miles, say, you can readily see that the energy cannot travel along this curve and get there, but will be immediately transformed into conduction currents, and these currents will travel like currents over a wire with a return. The energy will be recovered in the circuit, not by a beam that passes along this curve and is reflected and absorbed, . . . but it will travel by conduction and will be recovered in this way."

Researchers experimenting with Tesla's wireless energy transmission system design have made observations that may be inconsistent with a basic tenet of physics related to the scalar derivatives of the electromagnetic potentials, which are presently considered to be *nonphysical*.

The intention of the Tesla world wireless energy transmission system is to combine electrical power transmission along with broadcasting and point-to-point wireless telecommunications, and allow for the elimination of many existing high-tension power transmission lines, facilitating the interconnection of electrical generation plants on a global scale.

One of Tesla's patents suggests he may have misinterpreted 25–70 km nodal structures associated with cloud-ground lightning observations made during the 1899 Colorado Springs experiments in terms of circumglobally propagating standing waves instead of a local interference phenomenon of direct and reflected waves.

Regarding the recent notion of power transmission through the earth-ionosphere cavity, a consideration of the earth-ionosphere or concentric spherical shell waveguide propagation parameters as they are known today shows that wireless energy transfer by ***direct*** excitation of a Schumann cavity resonance mode is not realizable. "The conceptual difficulty with this model is that, at the very low frequencies that Tesla said that he employed (1-50 kHz), earth-ionosphere waveguide excitation, now well understood, would seem to be impossible with the either the Colorado Springs or the Long Island apparatus (at least with the apparatus that is visible in the photographs of these facilities)."

On the other hand, Tesla's concept of a global wireless electrical power transmission grid and telecommunications network based upon energy transmission by means of a spherical conductor transmission line with an upper three-space model return circuit, while perhaps not practical for power transmission, is feasible, defying no law of physics.

Global wireless energy transmission by means of a spherical conductor “single-wire” surface wave transmission line and a propagating TM_{00} mode may also be possible, a feasibility study using a sufficiently powerful and properly tuned Tesla coil earth-resonance transmitter being called for.

Tesla patents

Nikola Tesla had multiple patents disclosing long distance wireless transmission. U.S. Patent 0,645,576 *System of Transmission of Electrical Energy* and U.S. Patent 0,649,621 *Apparatus for Transmission of Electrical Energy*, describe useful combinations of transformer coils for this purpose. The transmitter is arranged and excited to cause electrical energy to propagate through the natural medium from one point to another remote point to a receiver of the transmitted signals. The production of currents at very high potential is attained in these oscillators. U.S. Patent 0,787,412 *Art of Transmitting Electrical Energy through the Natural Mediums* describes a combined system for broadcasting, point-to-point wireless telecommunications and electrical power distribution achieved through the use of earth-resonance principles.

Chapter-3

Non-Rocket Spacelaunch to Reduce SBSP Costs

Non-rocket spacelaunch (NRS) is the idea of reaching outer space specifically from the Earth's surface predominately without the use of conventional chemical rockets, which today is the only method in use.

Transportation to orbit is one factor in the expense of space endeavors; if it can be made more efficient the total cost of space flight can be reduced. Present-day launch costs are very high — $10,000 to $25,000 per kilogram from Earth to low Earth orbit, though some countries subsidize launches to prices nearer $4,000. To settle space, e.g. space exploration and space colonization, much cheaper launch methods are required, as well as a way to avoid serious damage to the atmosphere from the thousands, perhaps millions, of launches required. Another benefit may be increased safety and reliability of launches, which, in addition to lower cost, would avail for space disposal of radioactive waste. Once having overcome the Earth gravity barrier, vehicles may instead use other, non-rocket-based methods of propulsion, e.g. ion thrusters, which have a higher propellant efficiency (specific impulse) and potential maximum velocity than conventional rockets, but are not suitable for spacelaunch.

Several alternatives to conventional chemical rockets have been proposed. In some systems a rocket *is* involved, but it ignites after reaching space in another manner.

Comparison

Comparison of non-rocket spacelaunch methods
Initial operating condition for new systems

Method[(a)]	Publication year	Estimated build-cost US$B[(b)]	Payload Size kg	Estimated cost to LEO US$/kg[(b)]	Capacity metric tons per year	Technology readiness level
Conventional rocket			118,000	3,273	200~	9
Space elevator	2004	6.2-40	18,000+	220-400	2,000	2-4

Hypersonic Skyhook	1993	<1[c]	1,500[d]		30[e]	2
Rotovator	1977					2
HASTOL,	2000		15,000[f]			2
Space fountain						2+
Orbital ring	1980	15		<0.05		2
Launch loop (small)	1985	10	5,000	300	40,000	2+
Launch loop (large)	1985	30	5,000	3	6,000,000	2+
KITE Launcher	2005					2
StarTram		60		20~	2,000~	2
Mass driver						4
Ram accelerator	2004			<500		6
Space gun	1865[g]	0.5	450	500		6
Slingatron			100			2
Spaceplane	1992	10-15	12,000	3,000		7
Laser propulsion						up to 4

(a) References in this column apply to entire row unless specifically replaced
(b) All monetary values in un-inflated dollars based on reference publication date except as noted
(c) CY2008 estimate from description in 1993 reference system
(d) Requires first stage to ~5 km/s
(e) Subject to very rapid increase via bootstrapping
(f) Requires Boeing proposed DF-9 vehicle first stage to ~4 km/s
(g) Jules Verne's novel, *From the Earth to the Moon*. Newton's cannonball in the 1728 book *A Treatise of the System of the World* was considered a thought experiment.

Static structures

In this usage, the term "static" is intended to convey the understanding that the structural portion of the system has no internal moving parts. The structure as a whole, often being on orbit, will move at high velocities, but the parts of the structure do no move relative to other nearby parts.

Compressive structures

Compressive structures for non-rocket spacelaunch are proposals to use long, very strong structures like guyed antenna towers or artificial mountains up which payloads can be raised.

Space Tower

A *space tower* is a tower that would reach outer space. To fully replace rocket power and attain orbit, a tower would have to extend beyond the 100 km Kármán line (a common definition of outer space) to at least 23700 km above the Earth's surface. Release from this height will result in an elliptical orbit with the lowest altitude just high enough to prevent reentry. If the tower went all the way to geosynchronous orbit at approximately 36,000 km, objects released at this height could then drift away with minimal power and would be in a circular orbit at that height. The concept of a structure reaching to geosynchronous orbit was first conceived by Konstantin Tsiolkovsky, who proposed a compression structure, or "Tsiolkovsky tower."

A parallel-sided structure made of conventional brick and stone cannot reach past 2000 meters as bricks at the bottom would be crushed under the weight. Advanced materials would allow the tower to reach a usable height. A tapered structure could reach higher, but cost increases exponentially with construction height. A tower could form one component of a successful launch system, such as being the base station of a space elevator, or a support pillar for the distal part of a mass driver or the "gun barrel" of a space gun.

There are a number of other options to consider for building space towers: rigid, inflatable, kinetic, electrostatic and electronic structures.

Tensile structures

Tensile structures for non-rocket spacelaunch are proposals to use long, very strong cables (known as tethers) to drag a payload into, or fling it toward, space. Tethers can also be used for changing orbit once in space.

Orbital tethers can be tidally locked (skyhooks) or rotating (rotovators). They can be designed (in theory) to pick up the payload when the payload is stationary or when the payload is hypersonic (has a high but not orbital velocity).

Endo-atmospheric tethers can be used to transfer kinetics (energy and momentum) between large conventional aircraft (subsonic or low supersonic) or other motive force and smaller aerodynamic vehicles, propelling them to hypersonic velocities without exotic propulsion systems.

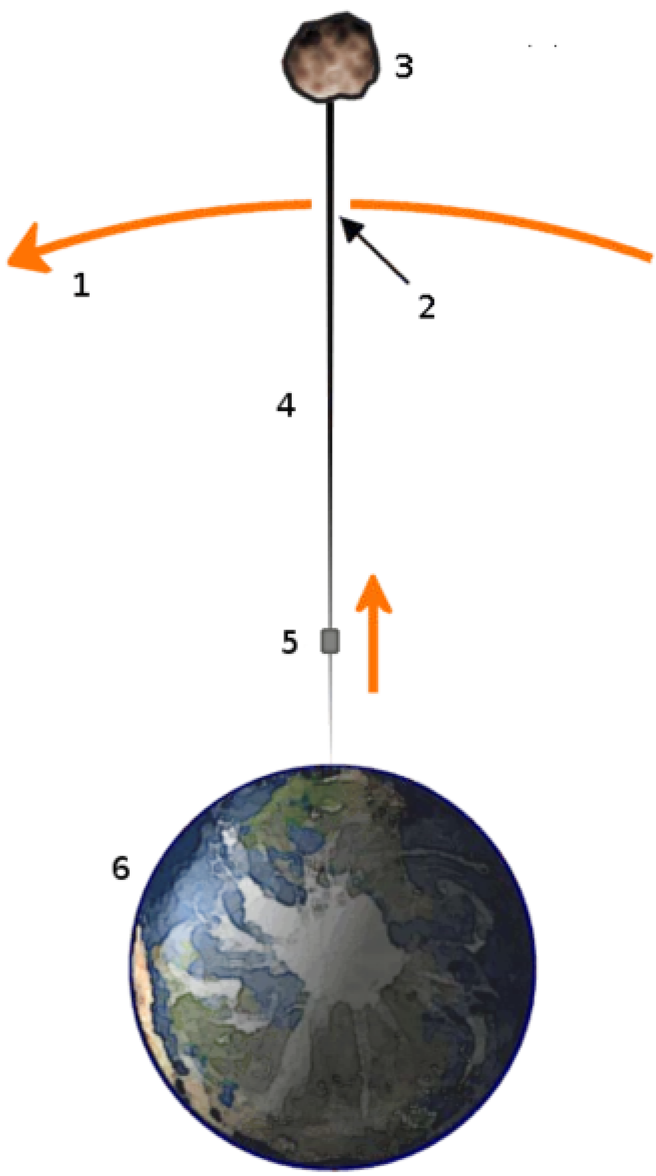
Skyhooks

A *skyhook* is a tidally locked tether, i.e., it rotates once each time it orbits around a planet or moon.

An example use of a skyhook is that a payload, launched from the ground, can be attached to the base of the skyhook, which is then carried to orbit. This means that a single stage to skyhook approach can be employed, and a high-specific-impulse drive or propellantless electromagnetic tether can be used to make up the momentum debt of the payload- or payload flow can be balanced from the moon.

Most skyhook designs require tapering of the cable towards the tips; this permits the cable material to be under constant stress throughout, and allows potentially indefinite tip speeds and length. However, in practice the cable taper ratios required can be too large for affordable systems to be able to handle desirable sizes of payloads above tip speeds of perhaps 2.5-3.5 km/s with current engineering materials.

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

The concept 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, tethers) reaching from 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*.

Current technology is not capable of manufacturing practical engineering materials that are sufficiently strong and light to build an Earth-based space elevator. 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 microscopic 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.

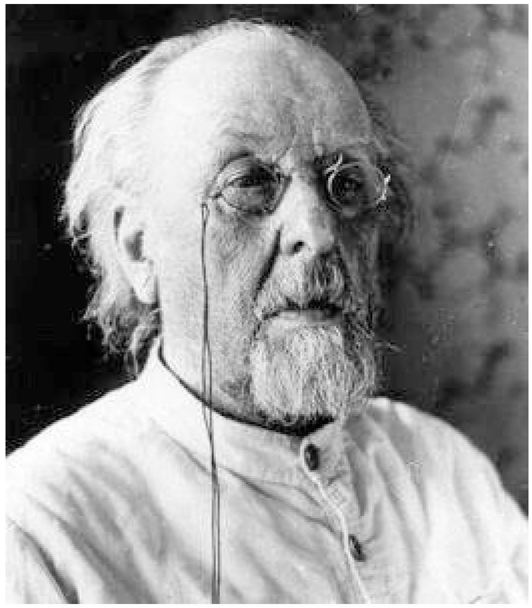
A further issue is that for human riders on an Earth-based elevator, space radiation due to the Van Allen belts would, if unshielded, give a dose well above permitted levels. This would not be an issue for non-living cargo, however.

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. Nevertheless, the LiftPort Group stated in 2002 that by developing the technology, the first space elevator could be operational by 2014.

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).

Tsiolkovsky's tower would be able to launch objects into orbit without a rocket. 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 tension 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 on Mars and also for natural resources mined on Mars to be able to leave Mars 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, the work of Edwards 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 space elevator is proposed to 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 of 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:

$g = -K \cdot M/r^2 + \omega^2 \cdot r$, where
g is the acceleration along the radius (m s^{-2}),
K 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:

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

$K \cdot M = g_0 \cdot r_0^2$, which gives the $K \cdot M$ 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 $K \cdot M/r_1^2 = \omega^2 \cdot r_1$, 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 main 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 ($m \cdot s^{-2}$),
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 ($kg \cdot m^{-3}$).
σ is the traction a given area can bear without splitting ($N \cdot m^{-2} = kg \cdot m^{-1} \cdot s^{-2}$), its elastic limit

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

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

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 centrifuge 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)
$\rho \approx 300 \cdot 10^3$ 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

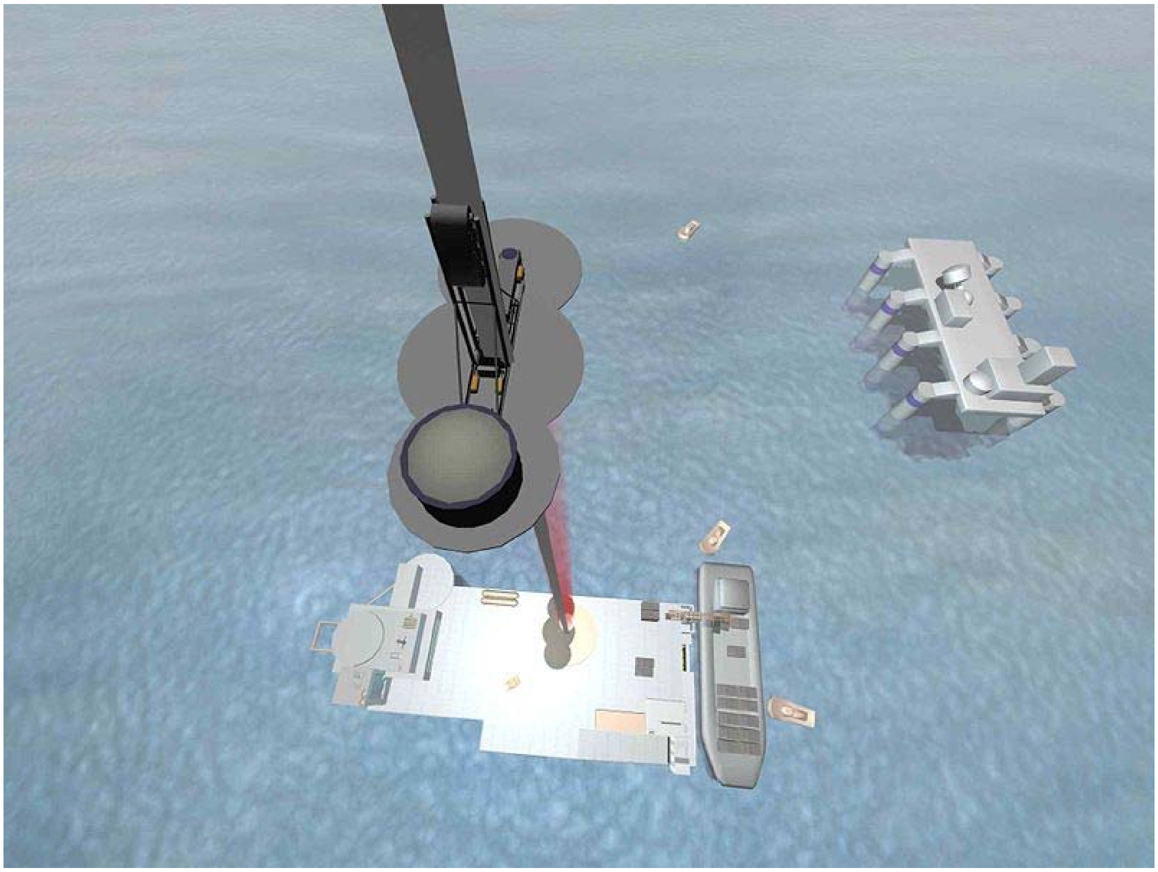
$\Delta\left[\ln(S)\right] = \rho/\sigma \cdot g_0 \cdot r_0 \cdot (1 + x/2 - 3/2 \cdot x^{1/3})$, where
$x = w^2 \cdot r_0/g_0$

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.

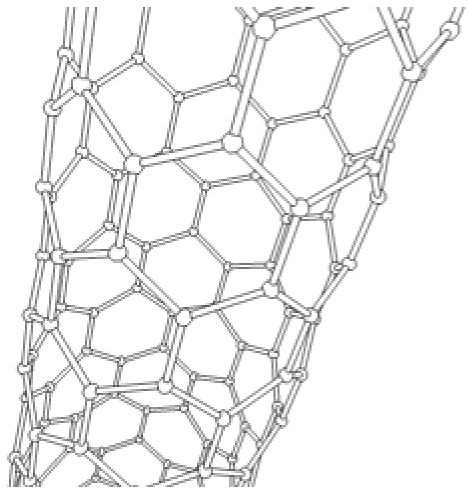
The centrifugal force of earth's rotation is the main principle behind the elevator. As the earth rotates, the centrifugal force tends to align the nanotube in a stretched manner. There are a variety of tether designs. Almost every design includes a base station, a cable, climbers, and a counterweight.

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



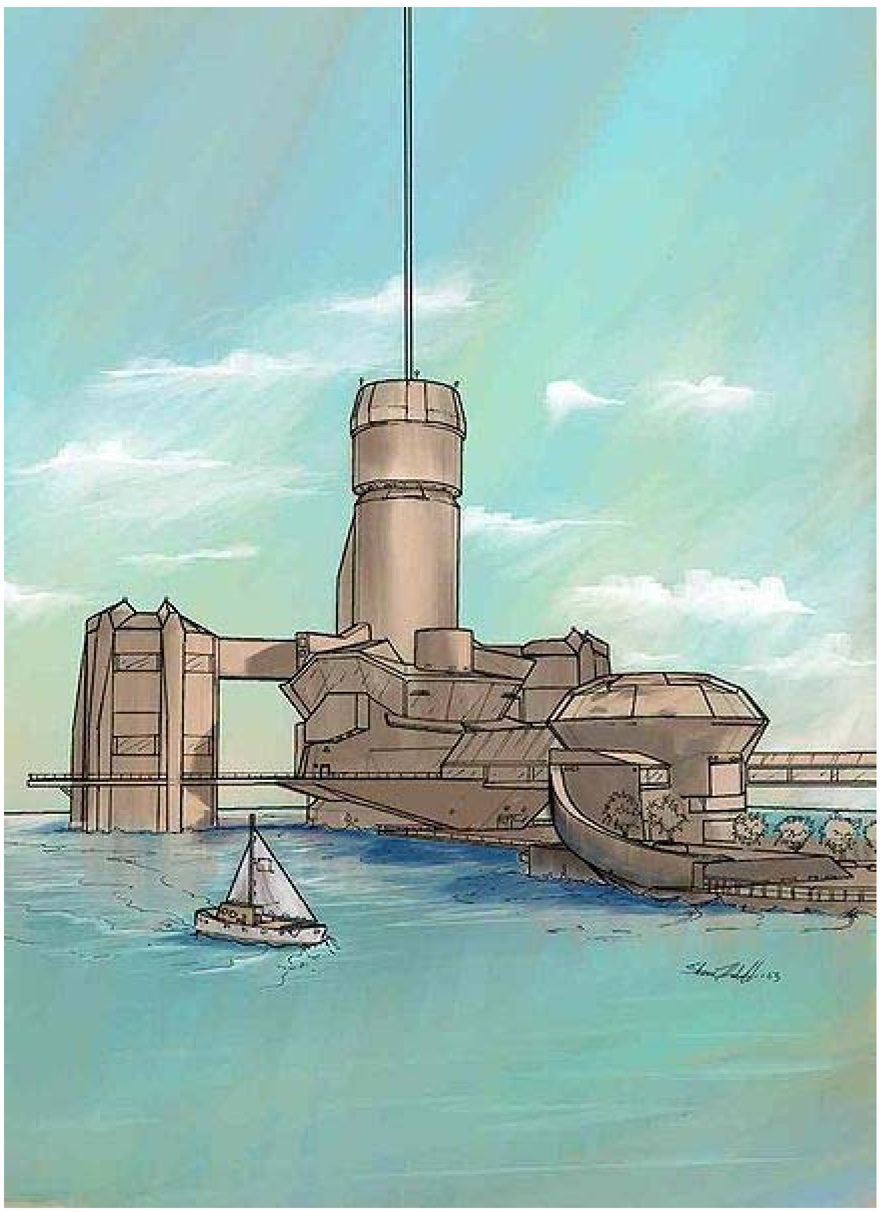
Carbon nanotubes are one of the candidates for a cable material

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 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. This is at least necessary value, and about 50,000 kN/(kg/m) if it shows by specific strength. Therefore, a material with very high strength and lightness is needed.

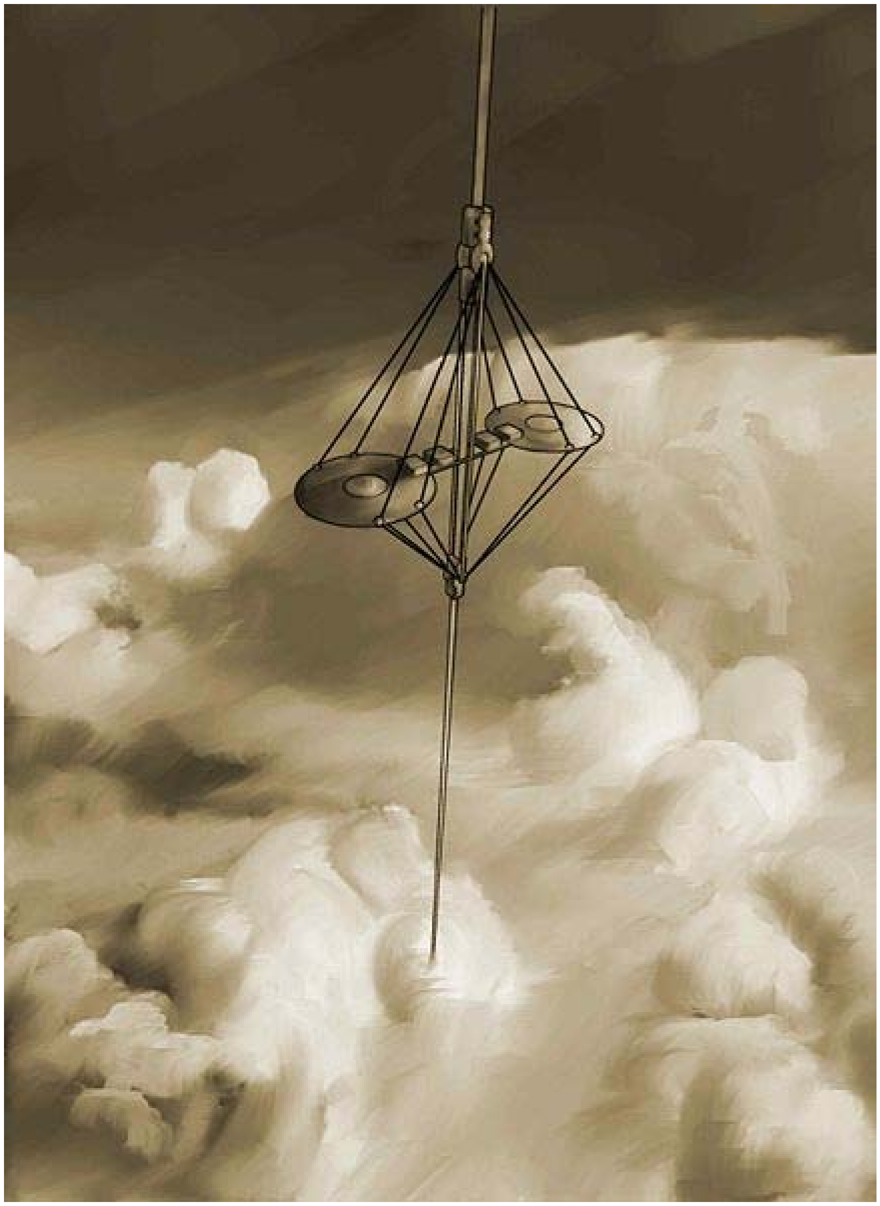
Carbon nanotubes' theoretical tensile strength has been estimated between 140 and 177 GPa (20.3-25.6 million psi) depending on their geometry and its measured tensile strength varies in the range 11–150 GPa (1.6-21.7 million psi), however only on a microscopic scale. The current (2009) technology allows growing tubes up to a few tens of centimeters. This limit can be mitigated by spinning nanotubes into a yarn, but at the price of lowering the cable strength.

The density of carbon nanotubes depends greatly on their packing and can be estimated as 1.3 g/cm^3 (0.75 oz/cubic in). Therefore, necessary tensile strength is 65–130 GPa (9.4-18.5 million psi) in density. By comparison, most steel has a tensile strength of under 2 GPa (290,000 psi), and the strongest steel resists no more than 5.5 GPa (798,000 psi). The much lighter material Kevlar has a tensile strength of 2.6–4.1 GPa (377,000-595,000 psi), while quartz fibers can reach 20 GPa (2.9 million psi). Quartz fibers have an advantage that they can be drawn to a length of hundreds of kilometers (270 km—168 mi) even with the present-day technology.



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

Climbers

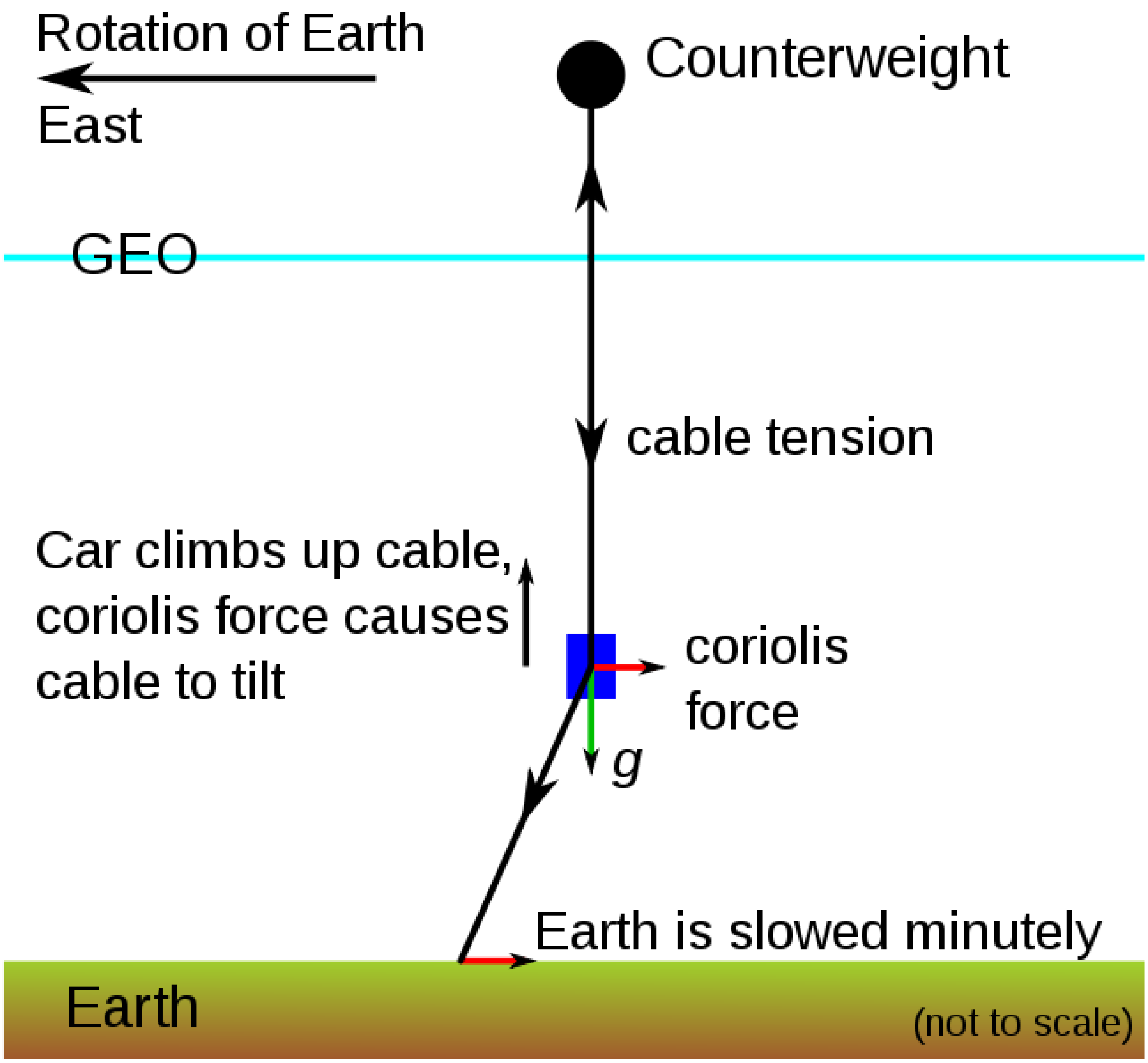


A conceptual drawing of a space elevator climbing through the clouds.

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

Many different types of structures for accessing space have been suggested. As of 2004, concepts using geostationary tethers seem to be the only space elevator concept that is the subject of active research and commercial interest in space.

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. 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 a unique challenge because the Martian moon Phobos 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.

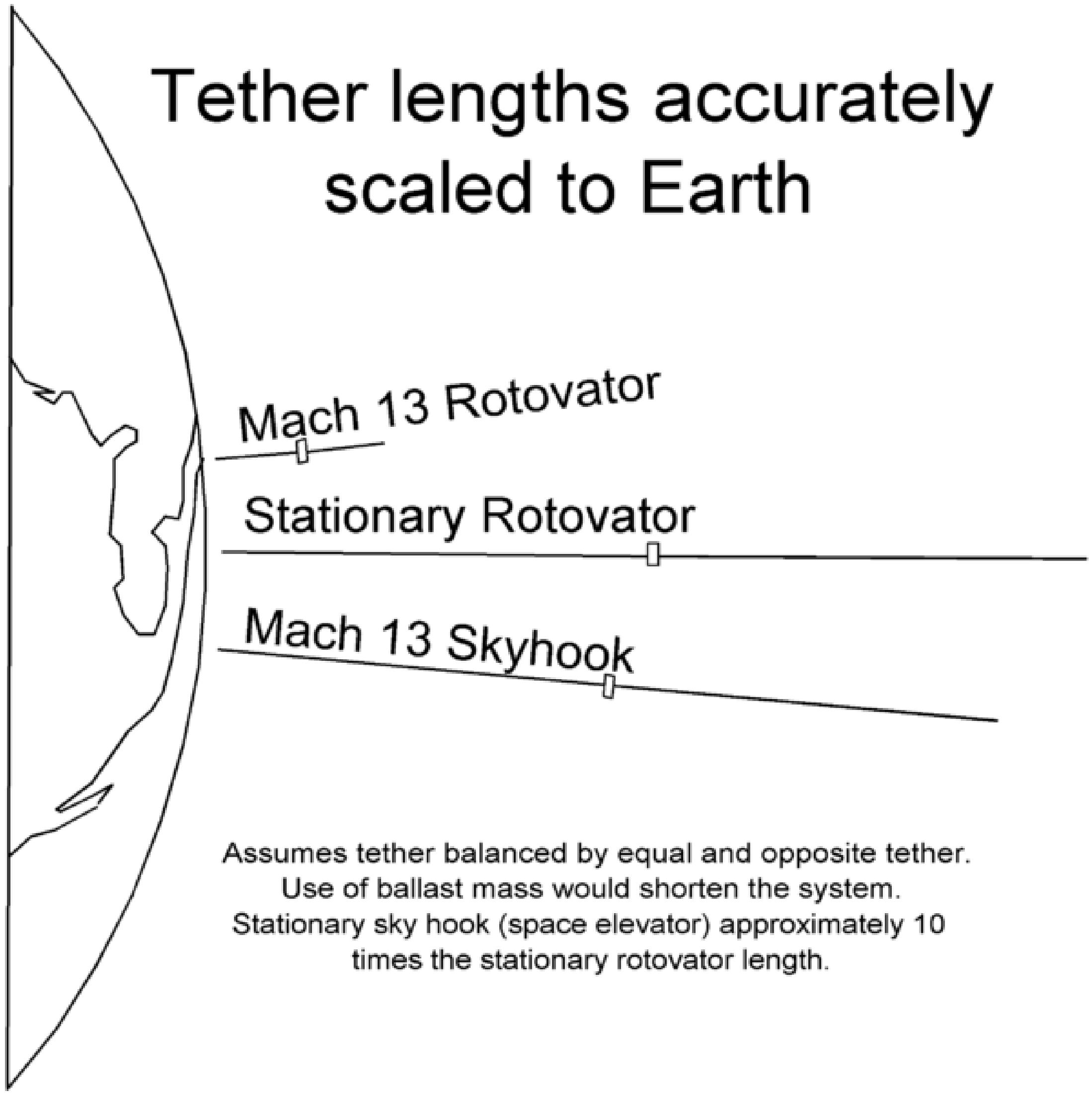
Impacts by space objects such as meteoroids, micrometeorites and orbiting man-made debris, pose a more difficult problem, because the potential of a strand break to cause a failure cascade is, according to Tom Nugent, the Research Director of LiftPort Inc., "A potential show-stopper for construction 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."

Hypersonic skyhook



Orbital tether lengths compared.

A *hypersonic skyhook* is a relatively short tether that reaches from just above the edge of space to its design length.

Without the two end ballasts, a space elevator would still be in geosynchronous orbit, and thus stationary relative to the ground. If that tether were to be shorter and still reach the surface, the center of gravity would need to drop also. This would cause the lower tip to have a velocity in the orbital direction. The shorter the tether is, the faster becomes the lower tip velocity. With higher tip velocity, lower material properties are needed to make a practical design but the less benefit is obtained from this method. Eventually, any such design becomes a balance between the expense of providing the velocity to the payload at pick-up and the expense of launching the mass of the tether and power plant as dictated by available materials. Also, the lower tip is raised out of the atmosphere to avoid heating problems.

A reference design was published using materials similar to Spectra 2000 and relying on one Titan IV launch to orbit a fully functional hypersonic skyhook. To keep the tether weight within the launch capacity, a payload pick-up velocity of 5 km/s was assumed. Though the reference design was limited to an Initial Operating Condition of 1,500 kg payload size, at a maximum rate of about one payload each 17 days, the prime limitation to higher capacity was power plant size. One launch of additional power plant would almost double the available power and capacity.

The problem is getting the payload to the altitude (100 km) and velocity (5 km/s) required for pick-up.

Rotovators

A *rotovator* is a tether that rotates more than once each time it orbits around a planet or moon. Rotovators rotate in the same sense as they orbit such that the lower tip has a retrograde motion relative to the center of gravity.

Rotovators in almost all ways have the same benefits as skyhooks. However, due to the retrograde velocity, the lower tip can achieve a specified Mach number with a shorter tether. This, despite the rotational forces, produces lower stresses in the tether so that lower strength to weight ratio materials can be used for the same results.

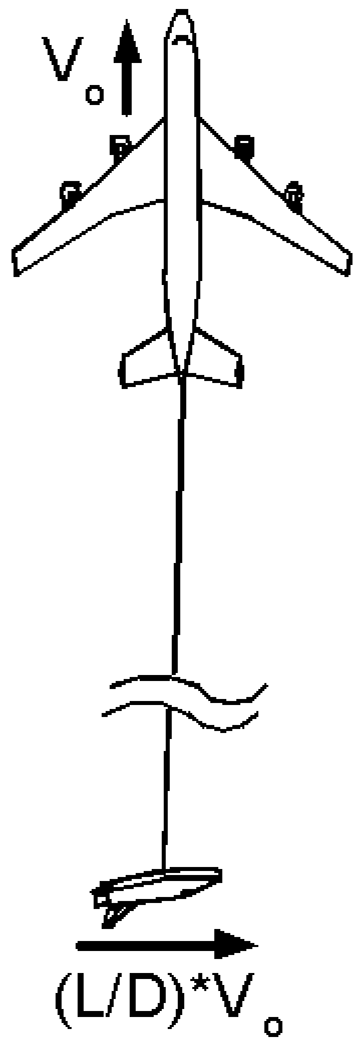
Stationary rotovators

A *stationary rotovator* implies only that the retrograde velocity of the tip fully cancels the orbital velocity. To a stationary payload, it appears as though the tether tip decelerates as it drops straight down from the sky, and then accelerates back upward. The payload must grapple the tip of the tether during that short duration when the tip has come to a stop. Hans Moravec's description of this was "a satellite that rotates like a wheel." With current materials a stationary rotovator to reach Earth's surface is impractical however; but is possible on other interplanetary bodies such as Mars and the Moon.

Hypersonic rotovator (HASTOL)

Similar to a hypersonic skyhook, a *hypersonic rotovator* uses a much shorter tether than its stationary equivalent and picks up its payload at hypersonic speeds. The Hypersonic Airplane, Space Tether, Orbital Launch (HASTOL) is one design for a hypersonic rotovator.

Endo-atmospheric tethers

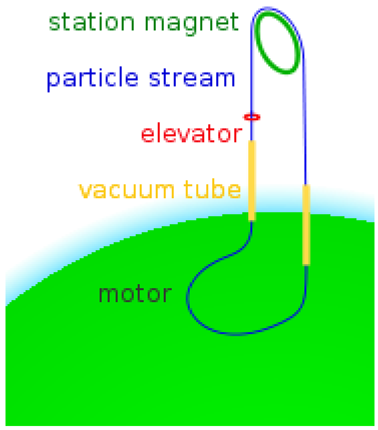


KITE Launcher - transferring momentum to the vehicle

An *endo-atmospheric tether* uses the long cable within the atmosphere to provide some or all of the velocity needed to reach orbit. The tether is used to transfer kinetics (energy and momentum) from a massive, slow end (typically a large subsonic or low supersonic aircraft) to a hypersonic end through aerodynamics or centripetal action. The *Kinetics Interchange TEther (KITE) Launcher* is one proposed endo-atmospheric tether.

Dynamic structures

Space fountain



The Hyde Design for a space fountain

A **space fountain** is a proposed form of space elevator that does not require the structure to be in geosynchronous orbit, and does not rely on tensile strength for support. In contrast to the original space elevator design (a tethered satellite), a space fountain is a tremendously tall tower extending up from the ground. Since such a tall tower could not support its own weight using traditional materials, fast moving pellets are projected upward from the bottom of the tower and redirected back down once they reach the top, so that the force of redirection holds the top of the tower aloft. Satellite payloads ascend or descend by coupling with this stream of pellets or by climbing up the side of the tower. The space fountain has several key advantages over a space elevator in that it does not require materials with extreme strength, can be located at any point on a planet's surface instead of just the lower latitudes, and can be raised to any height required. Its major disadvantage is that it is an active structure, and so requires constant power input to make up energy losses and remain erect.

History

The concept originated in a conversation on a computer net in the 1980s when some scientists who usually worked in artificial intelligence, Marvin Minsky of MIT and John McCarthy and Hans Moravec of Stanford, were speculating about variations on the skyhook concept with Roderick Hyde and Lowell Wood, scientists at Lawrence Livermore National Laboratory who usually work on laser-initiated fusion. As a means of supporting the upper end of a traditional space elevator at an altitude much less than geostationary, they proposed a ring of space stations hovering 2000 kilometers above Earth, motionless relative to the surface. These stations would not be in orbit; they would support themselves by deflecting a ring of fast-moving pellets circling Earth. The pellets would be moving at far greater speed than the orbital velocity for that altitude, so if the stations stopped deflecting them the pellets would move outward and the stations would fall inward.

Robert L. Forward joined the conversation at this point, suggesting that instead of using a pellet stream to support the top of a traditional tensional cable, a vertical pellet stream shot straight up from Earth's surface could support a station and provide a path for payloads to travel without requiring a cable at all. Problems that were initially raised with this proposal were friction of the pellet stream with Earth's atmosphere at lower altitudes and the Coriolis forces due to the rotation of the Earth, but Roderick Hyde worked out all the engineering design details for a space fountain and showed that these issues could theoretically be overcome.

Design

The space fountain acts as a continuous coil gun with captive projectiles travelling in a closed loop.

In the Hyde design for a space fountain a stream of projectiles is shot up through the bore of a hollow tower. As the projectiles travel upward through the tower they are slowed down by electromagnetic drag devices that extract kinetic energy from the upgoing stream and turn it into electricity. As the projectiles are braked they also transfer some of their upward momentum to the tower structure, exerting a lifting force to support some of its weight. When the projectiles reach the station at the top of the tower they are turned around by a large bending magnet. In the turnaround process they exert an upward force on the station at the top of the tower, keeping it levitated above the launch point.

As the projectiles travel back down the tower they are accelerated by coil guns that use the electrical energy extracted from the upgoing stream of projectiles. This provides the rest of the upward lifting force required to support the weight of the tower. The projectiles reach the bottom of the tower with almost the same speed that they had when they were launched, losing a small amount of energy due to inefficiencies in the electromagnetic accelerators and decelerators in the tower. This can be minimized by the use of superconductors.

When the stream of high speed projectiles reaches the bottom of the tower it is then bent through 90 degrees by a magnet at the tower's base so that it is traveling parallel to Earth's surface, through a large circular underground tunnel similar to a particle accelerator. Electromagnetic accelerators in this tunnel bring the projectiles back up to the original launch speed, and then the stream of projectiles is bent one more time by 90 degrees to send it back up the tower again to repeat the cycle.

The downward force from the weight of the tower is transmitted solely by the stream of projectiles to the bending magnet at the tower's base, and so no materials with extraordinary compressive strength are needed to support the tower itself. The tower's base requires a foundation capable of supporting the weight of the tower, but this can be constructed with conventional materials available cheaply on Earth's surface. Together, the stressed structure and flowing projectile stream form a rigid, stable structure that is not limited in height by the strength of materials.

The lower parts of the tower would have to be surrounded by an airtight tube to maintain a vacuum for the projectiles to travel through, reducing energy losses due to drag. After the first one hundred kilometers or so the tube would no longer be necessary and the only structure that would be needed is a minimal framework to hold communication and power lines, and the guide tracks for the elevator cars. When the projectiles return to the base of the tower they have nearly the same speed and energy as they started with, only with the opposite momentum (downward instead of upward). As a result, the input power required to support the space fountain is determined by the inefficiency in the electromagnetic motors and air drag on the projectiles.

The elevators that would take payloads up the space fountain could conceivably ride up tracks on the tower structure using electrical power supplied by the tower, treating the space fountain solely as a mechanical support. A more attractive option would be to design the tower structure so the elevator cars can interact directly with the projectile streams themselves, and not couple to the tower structure at all. In this manner the momentum needed to raise the elevator car up against Earth's gravity would come directly from the projectile stream.

Construction

In contrast to a traditional space elevator, which must be built from space downward, a space fountain concept can be built slowly from the ground up. The driver loop and the bending magnets at the base would be constructed first, then the top station with its turnaround magnets would be constructed right above it. The system could then be loaded with projectiles and turned on at low power, lifting the top station off the ground. The vacuum tube would be built as the top station rises, with the power increasing and more projectiles being added to the loop as the tower gets longer. The rate of construction is entirely controllable, and can be halted at any height. The tower would be capable of lifting payloads throughout its construction as well, including its own construction materials.

Safety measures

To provide redundancy, a space fountain could be built with more than one projectile loop and power supply. In the event of projectile loops failing, the remaining loops would be capable of supporting the structure until the others were repaired. A safety margin would be provided simply due to the extra lifting strength that would be required by the system to raise large payloads to orbit during routine operation. In an emergency, payloads in transit could be jettisoned from the tower to reduce tower loading. Valuable or manned payloads would likely be in capsules capable of emergency reentry as a matter of course.

Even if all of the tower's power sources failed simultaneously, it would still take a long time for the tower to begin suffering. The kinetic energy stored inside the circulating loop of projectiles is vastly greater than the amount lost to inefficiencies, so it would take many hours or even days for the velocity of the projectiles to drop enough to cause problems in supporting the tower's mass. The round trip time for the projectiles alone provides some safety margin; in Hyde's concept design it takes each projectile over three hours to complete one loop, so even if the projectile stream was completely cut off (by the destruction of the top or base station, for example) there would be some time for evacuation of the remaining tower structure and regions that might be affected by significant pieces of falling debris.

Variants

Two variant designs based on the space fountain are the launch loop and the orbital ring. In a sense they are variants of space fountains where the projectile stream is directed sideways.

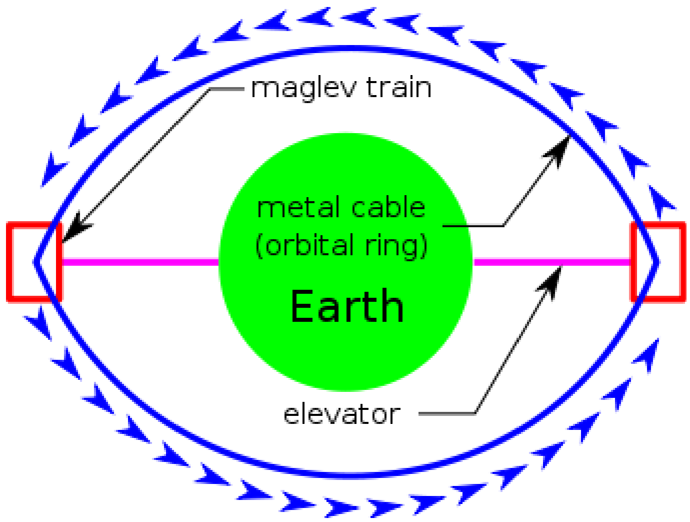
Near-term applications

A closed loop projectile system could be used for energy storage, similar to a very large flywheel, providing load levelling for terrestrial power grids. If the closed loop were long enough it could even be used for power transmission.

A very small-scale fountain tower could be used for constructing tall antenna masts rapidly, perhaps for news events and military operations. A larger and more permanent fountain tower could be ten or twenty kilometers tall, allowing one facility to provide radio and television broadcasts to enormous areas such as the steppes of Asia. Fountain towers might also prove to be an economical alternative to communication satellites for point-to-point television and FM radio communication between the various islands of some of the smaller nations in the Pacific Ocean. An elevator and observation platform could also be added as a tourist attraction.

Arched fountain structures similar to the launch loop could also have useful small-scale applications, notably the construction of bridges. Projectile-supported fountain bridges could be made arbitrarily long, without the need for support pillars anywhere along their span. However, they would of course require the continuous application of energy to maintain them, to make up for any losses.

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 18000 tons 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.

Orbital rings in fiction

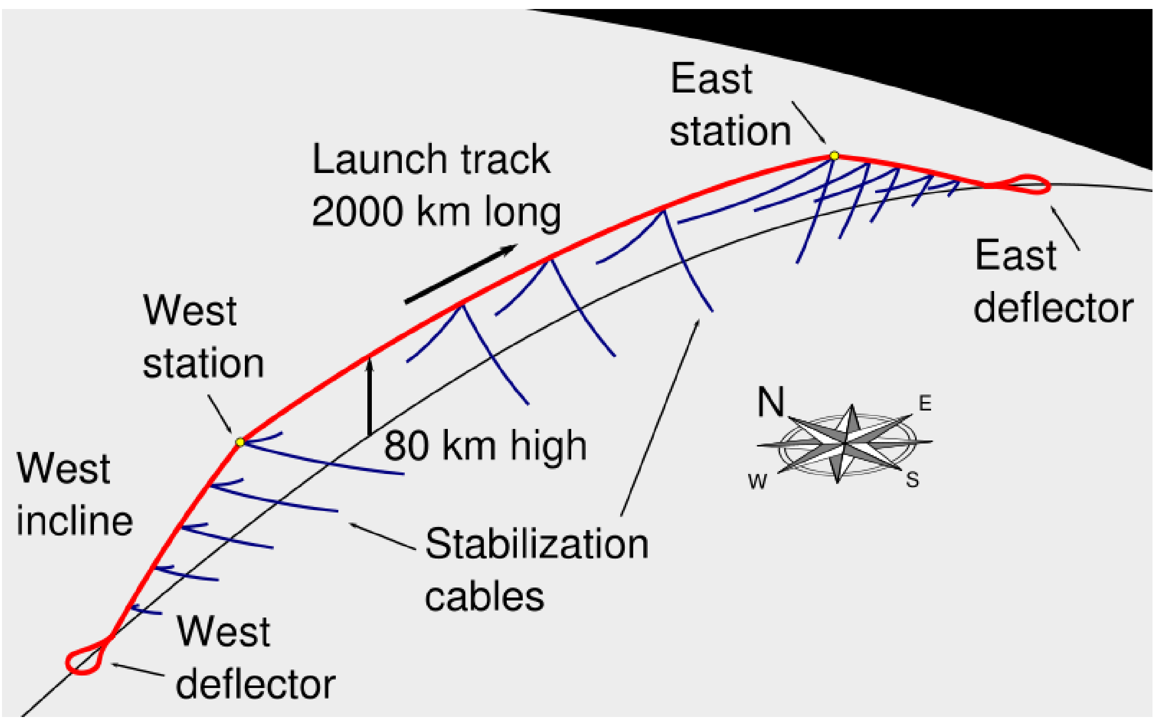
Donald Kingsbury described a partial ring (a few hundred kilometers long) in his novel *The Moon Goddess and the Son*.

The second iteration of the anime series Tekkaman features a complete ring, though abandoned and in disrepair due to war, and without surface tethers.

The anime series Kiddy Grade also uses orbital rings as a launch and docking bay for spaceships. These rings are connected to large towers extending from the planets surface.

Orbital rings are used extensively in the collaborative fiction worldbuilding website Orion's Arm.

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.

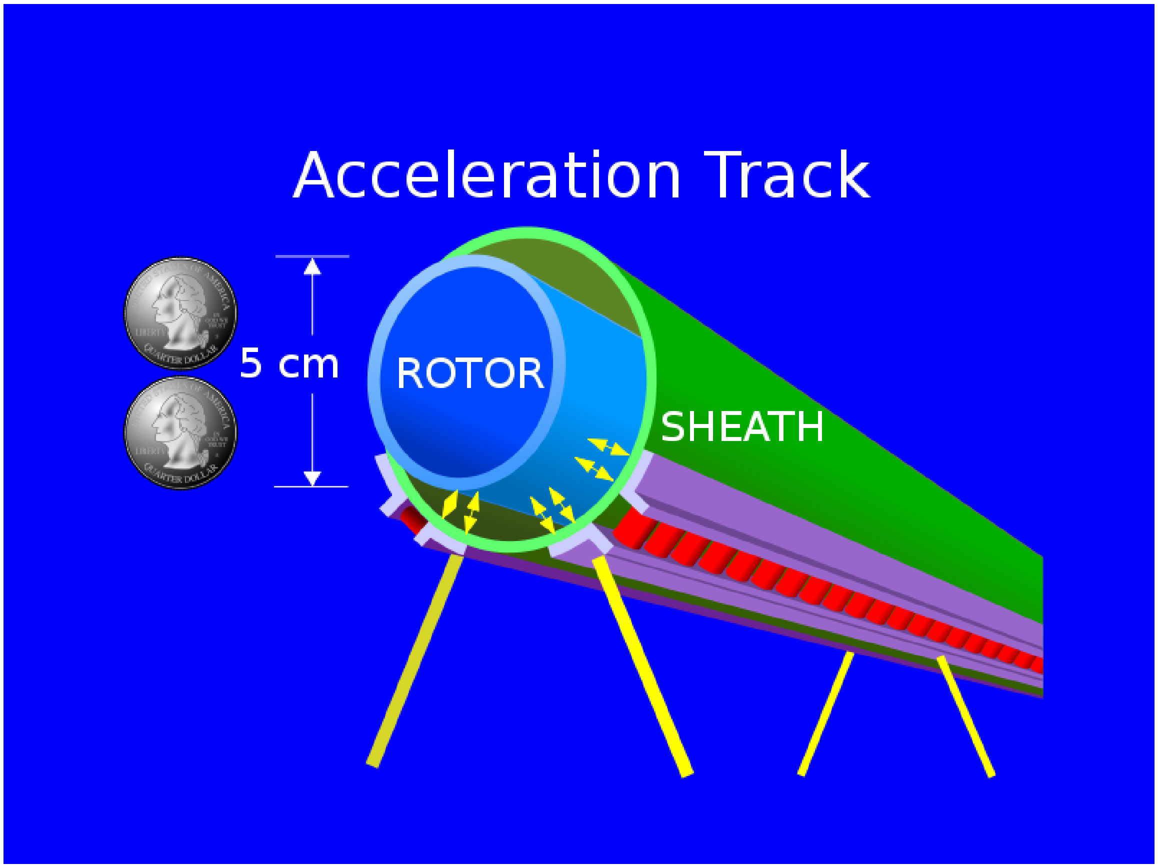
History

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 intended for launch assist for conventional rockets, and suborbital tourism.

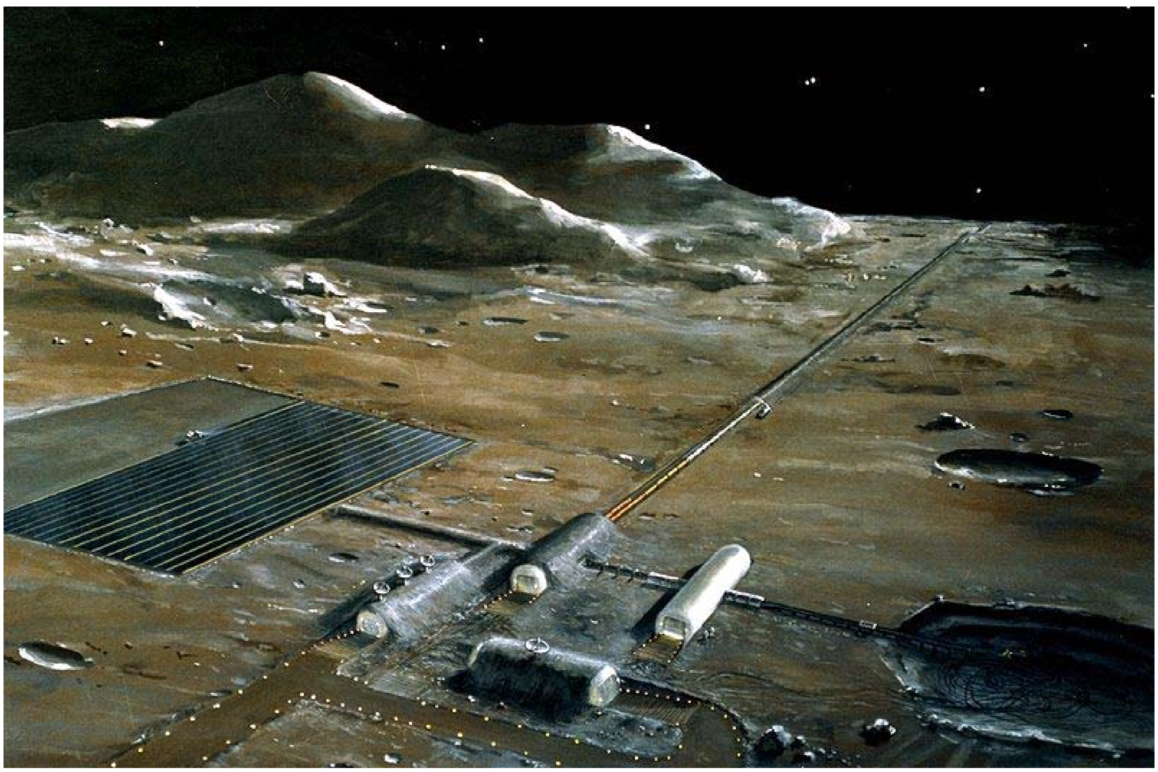
Projectile launchers

With any of these projectile launchers, the launcher gives a high velocity at, or near, ground level. In order to achieve orbit, the projectile must be given enough extra velocity to punch through the atmosphere. Also, the projectile needs either an internal or external means to perform orbital insertion. The designs below fall into three categories, electrically driven, chemically driven, and mechanically driven.

Chapter-4

Other Methods to Reduce SBSP Costs

Mass driver



A mass driver for lunar launch (artist's conception)

A **mass driver** or **electromagnetic catapult** is a proposed method of non-rocket spacelaunch which would use a linear motor to accelerate and catapult payloads up to high speeds. All existing and contemplated mass drivers use coils of wire energized by electricity to make electromagnets. Sequential firing of a row of electromagnets accelerates the payload along a path. After leaving the path, the payload continues to move due to inertia.

A mass driver is essentially a coilgun that magnetically accelerates a package consisting of a magnetisable holder containing a payload. Once the payload has been accelerated, the two separate, and the holder is slowed and recycled for another payload.

Mass drivers can be used to propel spacecraft in two different ways: A large, ground-based mass driver could be used to launch spacecraft away from the Earth or another planet. A spacecraft could have a mass driver on board, flinging large pieces of material into space to propel itself. A hybrid design is also possible.

Miniaturized mass drivers can also be used as weapons in a similar manner as classic firearms or cannon using chemical combustion.

Fixed mass drivers

Generally speaking, mass drivers are practical for small objects at a few kilometers per second; for example 1 kg at 2.5 km/s. Heavier objects go proportionally more slowly; and lighter objects may be projected at 20 km/s or more. The limits are generally the cost of the silicon to switch the current and the cost of the power supply and temporary energy storage for it. However, energy can be stored inductively in superconducting coils. A 1 km long mass driver made of superconducting coils can accelerate a 20 kg vehicle to 10.5 km/s at a conversion efficiency of 80%, and average acceleration of 5,600 g. Even so, Earth-based Mass drivers for propelling one-tonne vehicles to orbit are unlikely to be cost effective in the near future.

The Earth's strong gravity and thick atmosphere make such an installation difficult, so many proposals have been put forward to install mass drivers on the moon where the lower gravity and lack of atmosphere significantly reduce the required velocity to reach lunar orbit.

Most serious mass driver designs use superconducting coils to achieve reasonable energetic efficiency (approximately 50%). The best known performance occurs with an aluminum coil as the payload. The coils of the mass-driver induce eddy-currents in the payload's coil, and then act on the resulting magnetic field. There are two sections of a mass-driver. The maximum acceleration part spaces the coils at constant distances, and synchronize the coil currents to the bucket. In this section, the acceleration increases as the velocity increases, up to the maximum that the bucket can take. After that, the constant acceleration region begins. This region spaces the coils at increasing distances to give a fixed amount of velocity increase per unit of time.

In this mode, the major proposal for use of mass-drivers was to transport lunar surface material to space habitats so that it could be processed using solar energy. The Space Studies Institute showed that this application was reasonably practical.

In the prototypes, the payload would be held in a bucket and then released, so that the bucket can be decelerated and reused. A disposable bucket, on the other hand, would avail acceleration along the whole track.

On Earth

In contrast to a space gun, a mass driver can have a length of hundreds of kilometers and therefore achieve acceleration without excessive g forces to the passengers. It can be constructed as a very long and mainly horizontally aligned launch track for spacelaunch, targeted upwards at the end, partly by bending of the track upwards and partly by Earth's curvature in the other direction.

Natural elevations, such as mountains, may facilitate the construction of the distant, upwardly targeted part. The higher up the track terminates, the less resistance from the atmosphere the launched object will receive.

By being mainly located slightly above, on or beneath the ground, a mass driver may be easier to maintain compared with many other structures of non-rocket spacelaunch. If not underground then it still needs to be housed in a pipe that is constantly vacuum pumped in order to reduce drag.

In order to be able to launch humans and delicate instruments, it would need to be several hundreds of kilometres long. For rugged objects, with magnetic assistance, a significantly smaller, circular, track may suffice.

A mass driver on Earth would be a compromise system. A mass driver would accelerate a payload up to some high speed which would not be high enough for orbit. It would then release the payload, which would complete the launch with rockets. This would drastically reduce the amount of velocity needed to be provided by rockets to reach orbit. On Earth, a mass driver design could possibly use well-tested maglev components.

Spacecraft-based mass drivers

A spacecraft could carry a mass driver as its primary engine. With a suitable source of electrical power (probably a nuclear reactor) the spaceship could then use the mass driver to accelerate pieces of matter of almost any sort, boosting itself in the opposite direction. At the smallest scale of reaction mass, this type of drive is called an ion drive.

No theoretical limit is known for the size, acceleration or muzzle energy of linear motors. However, at higher muzzle velocities, energetic efficiency is inevitably very poor. While linear motors can, with current technology, convert up to about 50% of the electrical energy into kinetic energy of the projectile, the energy of interest is the kinetic energy of the vehicle, and as the muzzle velocity increases, this is a smaller and smaller percentage of the generated power.

Since kinetic energy of the projectile is $\frac{1}{2}mv^2$, the energy requirements vary with the square of the specific impulse, so in a design one must choose a tradeoff between energy consumption and consumption of reaction mass. In addition, since momentum of a particle of mass m has momentum mv- proportional to velocity, but energy is a square law, so the average thrust for a given energy is inversely proportional to the velocity of the particles. In other words, heavier projectile masses give lower specific impulse but proportionately higher thrust.

Since a mass driver could use any type of mass for reaction mass to move the spacecraft, this, or some variation, seems ideal for deep-space vehicles that scavenge reaction mass from found resources.

One possible drawback of the mass driver is that it has the potential to send solid reaction mass travelling at dangerously high relative speeds into useful orbits and traffic lanes. To overcome this problem, most schemes plan to throw finely-divided dust. Alternately, liquid oxygen could be used as reaction mass, which upon release would boil down to its molecular state. Propelling the reaction mass to solar escape velocity is another way to ensure that it will not remain a hazard.

Space is almost completely empty, so propellant sources are only to be found at asteroids, comets, moons and planets.

Hybrid mass drivers

Another variation is to have a mass-driver on a spacecraft, and use it to "reflect" masses from a stationary mass-driver. Each deceleration and acceleration of the mass contributes to the momentum of the spacecraft. The spacecraft need not carry reaction mass, and doesn't even need much electricity, beyond the amount needed to replace losses in the electronics. The system could also be used to deliver pellets of fuel to the spacecraft for use in powering some other propulsion system. This could be considered a form of beam-powered propulsion.

Another theoretical use for this concept of propulsion can be found in space fountains, a system in which a continuous stream of pellets in a circular track holds up a tall (and heavy) structure.

Mass drivers as weapons

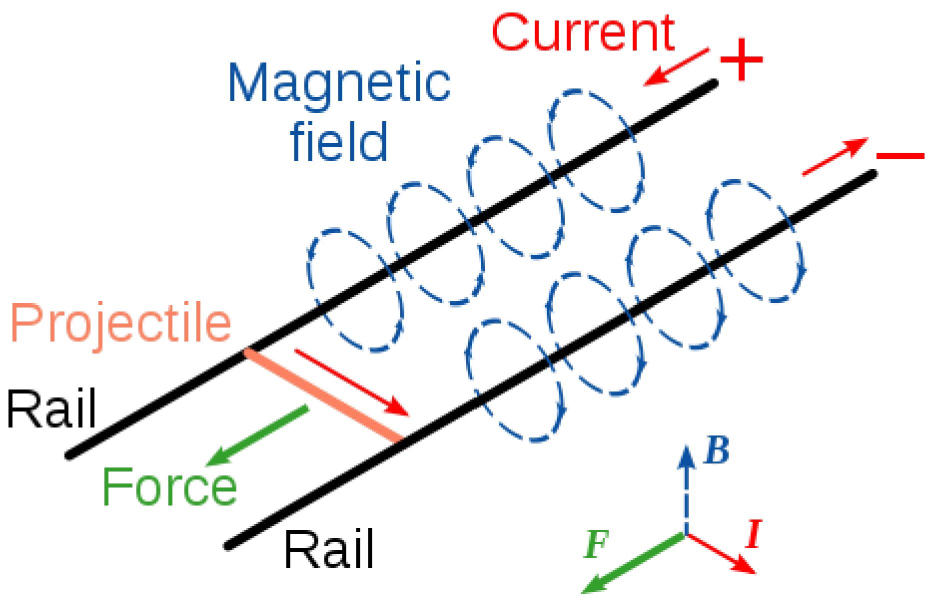
High-acceleration linear motors are currently undergoing active research by the military for use as (ground-based or ship-based) armor-piercing weapons. Since a mass driver is essentially a very large, very high-velocity linear motor, it could in principle be used as a very large weapon, either firing directly on a target in space, or used to attack a location on a planet's surface from a position in orbit, long range over-the-horizon indirect fire, or from a nearby planetary body, such as a moon.

Practical attempts

Prototype mass drivers have existed since 1976 (Mass Driver 1). Most were constructed by the US Space Studies Institute in order to prove their properties and practicality.

In fiction

Various types of devices resembling mass drivers have been a staple of science fiction for decades.



Electo-dynamic interactions in a rail gun

Rail Gun

A *rail gun* is a pair of conductive rails with a projectile between them. A high current passes to and from the projectile through the rails, and through an armature at the back of the projectile between the parallel rails. The interactions between the electrical and magnetic fields accelerate the projectile.

StarTram

StarTram is a proposal for an evacuated tube at 22 km for launching vehicles into space, held up by a large current in superconducting cables that repels another set of cables on the ground with an opposing current flow.

Chemical

Space gun

A **space gun** is a method of launching an object into outer space using a large gun, or cannon. It provides a method of non-rocket spacelaunch.

In the HARP Project a U.S. Navy 16 inch (406 mm) 100 caliber gun (40 m) was used to fire a 180 kilogram slug at 3,600 meters per second, reaching an apogee of 180 kilometers, hence performing a suborbital spaceflight.

However, a space gun has never been successfully used to launch an object into orbit.

Technical issues

The large g-force experienced by a ballistic projectile would likely mean that a space gun would be incapable of safely launching humans or delicate instruments, rather being restricted to freight or ruggedized satellites.

Atmospheric drag also makes it more difficult to control the trajectory of any projectile launched, subjects the projectile to extremely high forces, and causes severe energy losses that may not be easily overcome. A space gun with a "gun barrel" reaching above the lower troposphere, where the atmosphere is most densely packed, may mitigate the issue.

A space gun, by itself, is generally not capable of placing objects into stable orbit around the planet, unless the objects are able to perform course corrections after launch.

If acceptable solutions to these fundamental issues could be achieved, a space gun could offer access to space at an unprecedented low cost.

Getting to orbit

A space gun, by itself, is not capable of placing objects into stable orbit. The laws of gravitation make it impossible to reach a stable orbit without an active payload which performs orbital correction burns to change the shape of its orbit after launch. The orbit is a parabolic orbit, a hyperbolic orbit, or part of an elliptic orbit which ends at the planet's surface at the point of launch or another point. This means that an uncorrected ballistic payload will always strike the planet within its first orbit unless the velocity was so high as to reach or exceed escape velocity.

Isaac Newton avoided this objection in his thought experiment by positing an impossibly tall mountain from which his cannon was fired. The projectile, however, would still tend to circle the planet and strike the point of launch.

As a result, all payloads intended to reach a closed orbit would have at least to perform some sort of course correction to create another orbit that does not intersect the planet's surface. In addition a rocket can be used for additional boost, as planned in the Quicklaunch project.

It is conceivable that in a multi-body gravitational system, like the Earth-Moon system, that a trajectory could be found that does not re-intersect the Earth's surface, although these paths would likely not be very simple nor desirable, and would require much more energy.

Acceleration

A space gun with a "gun barrel" of length (l), and the needed velocity (v_e), the acceleration (a) is provided by the following formula:

$$a = \frac{v_e^2}{2l}$$

For instance, with a space gun with a vertical "gun barrel" through both the Earth's crust and the troposphere, totalling ~60 km of length (l), and a velocity (v_e) enough to escape the Earth's gravity (escape velocity, which is 11.2 km/s on Earth), the acceleration (a) would theoretically be more than 1000 m/s^2, which is more than 100 g-forces, which is about 3 times the human tolerance to g-forces of maximum 20 to 35 *g* during the ~10 seconds such a firing would take.

Any doubling of the barrel length would theoretically cut the generated g-force in half.

Practical attempts

The German V-3 cannon program (less well known than the V-2 rocket or V-1 flying bomb), during the Second World War was an attempt to build something approaching a space gun. Based in the Pas-de-Calais area of France it was planned to be more devastating than the other Nazi 'Vengeance weapons'. It was destroyed by RAF bombing using 'Tallboy' blockbuster bombs in July 1944.

Two sections of the Project Babylon gun

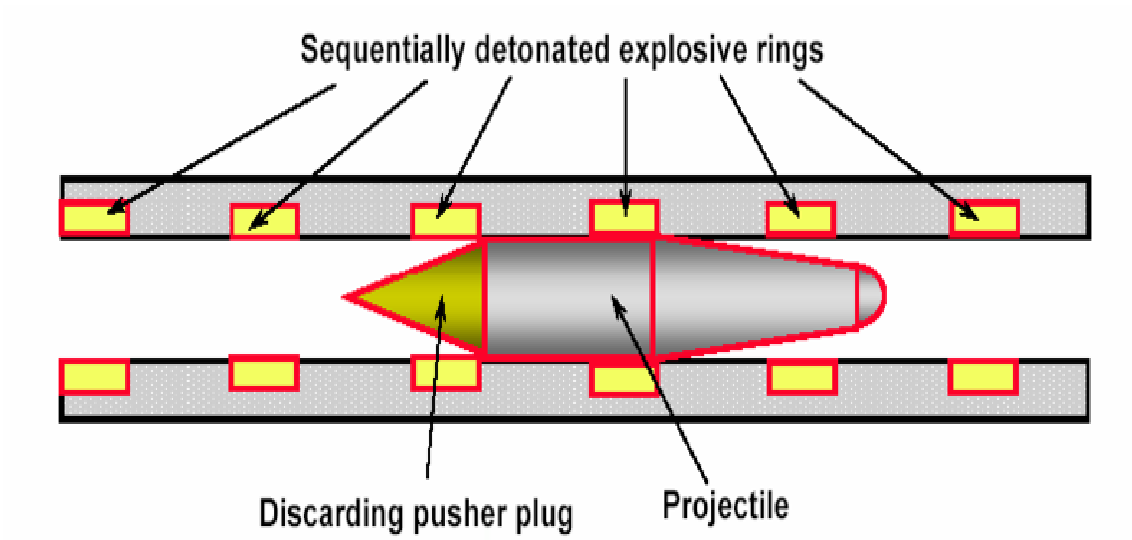
Project HARP, a prototype of a space gun.

On the practical side, the most prominent recent attempt to make a space gun was artillery engineer Gerald Bull's Project Babylon, which was also known as the 'Iraqi supergun' by the media. During Project Babylon, Bull used his experience from Project HARP to build a massive cannon for Saddam Hussein of Iraq. This gun, had it been completed, would have been the first true space gun capable of launching objects into space. However, Bull was assassinated before the project was completed.

Since Bull's death, few have seriously attempted to build a space gun. Perhaps most promisingly, the US Ballistic Missile Defense program sponsored the Super High Altitude Research Project in the 1980s. Developed at Lawrence Livermore Laboratory, it is a light gas gun and has been used to test fire objects at Mach 9. One of the lead developers John Hunter has since founded the Jules Verne Launcher Company in 1996, though has as yet been unable to find funding for the multi-billion dollar project. He has now founded the Quicklaunch company.

Ram accelerators have also been proposed as an alternative to light gas guns. Other proposals use electromagnetic techniques for accelerating the payload, such as coilguns and railguns.

Blast wave accelerator



Sequenced explosions keep acceleration high

A *blast wave accelerator* is similar to a *space gun* but it differs in that rings of explosive along the length of the barrel are detonated in sequence to keep the accelerations high. Also, rather than just relying on the pressure behind the projectile, the blast wave accelerator specifically times the explosions to squeeze on a tail cone on the projectile, as one might shoot a pumpkin seed by squeezing the tapered end.

Reaction drives (jets and unconventional rockets)

Spaceplanes

X-43A with scramjet attached to the underside

Liftoff of NASA Space Shuttle *Discovery*. The American Space Shuttles are manned orbital spaceplanes.

A **spaceplane** is an aircraft designed to fly up to extreme altitudes into space and back to the Earth's surface. It combines some of the features of an aircraft and some of a spacecraft. Typically, it takes the form of a spacecraft equipped with wings, although lifting bodies have been designed. The propulsion to reach space may be purely rocket based or may use the assistance of air-breathing engines.

To date, only pure rocket spaceplanes have succeeded in reaching space, although several have been carried up to an altitude of several tens of thousands of feet by conventional aircraft before release.

Description

A spaceplane features some differences from rocket launch systems.

Aerodynamic lift

All aircraft utilize aerodynamic surfaces in order to generate lift. Typically the force of lift generated by these surfaces is many times that of the drag that they induce. The ratio of these forces (the Lift-to-drag ratio or L/D) varies between different aircraft designs. It can be as high as 60 in high performance gliders, but is usually closer to 7 or less for typical supersonic aircraft configurations including aerospace planes.

In practice a lift to drag ratio of 7 means that a thrust force equal to 1/7th of the weight of the aircraft is sufficient to support it in flight. This low thrust requirement significantly reduces the amount of fuel required to carry the weight of an aerospace plane in comparison to rocket launch systems which must provide thrust greater than the weight of the vehicle.

A partially off-setting difference between these systems is that the aerospace plane would typically experience powered flight for much longer periods of time than a rocket. In addition winged vehicles need extra dry mass for the wings, and this penalizes vehicles towards the end of the flight. Rockets are also able to use their high thrust at an angle which gives reasonable lifting efficiency when burning for orbit, however spaceplanes typically undergo what is called a "zoom maneuver" when transitioning from air-breathing flight to pure rocket propulsion to reach space, in which they change their attitude and climb rate significantly, translating some forward velocity into vertical velocity in order to get above the remaining atmosphere so the rocket engine can operate most efficiently.

Atmospheric reentry

Because suborbital spaceplanes are designed for trajectories that do not reach orbital speed, they do not need the kinds of thermal protection orbital spacecraft required during the hypersonic phase of atmospheric reentry. The Space Shuttle thermal protection system, for example, protects the orbiter from surface temperatures that could otherwise reach as high as 3,000 °F (1,650 °C), well above the melting point of steel.

Propulsion

Rocket engines

All spaceplanes to date have used rocket engines. Rockets are currently the only kind of engines that work in space. Due to the circularising burn necessarily being done in space, orbital spaceplanes require rocket engines for at least that portion of the flight.

Air breathing engines

A difference between rocket based and air-breathing aerospace plane launch systems is that aerospace plane designs typically include minimal oxidizer storage for its propulsion. The air-breathing aerospace plane designs include engine inlets so its propulsion system uses atmospheric oxygen for combustion. Since the mass of the oxidizer is, at takeoff, the single largest mass of most rocket designs (the Space Shuttle's liquid oxygen tank weighs 629,340 kg, more than one of its solid rocket boosters), this provides a huge potential weight savings benefit. However, air breathing engines are usually very much heavier than rocket engines and the empty weight of the oxidiser tank, and since, unlike oxidiser, this extra weight must be carried into space it greatly offsets the overall system performance.

Types of air breathing engines proposed for spaceplanes include scramjet, liquid air cycle engines, precooled jet engines, pulse detonation engine and ramjets. Some engine designs combine several types of engines features into a combined cycle. For instance, the Rocket Based Combined Cycle engine uses a rocket engine inside a ramscoop so that at low speed, the rockets thrust is boosted by ejector augmented thrust. It then transitions to ramjet propulsion at near-supersonic speeds, then to supersonic combustion or scramjet propulsion, above Mach 6, then back to pure rocket propulsion above Mach 10.

Complexity

Because air-breathing aerospace planes must operate in harsh environments, utilize a number of different propulsion systems, and require more control systems (e.g. aerodynamic as well as thrust vectoring), they are typically far more complicated in design than equivalent rocket systems.

In fact, just a comparison of a typical jet engine to that of a rocket engine gives some indicator of the difference in complexity of the engine components.

However, modern combined cycle air-breathing engines, such as Rocket Based Combined Cycle or scramjets, have minimal number of parts, far less than turbopump-fed rocket engines, which burn rocket fuel in a closed turbine to power propellant pumps for the main combustion chamber. The X-43 and X-51 experimental test vehicles utilize such advanced propulsion. While earlier spaceplane designs typically had to depend on multiple types of engines on board, this is not necessary with modern technologies.

Harsh flight environment

The flight trajectory required of air-breathing aerospace vehicles to reach orbit is to fly what is known as a 'depressed trajectory' which places the aerospace plane in the high-altitude hypersonic flight regime of the atmosphere. This environment induces high dynamic pressure, high temperature, and high heat flow loads particularly upon the leading edge surfaces of the aerospace plane. These loads typically require special advanced materials, active cooling, or both for the structures to survive the environment.

However, even rocket powered spaceplanes can face a significant thermal environment if they are burning for orbit, but this is nevertheless far less severe than air-breathing spaceplanes.

Suborbital space planes designed to briefly reach space do not require significant thermal protection, as they experience peak heating for only a short time during re-entry. Intercontinental suborbital trajectories require much higher speeds and thermal protection more similar to orbital spacecraft reentry.

Center of mass issues

A wingless launch vehicle has lower aerodynamic forces affecting the vehicle, and attitude control can be active perhaps with some fins to aid stability. For a winged vehicle the centre of lift moves during the atmospheric flight as well as the centre of mass; and the vehicle spends longer in the atmosphere as well. Historically, the X-33 and HOTOL spaceplanes were rear engined and had relatively heavy engines. This puts a heavy mass at the rear of the aircraft with wings that had to hold up the vehicle. As the wet mass reduces, the centre of mass tends to move rearward behind the centre of lift, which tends to be around the centre of the wings. This can cause severe instability that is usually solved by extra fins which add weight and decrease performance.

Overall weight

A vertically-launched rocket forms the shape of a cylinder stood on end. This structure can be made very light and strong. A horizontally-launched spaceplane approximates a cylinder on its side. This structure experiences greater bending forces, so must be strengthened. This makes it heavier, requiring advanced materials and design techniques to reduce weight. For example Burt Rutan of Scaled Composites recently patented a method of gluing the fuel tank directly to the vehicle skin, saving the weight of fasteners while also stiffening both parts.

Single stage to orbit

Future orbital spaceplanes may take off, ascend, descend, and land like conventional aircraft, providing true single stage to orbit (SSTO) capability.

Proponents of scramjet technology often cite such a vehicle as being a possible application of that type of engine, however pure rocket and subsonic combustion jet designs have also been proposed and may be easier to design and build. The main problem with SSTO operation is overall weight.

Flown spaceplanes

Orbital spaceplanes

The Soviet space plane Buran on the launch pad

The *orbital* spaceplanes successfully flown to date include the piloted United States Space Shuttle, and the unmanned the Soviet Buran, the BOR-4 (subscale test vehicle for the Spiral spaceplane that was subsequently cancelled), and the Boeing X-37. These vehicles have used their wings to provide aerobraking to return from orbit and to provide lift, allowing the shuttle-style designs to land on a runway like conventional aircraft. These vehicles are still designed to ascend to orbit vertically under rocket power like conventional expendable launch vehicles. One drawback of spaceplanes is that they have a significantly smaller payload fraction than a ballistic design with the same takeoff weight. This is primarily due to the weight of the wings - around 9-12% of the weight of the atmospheric flight weight of the vehicle. This significantly reduces the payload size, but the reusability is intended to offset this disadvantage.

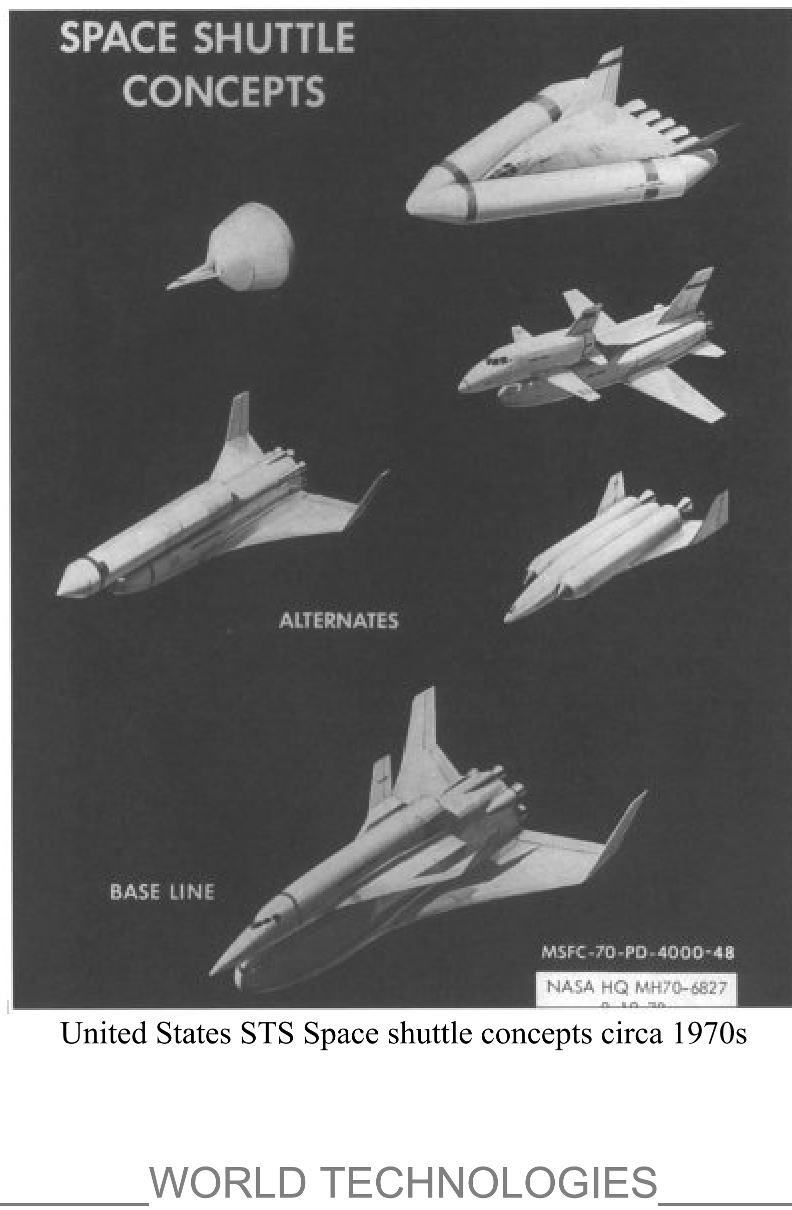
Suborbital spaceplanes

Other spaceplane designs are suborbital, requiring far less energy for propulsion, and can use the vehicle's wings to provide lift for the *ascent to* space in addition to the rocket. As of 2010, the only such craft to reach space have been the X-15, SpaceShipOne and ASSET (flown as a subscale precursor to the X-20 Dyna-Soar spaceplane program that was subsequently canceled). None of these craft were capable of entering orbit. The X-15 and SpaceShipOne both began their independent flight only after being lifted to high altitude by a carrier aircraft.

Scaled Composites and Virgin Galactic unveiled on December 7, 2009, the SpaceShipTwo space plane, the VSS Enterprise, and its WhiteKnightTwo mothership, "Eve". SpaceShipTwo is designed to carry two pilots and six passengers on suborbital flights, with flight testing scheduled to be completed in the 2012 time frame.

XCOR Aerospace signed a $30 million contract with Yecheon Astro Space Center to build and lease its Lynx Mark II spaceplane, which would be designed to take off from a runway under its own rocket power, and to reach the same altitude and speed range as SpaceShipOne and SpaceShipTwo, due to the fact that Lynx is propelled by higher specific impulse fuels. Lynx is designed to only carry a pilot and one passenger, although tickets are expected to be around half those quoted for Virgin Galactic services.

Other projects



United States STS Space shuttle concepts circa 1970s

Various types of spaceplanes have been suggested since the early twentieth century. Notable early designs include Friedrich Zander's spaceplane equipped with wings made of combustible alloys that it would burn during its ascent, and Eugen Sänger's Silbervogel bomber design. Also in Nazi Germany and then in the USA, winged versions of the V2 rocket were considered during and after World War II, and when public interest in space exploration was high in the 1950s and '60s, winged rocket designs by Wernher von Braun and Willy Ley served to inspire science fiction artists and filmmakers.

United States

The U.S. Air Force invested some effort in a paper study of a variety of spaceplane projects under their Aerospaceplane efforts of the late 1950s, but later ended these when they decided to use a modified version of Sänger's design. The result, X-20 Dyna-Soar, was to have been the first orbital spaceplane, but was canceled in the early 1960s in lieu of NASA's Project Gemini and the U.S. Air Force's Manned Orbiting Laboratory program. The Rockwell X-30 National Aero-Space Plane (NASP), begun in the 1980s, was an attempt to build a scramjet vehicle capable of operating like an aircraft and achieving orbit like the shuttle. It was canceled due to increasing technical challenges, growing budgets, and the loss of public interest. In 1994 Mitchell Burnside Clapp proposed a single stage to orbit peroxide/kerosene spaceplane called "Black Horse". This was notable in that it was to take off almost empty and undergo mid-air refueling before accelerating to orbit.

The Lockheed Martin X-33 was a prototype made as part of an attempt by NASA to build a SSTO hydrogen-fuelled spaceplane VentureStar that failed when the hydrogen tank design proved to be unconstructable in the planned way. The March 5, 2006 edition of Aviation Week & Space Technology published a story purporting to be "outing" a highly classified U.S. military two-stage-to-orbit spaceplane system with the code name Blackstar, SR-3/XOV among other nicknames. The alleged system, using an XB-70-like first-stage mother ship, capable of Mach 3, is said to launch an upper-stage "waverider" spaceplane capable of carrying small payloads and crews near to or into orbit or on skip-diving flights, ostensibly for reconnaissance and other missions, achieving surprise that cannot be attained by satellite. There has been considerable controversy over this story and its claims.

Soviet Union

The Soviet Union firstly considered a preliminary design of rocket-launch small spaceplane Lapotok in early 1960s. Then the Spiral airspace system with small orbital spaceplane and rocket as second stage was widely developed in the 1960s-1980s. Although test flights of prototypes of spaceplane were fulfilled in air (MiG-105) and space (BOR-4), program was canceled in 1987, a year before the first Buran flight. Project of Tupolev Design Bureau of military suborbital spaceplane-bomber Tu-136/139 Zvezda was canceled in early stage. Another project of Uragan spaceplane, a smaller sibling to Buran, launched by Proton and Zenit rockets, never been confirmed by Soviet or Russian authorities as really conducted, although an existence of similar project of Chelomei's LKS (Kosmolyot) spaceplane was confirmed.

In post-Soviet Russia a few projects of spaceplanes were proposed. The MAKS system includes the small spaceplane Molniya that launched by rocket from a board of An-225 superheavy aircraft. Also the Kliper spacecraft which first version was winged, SSTO-spaceplane Tu-444/2000 of Tupolev Design Bureau, and commercial Black Raven BR-009 and Cosmopolis XXI of Myasishchev Design Bureau for Space Adventures with small suborbital spaceplanes launched by airplane like SpaceShipOne and SpaseShipTwo.

Germany

After the German Sänger-Bredt RaBo and Silbervogel of the 1930s and 1940s, Eugen Sänger worked for time on various space plane projects, coming up with several designs for Messerschmitt-Bölkow-Blohm such as the MBB Raumtransporter-8. In the 1980s, West Germany funded design work on the MBB Sänger II with the Hypersonic Technology Program. Development continued on MBB/Deutsche Aerospace Sänger II/HORUS until the last 1980s, when it was canceled in favor of participation in the Ariane rocket, Columbus space station and Hermes spaceplane of ESA, Spacelab of ESA-NASA and *Deutschland* missions (non-U.S. funded Space Shuttle flights with Spacelab), despite predicted cost savings of up to 30 percent. The Daimler-Chrysler Aerospace RLV was a much later small reusable spaceplane prototype for ESA FLPP/FLTP program.

France

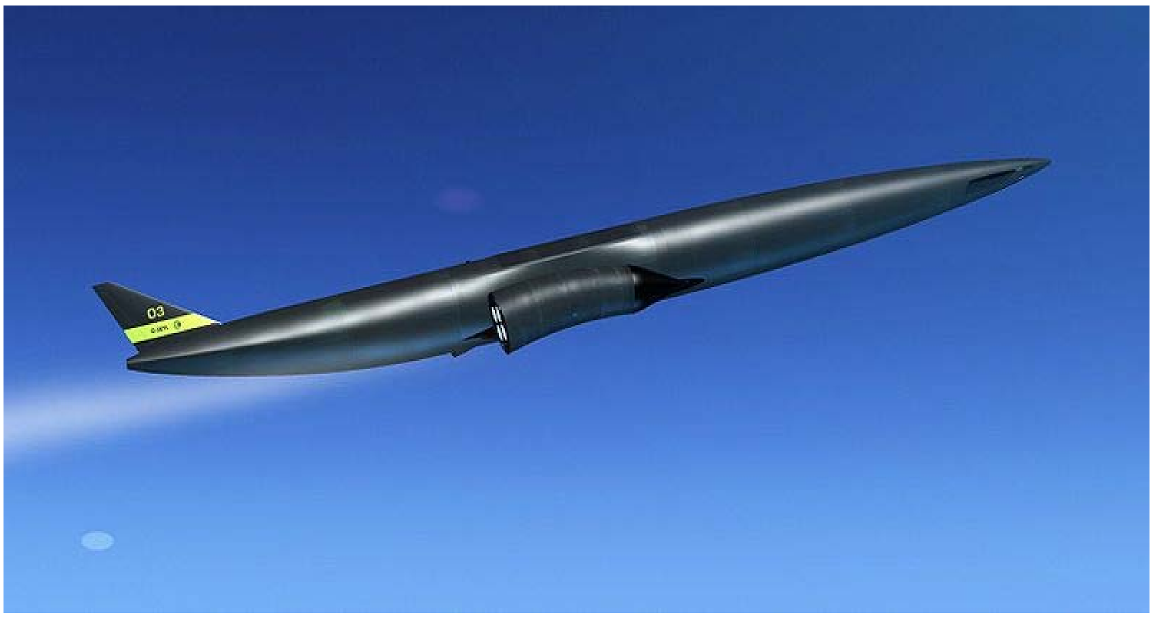
Initiated by France joint European program of ESA of Hermes manned spaceplane launched by Ariane rocket continued a few years before it was canceled in early 1990s. Earlier France Dassault-Avion company proposed Astrobus spaceplane and now develops ARES spaceplane as prototype for FLPP. Hopper was proposed as European spaceplane by EADS which also develops ARES spaceplane as prototype for ESA FLPP/FLTP program and commercial suborbital spaceplane for space tourism.

Chinese

China develops the Project 921-3, Shenlong Space Plane and larger other projects like SSTO. Beside of future SSTO concepts, Japan fulfilled the initial test flights of Hyflex/OREX subscale prototypes for rocket-launched manned Hope-X spaceplane that was later canceled. India developed a small Hyperplane spaceplane in past and continues to develop the winged reusable system RLV-Avatar. Private Canadian companies develops for space tourism small suborbital Wild Fire and orbital Silver Dart spaceplanes.

British

The Multi-Unit Space Transport And Recovery Device (MUSTARD) was a concept explored by the British Aircraft Corporation (BAC) around 1964-1965 for launching payloads weighing as much as 5,000 lb into orbit. It was never constructed. The British Government also began development of a SSTO-spaceplane, called HOTOL, but the project was canceled due to technical and financial issues.



Great Britain has had an (underfunded) spaceplane development community for the past five decades, and it remains a leader in powerplant innovations such as precooled jet engines.

The lead engineer from the HOTOL project has since set up a private company dedicated to creating a similar plane called Skylon with a different combined cycle rocket/turbine precooled jet engine called SABRE. This vehicle is intended to be capable of a single stage to orbit launch also and, if successful, would be far in advance of anything currently in operation.

Laser propulsion

Laser propulsion is a form of beam-powered propulsion where the energy source is a remote (usually ground-based) laser system and separate from the reaction mass. This form of propulsion differs from a conventional chemical rocket where both energy and reaction mass come from the solid or liquid propellants carried on board the vehicle.

History

The concept of laser propelled vehicles was first introduced by Arthur Kantrowitz in 1972. Laser propulsion systems may transfer momentum to a spacecraft in two different ways. The first way is that photon radiation pressure drives the momentum transfer, the principle behind the propulsion of solar sails and laser sails. A second way of driving momentum transfer to a spacecraft, used in the devices described below, which is more commonly proposed is using the laser to help expel mass from the spacecraft as in a conventional rocket. The second class of propulsion systems are fundamentally limited in their final spacecraft velocities by the rocket equation.

Forms

There are several forms of laser propulsion.

Ablative laser propulsion

Ablative Laser Propulsion (ALP) is a form of beam-powered propulsion in which an external pulsed laser is used to burn off a plasma plume from a solid metal propellant, thus producing thrust. The measured specific impulse of small ALP setups is very high at about 5000 s (49 kN·s/kg), and unlike the lightcraft developed by Leik Myrabo which uses air as the propellant, ALP can be used in space.

Material is directly removed from a solid or liquid surface at high velocities by laser ablation by a pulsed laser. Depending on the laser flux and pulse duration, the material can be simply heated and evaporated, or converted to plasma. Ablative propulsion will work in air or vacuum. Specific impulse values from 200 seconds to several thousand seconds are possible by choosing the propellant and laser pulse characteristics. Variations of ablative propulsion include double-pulse propulsion in which one laser pulse ablates material and a second laser pulse further heats the ablated gas, laser micropropulsion in which a small laser onboard a spacecraft ablates very small amounts of propellant for attitude control or maneuvering, and space debris removal, in which the laser ablates material from debris particles in low Earth orbit, changing their orbits and causing them to reenter.

ALP was being developed by Professor Andrew Pakhomov at the University of Alabama in Huntsville of the UAH Laser Propulsion Group, until he was convicted of murdering his wife and sentenced to 45 years in prison.

Pulsed plasma propulsion

A high energy pulse focused in a gas or on a solid surface surrounded by gas produces breakdown of the gas (usually air). This causes an expanding shock wave which absorbs laser energy at the shock front (a laser sustained detonation wave or LSD wave); expansion of the hot plasma behind the shock front during and after the pulse transmits momentum to the craft. Pulsed plasma propulsion using air as the working fluid is the simplest form of air-breathing laser propulsion. The record-breaking Lightcraft, developed by Leik Myrabo of RPI (Rensselaer Polytechnic Institute) and Frank Mead, works on this principle.

CW plasma propulsion

A continuous laser beam focused in a flowing stream of gas creates a stable laser sustained plasma which heats the gas; the hot gas is then expanded through a conventional nozzle to produce thrust. Because the plasma does not touch the walls of the engine, very high gas temperatures are possible, as in gas core nuclear thermal propulsion. However, to achieve high specific impulse, the propellant must have low molecular weight; hydrogen is usually assumed for actual use, at specific impulses around 1000 seconds. CW plasma propulsion has the disadvantage that the laser beam must be precisely focused into the absorption chamber, either through a window or by using a specially-shaped nozzle. CW plasma thruster experiments were performed in the 1970s and 1980s, primarily by Dr. Dennis Keefer of UTSI and Prof. Herman Krier of the University of Illinois at Urbana-Champaign.

Heat Exchanger (HX) Thruster

The laser beam heats a solid heat exchanger, which in turn heats an inert liquid propellant, converting it to hot gas which is exhausted through a conventional nozzle. This is similar in principle to nuclear thermal and solar thermal propulsion. Using a large flat heat exchanger allows the laser beam to shine directly on the heat exchanger without focusing optics on the vehicle. The HX thruster has the advantage of working equally well with any laser wavelength and both CW and pulsed lasers, and of having an efficiency approaching 100%. The HX thruster is limited by the heat exchanger material and by radiative losses to relatively low gas temperatures, typically 1000 - 2000 C, but with hydrogen propellant, that provides sufficient specific impulse (600 – 800 seconds) to allow single stage vehicles to reach low Earth orbit. The HX laser thruster concept was developed by Jordin Kare in 1991; a similar microwave thermal propulsion concept was developed independently by Kevin Parkin at Caltech in 2001.

Laser electric propulsion

A general class of propulsion techniques in which the laser beam power is converted to electricity, which then powers some type of electric propulsion thruster. Usually, laser electric propulsion is considered as a competitor to solar electric or nuclear electric propulsion for low-thrust propulsion in space. However, Leik Myrabo has proposed high-thrust laser electric propulsion, using magnetohydrodynamics to convert laser energy to electricity and to electrically accelerate air around a vehicle for thrust.

Photonic Laser Thruster (PLT)

Photonic Laser Thruster (PLT) is a pure photon laser thruster that amplifies photon radiation pressure by orders of magnitude by exploiting an active resonant optical cavity formed between two mirrors on paired spacecraft. PLT is predicted to be able to provide the thrust to power ratio (a measure of how efficient a thruster is in terms of converting power to thrust) approaching that of conventional thrusters, such as laser ablation thrusters and electrical thrusters. Yet, PLT has the highest specific impulse (a measure of how fast the fuel can propel spacecraft) orders of magnitude larger than that of other conventional thrusters. In December 2006, Dr. Young K. Bae has successfully demonstrated the photon thrust amplification in PLT for the first time with an amplification factor of 3,000 under NASA sponsorship (NIAC). Scaling-up of PLT is highly promising, and PLT is predicted to enable wide ranges of next generation space endeavors. Low thrust (milli-Newton) PLTs enable nanometer precision spacecraft formation, for example Photon Tether Formation Flight (PTFF), for forming ultralarge space telescopes and radars. Medium thrust (Newton) PLTs enable precision propellantless orbit changing and docking. High thrust (greater than kilo-Newton) PLTs enable propelling spacecraft at speeds beyond hundreds km/sec. At such speeds, spacecraft could transit from Earth to Mars in less than one week. Scaling up of PLTs seems promising owing to the recent development of high power laser weapons.

Buoyant space port

By using big balloons it is possible to construct a space port in the stratosphere. Rockets can start from it or a mass driver can accelerate payloads into the orbit. This has the advantage that most (about 90%) of the atmosphere is below the space port and that you start really high. *As a rough estimate, a rocket that reaches an altitude of 20 km when launched from the ground will reach 100 km if launched at an altitude of 20 km from a balloon.*