Gossamer Spacecraft Survey Study

Preliminary Report - Historical Survey

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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/m²)". 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
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
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
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
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/m², 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**
Description: 55 x 55 m square sail supported by 4 booms made of prestressed STEM tubalar spars. Control provided by 4 triangular vanes at the end of each boom of 15 m² 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**
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 m². 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**
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**
Description: Heliogyro with eight 83 x 1.5 m blades. Spin stabilized with 0.1 rpm. Control provided by strip of piezoelectric polyvinylidifluoride 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**
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**

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

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 m². 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

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 m². 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

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 m².

Square Rigged Clipper Sail
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 m². 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 m². 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

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 km².

Arsat Satellite with Square Solar Sail

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/m².

Ortoss Inflatable Ring Sail

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

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

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/m². 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
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
Description: Triangular 17,000 or 4,000 m² 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
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/m² 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/m². 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
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 reflect 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/m².

**Spin Deployed Square Solar Sail**
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 m². The booms are made from uncured graphite epoxy that cures after deployment. Before deployment, the sail is folded accordion-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**
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**
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**

**Statite**

**Dielectric Lightsails**
Ref: Geoffrey Landis

**Radioisotope Sails**
Strings

Geostationary Tower/Skyhook


Orbiting Vertical Elevator
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,

Cartwheelsing Rotovator

Free Space Bolo

Cable Catapult

Failsafe Tether Designs
Tethers for Solar Sail Construction and Deployment from the Space Station


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/

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


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


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

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 microwave radiation. A great deal of effort and money has been spent by NASA, DoD, and commercial communication and broadcast companies on unfurtable 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
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
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
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/m², 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**


**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/m², 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

Starwisp
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 interferometrically 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 Centauri system.

Planetary Lander
Description:

Perforated Lightsails
Ref:
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