Gossamer Spacecraft Survey Study

Preliminary Report - Historical Survey

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under

Purchase Order No. 1207157

with

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4800 Oak Grove Drive
Pasadena, CA 91109-8099

Under JPL Prime Contract NAS7-1407

JPL Contract Monitor
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Report Dated

18 July 1999

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Introduction

This is the first report on the Gossamer Spacecraft Survey Study. It is a historical survey of gossamer spacecraft concepts that have been discussed in the past. In general we will limit the listed concepts to those which have been fully developed to the point where the concept has been published in technical papers or journal articles, so that the reader can refer to those documents for further information. Occasionally, however, we will mention a unique or seminal concept that has had little technical evaluation, but seems worthy of future consideration. It is planned to turn the historical material in this report into a technical paper by Robert L. Forward, Benjamin L. Diedrich, and Artur B. Chmielewski, "The History of Gossamer Spacecraft", which will be presented at the IEEE Aerospace Conference to be held in Big Sky, Montana from 18-25 March 2000.

The phrase "gossamer spacecraft" has a broad and indeterminate definition. We will interpret the phrase broadly and include many concepts in this historical survey that are merely "long" or "large" for their mass, rather than "light" in the usual sense of "gossamer". The general structural categories that we will use are: Sails, Strings, Structures, Inflatables, Lenses, Meshes, and Fields. Some concepts fit into more than one category, but will only be listed in one category with a reference in the other categories. Within each category, there will be an attempt to list the concepts in chronological order, but because of the uncertain history of some of the concepts, it will not be possible to make this ordering perfect.

Each concept will be listed with one or two references that we feel gives a good summary of the concept. This reference will often not be the first paper on the concept, but the reference given will have in its reference section the prior art publications. There is one special reference, the "1980 JPL Gossamer Spacecraft Report", which is JPL Publication 80-26, Discussion Meeting on Gossamer Spacecraft (Ultralightweight Spacecraft): Final Report, edited by Roy G. Brereton, 15 May 1980. This report was a summary of a two-day meeting held at JPL on 19-20 December 1979, shortly after the abortive JPL effort to develop a solar sail capable of making a rendezvous with Comet Halley. Many of the historical concepts in this survey will be taken from this reference. In the 1980 JPL Gossamer Spacecraft Report, a gossamer structure is defined as "a generic class of spacecraft of space structures characterized by a low mass per unit area (~50 g/m^2)". The technology and "lightness" of gossamer spacecraft has progressed much since that time.

Major contributions to this report, especially in the Sails section, were made by Benjamin L. Diedrich, Aerospace Consultant, under a subcontract with Forward Unlimited.

Robert L. Forward
Forward Unlimited

Sails

A major category of gossamer spacecraft is solar sails. Rather than give just a few examples of a few generic types, we have expanded the list to include a number of variations, provided there was sufficient technical detail in the published description to allow a comparative evaluation of that particular concept with respect to the other concepts.

Angled Reflector Solar Sail for LEO
Ref: Paul D. Fiesler, "A Method for Solar Sailing in Low Earth Orbit", Acta Astronautica, Vol. 43, No. 9-10, pp. 531-541, (1998).
Description: 50,000 m^2 square three-axis stabilized solar sail with a sail surface composed of ramps or hexagonal spin stabilized sail with slats like a venetian blind so the thrust vector can be controlled without presenting a large frontal area for atmospheric drag. An angled shield placed between the incident flow of the atmosphere and the sail may reduce drag further by concealing the details of the sail from the flow. Both configurations use 2.5 micron Kapton sail film and 100 nm aluminum on both sides. The square ramp sail has a mass of 566 kg, characteristic acceleration of 0.18 mm/s^2, and travels from a 350 km circular orbit of 90 degree inclination to 1000 km in 27 days. The hexagonal slat sail has a mass of 364 kg, characteristic acceleration of 0.24 mm/s^2, and travels to the same location in 20 days.

Laser-Pushed Interstellar Lightsail
Ref: Geoffrey A. Landis, "Small Laser-Pushed Lightsail Interstellar Probe: A Study of Parameter Variations", Journal of the British Interplanetary Society, Vol. 50, pp. 149-154, (1997).
Ref: Robert L. Forward, "Roundtrip Interstellar Travel Using Laser-Pushed Lightsails", Journal of Spacecraft and Rockets, Vol. 21, No. 2, pp. 187-195, (1984).
Description: 764 m diameter circular spinning light sail accelerated by a laser with 22 GW output power with a 220 km diameter aperture and 500 nm wavelength. The sail is composed of a 16 nm thick beryllium sail with an 8 kg payload and a 30 kg total mass. The sail accelerates at 0.42 gravities to a velocity of 0.11 c in 0.27 years.

Mercury Orbiter Square Solar Sail
Ref: Manfred Leipold et. al., "Mercury Sun-Synchronous Polar Orbiter with a Solar Sail", Acta Astronautica, Vol. 39, No. 1-4, pp. 143-151, (1996).
Description: 86 x 86 m square three-axis stabilized sail with 4 carbon fiber reinforced plastic booms each made from 2 shells joined at the edges. Sail is composed of 4 triangles of 1.5-2 micron Kapton or Isaryl coated by vacuum deposition with 0.1 micron aluminum on the front for the reflector and 0.5 micron chromium on the back to radiate heat. Control in pitch and yaw is done with a gimballed boom with the bus at the end to displace the center of mass. Total mass is 242 kg including a 20 kg science payload. The characteristic acceleration of 0.25 mm/s^2 provides a flight time to Mercury of 1280 days and precesses a polar orbit around Mercury that keeps the spacecraft orbiting over the day-night terminator. A 150 m wide sail reduces flight time to 1.8 years.

GEOSTORMS Inflatable Boom Square Sail
Ref: Colin McInnes, Solar Sailing: Technology, Dynamics, and Mission Applications, Springer-Verlag, London, pp. 231-238, (1999).
Description: 67 x 67 m square solar sail supported by 4 10 cm diameter inflatable booms attached in the center to the spacecraft bus. Sail is 7.6 micron Kapton aluminized on 1 side.

Attitude control provided by hydrazine thrusters on bus. Sail loading is 29.6 g/m^2, sail and booms mass 70 kg, and total mass is 130 kg. Solar sail displaces L1 orbit 0.01 AU closer to sun.

World Space Foundation (WSF) Square Solar Sail
Ref: Colin McInnes, Solar Sailing: Technology, Dynamics, and Mission Applications, Springer-Verlag, London, pp. 99-102, (1999).
Ref: Robert L. Staehle et. al., "Solar sail expedition to the moon and Mars: Mission update", Spaceflight, Vol. 34, pp. 256- 258, August 1992.
Description: 55 x 55 m square sail supported by 4 booms made of prestressed STEM tubalar spars. Control provided by 4 triangular vanes a the end of each boom of 15 m^2 area each. Sail is a square of 2.5 micron Kapton aluminized on both sides. Total mass of 139 kg includes 10 kg sail film, 49 kg structure, and 80 kg bus.

Union pour la Promotion de la Propulsion Photonique (U3P) Square Solar Sail
Ref: Colin McInnes, Solar Sailing: Technology, Dynamics, and Mission Applications, Springer-Verlag, London, pp. 102-103, (1999).
Description: 63 x 63 m square solar sail supported by 4 booms made of composite epoxy coilable spars. Control provided by 8 triangular flaps, 2 attached to each edge of the sail, with a total area of 240 m^2. Sail is 7.6 micron Kapton aluminized on both sides. Total mass of 227 kg includes 55 kg sail film, 91 kg structure, and 81 kg bus.

Johns Hopkins University (JHU) Ring and Mast Supported Solar Sail
Ref: Colin McInnes, Solar Sailing: Technology, Dynamics, and Mission Applications, Springer-Verlag, London, pp. 103-104, (1999).
Description: 170 m diameter disc sail supported by an outer ring with 480 straight segments joined by stays to a 50 m long mast at the center. The sail is composed of 480 triangular petals of 7.6 micron aluminized Kapton etched down to 1.14 microns, except for unetched patterns to carry loads. Pitch and yaw are provided by tilting the mast, which has the payload attached to one end. Roll control provided by rotation outer edge of some petals by mechanisms in the ring. Total mass of 180 kg includes 23 kg sail film, 77 kg structure, and 80 kg bus.

Massachusetts Institute of Technology (MIT) Heliogyro
Ref: Colin McInnes, Solar Sailing: Technology, Dynamics, and Mission Applications, Springer-Verlag, London, pp. 104-105, (1999).
Description: Heliogyro with eight 83 x 1.5 m blades. Spin stabilized with 0.1 rpm. Control provided by strip of piezoelectric polyvinyldiflouride that joins each blade to the hub. Sail film is aluminized Kapton or Lexan. Deployed by spinning spacecraft to 40 rpm and releasing sail blades.

Cambridge Consultants Ltd (CCL) Wrapped Rib Disk Solar Sail
Ref: Colin McInnes, Solar Sailing: Technology, Dynamics, and Mission Applications, Springer-Verlag, London, pp. 104-105, (1999).
Description: 276 m diameter disc supported by 36 carbon fiber reinforced plastic profile booms. Control provided by applying bending moments to the base of each boom to warp the overall sail shape. Sail is aluminized 2 micron Kapton film. Booms and sail start wrapped around the central 4 m tall by 4 m diameter hub. Booms and sail deploy by releasing them. Deployment rate is controlled with viscoelastic damping with polymer threads.

ODISSEE Demonstration Square Solar Sail

Ref: Colin McInnes, Solar Sailing: Technology, Dynamics, and Mission Applications, Springer-Verlag, London, pp. 107-109, (1999).
Description: 40 x 40 m square solar sail supported by 4 STEM-type booms made from two laminated sheets of carbon fiber reinforced plastic. The spacecraft bus is placed on the end of a 10 m coilable boom at the center. Control in pitch and yaw are provided by displacing the center of mass using a 2 axis gimbal at the base of the 10 m boom. The sail is 4 triangular sheets of 7.6 micron Kapton with a 0.1 micron aluminum reflector on the front and a 0.015 micron chromium emitter on the back. Total mass of 77 kg includes 25 kg sail film, 16 kg structure, and 36 kg bus. Spacecraft is designed to deploy from small payload adapter of Ariane V to GTO.

High Performance Lattice Solar Sail
Ref: K. E. Drexler, "High performance solar sails and related reflecting devices", AIAA Paper 79-1418, 4th AIAA Conference on Space Manufacturing Facilities, Princeton University, Princeton, N.J., May 14-17, (1979).
Ref: Jerome Wright, Space Sailing, Gordon & Breach Science Publishers, Amsterdam, pp. 78-81, (1992).
Description: 1000 m diameter hexagonal sail stabilized in plane by spin and out of plane by sunlight. Sail consists of a hexagonal mesh of triangles. The payload is attached to the sail at many points across the surface by a mesh of tension lines on the illuminated side of the sail. Total area is 707,000 m^2. Mass of tension lines and tendons in the sail is 21 kg. Mass of 20 nm thick pure aluminum sail is 28 kg. A construction frame in orbit larger than the sail is required.

Halley Rendezvous Disc Sail
Ref: Jerome Wright, Space Sailing, Gordon & Breach Science Publishers, Amsterdam, pp. 73-77, (1992).
Description: 860 m diameter spin stabilized disk sail. Central section is open with 10% the diameter of the sail. Interior opening is edged by a structural ring that attaches to a short central mast by tension lines to transfer precessing torques between the sail and central structure. The sail is split into 20 segments of 1 or 2 micron thick Kapton substrate with reflective and emissive coatings. Total area is 576,600 m^2. The 2 micron thick sail has a total mass of 2413 kg, and the 1 micron sail has a total mass of 1594 kg, both excluding the operations module and payload.

Halley Rendezvous Heliogyro
Ref: Jerome Wright, Space Sailing, Gordon & Breach Science Publishers, Amsterdam, pp. 82-88, (1992).
Ref: R. L. Chase, "Solar Sail-Solar Electric Technology Readiness Assessment", AIAA Paper 78-640, (May 1978).
Description: 12 bladed heliogyro with 2 banks of 6 blades each. Blades have dimensions of 8 x 7340 m. Sail film is 2 microns thick with reflective and emissive coatings. Each bank is fixed to a hub so they co-rotate. Centrifugal loads are carried by edge members in the blades. Transverse battens restrain motion of the edge members. Small sail panels prevent wrinkling from curvature in edge members between battens. Control is provided by cyclically twisting individual blades to precess the vehicle. Total mass excluding bus and payload is 3995 kg and total area is 611,000 m^2.

Square Rigged Clipper Sail
Ref: Jerome Wright, Space Sailing, Gordon & Breach Science Publishers, Amsterdam, pp. 63-68, (1992).
Ref: J. Wright and J. Warmke, "Solar sail mission applications", AIAA Paper 76-808, AIAA/AAS Astrodynamics Conference, San Diego, California, August 18-20, (1976). Ref:

Description: 820 x 820 m square sail stabilized by a combination of compression bearing booms and masts and tension bearing stays. One configuration uses a single square sail section with a hole in the center with a total area of 641,200 m^2. The booms are curved and most of the stays are on the concave side to prevent the rigging from touching the sail. A second configuration has 4 triangular sail sections, straight booms, evenly distributed stays, and a total area of 580,000 m^2. The baseline sail has a 2 micron thick sail with reflective and emissive coatings and a total mass of 3382 kg excluding operations module and payload. Control can be accomplished with steering vanes at the tips of the booms or displacement of the corners of the sail sections for the 4-piece sail.

Thin-Film Photovoltaic Light Sail

Ref: Seth D. Potter and Gregory L. Matloff, "Light Sail Propulsion Using Thin-Film Photovoltaic Technology", Journal of the British Interplanetary Society, Vol. 49, pp. 345-350, (1996).

Description: 2 km diameter spin stabilized disc with thin-film photovoltaic sail, mast, and tension lines connecting mast to the sail edge. Laser illumination provides power to solid state microwave transmitters integrated with solar cells to allow communications and thrust very far from the sun. The sail is 7 micron thick Kapton substrate with a 1.9 micron thick amorphous silicon solar cell layer. A 5% filled 7.5 micron metal layer provides connections to the cells. Two masts project out both sides of the sail from the center and are made from glass ceramic. Silicon carbide cables connect the top of each mast to the edge of the sail. Total mass is 60,000 kg and total area is 3.14 km^2.

Arsat Satellite with Square Solar Sail

Ref: Christian Marchal, "Solar sails and the Arsat satellite - Scientific applications and techniques", L'Aeronautique et l'Astronautique, No. 127, pp. 53-57, 1987.

Description: 42 x 42 m square sail stabilized by 4 inflatable booms attached to a satellite. Total spacecraft mass is 150 kg. Area loading is 84 gm/m^2.

Ortoss Inflatable Ring Sail

Ref: Dieter Hayn, "Ortoss - The Orbital Torus Solar Sail vehicle", Luft- und Raumfahrt, Vol. 11, 3rd quarter, pp. 34-36, 1990.

Description: 50 m diameter sail with an inflatable outer ring and 4 symmetrically mounted triangular steering vanes. Inflatable sections harden by exposure to UV radiation. Components, including inflatable structures, decentralized spacecraft bus, and telescoping mast for steering vanes is readily available. Total mass is 440 kg, and area is 1800 m^2.

Disc Solar Sail Star Occulter

Ref: E. Trunkovsky and E. Moskalenko, "Observations of the occultations of stars by solar sails", Astronomical and Astrophysical Transactions, Vol. 6, No. 3, pp. 181-185, March 1995.

Description: 100 m diameter flat disk sail. With an altitude of 40,000 km, 1.5 m telescope will observe occultations every 1100 hours with sensitivity of 7.3 m. Altitude of 100,000 km allows Hubble Space Telescope occultations every 2 months with sensitivity of 8.1 m.

Serially Connected Multiple Unit Solar Sail

Ref: A. V. Lukyanov, "Space sail liner", Acta Astronautica, Vol. 9, No. 6-7, pp. 359-364, 1982.

Description: Multiple solar sail units connected in line by a tether for hauling multi-ton payloads. Square 200 x 200 m units with 4 booms and a long mast on sunward side combine to haul 10-

100 ton loads. Control is provided by reeling in and out the tension lines connecting the boom tips the mast tip to rotate booms and sail about a biaxial joint at the mast base. Booms and masts are 1 m wide triangular trusses with 1 cm diameter elements composed of 20 micron thick graphite polyamide strap with linear density of 5 g/m. Sail film areal density is 2 g/m^2. Tether connects to tip and base of mast and goes through a hole in the center of the sail. Units composed of two tandem 500 m diameter high performance spinning sails with 200 m long control blades are used are used for higher performance.

Hollow Body Solar Sail
Ref: Jorg Strobl, "The hollow body solar sail", Journal of the British Interplanetary Society, Vol. 42, pp. 515-520, (1989).
Ref: Jorg Strobl, "The hollow body solar sail as a possible transporter of a radio telescope", Journal of the British Interplanetary Society, Vol. 47, No. 2, pp. 67-70, (1994).
Description: 1786 m diameter non-rotating hydrogen inflated hollow circular sail designed for 434 km/s solar escape via 1.7 solar radii approach to sun. 1000 kg payload pushed by sail at center of dark side. Control provided by radiation pressure flaps or thrusters mounted at the outer edge. Front reflector is a smooth plane with low stresses from balance of internal pressure, solar pressure, and a perimeter ring. Reflector is 53 nm molybdenum. Backside is black for thermal radiation and is made from tungsten with a minimum thickness of 29 nm. Total mass is 6342 kg. Larger sails and payloads discussed.

Solar Sail Supported by Microspacecraft at Each Corner
Ref: Rudolf X. Meyer et. al., "Space hardware designs, Volume 1, Final report", NASA-CR-197209, N95-12663, NASw-4435, 1993-94 Advance Design Program University Space Research Association, Mechanical, Aerospace and Nuclear Engineering Department, University of California, Los Angeles, California.
Description: Triangular 17,000 or 4,000 m^2 sail deployed and spin stabilized by three 20 kg microspacecraft. Total mass including sail is 150 kg. Control provided by hydrazine thrusters in each microspacecraft. Undeployed vehicle fits within 84 cm diameter cylinder.

Large Square Rigged Clipper Sail

Ref: J. M. Garvey, "Space station options for constructing advanced solar sails capable of multiple mars missions", AIAA Paper 87-1902, AIAA/SAE/ASME 23rd Joint Propulsion Conference, San Diego, California, June 29-July 2, (1987).
Ref: Robert L. Staehle, "An expedition to mars employing shuttle- era systems, solar sail and aerocapture", Journal of the British Interplanetary Society, Vol. 35, pp. 327-335, (1982).
Description: 2 x 2 km square sail supported by 4 booms, 2 masts, and stays for carrying 32 ton payloads to Mars. A deployable sail with 2.5 micron sail film has an unloaded mass of 19,200 kg and 4.8 g/m^2 unloaded sail loading. A sail constructed in orbit on a construction platform has a pure aluminum sail film 15-100 nm thick and unloaded sail loading of 1 g/m^2. Control provided by 4 steering vanes at the ends of the booms of 20,000 m area each.

Three Layer High Performance Solar Sail for LEO Operation

Ref: G. L. Matloff, "Hyperthin and perforated solar sails in low earth orbit (LEO): A step to the moon, Mars, and beyond", AIAA Paper 89-2442, AIAA/ASME/SAE/ASEE 25th Joint Propulsion Conference, Monterey, California, July 10-12, (1989).
Description: 12 km diameter gravity gradient stabilized solar sail in LEO propelled by reflected Earth light and infrared radiation, and propelled by sunlight farther from Earth. The payload is suspended from cables facing toward the Earth. The sail film has three layers. The first layer,

facing the Earth, is a wire mesh spaced to reflect infrared radiation. The next layer is a 30 nm thick aluminum film to for reflecting sunlight reflected from the Earth while in LEO and for directly reflecting sunlight while in higher orbits. The third layer is a 30 nm thick boron film for reducing the effect of direct sunlight while in LEO. The sail mass is 17,000 kg and the cable and payload mass is 140,000 kg, resulting in a total areal density of approximately 1.5 g/m^2.

Spin Deployed Square Solar Sail

Ref: Richard Eastridge et. al., "Design of a solar sail mission to Mars - Final Report", CASI Accession Number: 90N11771, Report Number: NASA-CR-186045, May 5, (1989).

Description: 160 x 160 m square sail supported by 4 114 m booms connected tangentially to a 1.4 m diameter by 1 m tall cylindrical bus with 1 cm thick walls. Sail consists of 4 triangular sections with a total area of 25,992 m^2. The booms are made from uncured graphite epoxy that cures after deployment. Before deployment, the sail is folded accordian-style into a wedge between the booms. The booms and sail are wrapped 26 times around the bus. The bus starts rotating at 100 rpm, the sails and booms are released, and the spacecraft slows to 0.8 rpm when the booms and sail are fully deployed. The booms cure, and the ACS stops the rotation. Total mass is 487 kg at launch and 412 kg after deployment, including 51 kg payload, 165 kg sail, 63 kg booms, and 133 kg bus.

Wrapped Rib Square Solar Sail

Ref: T. Williams & P. Collins, "Design considerations for an ameteur solar sail spacecraft", IAF Paper 83-395, 34th Congress of the International Astronautical Federation, Budapest, Hungary, October 10-15, (1983).

Description: 50 x 50 m square sail with 4 booms each attached tangentially to a 1 m high by 1.6 m diameter cylindrical bus. Booms and sail are initially wrapped around the bus. Deployment is achieved by strain energy stored in the glass fiber epoxy booms. Deployment speed controlled by passively braked spools of cord joining the tips of the booms together. Pitch and yaw control achieved by displacing 5 kg mass by up to 1.58 m. Total spacecraft mass is 197 kg, including 60 kg booms, 25 kg sail, 2 kg deployment spools, 100 kg bus, and 10 kg sail cover that is ejected in deployment.

Electrodynamic Tethers for Solar Sail Operation from LEO

Ref: Richard Moss and Manuel Martinez-Sanchez, "Extending the operational altitude of solar sails down to Space Station altitudes with an electrodynamic tether", CASI Accession Number: 92A17770, Space manufacturing 8 - Energy and materials, from space; Proceedings of the 10th, Princeton/AIAA/SSI Conference, Princeton, NJ, May, 15-18, 1991 (A92-17751 05-12). Washington, DC, American Institute of Aeronautics and Astronautics, 1991, p. 159-174.

Description: Electrodynamic tether, either deployable or fixed, is integrated with a square or heliogyro solar sail for operation from LEO to altitudes where the sail can operate. Three different configurations are given.

Solar Photon Thrustor

Ref: Robert L. Forward, "Solar Photon Thrustor", J. Spacecraft 27, 411-416 (July-August 1990).

Statite

Ref: Robert L. Forward, "Statite: A Spacecraft That Does Not Orbit", J. Spacecraft and Rockets, 28, #5, 606-611 (Sept-Oct 1991).

Dielectric Lightsails

Ref: Robert L. Forward, "Laser Weapon Target Practice with Gee-Whiz Targets", pp. 41-44 in Proceedings SDIO/DARPA Workshop on Laser Propulsion, Livermore, California (7-18 July 1986), Vol. 2, J.T. Kare, Editor (Publication CONF-860778, Lawrence Livermore National Lab, Livermore, CA, April 1987).
Ref: Geoffrey Landis

Radioisotope Sails
Ref: Robert L. Forward, "Radioisotope Sails for Deep Space Propulsion and Electrical Power", J. British Interplanetary Society 49, 147-149 (April 1996).
Ref: G. L. Grodzovskii, Y. N. Ivanov, and V. V. Tokarev, Mechanics of Low Thrust Space Flight, Israel Program for Scientific Translation Press, Jerusalem, Israel, pp. 323-325, (1969).

Strings

Geostationary Tower/Skyhook
John Isaacs et al, "Satellite Elongation into a True Sky-Hook," Science, Vol. 151, February 11, 1966, pp. 682-683; also Vol. 152, p 800 and Vol. 158, p. 947.

Vladimir Lvov "Sky-Hook: Old Idea," Science, Vol. 158, November 17, 1967, pp. 946-947.
Ref: Geoffrey A. Landis and Craig Cafarelli, "The Tsiolkovskii Tower Reexamined", IAF-95-V.4.07, 46th International Astronautical Congress, Oslo, Norway, (October 2-6th, 1995).
Ref: Jerome Pearson, "The Orbital Tower: a Spacecraft Launcher Using the Earth's Rotational Energy", Acta Astronautica, vol. 2, no. 9-10, pp. 785-799, (September-October 1975).

Orbiting Vertical Elevator
Ref: Robert Zubrin, "The Hypersonic Skyhook," Analog Science Fiction/Science Fact, Vol. 113, No. 11, September 1993, pp. 60-70.
Ref: Eagle Sarmont, "How an Earth Orbiting Tether Makes Possible an Affordable Earth-Moon Space Transportation System," SAE Technical Paper 942120, Aerotech '94, Los Angeles, CA, October 3-6 1994.
Ref: Robert Zubrin, "The Hypersonic Skyhook," Journal of the British Interplanetary Society, Vol. 48, No. 3, March 1995, pp. 123-128.
Description: The orbital vertical elevator is a short variant of skyhook. A sounding rocket carries cargo to the bottom end of an elevator orbiting the Earth at 6 km/s. The cargo gains only 1 km/s when it travels up the elevator.
The elevator is extremely massive, unless it is made of a material having great specific strength, The Coriolis force of moving cargo compromises the stability of the elevator.

Orbiting Rotating Tether
Ref: Joseph Carroll,
Ref: Robert L. Forward, "Tether Transport From LEO to the Lunar Surface", Paper AIAA-91-1921, 27th AIAA/SAE/ASME Joint Propulsion Conference, Sacramento, California (24-26 June 1991).

Cartwheeling Rotovator

Free Space Bolo

Cable Catapult
Ref: Robert L. Forward, "The Cable Catapult", Paper AIAA-90-2108, AIAA/ASME/SAE/ASEE 26th Joint Propulsion Conference, Orlando, Florida (16-18 July 1990).
Ref: Robert L. Forward, Buford Ray Conley, Clay Stanek, and William Ramsey, "The Cable Catapult: Putting It There and Keeping It There", Paper AIAA-92-3077, 28th AIAA/SAE/ASME/ASEE Joint Propulsion Conference, Nashville, Tennessee (6-8 July 1992).

Failsafe Tether Designs
Ref: Robert P. Hoyt and Robert L. Forward, "Failsafe Multiline Hoytether Lifetimes", Paper AIAA 95-2890, 31st AIAA/ASME/SAE/ASEE Joint Propulsion Conference, San Diego, CA (10-12 July 1995).

Tethers for Solar Sail Construction and Deployment from the Space Station

Ref: J. M. Garvey, "Space station options for constructing advanced solar sails capable of multiple Mars missions", AIAA Paper 87-1902, AIAA, ASME, SAE 23rd Joint Propulsion Conference, San Diego, CA, June 29-July 2, 1987.

Ref: J. M. Garvey and R. W. Adkisson, "The use of tethers to construct and deploy solar sails from the Space Station", Space tethers for science in the space station era, Proceedings of the 2nd International Conference, Venice, Italy, Oct. 4-8, 1987, pp. 545-550.

Description: 50-100 km tethers connect space station to sail construction platform. 1 km tether on construction platform connects to sail to reduce structural deformation. During deployment, primary (50-100 km) tether boosts sail into acceptable transfer orbit. Used to construct 2 x 2 km high performance square sails.

Orbital Loop

Ref: Andrew Nowicki, Earth to Orbit Transportation Biography, http://www.isd.net/anowicki/

Ref: Andrew Nowicki, "Diversity", The Trumpeter, Vol. 10, No. 2, pp. 65-68, (Spring 1993).

Description: A loop in a low eccentric Earth orbit consisting of a 200 km tubular section and winches placed periodically along the rest of the loop. Payloads in a spherical shroud and on a sub-orbital trajectory enter the tubular section when it is at perigee. Friction inside the tube accelerates the payload to orbital velocity. Stability of the loop and energy replenishment is accomplished by reeling in and out sections of the loop using the winches.

Orbital Ring

Ref: Paul Birch, "Orbital Ring Systems and Jacob's Ladders - I", Journal of the British Interplanetary Society, Vol. 35, pp. 475-497, (1982).

Ref: Paul Birch, "Orbital Ring Systems and Jacob's Ladders - II", Journal of the British Interplanetary Society, Vol. 36, pp. 115-128, (1983).

Ref: Paul Birch, "Orbital Ring Systems and Jacob's Ladders - III", Journal of the British Interplanetary Society, Vol. 36, pp. 231-238, (1982).

Description: Loop located in low circular equatorial orbit moving slightly in excess of orbital velocity. Excess velocity supports stationary tethers connected to the Earth. Stationary tethers connect to the ring by magnetic levitation. Low orbit is used to obviate the necessity for very high strength materials. Various additional features described.

Rotating Orbital Eddy Current Launch Track

Ref: C.S. Welch and C. Jack, "A Kinetic Tether System for Launching Payloads", IAF Paper IAF-95-V.4.06, 46th International Astronautical Congress, Oslo, Norway (2-6 October 1995).

Description: A long orbiting tether with a conductive track is kept extended by centrifugal force from rotation about its center-of-mass. A payload launched into a suborbital trajectory meets with the track and couples to the conductive track by eddy currents generated by magnets on the payload. The payload is accelerated further into space by the orbital and rotational motion of the track.

Structures

GEO Tower
Ref: Geoffrey A. Landis and Craig Cafarelli, "The Tsiolkovskii Tower Reexamined", IAF-95-V.4.07, 46th International Astronautical Congress, Oslo, Norway, (2-6 October 1995).

Dynamic Tower

Stabilized Tower

Inflatables

ECHO Balloon

Solar Concentrator

Solar Thermal Rocket

Inflatable Dish

Mars Balloon Lander

Transhab

Hollow Body Solar Sail
See under Sails

Bubbles
Ref: R. Gilbert Moore, Thiokol Corp., GSR.

Lenses

Lenses are defined for this section as a gossamer structure that has the ability to focus electromagnetic radiation, typically optical, infrared or micowave radiation. A great deal of effort and money has been spent by NASA, DoD, and commercial communication and broadcast companies on unfurable or unfoldable microwave dishes for beaming microwave signals to and from spacecraft. Although some of the larger versions of these "conventional" microwave dishes, especially some of the newer dishes made with fine gold-plated mesh membranes, might fit into the category of "gossamer structures", we have not included them here. We have also not included any new designs for "lightweight" versions of conventional gamma-ray, X-ray, optical, or infrared telescopes, since even the lightest are far from "gossamer". Interferometric "telescopes" with widely spaced collecting elements have large "apertures" compared to their total mass, but since the aperture is not filled, interferometers don't really qualify as a "gossamer structure" unless their individual elements are "gossamer structures". In this section, we will limit our entries to unconventional "filled aperture" lens and dish designs.

Aerosol Lens
Ref: A. J. Palmer, "Aerosol Lens", J. Optical Society of America, Vol. 73, p. 1568 ff, (1983).
Description: A cloud of glass beads or aerosol droplets with a highly nonlinear optical index of refraction is distributed in free fall, and "organized" by a structured "lens-forming" laser beam that interacts with the nonlinear optical index of the beads to put forces on the beads that "trap" the beads into fresnel-zone-like three-dimensional holographic-grating lens structures. A second laser beam is then deflected by the holographic-grating lens structures into the desired outgoing beam. In some designs, the lens-forming beam is also the outgoing beam. In other designs, the outgoing beam has been doubled or tripled in frequency by the strong nonlinear interaction of the laser light with the beads.

Laser Relay Lens System
Ref: Robert L. Forward, Advanced Propulsion Concepts Study-Comparative Study of Solar Electric Propulsion and Laser Electric Propulsion (June 1975). Final Report on JPL Contract 954085, Subcontract under NASA Contract NAS7-100, Task Order RD-156.
Description: A given diameter lens can project a beam only so far before it starts to spread. If another lens is inserted into the beam before the spreading starts, then the second lens can capture essentially all of the energy in the beam and refocus it to form a completely new beam. For some beam power applications, a relay system of small lenses may outperform a single lens.

Optical Paralens
Ref: Robert L. Forward, "Roundtrip Interstellar Travel Using Laser-Pushed Lightsails," J. Spacecraft 21, 187-195 (March-April 1984) [See pages 191-192.]
Description: A 1000-km diameter (Texas-sized) Fresnel-phase-zone plate made of a rotating spider-web-like tension structure supporting alternate rings of nothing and a plastic film 1 µm thick with an index of refraction of 1.5. This is designed to focus laser light at 1 µm. It will make a spot size equal to its diameter (1000 km spot size) at 44 lightyears distance, and focus the laser light to a 100-km diameter spot at 4.4 lightyears (the distance to Alpha Centauri). Assuming a specific density of 1.4 for the plastic film, the 1000-km lens would mass 560,000 metric tons, or 0.44 g/m^2 , which makes it a gossamer structure despite its large total mass. For an operational wavelength of 1 µm, there will be 111,410 zones in the lens. The radius of the first zone is 1.5 km, while the width of the outermost ring is 2.25 m, so the fabrication of this structure does not need high tolerances on the film. The reference goes into detail on the tolerances required.

Microwave Paralens

Ref: Robert L. Forward, "Starwisp: An Ultra-Light Interstellar Probe," J. Spacecraft 22, # 3, 345-350 (1985). [See page 348, lower right.]

Description: A microwave version of the Optical Paralens to operate in the X-band region of the microwave spectrum. For the mission analyzed, the diameter of the lens is required to be 50,000 km (four times the diameter of Earth). The rings of wire mesh are so fine, total mass of the lens is only 50,000 tons, which at 0.000016 g/m^2, makes this the most gossamer 2-D structure proposed to date. There is a serious concern about the physical feasibility of the concept expressed by the author in the last sentence on page 347. The microwave resistivity of the fine wires in the mesh could range from zero (superconducting) to extremely high (quantum-caused current blockage). Only experiments on free-standing mesh structures will give believable numbers.

Starwisp [See Mesh Section]

The Microwave Paralens above focuses a microwave beam on a mesh sail to push the sail to the Alpha Centauri system. The Starwisp sail is also a lens.

Benchless Telescope

Ref: Robert A. Preston, CalTech, GSR, pp. 149-150 (Fig. 76).

Ref: Ivan Bekey,

Description: A normal dish or telescope has a physical connection (bench) between the primary collecting aperture and the "eyepiece" or "horn" or "intermediate lens". In order to maintain tolerances to a fraction of a wavelength, the "bench" is typically quite heavy. The idea behind the benchless telescope is to float the primary collecting aperture, any intermediate lenses, and the collecting lens, in the free-fall of space, and use sensors to sense, and feedback mechanisms to correct, any misalignment or warping of the structure to within fractions of a wavelength.

Meshes

Golden Globe
Ref: Robert L. Forward, "A Programme for Interstellar Exploration," J. British Interplanetary Society 29, 611-632 (1976).

Starwisp
Ref: Robert L. Forward, "Starwisp: An Ultra-Light Interstellar Probe," J. Spacecraft 22, # 3, 345-350 (1985).
Description: 1-km diameter ultrafine wire mesh microwave-beam-pushed sail with distributed microcircuitry for a payload. A 10 GW microwave beam from a solar power satellite that is focused by a 50,000-km diameter microwave mesh fresnel zone plate lens [See Microwave Paralens in the Lens section]. The microwave beam accelerates the mesh at 115 g's to 0.2 c in a few days. The mesh has a mass of 16 grams, with 4 grams of microcircuitry. After arriving at Alpha Centauri 22 years later, the circuits reconfigure the mesh wires into half-wavelength microwave antennas which collect and rectify microwave power beamed from the Solar System to provide 10 W of electricity to power the microwave circuits, which have optical sensors which interferometically collect images and retro-transmit the images back to Earth as a 1W microwave beam, of which 5 pW is collected by the 50,000-km diameter microwave lens, enough for transmission of color television images during the 40 hour flythrough of the Alpha Centarui system.

Planetary Lander
Ref: Robert L. Forward, "Microwave Beam Riders for Planetary Exploration", Paper AIAA-90-1996, AIAA/ASME/SAE/ASEE 26th Joint Propulsion Conference, Orlando, Florida (16-18 July 1990).
Description:

Perforated Lightsails
Ref: Robert L. Forward, "Light-Levitated Geostationary Cylindrical Orbits Using Perforated Light Sails," J. Astronautical Sciences 32, 221-116 (April-June 1984).
Ref:

Fields

High Temperature Superconductor Magnetic Sail
Ref: Robert M. Zubrin, "The use of magnetic sails to escape from low earth orbit", Journal of the British Interplanetary Society, Vol. 46, pp. 3-10, (1993).
Description: 64 km diameter hoop of high temperature (77 Kelvin) superconductor connected to a central bus and payload via hroud lines. Hoop requires simple multi-layer insulation and reflective coatings to maintain temperature. A 200 kg 10 kW solar panel can fully power and deploy the sail in 2.2 hours. Total mass is 20,000 kg including 5000 kg hoop, 1000 kg structure and bus, and 14,000 kg payload. This payload can be delivered to Earth escape from LEO in about 2 months.

Solar Sail Shielded Magnetic Sail
Ref: Giovanni Vulpetti, "The two-sail propulsion concept", IAF Paper 91-721, IAF 42nd International Astronautical Congress, Montreal, Canada, Oct. 5-11, 1991.
Ref: Gregory L. Matloff, "Solar sailing for radio astronomy and SETI: An extrasolar mission to 550 AU", Journal of the British Interplanetary Society, Vol. 47, pp. 476-484, 1994.
Description: 100 km diameter superconducting loop with a 1 micron thick solar sail occulter. Superconductor is niobium and titanium or copper. Occulter allows cooling of superconductor to 6 degrees Kelvin. Loop is over-built to handle variations in the solar wind flux. Total mass including a small payload is 8000 kg.

Lorentz Force Divert Propulsion of Electrostatically Charged Vehicle
Ref: Robert L. Forward, "Zero Thrust Velocity Vector Control for Interstellar Probes: Lorentz Force Navigation and Circling," AIAA J. 2, 885-889 (1964) [See also AIAA Preprint 64-53, Aerospace Sciences Meeting, New York, NY (20-22 January 1964)].

Plasma Expanded Magnetic Field Sail