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Tethers

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A tether of sufficient strength, capable of being lengthened or shortened and having appropriate apparatuses for capturing and releasing bodies at its ends, may be useful in propulsion applications. For example, a tether could allow rendezvous between spacecraft in substantially different orbits without using propellant. A tether could also allow co-orbiting spacecraft to exchange momentum and separate. Thus, a reentering spacecraft (such as the Shuttle) could give its momentum to one remaining on orbit (such as the space station). Similarly, a tether facility could gain momentum from a high I_{sp}/low thrust mechanism (which could be an electrodynamic tether) and transfer that momentum by means of a tether to payloads headed for many different orbits. Such a facility would, in effect, combine high I_{sp} with high thrust, although only briefly. An electrodynamic tether could propel a satellite from its launch inclination to a higher or lower inclination. Tethers could also allow samples to be taken from bodies such as the Moon. Three types of tether operations are illustrated in figure 23.

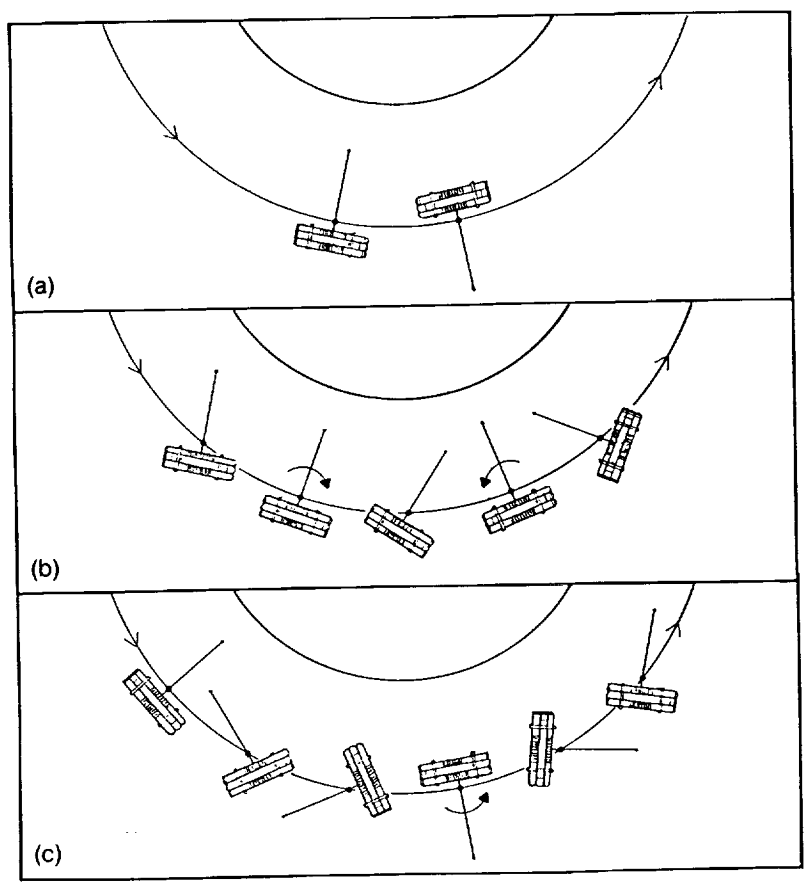


Figure 23

Three Modes of Tether Operation

a. Hanging, with the tether stably pointing toward or away from a massive object.

b. Swinging about a stable position, with the tether pointing toward a massive object.

c. Spinning in the orbital plane and in the same direction as the orbiting system (posigrade).

Whether hanging, swinging, or spinning, the tether works by releasing its payload at a favorable point in its motion. The center of gravity of the system is indicated by a dot along the tether and is shown orbiting about a massive object. The size of the platform and the distance of the center of gravity from the platform have been exaggerated for clarity.

Taken from Martin O. Stern, 1988, Advanced Propulsion for LEO-Moon Transport, Progress Report on work performed under NASA grant 9-186 (James R. Arnold, Principal Investigator), Calif. Space Inst., Univ. of Calif., San Diego, June.

Electrically conducting tethers will couple to the Earth's magnetic field. In low Earth orbit (LEO) there is sufficient plasma density to allow large currents to flow through the tether and close the loop efficiently through the plasma. The interaction between the current and the magnetic field produces a force that propels the tether. Such a tether can convert electrical energy (from a photovoltaic array, for example) to thrust with high efficiency (2-8 kW/N), without expending propellant. Vehicles with a hanging electrodynamic tether propulsion system could go from any arbitrary low Earth orbit to any other arbitrary low Earth orbit in a few months.

Tether Characteristics

A tether is a long tensile structure in space. In the applications discussed here, it is generally 10 to 200 kilometers long and is under a tension of hundreds to a few tens of thousands of newtons. There are usually objects at the ends of the tether which are more massive than the tether itself. An introductory handbook on tethers is available (Carroll 1985), and many prospective tether applications are described by Carroll (1986).

A tether in orbit will experience a gravity gradient force orienting it toward the local vertical. In LEO this force is about 4×10^{-4} gravities per kilometer from the center of mass of the tethered system. The tether may oscillate about the local vertical. These oscillations can be broken into components parallel and perpendicular to the plane of orbital motion. The out-of-plane potential function is symmetrical with respect to position and velocity. The in-plane potential function is not symmetrical. Tension is greater for a swing in the direction of orbital motion (posigrade) than it is for a swing contrary to the direction of orbital motion (retrograde).

Since the tether exerts a net force on the mass at either end of it, the path the mass follows is not a free orbit. If an object is released by a hanging tether of length ℓ, the orbits of the two end masses will be separated by ℓ at that point and by about 7 ℓ half an orbit later. If release is from the top or bottom of the swing of a widely swinging tether, the initial separation will again be ℓ and the separation half an orbit later will be about 14 ℓ.

A current-carrying tether in orbit around a body with a significant magnetic field (such as Earth or Jupiter, but not the Moon or Mars) experiences a JxB magnetic force perpendicular to both the tether and the magnetic field. (This is the force that results when an electric current of density J is passed through a magnetic field of inductance B.) The tether will usually be held close to the local vertical by gravity gradient forces, so the direction of thrust is not arbitrarily selectable and it will generally have an out-of-plane component which varies with time. Appropriate current control strategies will be necessary to allow use of electrodynamic tethers as efficient thrusters. Reasonable estimates of power per thrust are 2 to 8 kilowatts per newton, depending on the orbital inclination. For Earth, the lower power consumption is at high inclinations, where fewer lines of the magnetic field are crossed.

One would expect the best electrodynamic tether material to be that with the highest specific conductivity—lithium or sodium. However, these high specific conductivity materials are not very dense and therefore have a low areal conductivity. That is, wire made of lithium or sodium is larger in diameter than wire with the same conductivity but made of a more dense material, such as copper. Typical electrodynamic tethers operating at kilovolt potentials must be insulated against current loss. Because insulation is of roughly the same thickness whether it is applied to small- or large-diameter wire, the less dense conducting wires require more massive insulation. Tradeoffs between high specific conductivity and high areal conductivity must therefore be studied for each application.

Tether materials are subject to degradation in the space environment. High-strength plastics will be degraded by ultraviolet and ionizing radiation and by atomic oxygen in LEO. The effects of these degradational influences and the utility of protective coatings must be studied.

Although tethers are typically quite thin, their great length gives them a large impact area. Thus, they have a significant chance of failure due to micrometeoroid impact. This chance is conservatively estimated to be 1 cut per kilometer-year of exposure of a heavily loaded 1-millimeter-thick tether in LEO. The risk of system failure can be reduced by using multiple independent strands or a tape. While a tape would be hit more often, a micrometeoroid would only punch a hole in it and not sever it, as it might a single strand. However, additional insulation would be required for multiple strands or a tape.

Tether Propulsion

Basics

The simplest operation with a tether is to raise or lower an object and release it from a hanging tether. Since a tethered object is not in a free orbit (the tether exerts a net force on it), this method can be used to change velocity without using rocketry. Even in this nominally hanging case, there will be some libration of the tether. By controlling the tether tension and thus mechanically pumping energy into these librations (like a child pumping a swing), the tether can be made to swing.

The characteristic velocity, V_C, of a tether can be defined as the square root of its specific strength (that is, its tensile strength divided by its density):

$$V_C = \sqrt{\frac{s}{\rho}}$$

where *s* is the tensile strength (that is, force per unit area which the tether can withstand without breaking) and ρ is the density. Typical numbers for reasonable engineering systems are 350 meters/second for steel, 700 m/sec for Kevlar, and 1000 m/sec for high-density polyethylene fibers. These characteristic velocities incorporate an adequate safety factor to account for manufacturing variations in the material and for degradation in use. The higher the effective V_C, the lower the tether mass for a given operation.

The characteristic velocity just defined is for a spinning tether. The effective characteristic velocity depends on the type of tether operation. To convert V_C for a spinning tether to V_C for some other operation, multiply by the factor given below.

Hanging $\sqrt{\frac{4}{3}}$

Swinging $\sqrt{\frac{3}{2}}$

Winching $\sqrt{2}$

Thus, to impart a velocity change much less than V_C to a unit payload mass, the ratios of required tether mass to that of a spinning tether are as follows:

Hanging : Spinning $\frac{3}{4}$: 1

Swinging : Spinning $\frac{2}{3}$: 1

Winching : Spinning $\frac{1}{2}$: 1

The velocity that a tether imparts to a payload depends on the orbital velocity of the tether, the speed at which it is swinging or spinning, and the length of the tether. The tether can be lighter than its tip mass if the desired velocity change is much lower than the characteristic velocity. As the desired velocity approaches V_C, the mass of the tether becomes appreciable. As a propulsion system, a tether is more efficient than a rocket for small velocity changes (that is, it weighs less than the rocket propellant necessary), but it is less efficient for large changes. Thus, a tether will not be cost-effective in comparison with a rocket if a large velocity change must be made and the tether is used only once. If the tether can be used for more than one operation, the velocity at which the tether is more mass-efficient than a rocket becomes larger. Using a tether for part of any required velocity change will always be beneficial if the momentum has different costs (or values) at the two ends of the tether.

Propulsion via Momentum Transfer

There are many potential propulsive uses of tethers. Rockets from Earth, orbital maneuvering vehicles (OMVs), and orbital transfer vehicles (OTVs) could be boosted and deboosted with tethers to reduce their rocket-supplied velocity changes by hundreds of meters per second. A permanent facility in Earth orbit would serve as a momentum storage bank. (See figure 24.) It could lend momentum to a vehicle launched from Earth; by so doing, its own orbit would be lowered. It could regain momentum by releasing a spacecraft which is returning to Earth; by doing this, the

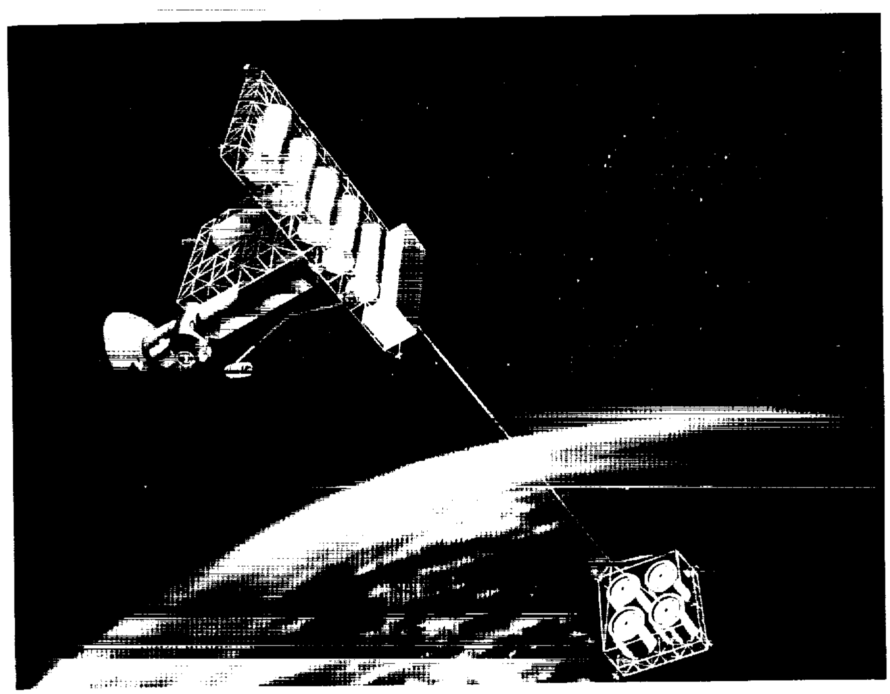


Figure 24

Concept for a Spinning Tether System in Low Earth Orbit

The tether facility rotates around the Earth in an eccentric orbit such that the end of the 100-km-long tether can rendezvous with a payload in orbit with the space station. The payload is then swung on the tether to the release point, where it receives additional velocity toward the Moon. The transfer of momentum to the payload reduces the momentum of the tether facility and thus lowers its orbit. This momentum can be recovered by the facility if it catches and slows a payload returning from the Moon to low Earth orbit.

Taken from Eagle Engineering, Inc., 1988, LEO/Moon Transport: Advanced Propulsion Concepts Assessment, EEI Report 88-217, Oct. 26.

Artist: John Michael Stovall

facility's orbit would be raised. Space-based vehicles (OMVs and OTVs) could also benefit. If the tether propelling it broke, the OMV or OTV could rely on built-in propulsive capability to return to the space station and try again. This operation is described in more detail in the appendix.

The greater the tether facility mass, the smaller the effect on its orbit produced by the momentum loaned to it or borrowed from it. Thus, accumulating mass would be desirable and would give the system more flexibility. Mass could be accumulated at the facility by collecting massive disposable items, such as external tanks. Tether operations that provide velocity changes of up to 1000 m/sec are feasible using currently available materials. Larger velocity changes are possible, but they require tapered tethers more massive than the payloads boosted.

The net impulse invested in the OMVs and OTVs, in their payloads, and in the propellant they consume must be made up. It could be made up by a second tether at the same orbiting facility. This second tether would be an electrodynamic tether with a solar power source. It would slowly convert solar-generated electricity to thrust. This tether thruster would work continuously at low thrust (high specific impulse) to raise the facility's orbit. Periodically, the orbit would suddenly be lowered when the other tether—the one providing high thrust—accelerated a payload.

As this thruster would not travel with the payloads or undergo significant velocity changes, it could have a relatively large inert mass, compared to that permissible on an OTV. The expense of transporting the thruster mass into orbit would quickly be paid for in vehicle propellant savings. Other advantages to such a thruster are that it would be accessible for maintenance and repair at all times and that its power supply would not be repeatedly exposed to radiation trapped in the Van Allen belt. Its duty cycle would have to be high enough to provide impulse at the rate that OMV and OTV launches used it up. The mass of the tether facility would damp out small variations in orbital energy due to tethered boosts and erratic thruster use.

This tether system could be located at the space station. If so, tethered rendezvous, boost, and deboost would have an impact on space station design. These operations would exert net forces on the space station. Using ambitious Shuttle capture schemes, these forces would be much larger than the forces from any other operation. Solar cell arrays and other extended structures would be particularly sensitive to such forces.

Electrodynamic Tether Propulsion

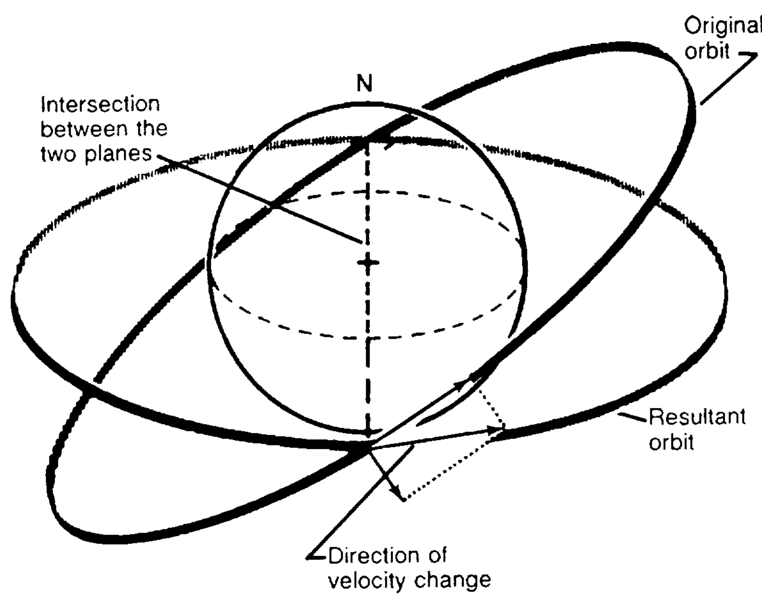
A vehicle driven by an electrodynamic tether is capable of changing the inclination of its low Earth orbit in a month or so. (See figure 25.) Such a vehicle would make all satellites in low Earth orbit serviceable from a space station orbiting at a 28.5-degree inclination. Payloads destined for high-inclination orbits could be launched into 28.5-degree orbit (or any other orbit easily accessible from the launch site) and then delivered by an orbital maneuvering vehicle to the higher inclination. Spacecraft could also be delivered to an inclination lower than 28.5 degrees. Delivery to lower inclinations would reduce the amount of fuel required for orbital plane changes in going to geosynchronous equatorial orbit. Instruments and experiments (biological or other) that are affected by exposure to the South Atlantic anomaly could be placed in orbits with inclinations low enough to greatly reduce overall radiation exposure.

Figure 25

Orbital Plane Change

The angle between the plane of a spacecraft's orbit and some reference plane, such as the equator, is called its inclination. A spacecraft can change its inclination by firing its engines while pointed at an angle to the plane of the spacecraft's current orbit. As shown in the figure, the new orbit plane will be the resultant of the vector addition of the original velocity and the velocity change accomplished with the engine firing. Plane changes and orbit altitude changes are often accomplished in the same maneuver. These orbit changes can be accomplished by low thrust propulsion or by tether momentum management techniques as well as by conventional rocketry.

Taken from AC Electronics Division, General Motors Corp., 1969, Introduction to Orbital Mechanics and Rendezvous Techniques, Text 2, prepared under NASA contract 9-497, Nov.



Because its electrodynamic tether would need a relatively dense plasma to close the current loop, such an OMV would be limited to low Earth orbits. With currently projected solar or nuclear power sources, an electrodynamic OMV could move a payload heavier than itself from a 28.5-degree orbit to a 104-degree orbit in a few months. Thus, all payloads for high-inclination orbits could be launched due east to maximize mass on orbit and then be moved to their final destination. This two-step method could double the Shuttle's capacity to deploy payloads destined for high-inclination orbits. This method would also allow any low-Earth-orbit satellite to be returned to the space station for servicing and then be redeployed.

An alternative means of turning spacecraft power into orbital changes is by mechanically pumping a tethered system in resonance with its orbital period (to couple to orbital eccentricity or to nonspherical terms in the gravitational field). This means would be less effective than an electrodynamic tether at low altitudes, but it could be superior at altitudes from 3000 to 8000 km. Accelerations at these altitudes are less than 1/20th those achievable in LEO. Above these altitudes, neither mechanical nor electrodynamic tether propulsion is effective.

Planetary Exploration

Sample recovery from celestial bodies is a challenging propulsion problem. Conventional approaches require large, low-specific-impulse propulsion systems to provide enough thrust to land and take off again. Sampling is restricted to a small area because of the difficulty of moving about on the surface of the body. Tethers offer a unique and desirable solution to this problem.

With currently available engineering materials, it is possible to sample from orbit the surface of bodies the size of the Moon and smaller which have no appreciable atmosphere. A long tether would be deployed from an orbiting spacecraft and spun so that its tip touched the body's surface at a relative velocity near 0. Such a vehicle in polar orbit around a celestial body could, in principle, sample any place on the body's surface. A high-specific-impulse, low-thrust propulsion system (which could not land on the body's surface) could be used to accumulate momentum for such sample-boosting operations. Most small bodies on which this operation is practical do not have enough plasma or magnetic field to allow the use of electrodynamic tethers.

A lunar polar orbiting skyhook equipped with ten 200-kg tapered

Kevlar tethers (or ten 50-kg Allied-1000 tethers) could recover about 700 10-kg samples from any desired locations on the lunar surface. Using an electric thruster with a specific impulse of 1000 seconds in conjunction with such a mechanical tether system, the ratio of recovered samples to tethers and propellant is 2.2 : 1 (or 4.3 : 1 for the lighter tethers). Reasonably sized vehicles (5 000-10 000 kg) could return many large samples of material from the Moon or any of the satellites of the outer planets using this technique.

Tether life will be limited by micrometeoroid damage. Using multiple tethers allows missions to be planned on the basis of average tether life, and, if the actual life is shorter than expected, such use allows a rational sampling program to be built.

Conclusions About Tethers

Tethers for rendezvous, boost, and deboost can be deployed and in use by the year 2000. Electrodynamic tether OMVs could be ready by the same year. The only problems may be plasma coupling and plasma conductivity, both of which are to be measured by the Tethered Satellite System experiment in the next 5 years (see fig. 26). A lunar surface sampling tether is possible by 2000 and reasonable by 2010. Tether sampling of other small bodies could follow rapidly.

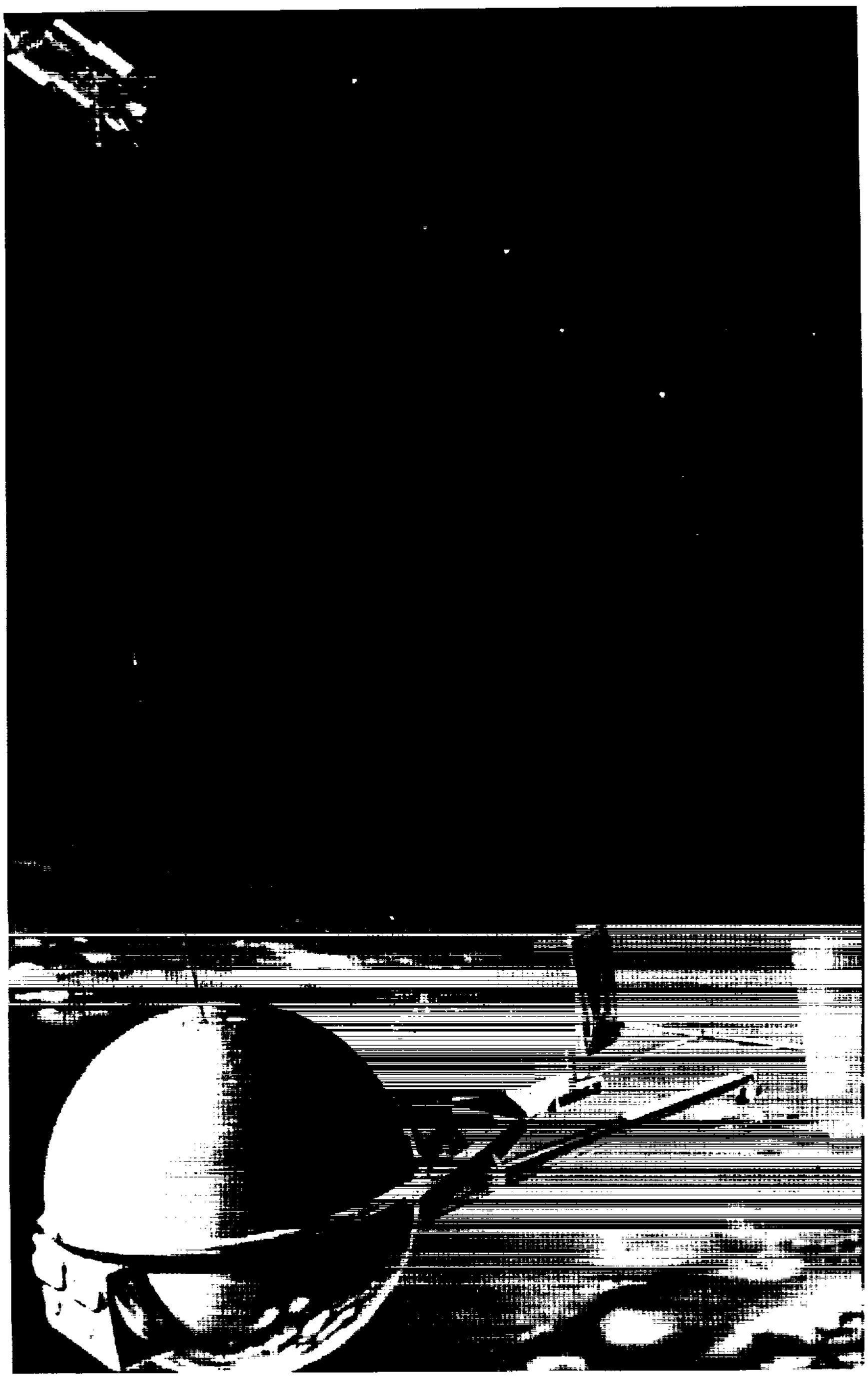


Figure 26

A Tethered Satellite Attached to the Shuttle Orbiter

In this concept, the tethered satellite would be suspended by a cable down as far as 60 miles below the orbital altitude of the orbiter. It would skim through the upper atmosphere, where it could collect gas samples for subsequent analyses.

Use of tethers implies important changes in propulsion for low Earth orbit and elsewhere. Significant efficiencies can be gained using tethers in combination with conventional rockets. Operations will be different, however, and substantial development of operational procedures will be necessary.

There are some specific research questions which will have significant impact on tether systems and which can be addressed now. These questions concern electrical coupling to the space plasma; developing materials with high specific strength; degradation of high-strength polymers in the space environment; micrometeoroid hazards; minimizing wire-plus-insulation mass for materials with high specific conductivity, such as lithium, sodium, and aluminum; tether behavior under perturbations; and tether control laws.

Tethers can do things that rockets and reaction thrusters cannot. They could be a valuable enhancement to the Space Transportation System. Tethers cannot replace rockets and reaction thrusters, but reaction thrusters and rockets cannot replace tethers, either. The combination of tethers and thrusters is much more capable than either one alone.

References

Carroll, J. A. 1985. Guidelines for Analysis of Tether Applications. Available from Marshall Space Flight Center.

Carroll, J. A. 1986. Tether Applications in Space Transportation. Acta Astronautica **13** (April): 165-174.

Appendix

Tethers may be used to mediate Shuttle-to-space-station rendezvous. One part of the space station may be a transportation node, which serves as a service and propellant-transfer area and as a momentum storage device. The Shuttle could be launched into a 73- by 400-kilometer direct-insertion trajectory and rendezvous with a 55-kilometer tether hanging down from the space station at Shuttle apogee. The tether would then be reeled in to recover the Shuttle. After the Shuttle completed its operations at the space station, it could be swung down and back at the end of the 55-kilometer tether.

Such tethered rendezvous between the Shuttle and the space station have a flexibility that contributes to both safety and reliability. The multistrand tether would have an orbital maneuvering vehicle at its tip; both would be deployed and checked before the Shuttle was launched. If the tether broke during the 6 hours between deployment and rendezvous, the OMV could take the Shuttle to the station. If both the tether and the OMV failed, the Shuttle could use its orbital maneuvering system (OMS) to climb to the space station's altitude, provided it carried enough OMS propellant. If it did not, then the Shuttle could abort to a lower orbit and await another OMV, if one was available. The probability that one strand of a tether would be cut by micrometeoroids during a 6-hour period is less than once in 1250 flights for a tether sized to take the required load. The probability that the OMV would fail during this time is also low.

The chances of successful rendezvous are also enhanced by the tether method. If the Shuttle failed to rendezvous with the tether tip, the OMV could be released to rendezvous with the co-orbital Shuttle using free-fall techniques. (In this case, it would be necessary to burn OMS fuel to raise the Shuttle's perigee to about 185 kilometers to prevent reentry.)

Reeling the Shuttle up to the space station by tether would save 6 tons of OMS propellant. It would cost about 1200 pounds of OMS propellant per minute for the Shuttle to hover near the tether tip. So, the quicker the connection is made, the greater the savings in propellant. Lowering the Shuttle by tether to allow it to reenter the atmosphere would save a further 3 tons of OMS propellant and recover more momentum from the Shuttle than was loaned to it. The added momentum would reduce or eliminate the need to make up for space station drag.

Since there are commercial plans to use OMS-type propellant (monomethylhydrazine oxidized by nitrogen tetroxide) for integral rockets to boost satellites to geosynchronous equatorial orbit, OMS propellant will be a valuable commodity and saving it will be desirable even in cases where the mass savings cannot be converted into extra payload.

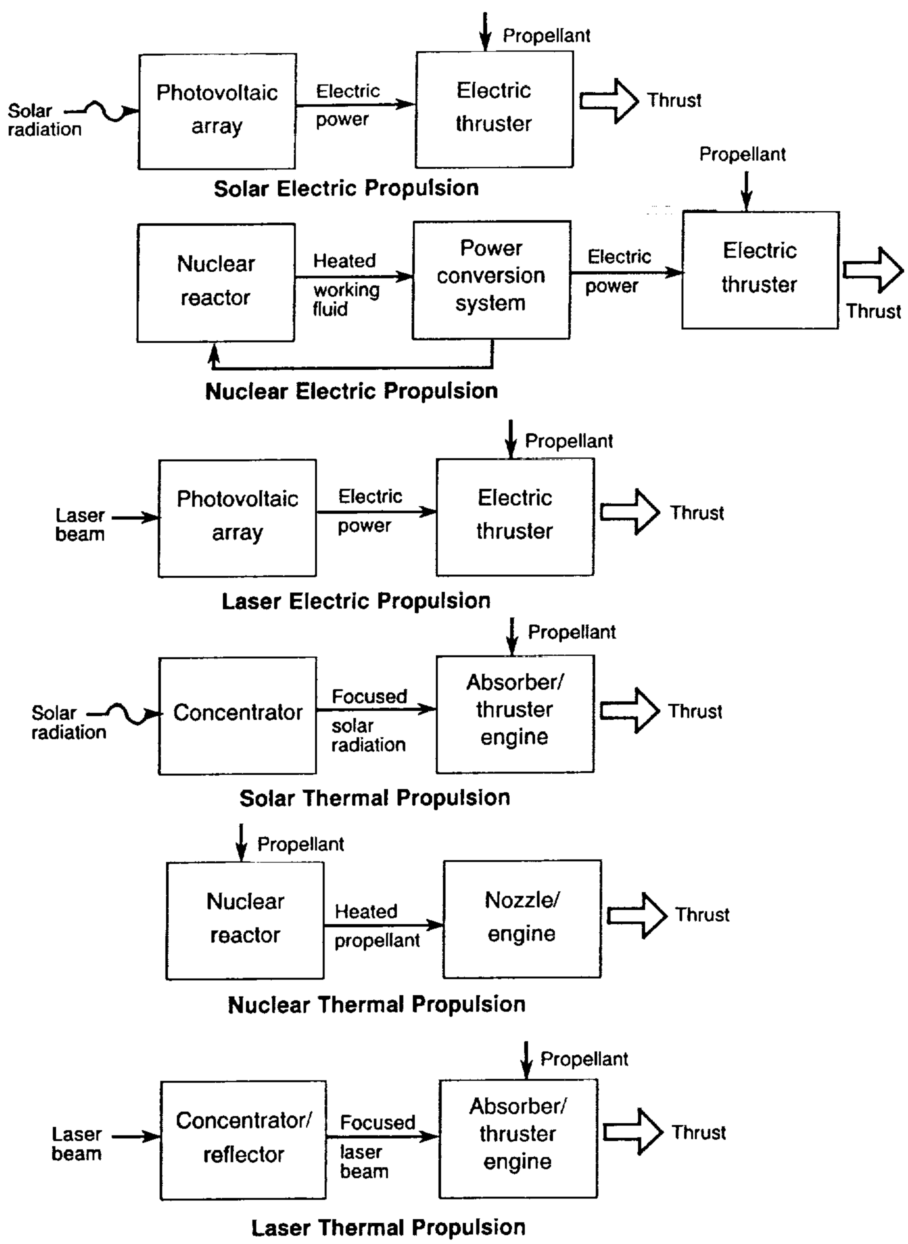


Figure 27

Electric and Thermal Propulsion Systems

Sometimes it's a little hard to tell the technologies without a scorecard. So here's a block diagram to keep things sorted out as you read the two remaining papers in this volume. In the first half of this volume, "Energy and Power," Henry Brandhorst described photovoltaic and solar dynamic power sources, Dave Buden discussed two types of nuclear power generation (radioisotope generators and nuclear reactor power plants like the SP-100), and Ed Conway presented three ways in which the Sun's energy can be used to generate a laser beam, which can then transmit its power to a distant use site. In the second half of this volume, "Transport," particularly in these last two papers, we look at ways in which these three main sources of power (solar, nuclear, and laser) can be used to drive propulsion devices.

In the paper immediately following, Phil Garrison describes developments in solar electric propulsion (SEP) and nuclear electric propulsion (NEP). He discusses three types of electric propulsion devices: ion thrusters, magnetoplasmadynamic (MPD) thrusters, and arc jets. Ion thrusters can get their power from either solar or nuclear sources; MPD thrusters and arc jets use only nuclear power.

In the last paper, Jim Shoji presents two types of propulsion systems in which beamed energy is used to heat a propellant, which then provides thrust. These are solar thermal propulsion and laser thermal propulsion systems. Notice that in these cases there is no power conversion; concentrated heat from the radiation source is used directly. [A solar thermal propulsion device may be seen as analogous to a solar dynamic power

(continued)

Figure 27 (concluded)

system (though in solar dynamic systems mechanical energy is finally converted to electrical power) or to the direct use of solar energy in the form of heat.] Shoji does not discuss nuclear thermal propulsion, though he is certainly aware of developments in this advanced propulsion technology. Nuclear thermal propulsion can be seen as analogous to nuclear electric propulsion, with the power conversion step omitted.

Tucked into the paper by Shoji is a short discussion by Ed Conway of laser electric propulsion (LEP). It is a form of beamed energy propulsion in which a laser beam transmits power to a photovoltaic collector on a space vehicle, where it is converted to electricity to drive the vehicle's ion engine. Thus, LEP might be seen as a variant of SEP.