Solar Sail Mission Requirements

Final Report

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Prepared for

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This report consists of a set of one−page sheets, each documenting one of a large number of solar sail missions and the requirements those missions place on the sail materials, design, structure, and operations needed to carry out the planned mission. Some sheets contain data for two or more similar sails, usually differing only in area. The matrix format and the units used in the matrix have been kept the same on all sheets so that comparisons can be made between the sail requirements posed by each mission. The matrix sheets have no formal order, but an attempt has been made to group similar missions near each other.

The major contributors to this report were Prof. Colin McInnes of the University of Glasgow, Benjamin Diedrich, now a graduate student at the University of Washington, and Dr. Robert L. Forward of Forward Unlimited.

An electronic version of this report can be obtained by contacting Dr. Robert L. Forward at <forward@whidbey.com> .

A paper copy of this report can be obtained by writing, emailing, calling, or faxing Dr. Forward at the contact points given on the cover.

Sail or Mission Name:	Human Exploration of Barnard Star System (lifelong mission)

Sail and Mission Description:

1000 km diameter laser−pushed lightsail with inner deceleration stage sail 300 km in diameter, for human exploration of Barnard Star system. Carries crew of 20 and their consumables at 300 tons, four landing rockets at 500 tons each, and 4 nuclear−powered VTOL exploration airplanes at 80 tons each, for a total payload of 3,500 tons. Sails at 0.10 g/m². mass 7000 tons and 78,500 tons. Total starting mass 82,000 tons. Driven by 1300 TW of laser power focused into a beam by a 100 km dia Fresnel lens. Accelerates at 0.01 gee. Travel time is 42 years. (can be shortened using more laser power). Upon arrival at Barnard, inner sail separates from outer ring sail and turns 180 degrees to face ring sail. 1500 TW of laser light from Solar System reflects off curved ring sail onto inner sail, decelerating it at 0.1 gee to come to a stop in Barnard Star system. Inner sail is then used as a solar sail to move from one planet to another in Barnard system. This is the first publication of a concept for human exploration of another star system using known technology.

References:

Robert L. Forward, Rocheworld (Baen Books, New York, 1990), pp 436−441. (Condensed version appeared in Analog Science Fiction/Science Fact in 1982.)

Sail Grand Unified Requirements

Sail Configuration		Two−stage sail, 300 km dia. sail inside 1000 km dia ring sail	
Sail Dimensions	m	300,000	1000,000
Sail Area	m^2	7.00×10^{10}	7.85×10^{11}
Sail Film Thickness	µm	Not Applicable (perforated aluminum film)	
Sail & Structure Mass	kg	7,000,000	78,500,000
Sail Areal Density	g/m^2	0.1	0.1
S/C+Payload Mass	kg	3,500,000	3,500,000
Total Mass	kg	10,500,000	82,000,000
Total Areal Density	g/m^2	0.15	0.104
Acceleration in laser beam	mm/s^2	1.0 (decel)	0.1 (accel)
Launch Mass	kg	Fabricated in space from space resources	
Storage Volume	m^3	Fabricated in space from space resources	
Launch Vehicle		300 km dia	100 km dia Fresnel Zone lens formed laser beam
Trip Time	years	42 (one way)	
Sail Temp Max/Min	°C	TBD (high)	
Other Environmental		2% loss of sail area due to dust impacts	
Spin Rate	deg/s	TBD (slow)	
Front Optical Reflect.			
Front Optical Absorb.			
Front IR Emissivity			
Back IR Emissivity			
Upper Stage Maneuvers			
Station Keeping Man'vrs			
Trajectory Maneuvers		Separate inner sail from outer ring sail and rotate 180 deg	
Science Maneuvers			
Laser Power	TW	1500 (green)	1300 (IR) (Could be increased for shorter trip)

Preparer and Date:	Robert L. Forward 31 July 1999

Sail or Mission Name:	Roundtrip Human Exploration of Nearby Stars By Laser−Pushed Lightsails

Sail and Mission Description:

Three−stage roundtrip laser−pushed lightsail capable of exploring any star system within 12 lightyears within a human working lifetime (50 years). 1000 km diameter outer acceleration stage surrounding a 320 km diameter rendezvous stage surrounding a 100 km diameter return stage. Laser transmitter lens 1000 km. Laser power of 45,000 TW pushes all three nested sails with total mass of 78,500 Mg at 0.3 gees, reaching 0.5c cruise speed in 1.6 years. Relativistic time dilation factor 13%. For constant acceleration laser power needs to increase to 75,000 TW. Deceleration stage carries crew, habitat, consumables, and exploration vehicles of 2900 Mg. Return stage only carries crew, habitat, and depleted consumables at 290 Mg. First technical publication of a method for accomplishing round−trip human exploration of the nearby star systems using known technology.

References:

Robert L. Forward, "Roundtrip Interstellar Travel Using Laser−Pushed Lightsails", J. Spacecraft, Vol. 21, No. 2, pp. 187−195 (March−April 1984). [See specifically pages 193−194.]

Sail Grand Unified Requirements

Sail Configuration		Three−stage sail laser−pushed rotating lightsail			
Sail Dimensions	m	100,000	320,000	1000,000	(diameter)
Sail Area	m^2	785×10^9	7.85×10^{10}	7.85×10^{11}	
Sail Film Thickness	µm	0.016 aluminum film (0.043 g/m^2)			
Sail & Structure Mass	kg	495,000	4,950,000	75,600,000	
Sail Areal Density	g/m^2	0.063	0.063	0.096	
S/C+Payload Mass	kg	290,000	2,900,000	2,900,000	
Total Mass	kg	785,000	7,850,000	78,500,000	
Total Areal Density	g/m^2	0.1	0.1	0.1	
Acceleration in laser beam	mm/s^2	3000	3000	3000	[thermally limited]
Launch Mass	kg	Not applicable (fabricated in space)			
Storage Volume	m^3	Not applicable (fabricated in space)			
Launch Vehicle		Not applicable (fabricated in space)			
Trip Time	years	51 years round−trip (5 years exploring), crew ages only 46 years			
Sail Temp Max/Min	°C	327 (600K) max [thermally limited]			
Other Environmental		TBD loss of sail area from impacts by interstellar dust at 0.5 c			
Spin Rate	deg/s	TBD (slow)			
Front Optical Reflect.					
Front Optical Absorb.					
Front IR Emissivity					
Back IR Emissivity					
Upper Stage Maneuvers					
Station Keeping Man'vrs					
Trajectory Maneuvers		Separate inner sail from outer ring sail and rotate 180 degrees			
Science Maneuvers					
Laser Power	TW	43,000 at launch to 75,000 end of acceleration, <10,000 rendezvous			
Preparer and Date:	Robert L. Forward 31 July 1999				

Sail or Mission Name:	One−Ton Alpha Centauri Flyby Probe Using Laser−Pushed Lightsail

Sail and Mission Description:

3.6 km diameter aluminum−film lightsail pushed to 0.11 c by 65 GW of laser power focused by a 1000 km diameter Fresnel lens. Lightsail total mass 1000 kg, 1/3 each sail, structure and payload. Accelerates at 0.36 m/s for 0.17 lightyears to reach a cruise velocity of 0.11 c. Reaches alpha Centauri at 4.3 lightyears distance 40 years after launch. Data back to Earth 44.3 years after launch.

References:

Robert L. Forward, "Roundtrip Interstellar Travel Using Laser−Pushed Lightsails", J. Spacecraft, Vol. 21, No. 2, pp. 187−195 (March−April 1984). [See specifically page 192.]
[See also: Geoffrey A. Landis, "Small Laser−Pushed Lightsail Interstellar Probe: A Study of Parameter Variations", J. British Interplanetary Society, Vol. 50, pp. 149−154 (1997).]

Sail Grand Unified Requirements

Sail Configuration		Circular spinner
Sail Dimensions	m	3600 diameter
Sail Area	m^2	10,000,000
Sail Film Thickness	µm	0.016 aluminum film (0.043 g/m^2)
Sail & Structure Mass	kg	667
Sail Areal Density	g/m^2	0.066
S/C+Payload Mass	kg	333
Total Mass	kg	1000
Total Areal Density	g/m^2	0.1
Acceleration in laser beam	mm/s^2	360 (0.036 gees) [thermally limited]
Launch Mass	kg	TBD
Storage Volume	m^3	TBD
Launch Vehicle		1000 km dia 560,000 ton Fresnel lens focusing a 65 GW laser
Trip Time	years	40
Sail Temp Max/Min	°C	327 (600K) [thermally limited}
Other Environmental		TBD% of sail area lost by collisions with interstellar dust
Spin Rate	deg/s	TBD
Front Optical Reflect.		0.82
Front Optical Absorb.		0.14
Front IR Emissivity		0.06
Back IR Emissivity		0.06
Upper Stage Maneuvers		
Station Keeping Man'vrs		
Trajectory Maneuvers		
Science Maneuvers		
Miscellaneous		Terminal speed 0.11 c
Preparer and Date:	Robert L. Forward 31 July 1999	

Sail or Mission Name:	Robotic Explorer Laser−Pushed Lightsail Alpha Centauri Rendezvous

Sail and Mission Description:

100 km diameter two−stage laser−pushed lightsail to deliver a 26 ton science exploration payload to alpha Centauri. 100 km diameter 785 ton sail surrounds a 30 km diameter 71 ton sail (mass includes the 26 ton science payload). The two nested sails are accelerated at a low 0.005 gees over the entire 40 year journey to minimize the laser power needed to 7.2 TW (higher power levels would drastically lower the trip time). The sail reaches 0.21c shortly before arrival. To stop, the laser power is increased to 26 TW to decelerate the 30 km diameter 71 ton sail at 0.2 gees. This high deceleration is needed in order to stop the payload sail before the first stage retromirror outer sail is pushed too far away. Requires a 1000 km diameter 560,000 ton Fresnel zone lens to focus laser beam.

References:

Robert L. Forward, "Roundtrip Interstellar Travel Using Laser−Pushed Lightsails", J. Spacecraft, Vol. 21, No. 2, pp. 187−195 (March−April 1984). [See specifically pages 192−193.]

Sail Grand Unified Requirements

Sail Configuration		Two−stage circular spinner	
Sail Dimensions	m	30,000	100,000
Sail Area	m^2	7.07×10^8	7.85×10^9
Sail Film Thickness	µm	0.016 aluminum film (0.043 g/m^2)	
Sail & Structure Mass	kg	45,000	759,000
Sail Areal Density	g/m^2	0.064	0.094
S/C+Payload Mass	kg	26,000	26,000
Total Mass	kg	71,000	785,000
Total Areal Density	g/m^2	0.10	0.10
Acceleration in laser beam	mm/s^2	2000	50
Launch Mass	kg	Not applicable (space fabricated)	
Storage Volume	m^3	Not applicable (space fabricated)	
Launch Vehicle		1000 km dia 560,000 ton Fresnel Lens focusing laser beam	
Trip Time	years	40	
Sail Temp Max/Min	°C	TBD (low since accelerations are low)	
Other Environmental		TBD % area lost due to impacts by interstellar dust	
Spin Rate	deg/s	TBD (slow)	
Front Optical Reflect.		0.82	0.82
Front Optical Absorb.		0.135	0.135
Front IR Emissivity		0.06	0.06
Back IR Emissivity		0.95	0.95
Upper Stage Maneuvers			
Station Keeping Man'vrs			
Trajectory Maneuvers		Separate inner sail from outer ring sail and rotating 180 degrees	
Science Maneuvers		Uses 30 km sail as solar sail in Alpha Centauri system	
Laser Power	TW	26 (decel)	7.2 (accel)

Preparer and Date:	Robert L. Forward 31 July 1999

Sail or Mission Name:	Small Alpha Centauri Flyby Probe Using Laser−Pushed Lightsail

Sail and Mission Description:

1000 meter lightsail massing 100 kg including 33 kg payload is pushed at 0.27 gees to 0.1c by 25 GW of laser power focused by a 200 km diameter lens. Thrust duration is 250 days and thrust length is 1100 AU (0.018 lightyears). Will reach Alpha Centauri in 44 years, with data back just under 50 years.

References:

Geoffrey A. Landis, "Report of Splinter Group on Beamed Energy Propulsion", Workshop on Robotic Interstellar Exploration in the Next Century, CalTech, Pasadena, CA (28−30 July 1998).
[See also: Geoffrey A. Landis, "Small Laser−Pushed Lightsail Interstellar Probe: A Study of Parameter Variations", <u>J. British Interplanetary Society</u>, Vol. 50, pp. 149−154 (1997).]

Sail Grand Unified Requirements		
Sail Configuration		Circular spinner
Sail Dimensions	m	1000 diameter
Sail Area	m^2	785,400
Sail Film Thickness	µm	TBD
Sail & Structure Mass	kg	67
Sail Areal Density	g/m^2	0.085
S/C+Payload Mass	kg	33
Total Mass	kg	100
Total Areal Density	g/m^2	0.13
Acceleration at 1 A.U.	mm/s^2	2700 (0.27 gees) terminal speed 0.11c
Launch Mass	kg	TBD
Storage Volume	m^3	TBD
Launch Vehicle		200 km diameter Fresnel lens focusing 25 GW laser
Trip Time	years	44
Sail Temp Max/Min	°C	TBD
Other Environmental		TBD % sail area loss from impacts by interstellar dust
Spin Rate	deg/s	TBD (slow)
Front Optical Reflect.		
Front Optical Absorb.		
Front IR Emissivity		
Back IR Emissivity		
Upper Stage Maneuvers		
Station Keeping Man'vrs		
Trajectory Maneuvers		
Science Maneuvers		
Laser Power	GW	25
Preparer and Date:	Robert L. Forward 31 July 1999 (Using Landis data)	

Sail or Mission Name:	Small Laser Pushed Interstellar Lightsail

Sail and Mission Description:

A 40% efficient 500 nm wavelength 54 GW laser, 212 km diameter Fresnel zone plate lens, and an ultralight beryllium lightsail are constructed in the solar system. The laser and lens accelerate the lightsail to 0.11c over a distance of 0.015 light years for a 40 year trip to an Alpha Centauri flyby.

References:

Landis, Geoffrey A., "Small Laser−Pushed Interstellar Lightsail Interstellar Probe: A Study of Parameter Variations", Journal of the British Interplanetary Society, Vol. 50, pp. 149−154, 1997.

Sail Grand Unified Requirements

Sail Configuration		Ultralight disk sail.
Sail Dimensions	m	764
Sail Area	m^2	458434
Sail Film Thickness	µm	0.02
Sail & Structure Mass	kg	22
Sail Areal Density	g/m^2	0.05
S/C+Payload Mass	kg	8
Total Mass	kg	30
Total Areal Density	g/m^2	0.07
Acceleration at 1 A.U.	mm/s^2	114
Launch Mass	kg	TBD
Storage Volume	m^3	TBD
Launch Vehicle		
Trip Time	years	40
Sail Temp Max/Min	°C	760
Other Environmental		TBD
Spin Rate	deg/s	TBD
Front Optical Reflect.		0.82
Front Optical Absorb.		0.14
Front IR Emissivity		0.06
Back IR Emissivity		0.06
Upper Stage Maneuvers		
Station Keeping Man'vrs		
Trajectory Maneuvers		
Science Maneuvers		
Miscellaneous		

Preparer and Date:	Benjamin L. Diedrich, July 28 1999 (using Landis data).

Sail or Mission Name:	Heliopause		
Sail and Mission Description:			
Deploy sail after injection into Earth escape trajectory toward the Sun. Fly to within 0.20−0.35 AU (Mercury at 0.387 AU) of Sun for higher solar pressure. Accelerate to Solar escape velocity. Jettison sail after acceleration drops off at around 5 AU. Two sail designs considered. A thin 1060 m diameter sail gets to the Heliopause in 10 years and a thicker 800 m diameter sail gets there in 20 years.			
References:			
Juan Ayon, Heliopause Explorer Viewgraph dated 10/06/98. Carl Sauer, Graphs dated 11−12 August 1998.			
Sail Grand Unified Requirements			
Sail Configuration		Not stated, will assume circular spinner since payload spins	
Sail Dimensions	m	1060	800
Sail Area	m^2	882,473	502,655
Sail Film Thickness	µm	not specified	
Sail & Structure Mass	kg	882	2,011
Sail Areal Density	g/m^2	1.0	4.0
S/C+Payload Mass	kg	200	200
Total Mass	kg	1082	2,211
Total Areal Density	g/m^2	1.23	4.4
Acceleration at 1 A.U.	mm/s^2	6.60	1.84
Launch Mass	kg	1082	2,211
Storage Volume	m^3		
Launch Vehicle			
Trip Time	years	10	20
Sail Temp Max/Min	°C	0.26 AU	0.28 AU
Other Environmental			
Spin Rate	deg/s	TBD (moderate for payload sensor modulation)	
Front Optical Reflect.			
Front Optical Absorb.			
Front IR Emissivity			
Back IR Emissivity			
Upper Stage Maneuvers		Launch into Earth escape	
Station Keeping Man'vrs		Spacecraft spinning for sensor modulation	
Trajectory Maneuvers		Use sail to fly near Sun to attain Solar System escape	
Science Maneuvers		Payload ACS	
Miscellaneous			
Preparer and Date:	Robert L. Forward, 1 August 1999 (using Frisbee chart)		

Sail or Mission Name:	Interstellar Probe through Heliopause into Interstellar Medium

Sail and Mission Description:

The mission formerly known as Heliopause, but "Interstellar Probe" was felt to be a jazzier name. The mission and sail design went through a $850K JPL study and Team−XT assessment in early 1999, which means a baseline end−to−end design has been achieved and even priced. Mission is to reach 200 AU in 15 years (63 km/s ave. speed), and continue on to 400 AU. $400M total mission cost. Science payload 25 kg, spacecraft 190.8 kg (wet with 30% contingency), sail 122.6 kg, launch mass including deployment mechanisms and spin−up RCS, 564 kg. Sail is 400 m diameter hexagonal spinner with areal density of 1.0 g/sq.m. If sail areal density can be lowered below 0.75 g/sq.m., then a 600 m diameter sail can reach 200 AU in 10 years. Sail is used to drop inward toward and then around Sun, with closest approach to Sun at 0.25 AU (Mercury is at 0.387 AU). Sail is jettisoned on the way out at 5 AU, only 15 months after launch. Trajectory direction is the "nose" of the heliopause, which is 7.5 degrees off the ecliptic plane, so spacecraft will pass through Kuiper Belt.

References:

Juan Ayon and Team−XT Report in Briefing Charts Book of Meeting #3 of the Interstellar Probe Science and Technology Definition Team, Richard Mewaldt., CalTech, Chair and Paulett Liewer, JPL, Study Scientist (17−19 May 1999).

Sail Grand Unified Requirements

Sail Configuration		Hexagonal spinner	
Sail Dimensions	m	400	600 (diameter)
Sail Area	m^2	122,600	276,000
Sail Film Thickness	µm	TBD (may use carbon mat backing for aluminum film)	
Sail & Structure Mass	kg	<122.6	<207
Sail Areal Density	g/m^2	<1.0 (goal)	<0.75 (goal)
S/C+Payload Mass	kg	190.8	190.8 (wet with 30% contingency)
Total Mass	kg	313.4	397.8
Total Areal Density	g/m^2	2.56	1.44
Acceleration at 1 A.U.	mm/s^2	3.039	5.4
Launch Mass	kg	564	TBD (includes contingency)
Storage Volume	m^3	will fit 10 foot fairing	
Launch Vehicle		Delta 7435 (719.3 kg capability)	
Trip Time	years	15 years to 200 AU, ~30 years to 400 AU	
Sail Temp Max/Min	°C	environment at 0.25 AU from Sun	
Other Environmental			
Spin Rate	deg/s	0.3 rpm, 8 degree / day precession rate	
Front Optical Reflect.			
Front Optical Absorb.			
Front IR Emissivity			
Back IR Emissivity			
Upper Stage Maneuvers		Spin up sail using 4 each 30 m long booms and cold gas	
Station Keeping Man'vrs		Spin stabilized along flight direction	
Trajectory Maneuvers		Decelerate from Earth orbit, drop into Sun, 0.25 AU close flyby	
Science Maneuvers		Drop sail at 5 AU, spacecraft spin stabilized with gas ACS	
Sail ACS		Spacecraft on boom to shift C−Mass wrt sail C−Pressure	

Preparer and Date:	Robert L. Forward 31 July 1999 (Using Ayon data)

Sail or Mission Name:	Gravity Lens

Sail and Mission Description:

2 km diameter sail massing 2.5 tons with a 2.5 ton science payload drops in to 0.186 AU (40 solar radii) from Sun (Mercury is at 0.387 AU), then builds up speed as it heads outward. Spinning sail will be dropped after acceleration drops off at about 5 AU. Payload will go into 3−axis orientation mode. Time to reach 550 AU distance where gravity lens effect starts to take place is 26.7 years. Thicker, heavier sails take longer.

References:

J. West, "Design Issues to Exploit the Gravity Lens Effect at 550 AU", 2nd AIAA Symposium on Realistic Near−Term Advanced Science Space Missions.

Sail Grand Unified Requirements

Sail Configuration		rotating 12−sided polygon with 12 inflatable tension struts
Sail Dimensions	m	2060 diameter
Sail Area	m^2	3,333,333
Sail Film Thickness	µm	0.1 to 1.0 perforated membrane
Sail & Structure Mass	kg	2500
Sail Areal Density	g/m^2	0.75
S/C+Payload Mass	kg	2500
Total Mass	kg	5000
Total Areal Density	g/m^2	1.5
Acceleration at 1 A.U.	mm/s^2	5.4
Launch Mass	kg	5000
Storage Volume	m^3	TBD
Launch Vehicle		
Trip Time	years	26.7
Sail Temp Max/Min	°C	equilibrium temperature at 0.186 AU
Other Environmental		
Spin Rate	deg/s	TBD (slow)
Front Optical Reflect.		
Front Optical Absorb.		
Front IR Emissivity		
Back IR Emissivity		
Upper Stage Maneuvers		TBD
Station Keeping Man'vrs		flythrough
Trajectory Maneuvers		Use sail to fly into 0.186 AU, then accelerate to solar escape
Science Maneuvers		3−axis ACS
Miscellaneous		

Preparer and Date:	Robert L. Forward, 1 August 1999 (based on Frisbee data sheet)

Sail or Mission Name:	KBO Rendezvous Using Solar Sail Concentrator Electric Propulsion

Sail and Mission Description:

Carry out the difficult Kuiper Belt Object Rendezvous Mission at 40 AU using electric propulsion powered by a modest−sized standard solar cell array illuminated by a large solar light concentrator designed using solar sail technology. Mission presently requires NEP, which is not politically acceptable. Since the "sail" is non−loadbearing, this may help in lowering the mass required for support of the sail reflective film. Frisbee sized the concentrator to produce 100 kWe at 40 AU. Perhaps less power toward end of mission out at 40 AU might be adequate for rendezvous propulsion, reducing concentrator size at the cost of increased mission time. Frisbee analysis does not include choosing photovoltaic cells optimized for high concentration, which should cut mass of array. Amount of concentration needed is small, 40:1 in diameter, 1600:1 in area (10,000:1 has been done with inflatables).

References:

Robert H. Frisbee email to Sara Gavit, "KBO Propulsion Alternatives", 1620 PDT 28 May 1999.

Sail Grand Unified Requirements

Sail Configuration		Circular curved concentrator, probably 3−axis stabilized
Sail Dimensions	m	916 diameter
Sail Area	m^2	659,000
Sail Film Thickness	µm	
Sail & Structure Mass	kg	659 (calculated from assumed areal density and area)
Sail Areal Density	g/m^2	1.0 (assumed)
S/C+Payload Mass	kg	1500 for photovoltaic array + TBD propulsion + TBD payload
Total Mass	kg	>2500
Total Areal Density	g/m^2	N/A
Acceleration at 1 A.U.	mm/s^2	
Launch Mass	kg	>2500
Storage Volume	m^3	
Launch Vehicle		
Trip Time	years	TBD
Sail Temp Max/Min	°C	1−40 AU
Other Environmental		
Spin Rate	deg/s	0
Front Optical Reflect.		
Front Optical Absorb.		
Front IR Emissivity		
Back IR Emissivity		
Upper Stage Maneuvers		Put into Earth escape toward target KBO
Station Keeping Man'vrs		Electric propulsion subsystem
Trajectory Maneuvers		Electric propulsion subsystem
Science Maneuvers		Electric propulsion subsystem
Power System Specific Mass	kg/kWe	PV Array: 15.0 / Concentrator: 6.58

Preparer and Date:	Robert L. Forward, 1 August 1999 (using Frisbee chart)

Sail or Mission Name:	Solar Polar

Sail and Mission Description:

150−200 m square sail. Deploy sail after injection into Earth escape. Fly to within 0.48 AU (Mercury at 0.387 AU) for higher solar pressure. Crank orbit inclination to 83 degrees above ecliptic. Transfer to desired orbital radius after orbit inclination is reached. Jettison sail when final orbit is attained. Various sized sails and sail areal densities give trip times from 3.48 to 5.15 years.

References:

R. Wallace, te al., "A Solar Polar Sail Mission", 2/2/1998.

Sail Grand Unified Requirements

Sail Configuration		Square sail with sail ACS done by moving S/C on boom	
Sail Dimensions	m	150	200
Sail Area	m^2	22,500	40,000
Sail Film Thickness	µm	2.0	2.0
Sail & Structure Mass	kg	152	232
Sail Areal Density	g/m^2	6.8	5.8
S/C+Payload Mass	kg	230	230
Total Mass	kg	382	462
Total Areal Density	g/m^2	17.0	11.55 (these are wrong on Frisbee charts)
Acceleration at 1 A.U.	mm/s^2	0.477	0.702 (these are wrong in Frisbee charts)
Launch Mass	kg	382	462
Storage Volume	m^3	TBD	
Launch Vehicle		TarusXL+Star37FM	Delta II/7326
Trip Time	years	5.15	3.48
Sail Temp Max/Min	°C	nominal for 0.48 AU from Sun	
Other Environmental			
Spin Rate	deg/s	0	
Front Optical Reflect.			
Front Optical Absorb.			
Front IR Emissivity			
Back IR Emissivity			
Upper Stage Maneuvers		Escape from Earth toward Sun	
Station Keeping Man'vrs		Reaction wheels plus 22 kg hydrazine RCS	
Trajectory Maneuvers		Sail used to put payload in desired solar polar orbit	
Science Maneuvers		1 degree pointing accuracy, full view of Sun	
Miscellaneous			

Preparer and Date:	Robert L. Forward, 1 August 1999 (using Frisbee charts)

Sail or Mission Name:	Geostorm (Rocket into position − Lighter)

Sail and Mission Description:

Use direct injection from launch to point 0.98 AU from Sun on other side of L1. Use first solid for insertion into solar orbit at 0.98 AU. Jettison first solid. Deploy sail. If sail deploys, jettison second solid. If sail doesn't deploy, use second solid to transfer to L1 at 0.993 AU.

References:

JPL D−13986, J. West, 10/18/96

Sail Grand Unified Requirements

Sail Configuration		Square sail with inflatable booms, pyramid with S/C at apex
Sail Dimensions	m	67 x 67
Sail Area	m^2	4489
Sail Film Thickness	µm	7.62 (0.3 mil)
Sail & Structure Mass	kg	72
Sail Areal Density	g/m^2	16.0
S/C+Payload Mass	kg	61
Total Mass	kg	133 (on station mass)
Total Areal Density	g/m^2	29.6 (required to carry out mission)
Acceleration at 1 A.U.	mm/s^2	0.273 (based on areal density and 0.90 reflectivity)
Launch Mass	kg	263 (includes two solids)
Storage Volume	m^3	0.3 + TBD for solids
Launch Vehicle		Taurus+Star 27XFP or Pegasus XL + Star 27
Trip Time	years	0.52 (190 days)
Sail Temp Max/Min	°C	nominal for 0.98 AU from Sun
Other Environmental		
Spin Rate	deg/s	0
Front Optical Reflect.		
Front Optical Absorb.		
Front IR Emissivity		
Back IR Emissivity		
Upper Stage Maneuvers		1025 m/s insertion into 0.98 AU solar orbit, 900 m/s back to L1
Station Keeping Man'vrs		continuous thrust from sail
Trajectory Maneuvers		none
Science Maneuvers		25 m/s per year by hydrazine ACS for 3−axis orientation
Miscellaneous		1 degree pointing accuracy for magnetic field direction

Preparer and Date:	Robert L. Forward, 1 August 1999 (Using Frisbee data)

Sail or Mission Name:	Geostorm (Sail into position − Heavy)

Sail and Mission Description:

Use hydrazine powered Auxiliary Upper Stage (AUS) based on OSC HAPS, to inject from a GTO piggyback mission to L1 at 0.993 AU. Use AUS to stop at L1, then jettison AUS. Deploy sail. If sail deploys, use sail to transfer to 0.98 AU. If sail doesn't deploy, stay at L1.

References:

JPL 10M, 621−EHK−Geostorm, 11/19/97

Sail Grand Unified Requirements		
Sail Configuration		Square sail with inflatable booms, pyramid with S/C at apex
Sail Dimensions	m	144 x 144
Sail Area	m^2	5,274
Sail Film Thickness	µm	7.62 (0.3 mil)
Sail & Structure Mass	kg	90.7
Sail Areal Density	g/m^2	17.2
S/C+Payload Mass	kg	65.4
Total Mass	kg	156.1 (on station mass)
Total Areal Density	g/m^2	29.6 (required to carry out mission)
Acceleration at 1 A.U.	mm/s^2	0.274 (based on areal density and 0.90 reflectivity)
Launch Mass	kg	346.3 (includes Auxiliary Upper Stage)
Storage Volume	m^3	0.3 + 1.1 for AUS
Launch Vehicle		Atlas Centaur (GTO Piggyback)
Trip Time	years	0.52 (190 days)
Sail Temp Max/Min	°C	nominal for 0.98 AU from Sun
Other Environmental		
Spin Rate	deg/s	0
Front Optical Reflect.		
Front Optical Absorb.		
Front IR Emissivity		
Back IR Emissivity		
Upper Stage Maneuvers		743 m/s by AUS for insertion into L1 at 0.993 AU
Station Keeping Man'vrs		continuous thrust from sail
Trajectory Maneuvers		none
Science Maneuvers		25 m/s per year by hyudraxine ACS for 3−axis orientation
Miscellaneous		1 degree pointing accuracy for magnetic field direction
Preparer and Date:		Robert L. Forward, 1 August 1999 (Using Frisbee data)

Sail or Mission Name:	Aurora

Sail and Mission Description:

A solar sail launched from Earth sheds the plastic substrate of its sail in orbit to dramatically improve performance. The spacecraft sails to Earth escape, then performs an orbital angular−momentum reversal maneuver around the Sun with a heliocentric periapsis of 0.152 AU. Cruise speed after 2.5 AU distance is 16.8 AU/year (80 km/s). The Kuiper belt is reached after 3.9 years from launch. The heliopause, if at 120 AU, is reached in 8.3 years. Final destination of 200 AU reached in 13 years.

References:

Vulpetti, Giovanni, "A Sailing Mode in Space: 3D Fast Trajectories by Orbital Angular−Momentum Reversal", NASA−JPL Ninth Advanced Space Propulsion Research Workshop and Conference, March 11−13, 1998, Pasadena, CA.

Sail Grand Unified Requirements

Sail Configuration		Square sail with triangular panels. Lightweight (50 g/m) booms.
Sail Dimensions	m	313.4 x 313.4
Sail Area	m^2	98220
Sail Film Thickness	µm	0.170 Al reflector, 0.01 Cr emitter.
Sail & Structure Mass	kg	104
Sail Areal Density	g/m^2	1.06
S/C+Payload Mass	kg	98
Total Mass	kg	202
Total Areal Density	g/m^2	2.06
Acceleration at 1 A.U.	mm/s^2	3.4
Launch Mass	kg	212 + mass of substrate
Storage Volume	m^3	
Launch Vehicle		
Trip Time	years	13
Sail Temp Max/Min	°C	300 max, ambient at 200 AU min.
Other Environmental		
Spin Rate	deg/s	0
Front Optical Reflect.		
Front Optical Absorb.		
Front IR Emissivity		
Back IR Emissivity		
Upper Stage Maneuvers		
Station Keeping Man'vrs		Chemical in Earth orbit, field−emission ion in heliocentric.
Trajectory Maneuvers		Included.
Science Maneuvers		Included.
Miscellaneous		

Preparer and Date:	Benjamin L. Diedrich, July 27 1999 (Using Vulpetti data)

Sail or Mission Name:	Pluto Express

Sail and Mission Description:

Taurus and Star 37FM upper stage deliver spacecraft to 1.77x0.45 AU heliocentric orbit. Sail deploys and uses increased solar radiation pressure to escape from the sun and perform a flyby of Pluto.

References:

Leipold, Manfred, "Solar Sail Mission Applications", NASA−JPL Workshop on Solar Sail Propulsion, Jet Propulsion Laboratory, Pasadena, California, February 13, 1997.

Sail Grand Unified Requirements

Sail Configuration		Square sail with carbon fiber reinforced plastic profile booms.
Sail Dimensions	m	195x195
Sail Area	m^2	38025
Sail Film Thickness	µm	1−3
Sail & Structure Mass	kg	210
Sail Areal Density	g/m^2	5.5
S/C+Payload Mass	kg	100
Total Mass	kg	310
Total Areal Density	g/m^2	8.15
Acceleration at 1 A.U.	mm/s^2	1
Launch Mass	kg	310 + mass of upper stage if present.
Storage Volume	m^3	
Launch Vehicle		Taurus
Trip Time	years	10.3
Sail Temp Max/Min	°C	Nominal for 0.45 AU to Pluto.
Other Environmental		
Spin Rate	deg/s	0
Front Optical Reflect.		
Front Optical Absorb.		
Front IR Emissivity		
Back IR Emissivity		
Upper Stage Maneuvers		
Station Keeping Man'vrs		
Trajectory Maneuvers		
Science Maneuvers		
Miscellaneous		

Preparer and Date:	Benjamin L. Diedrich, July 28 1999 (using Leipold data).

Sail or Mission Name:	Solar Probe

Sail and Mission Description:

Delta Lite launches spacecraft to Earth escape with C3=0. Solar sail deploys and spirals down to a circular heliocentric orbit of ~0.35 AU. Sail cranks orbit inclination to 90°. Sail extends apoapsis to 1.5 AU and delivers payload to 0.02 AU.

References:

Leipold, Manfred, "Solar Sail Mission Applications", NASA−JPL Workshop on Solar Sail Propulsion, Jet Propulsion Laboratory, Pasadena, California, February 13, 1997.

Sail Grand Unified Requirements

Sail Configuration		Square sail with carbon fiber reinforced plastic profile booms.
Sail Dimensions	m	250x250
Sail Area	m^2	62500
Sail Film Thickness	µm	1−3
Sail & Structure Mass	kg	320
Sail Areal Density	g/m^2	5
S/C+Payload Mass	kg	200
Total Mass	kg	520
Total Areal Density	g/m^2	8.32
Acceleration at 1 A.U.	mm/s^2	1
Launch Mass	kg	520
Storage Volume	m^3	
Launch Vehicle		Delta Lite
Trip Time	years	2.8
Sail Temp Max/Min	°C	Min: 1.5 AU, max: 0.35 AU or closest approach after probe release.
Other Environmental		
Spin Rate	deg/s	0
Front Optical Reflect.		
Front Optical Absorb.		
Front IR Emissivity		
Back IR Emissivity		
Upper Stage Maneuvers		
Station Keeping Man'vrs		
Trajectory Maneuvers		
Science Maneuvers		
Miscellaneous		
Preparer and Date:		Benjamin L. Diedrich, July 28 1999 (using Leipold data).

Sail or Mission Name:	MESSAGE (Mercury Solar Sailing Advanced Geoscience Explorer)

Sail and Mission Description:

Use upper stage of Taurus or Rockot to launch spacecraft to Earth escape with C3=0. Jettison upper stage and deploy solar sail. Sail delivers spacecraft to Mercury rendezvous in 3.5 years. Sail places spacecraft into a polar orbit with periapsis altitude 200 km and apoapsis altitude between 6350 and 7200 km. Sail precesses orbit to be sun−synchronous and to follow the terminator to improve surface imaging and reduce thermal loads.

References:

Leipold, M., et. al., "Mercury Sun−Synchronous Polar Orbiter with a Solar Sail", Acta Astronautica, Vol. 39, No. 1−4, pp. 143−151, 1996.
McInnes, Colin R., Solar Sailing: Technology, Dynamics, and Mission Applications, Springer−Verlag, London, pp. 231−238, 1999.

Sail Grand Unified Requirements

Sail Configuration		Square sail with carbon fiber reinforced plastic profile booms.
Sail Dimensions	m	86x86 150x150
Sail Area	m^2	7396 22500
Sail Film Thickness	µm	1.5−2.5
Sail & Structure Mass	kg	56 164
Sail Areal Density	g/m^2	7.6 7.3
S/C+Payload Mass	kg	186
Total Mass	kg	242 350
Total Areal Density	g/m^2	32.7 15.6
Acceleration at 1 A.U.	mm/s^2	0.25 0.55
Launch Mass	kg	242 350 + mass of upper stage
Storage Volume	m^3	
Launch Vehicle		Rockot or Taurus, Taurus
Trip Time	years	3.5 1.8
Sail Temp Max/Min	°C	Max 234
Other Environmental		Max 240−260 for spacecraft bus in front of sail
Spin Rate	deg/s	0
Front Optical Reflect.		
Front Optical Absorb.		
Front IR Emissivity		
Back IR Emissivity		
Upper Stage Maneuvers		
Station Keeping Man'vrs		2 DOF gimbaled boom for center of mass displacement.
Trajectory Maneuvers		Included
Science Maneuvers		Included
Miscellaneous		

Preparer and Date:	Benjamin L. Diedrich, July 26 1999 (using Leipold et. al. data).

Sail or Mission Name:	Comet Encke Sample Return

Sail and Mission Description:

Taurus XL launch of spacecraft to Earth escape C3=0. Sail deploys and performs a rendezvous with comet Encke. Sail enters orbit around Encke. Lander detaches from sail and lands on comet. Rocket returns sample capsule to sail. Sail returns to Earth and drops capsule into atmosphere.

References:

Leipold, Manfred, "Solar Sail Mission Applications", NASA−JPL Workshop on Solar Sail Propulsion, Jet Propulsion Laboratory, Pasadena, California, February 13, 1997.
McInnes, Colin R., Solar Sailing: Technology, Dynamics, and Mission Applications, Springer−Verlag, London, pp. 247−250, 1999.

Sail Grand Unified Requirements

Sail Configuration		Square sail with carbon fiber reinforced plastic profile booms.
Sail Dimensions	m	150x150
Sail Area	m^2	22500
Sail Film Thickness	µm	1−3
Sail & Structure Mass	kg	110
Sail Areal Density	g/m^2	5
S/C+Payload Mass	kg	100
Total Mass	kg	210
Total Areal Density	g/m^2	9.3
Acceleration at 1 A.U.	mm/s^2	0.85 outbound, 1.0 Earth return.
Launch Mass	kg	210 + upper stage mass
Storage Volume	m^3	
Launch Vehicle		
Trip Time	years	3 outbound, 2.5 for Earth return, 6.4 total.
Sail Temp Max/Min	°C	Nominal for Earth to Encke.
Other Environmental		
Spin Rate	deg/s	0
Front Optical Reflect.		
Front Optical Absorb.		
Front IR Emissivity		
Back IR Emissivity		
Upper Stage Maneuvers		
Station Keeping Man’vrs		
Trajectory Maneuvers		
Science Maneuvers		
Miscellaneous		

Preparer and Date:	Benjamin L. Diedrich, July 28 1999 (using Leipold & McInnes data).

Sail or Mission Name:	Dual Main Belt Asteroid Sample Return

Sail and Mission Description:

Two identical solar sails launched by a Delta II to Earth escape. Sails detach from Delta II and separate from each other. Sails deploy. One sail travels to asteroid Vesta, and the other to Metis. Each enters orbit, then delivers a lander to the asteroid surface. 0.5 kg samples are returned to each sail. The sails return to Earth and drop the samples into Earth's atmosphere.

References:

Leipold, Manfred, "Solar Sail Mission Applications", NASA−JPL Workshop on Solar Sail Propulsion, Jet Propulsion Laboratory, Pasadena, California, February 13, 1997.
McInnes, Colin R., Solar Sailing: Technology, Dynamics, and Mission Applications, Springer−Verlag, London, pp. 247−250, 1999.

Sail Grand Unified Requirements

Sail Configuration		Square sail supported by 4 booms.
Sail Dimensions	m	265x265
Sail Area	m^2	70225
Sail Film Thickness	µm	1.5
Sail & Structure Mass	kg	383
Sail Areal Density	g/m^2	5.45
S/C+Payload Mass	kg	285
Total Mass	kg	668
Total Areal Density	g/m^2	9.51
Acceleration at 1 A.U.	mm/s^2	0.75 outbound, 0.8 Earth return.
Launch Mass	kg	668 + upper stage masses
Storage Volume	m^3	
Launch Vehicle		Delta II 7925
Trip Time	years	3.3 to asteroids, 6.6−7 total for return to Earth.
Sail Temp Max/Min	°C	Nominal for Earth to Vesta and Metis.
Other Environmental		
Spin Rate	deg/s	0
Front Optical Reflect.		
Front Optical Absorb.		
Front IR Emissivity		
Back IR Emissivity		
Upper Stage Maneuvers		
Station Keeping Man'vrs		
Trajectory Maneuvers		
Science Maneuvers		
Miscellaneous		
Preparer and Date:	Benjamin L. Diedrich, July 28 1999 (using Leipold & McInnes data).	

Sail or Mission Name:	World Space Foundation Solar Sail Race Vehicle

Sail and Mission Description:

Spacecraft is launched as a secondary payload on an Ariane IV to a 250 km x 36000 km altitude GTO. The spacecraft is mated to two other solar sail spacecraft as a launch vehicle interface, propulsion, and communication platform before separation. The three spacecraft are spin stabilized. A FW−5 booster raises the perigee above 15,000 km to avoid the Van Allen radiation belts and atmospheric drag. Spacecraft are despun, separate, and deploy. 2−3 weeks are taken to prepare for the race, during which time none go above 50,000 km altitude. The spacecraft spiral outwards to the moon to take a picture of the center of the far side. If this stage is accomplished, the spacecraft continues on to Mars.

References:

Staehle, Robert L., Graham, John M., and Champa, John, "Solar Sail Expedition to the Moon and Mars: Mission Update", Spaceflight, Vol. 34, pp. 256−258, August 1992.
McInnes, Colin R., Solar Sailing: Technology, Dynamics, and Mission Applications, Springer−Verlag, London, pp. 99−102, 1999.

Sail Grand Unified Requirements

Sail Configuration		Square sail with STEM tubular booms
Sail Dimensions	m	55x55
Sail Area	m^2	3000
Sail Film Thickness	µm	2.5
Sail & Structure Mass	kg	59
Sail Areal Density	g/m^2	19.7
S/C+Payload Mass	kg	80
Total Mass	kg	139
Total Areal Density	g/m^2	46.3
Acceleration at 1 A.U.	mm/s^2	0.17
Launch Mass	kg	533 + mass of other 2 solar sails
Storage Volume	m^3	
Launch Vehicle		
Trip Time	years	
Sail Temp Max/Min	°C	Nominal for Earth GTO to the moon and Mars.
Other Environmental		
Spin Rate	deg/s	360−540 during upper stage burn, 0 otherwise.
Front Optical Reflect.		
Front Optical Absorb.		
Front IR Emissivity		
Back IR Emissivity		
Upper Stage Maneuvers		
Station Keeping Man'vrs		
Trajectory Maneuvers		Steering vanes at 4 corners of the sail.
Science Maneuvers		
Miscellaneous		

Preparer and Date:	Benjamin L. Diedrich, July 30 1999 (using Staehle et. al. data)

Sail or Mission Name:	U3P Solar Sail Race Vehicle

Sail and Mission Description:

Spacecraft is launched as a secondary payload on a launch vehicle to GTO. A secondary stage may raise the perigee. Sail deploys. The spacecraft spirals outward to the moon to take a picture of the center of the far side.

References:

McInnes, Colin R., Solar Sailing: Technology, Dynamics, and Mission Applications, Springer−Verlag, London, pp. 99−102, 1999.
Staehle, Robert L., Graham, John M., and Champa, John, "Solar Sail Expedition to the Moon and Mars: Mission Update", Spaceflight, Vol. 34, pp. 256−258, August 1992.

Sail Grand Unified Requirements

Sail Configuration		Square sail with coilable carbon epoxy booms.
Sail Dimensions	m	64x64
Sail Area	m^2	4000
Sail Film Thickness	µm	7.6
Sail & Structure Mass	kg	146
Sail Areal Density	g/m^2	36.5
S/C+Payload Mass	kg	81
Total Mass	kg	227
Total Areal Density	g/m^2	56.8
Acceleration at 1 A.U.	mm/s^2	0.14
Launch Mass	kg	
Storage Volume	m^3	
Launch Vehicle		
Trip Time	years	
Sail Temp Max/Min	°C	Nominal for Earth GTO to the moon.
Other Environmental		
Spin Rate	deg/s	
Front Optical Reflect.		
Front Optical Absorb.		
Front IR Emissivity		
Back IR Emissivity		
Upper Stage Maneuvers		
Station Keeping Man'vrs		
Trajectory Maneuvers		8 large triangular flaps, 2 attached to each sail edge.
Science Maneuvers		
Miscellaneous		

Preparer and Date:	Benjamin L. Diedrich, July 30 1999 (using McInnes et. al. data)

Sail or Mission Name:	MIT Heliogyro Solar Sail Race Vehicle

Sail and Mission Description:

Spacecraft is delivered to GTO as a secondary payload. Chemical stage may raise perigee above atmospheric drag altitude. Upper stage spins spacecraft to 40 rpm. Angular momentum rapidly deploys sail blades and provides final spin rate of 0.1 rpm. The sail delivers the spacecraft to a lunar flyby.

References:

McInnes, Colin R., Solar Sailing: Technology, Dynamics, and Mission Applications, Springer−Verlag, London, pp. 100, 104−105, 1999.

Sail Grand Unified Requirements		
Sail Configuration		Eight bladed heliogyro with piezoelectric actuators for control.
Sail Dimensions	m	Dimensions of each blade: 83x1.5
Sail Area	m^2	996
Sail Film Thickness	µm	
Sail & Structure Mass	kg	12
Sail Areal Density	g/m^2	12
S/C+Payload Mass	kg	3
Total Mass	kg	15
Total Areal Density	g/m^2	15
Acceleration at 1 A.U.	mm/s^2	0.52
Launch Mass	kg	
Storage Volume	m^3	
Launch Vehicle		
Trip Time	years	
Sail Temp Max/Min	°C	Nominal for transfer from GTO to the moon.
Other Environmental		
Spin Rate	deg/s	0.6
Front Optical Reflect.		
Front Optical Absorb.		
Front IR Emissivity		
Back IR Emissivity		
Upper Stage Maneuvers		
Station Keeping Man'vrs		Piezoelectric actuator at the base of each blade.
Trajectory Maneuvers		Included.
Science Maneuvers		Included.
Miscellaneous		
Preparer and Date:		Benjamin L. Diedrich, July 27 1999 (using McInnes data).

Sail or Mission Name:	Cambridge Consultants Ltd. Solar Sail Race Vehicle

Sail and Mission Description:

Spacecraft is launched into Earth orbit. Sail deploys using spring force from 36 wrapped rib booms. The spacecraft spirals outward to the Moon and then to Mars.

References:

McInnes, Colin R., Solar Sailing: Technology, Dynamics, and Mission Applications, Springer−Verlag, London, pp. 99−102, 1999.

Sail Grand Unified Requirements

Sail Configuration		Wrapped rib disk sail supported by 36 CFRP booms.
Sail Dimensions	m	276 diameter
Sail Area	m^2	60000
Sail Film Thickness	µm	2
Sail & Structure Mass	kg	240
Sail Areal Density	g/m^2	4
S/C+Payload Mass	kg	60
Total Mass	kg	300
Total Areal Density	g/m^2	5
Acceleration at 1 A.U.	mm/s^2	1.55
Launch Mass	kg	
Storage Volume	m^3	4 m diameter, 4 m height, 50 m^3 total.
Launch Vehicle		
Trip Time	years	
Sail Temp Max/Min	°C	Nominal for Earth to the moon and Mars.
Other Environmental		
Spin Rate	deg/s	
Front Optical Reflect.		
Front Optical Absorb.		
Front IR Emissivity		
Back IR Emissivity		
Upper Stage Maneuvers		
Station Keeping Man'vrs		
Trajectory Maneuvers		Warping sail shape by tilting booms at base.
Science Maneuvers		
Miscellaneous		
Preparer and Date:	Benjamin L. Diedrich, July 30 1999 (using McInnes data)	

Sail or Mission Name:	Johns Hopkins University Solar Sail Race Vehicle

Sail and Mission Description:

Spacecraft is launched into Earth orbit. Sail deploys. The spacecraft spirals outward to the moon and then to Mars.

References:

McInnes, Colin R., Solar Sailing: Technology, Dynamics, and Mission Applications, Springer−Verlag, London, pp. 99−102, 1999.

Sail Grand Unified Requirements

Sail Configuration		480 segment ring sail. Payload attaches to central mast.
Sail Dimensions	m	170 diameter
Sail Area	m^2	22700
Sail Film Thickness	µm	1.14
Sail & Structure Mass	kg	100
Sail Areal Density	g/m^2	4.4
S/C+Payload Mass	kg	80
Total Mass	kg	180
Total Areal Density	g/m^2	7.9
Acceleration at 1 A.U.	mm/s^2	0.98
Launch Mass	kg	
Storage Volume	m^3	
Launch Vehicle		
Trip Time	years	
Sail Temp Max/Min	°C	Nominal for Earth to the moon and Mars.
Other Environmental		
Spin Rate	deg/s	
Front Optical Reflect.		
Front Optical Absorb.		
Front IR Emissivity		
Back IR Emissivity		
Upper Stage Maneuvers		
Station Keeping Man'vrs		
Trajectory Maneuvers		Tilt central mast for pitch & yaw, twist sail segments for roll.
Science Maneuvers		
Miscellaneous		

Preparer and Date:	Benjamin L. Diedrich, July 30 1999 (using McInnes data)

Sail or Mission Name:	Halley Rendezvous	
Sail and Mission Description:		
Although the mission opportunity for Halley's comet has passed, rendezvous with other long period comets could use a similar mission profile. Technology improvements allow using a much smaller sail and payload with similar performance. The spacecraft is launched on an Earth escape trajectory with C3=12 km^2/s^2. The sail deploys and delivers the spacecraft to a 0.25 AU heliocentric circular orbit. The sail cranks the inclination 162° to match the inclination of Halley's retrograde orbit. The sail spirals out from the sun to rendezvous with the comet. A lander separates from the sail and uses a chemical stage to land on the comet.		
References:		
Wright, Jerome, Space Sailing, Gordon and Breach Science Publishers, Amsterdam, 1992.		
Sail Grand Unified Requirements		
Sail Configuration		Square sail with stays and deployable truss masts and booms.
Sail Dimensions	m	820x820
Sail Area	m^2	641200
Sail Film Thickness	µm	2
Sail & Structure Mass	kg	3382
Sail Areal Density	g/m^2	5.27
S/C+Payload Mass	kg	1555
Total Mass	kg	4937
Total Areal Density	g/m^2	7.7
Acceleration at 1 A.U.	mm/s^2	1.05
Launch Mass	kg	4937 + mass of upper stage
Storage Volume	m^3	
Launch Vehicle		
Trip Time	years	4.4
Sail Temp Max/Min	°C	Max at 0.25 AU, min at ~2.5 AU
Other Environmental		
Spin Rate	deg/s	0
Front Optical Reflect.		
Front Optical Absorb.		
Front IR Emissivity		
Back IR Emissivity		
Upper Stage Maneuvers		
Station Keeping Man'vrs		
Trajectory Maneuvers		Steering vanes at 4 corners of the sail.
Science Maneuvers		Lander requires max 500 m/s Δv.
Miscellaneous		
Preparer and Date:	Benjamin L. Diedrich, July 29 1999 (using Wright data).	

Sail or Mission Name:	Interplanetary Shuttle

Sail and Mission Description:

Reusable solar sail based on the Halley Rendezvous square sail. Carries multi−ton payloads to various destinations throughout the solar system. Can deliver large science spacecraft, perform large (500 kg) sample return missions to planets and small bodies, deliver 5−10 ton payloads for human Mars exploration, and return to Earth from as far away as Saturn.

References:

Wright, J., and Warmke, J., "Solar Sail Mission Applications", AIAA 76−808, AIAA/AAS Astrodynamics Conference, San Diego, California, August 18−20, 1976.
Wright, Jerome, Space Sailing, Gordon and Breach Science Publishers, Amsterdam, 1992.

Sail Grand Unified Requirements

Sail Configuration		Square sail with stays and deployable truss masts and booms.
Sail Dimensions	m	820x820
Sail Area	m^2	641200
Sail Film Thickness	µm	2
Sail & Structure Mass	kg	3382
Sail Areal Density	g/m^2	5.27
S/C+Payload Mass	kg	
Total Mass	kg	
Total Areal Density	g/m^2	
Acceleration at 1 A.U.	mm/s^2	
Launch Mass	kg	
Storage Volume	m^3	
Launch Vehicle		
Trip Time	years	
Sail Temp Max/Min	°C	
Other Environmental		
Spin Rate	deg/s	0
Front Optical Reflect.		
Front Optical Absorb.		
Front IR Emissivity		
Back IR Emissivity		
Upper Stage Maneuvers		
Station Keeping Man'vrs		
Trajectory Maneuvers		Steering vanes at 4 corners of the sail.
Science Maneuvers		
Miscellaneous		
Preparer and Date:		Benjamin L. Diedrich, July 29 1999 (using Wright & Warmke data).

Sail or Mission Name:	Venus Interplanetary Shuttle

Sail and Mission Description:

Reusable solar sail based on the Halley Rendezvous square sail is launched and deployed in Earth orbit. Payloads bound for Venus of 1.4 and 4.6 tons are launched to rendezvous with the sail, or are launched with it. The sail docks with the payloads and spirals out to an Earth escape. The sail delivers the payloads to a Venus rendezvous. Advanced landers might deliver samples for return by the sail.

References:

Wright, J., and Warmke, J., "Solar Sail Mission Applications", AIAA 76−808, AIAA/AAS Astrodynamics Conference, San Diego, California, August 18−20, 1976.

Sail Grand Unified Requirements

Sail Configuration		Square sail with stays and deployable truss masts and booms.
Sail Dimensions	m	820x820
Sail Area	m^2	641200
Sail Film Thickness	µm	2
Sail & Structure Mass	kg	3382
Sail Areal Density	g/m^2	5.27
S/C+Payload Mass	kg	1400, 4600
Total Mass	kg	4782, 7982
Total Areal Density	g/m^2	7.46, 12.4
Acceleration at 1 A.U.	mm/s^2	1.1, 0.65
Launch Mass	kg	
Storage Volume	m^3	
Launch Vehicle		
Trip Time	years	Earth escape to Venus rendezvous: 0.55, 0.74
Sail Temp Max/Min	°C	Nominal for Earth to Venus.
Other Environmental		
Spin Rate	deg/s	0
Front Optical Reflect.		
Front Optical Absorb.		
Front IR Emissivity		
Back IR Emissivity		
Upper Stage Maneuvers		
Station Keeping Man'vrs		
Trajectory Maneuvers		Steering vanes at 4 corners of the sail.
Science Maneuvers		
Miscellaneous		
Preparer and Date:	Benjamin L. Diedrich, July 29 1999 (using Wright & Warmke data).	

Sail or Mission Name:	Mercury Interplanetary Shuttle	

Sail and Mission Description:

Reusable solar sail based on the Halley Rendezvous square sail is launched and deployed in Earth orbit. Payloads bound for Mercury in the range of 10, 20, 30, and 40 tons are launched to rendezvous with the sail, or are launched with it. The sail docks with the payloads and spirals out to an Earth escape. The sail delivers the payloads to a Mercury rendezvous. The sail can return to Earth with significant sample returns.

References:

Wright, J., and Warmke, J., "Solar Sail Mission Applications", AIAA 76−808, AIAA/AAS Astrodynamics Conference, San Diego, California, August 18−20, 1976.
Wright, Jerome, Space Sailing, Gordon and Breach Science Publishers, Amsterdam, 1992.

Sail Grand Unified Requirements

Sail Configuration		Square sail with stays and deployable truss masts and booms.
Sail Dimensions	m	820x820
Sail Area	m^2	641200
Sail Film Thickness	µm	2
Sail & Structure Mass	kg	3382
Sail Areal Density	g/m^2	5.27
S/C+Payload Mass	kg	10000, 20000, 30000, 40000
Total Mass	kg	13382, 23382, 33382, 43382
Total Areal Density	g/m^2	20.9, 36.4, 52.1, 67.6
Acceleration at 1 A.U.	mm/s^2	0.39, 0.22, 0.15, 0.12
Launch Mass	kg	
Storage Volume	m^3	
Launch Vehicle		
Trip Time	years	Earth escape to Mercury rendezvous: 1.6, 2.5, 3.3, 4.1
Sail Temp Max/Min	°C	Nominal for Earth to Mercury.
Other Environmental		
Spin Rate	deg/s	0
Front Optical Reflect.		
Front Optical Absorb.		
Front IR Emissivity		
Back IR Emissivity		
Upper Stage Maneuvers		
Station Keeping Man'vrs		
Trajectory Maneuvers		Steering vanes at 4 corners of the sail.
Science Maneuvers		
Miscellaneous		
Preparer and Date:	Benjamin L. Diedrich, July 29 1999 (using Wright & Warmke data).	

Sail or Mission Name:		Mars Interplanetary Shuttle
Sail and Mission Description:		
Reusable solar sail based on the Halley Rendezvous square sail is launched and deployed in Earth orbit. Payloads bound for Mars in the range of 2, 5, and 10 tons are launched to rendezvous with the sail, or are launched with it. The sail docks with the payloads and spirals out to an Earth escape. The sail delivers the payloads to a Mars rendezvous or aerobrake the payloads in Mars' atmosphere. A sail in Mars orbit can return to Earth with significant (200 kg) sample returns. A sail can return directly to Earth with asteroid flybys after aerobraking a payload at Mars.		
References:		
Wright, J., and Warmke, J., "Solar Sail Mission Applications", AIAA 76−808, AIAA/AAS Astrodynamics Conference, San Diego, California, August 18−20, 1976. Wright, Jerome, Space Sailing, Gordon and Breach Science Publishers, Amsterdam, 1992.		
Sail Grand Unified Requirements		
Sail Configuration		Square sail with stays and deployable truss masts and booms.
Sail Dimensions	m	820x820
Sail Area	m^2	641200
Sail Film Thickness	µm	2
Sail & Structure Mass	kg	3382
Sail Areal Density	g/m^2	5.27
S/C+Payload Mass	kg	2000, 5000, 10000
Total Mass	kg	5382, 8382, 13382
Total Areal Density	g/m^2	8.4, 13.1, 20.9
Acceleration at 1 A.U.	mm/s^2	0.97, 0.62, 0.39
Launch Mass	kg	
Storage Volume	m^3	
Launch Vehicle		
Trip Time	years	Earth to Mars: Rndzvs/Flyby: 1.1/0.36, 1.4/0.55, 1.9/0.93
Sail Temp Max/Min	°C	Nominal for Earth to Mars and asteroid belt.
Other Environmental		
Spin Rate	deg/s	0
Front Optical Reflect.		
Front Optical Absorb.		
Front IR Emissivity		
Back IR Emissivity		
Upper Stage Maneuvers		
Station Keeping Man'vrs		
Trajectory Maneuvers		Steering vanes at 4 corners of the sail.
Science Maneuvers		
Miscellaneous		
Preparer and Date:		Benjamin L. Diedrich, July 29 1999 (using Wright & Warmke data).

Sail or Mission Name:	Martian Solar Sail Cargo Vehicle

Sail and Mission Description:

The sail and an attached Centaur derived booster stage are launched into a 250 km altitude circular Earth orbit by a space shuttle modified for increased payload. The payload is attached at a LEO space station and the booster places both in a 2000 km altitude circular orbit. The sail deploys and the booster is jettisoned. The sail delivers the payload to a 3000 km altitude circular Martian orbit.

References:

Staehle, Robert L., "An Expedition to Mars Employing Shuttle−Era Systems, Solar Sail and Aerocapture", Journal of the British Interplanetary Society, Vol. 35, pp. 327−335, 1982.

Sail Grand Unified Requirements

Sail Configuration		Square sail with stays and deployable truss masts and booms.
Sail Dimensions	m	2000x2000
Sail Area	m^2	$4x10^6$
Sail Film Thickness	µm	2.5
Sail & Structure Mass	kg	19200
Sail Areal Density	g/m^2	4.8
S/C+Payload Mass	kg	32000
Total Mass	kg	51200
Total Areal Density	g/m^2	12.8
Acceleration at 1 A.U.	mm/s^2	0.6
Launch Mass	kg	34500
Storage Volume	m^3	
Launch Vehicle		Space shuttle modified for 38500 kg LEO capacity.
Trip Time	years	4.2
Sail Temp Max/Min	°C	Nominal for Earth to Mars transfer.
Other Environmental		
Spin Rate	deg/s	0
Front Optical Reflect.		
Front Optical Absorb.		
Front IR Emissivity		
Back IR Emissivity		
Upper Stage Maneuvers		
Station Keeping Man'vrs		
Trajectory Maneuvers		20000 m^2 steering vanes at 4 corners of the sail.
Science Maneuvers		
Miscellaneous		

Preparer and Date:	Benjamin L. Diedrich, July 28 1999 (using Staehle data).

Sail or Mission Name:		Advanced Solar Sail Cargo Vessel

Sail and Mission Description:

An existing LEO space station has a 31000 kg sail construction platform attached to it by a 100 km tether, that aligns vertically by gravity gradient stabilization. Sail is constructed at the platform. The sail is tether released to an orbit where it is above, or can raise itself above atmospheric drag altitude. The payload is launched to an automated rendezvous with the sail at about 10,000 km altitude. The sail delivers the payload to a Mars rendezvous at Deimos, 23,500 km altitude. A tether release at Deimos sends the sail on an escape from Mars. The sail returns to Earth and assumes a 10,000 km altitude orbit for additional cargo.

References:

Garvey, J. M., "Space Station Options for Constructing Advanced Solar Sails Capable of Multiple Mars Missions", AIAA 87−1902, AIAA/SAE/ASME 23rd Joint Propulsion Conference, June 29−July 2, 1987, San Diego, California.

Sail Grand Unified Requirements

Sail Configuration		Square sail with stays and deployable truss masts and booms.
Sail Dimensions	m	2000x2000
Sail Area	m^2	$4x10^6$
Sail Film Thickness	µm	0.015−0.1 pure aluminum
Sail & Structure Mass	kg	4000
Sail Areal Density	g/m^2	1
S/C+Payload Mass	kg	32000
Total Mass	kg	36000
Total Areal Density	g/m^2	9
Acceleration at 1 A.U.	mm/s^2	0.95
Launch Mass	kg	
Storage Volume	m^3	
Launch Vehicle		
Trip Time	years	2 for Mars rendezvous, another 0.5 for Earth return.
Sail Temp Max/Min	°C	Nominal for Earth to Mars transfer.
Other Environmental		
Spin Rate	deg/s	0
Front Optical Reflect.		
Front Optical Absorb.		
Front IR Emissivity		
Back IR Emissivity		
Upper Stage Maneuvers		
Station Keeping Man'vrs		
Trajectory Maneuvers		20000 m^2 steering vanes at 4 corners of the sail.
Science Maneuvers		
Miscellaneous		
Preparer and Date:		Benjamin L. Diedrich, July 28 1999 (using Garvey data).

Sail or Mission Name:	Inflatable Solar Sail Microspacecraft Mars Mission	
Sail and Mission Description:		
Pegasus XL + Star 27 upper stage inject spacecraft into C3=0 Earth escape trajectory. Inflatable sail deploys and delivers spacecraft to rendezvous with Mars after 725 days.		
References:		
Frisbee, Robert H., and Brophy, John R., "Inflatable Solar Sails for Microspacraft Planetary Missions", NASA−JPL Workshop on Solar Sail Propulsion, Jet Propulsion Laboratory, Pasadena, California, February 13, 1997.		
Sail Grand Unified Requirements		
Sail Configuration		Inflatable ring sail based on Inflatable Antenna Experiment.
Sail Dimensions	m	100 diameter
Sail Area	m^2	7854
Sail Film Thickness	µm	
Sail & Structure Mass	kg	62
Sail Areal Density	g/m^2	8
S/C+Payload Mass	kg	48
Total Mass	kg	110
Total Areal Density	g/m^2	14
Acceleration at 1 A.U.	mm/s^2	0.6
Launch Mass	kg	110 + mass of Star 27 upper stage
Storage Volume	m^3	0.2 for payload, 0.2 for sail.
Launch Vehicle		Pegasus XL + Star 27 upper stage
Trip Time	years	2
Sail Temp Max/Min	°C	Nominal for Earth to Mars transfer
Other Environmental		
Spin Rate	deg/s	0
Front Optical Reflect.		
Front Optical Absorb.		
Front IR Emissivity		
Back IR Emissivity		
Upper Stage Maneuvers		
Station Keeping Man'vrs		
Trajectory Maneuvers		
Science Maneuvers		
Miscellaneous		
Preparer and Date:	Benjamin L. Diedrich, July 27 1999 (using Frisbee and Brophy data).	

Sail or Mission Name:	Auburn University Mars Solar Sail	
Sail and Mission Description:		
Spacecraft launches as a secondary payload on a launch of a larger spacecraft. An attached rocket motor sends the spacecraft on an Earth escape trajectory. Spacecraft is spun to 100 rpm to deploy the wrapped booms and sail. Once fully deployed, UV radiation cures the booms. Attitude control system removes residual 0.78 rpm spin. Sail delivers spacecraft to Mars rendezvous.		
References:		
Eastridge, Richard, et. al., "Design of a solar sail mission to Mars − Final Report", CASI Accession Number: 90N11771, Report Number: NASA−CR−186045, May 5, 1989.		
Sail Grand Unified Requirements		
Sail Configuration		Spin deployed, 3−axis operation square sail with UV cured booms.
Sail Dimensions	m	160x160
Sail Area	m^2	25992
Sail Film Thickness	µm	
Sail & Structure Mass	kg	227
Sail Areal Density	g/m^2	8.7
S/C+Payload Mass	kg	185
Total Mass	kg	412
Total Areal Density	g/m^2	15.8
Acceleration at 1 A.U.	mm/s^2	0.51
Launch Mass	kg	487
Storage Volume	m^3	1.54
Launch Vehicle		
Trip Time	years	~1.6
Sail Temp Max/Min	°C	Nominal for Earth to Mars.
Other Environmental		
Spin Rate	deg/s	600 (100 rpm) before deployment,4.7 (0.78 rpm) after, 0 in operation
Front Optical Reflect.		
Front Optical Absorb.		
Front IR Emissivity		
Back IR Emissivity		
Upper Stage Maneuvers		
Station Keeping Man'vrs		
Trajectory Maneuvers		
Science Maneuvers		
Miscellaneous		
Preparer and Date:	Benjamin L. Diedrich, July 28 1999 (using Eastridge et. al. data).	

Sail or Mission Name:	ODISSEE

Sail and Mission Description:

ODISSEE (Orbital Demonstration of an Innovative Solar Sail driven Expandable structure Experiment) is a solar sail demonstration mission for operation from GTO to Earth escape. Spacecraft is delivered to GTO as an auxiliary payload on the ASAP ring of the Ariane V. Coilable control boom deploys, separating bus from stowed sail. Booms deploy while pulling out the folded sails. Perigee is raised to 1400 km altitude over the first 110 days to prevent atmospheric drag. A steering law that maximizes the increase of the semi−major axis sends the spacecraft to a lunar polar flyby by 550 days, and Earth escape in 630 days.

References:

McInnes, Colin R., Solar Sailing: Technology, Dynamics, and Mission Applications, Springer−Verlag, London, pp. 100, 107−109, 1999.

Sail Grand Unified Requirements

Sail Configuration		Square sail with carbon fiber reinforced plastic profile booms.
Sail Dimensions	m	40 x 40
Sail Area	m^2	1600
Sail Film Thickness	µm	7.6 Kapton substrate, 0.1 Al reflector, 0.01 Cr emitter.
Sail & Structure Mass	kg	41
Sail Areal Density	g/m^2	25.6
S/C+Payload Mass	kg	36
Total Mass	kg	77
Total Areal Density	g/m^2	48.1
Acceleration at 1 A.U.	mm/s^2	0.16
Launch Mass	kg	77
Storage Volume	m^3	0.29
Launch Vehicle		Ariane V
Trip Time	years	1.5 to lunar flyby, 1.7 to Earth escape.
Sail Temp Max/Min	°C	Nominal for GTO, lunar flyby, and Earth escape.
Other Environmental		
Spin Rate	deg/s	0
Front Optical Reflect.		
Front Optical Absorb.		
Front IR Emissivity		
Back IR Emissivity		
Upper Stage Maneuvers		
Station Keeping Man'vrs		Center−of−mass displacement, nitrogen gas thrusters.
Trajectory Maneuvers		Included.
Science Maneuvers		Included.
Miscellaneous		

Preparer and Date:	Benjamin L. Diedrich, July 27 1999 (Using McInnes data).

Sail or Mission Name:	LEO Operating Slat Solar Sail

Sail and Mission Description:

Spacecraft starting from 90° inclination 350 km altitude orbit sails to 1000 km altitude in 20 days in edge−on orientation to the atmosphere, then sails by tilting the entire sail to Earth escape in 198 days. Sail is a hexagon composed of six triangular sections. Each section is split into thin slats which can be rotated like the slats of a window blind. The sail rotates, and cyclic rotation of the slats of each section are used for control. This allows full control while sailing the spacecraft edge−on to the atmosphere for reduced drag in LEO. Shields at the outer edges of the sail prevent atmospheric interaction with the rest of the sail.

References:

Fieseler, Paul D., "A Method for Solar Sailing in a Low Earth Orbit", Acta Astronautica, Vol. 43, No. 9−10, pp. 531−541, 1998.

Sail Grand Unified Requirements

Sail Configuration		Spin stabilized. Hexagonal with movable slats and drag shield.
Sail Dimensions	m	250 diameter
Sail Area	m^2	50000
Sail Film Thickness	µm	2.5
Sail & Structure Mass	kg	314
Sail Areal Density	g/m^2	6.28
S/C+Payload Mass	kg	50
Total Mass	kg	364
Total Areal Density	g/m^2	7.28
Acceleration at 1 A.U.	mm/s^2	1.1
Launch Mass	kg	
Storage Volume	m^3	
Launch Vehicle		
Trip Time	years	0.54
Sail Temp Max/Min	°C	Nominal for 350 km LEO to Earth escape.
Other Environmental		
Spin Rate	deg/s	
Front Optical Reflect.		
Front Optical Absorb.		
Front IR Emissivity		
Back IR Emissivity		
Upper Stage Maneuvers		
Station Keeping Man'vrs		
Trajectory Maneuvers		Tilting sail slats.
Science Maneuvers		
Miscellaneous		

Preparer and Date:	Benjamin L. Diedrich, July 28 1999 (using Fieseler data).

Sail or Mission Name:	LEO Operating Ramp Solar Sail

Sail and Mission Description:

Spacecraft starting from 90° inclination 350 km altitude orbit sails to 1000 km altitude in 27 days in edge−on orientation to the atmosphere, then sails by tilting the entire sail to Earth escape in 235 days. The sail is square and supported by 4 booms. The sail surface is composed of slanted ramps, all oriented with the same angle of tilt and in the same direction. The tilted ramps provide a thrust vector parallel to the plane of the sail for raising the orbit of a sail in low Earth orbit that is oriented edge−on to the atmosphere for reduced drag. Thus, the direction of this lateral thrust component is controlled by orientation of the sail normal axis. At higher elevations, the entire sail tilts for thrust vector control.

References:

Fieseler, Paul D., "A Method for Solar Sailing in a Low Earth Orbit", Acta Astronautica, Vol. 43, No. 9−10, pp. 531−541, 1998.

Sail Grand Unified Requirements

Sail Configuration		Square sail with moveable ramp sail surfaces and drag shield.
Sail Dimensions	m	225x225
Sail Area	m^2	50000
Sail Film Thickness	µm	2.5
Sail & Structure Mass	kg	516
Sail Areal Density	g/m^2	10.3
S/C+Payload Mass	kg	50
Total Mass	kg	566
Total Areal Density	g/m^2	11.3
Acceleration at 1 A.U.	mm/s^2	0.72
Launch Mass	kg	
Storage Volume	m^3	
Launch Vehicle		
Trip Time	years	0.64
Sail Temp Max/Min	°C	Nominal for 350 km LEO to Earth escape.
Other Environmental		
Spin Rate	deg/s	0
Front Optical Reflect.		
Front Optical Absorb.		
Front IR Emissivity		
Back IR Emissivity		
Upper Stage Maneuvers		
Station Keeping Man'vrs		
Trajectory Maneuvers		Tilting sail ramps.
Science Maneuvers		
Miscellaneous		

Preparer and Date:	Benjamin L. Diedrich, July 28 1999 (using Fieseler data).

Sail or Mission Name:	Hollow Body Solar Sail

Sail and Mission Description:

Ultra−thin rotationally symmetric inflatable body solar sail makes a 1.7 solar radii approach to the sun for a final escape velocity from the solar system at 434.3 km/s. Can deliver a radio telescope to the gravitational lens, at 550 AU. Configuration is a flat disk reflector supported by a hollow inflatable body on the dark side and a tensile hoop around the perimeter. The payload rests in the center of the back side, pressing it down inside the inflatable body. A reflective area around the payload reduces thermal loads. The reflector is an alloy of molybdenum, and the non−reflecting body is an alloy of tungsten.

References:

Strobl, Jorg, "The Hollow Body Solar Sail", Journal of the British Interplanetary Society, Vol. 42, pp. 515−520, 1989.
Strobl, Jorg, "The Hollow Body Solar Sail as a Possible Transporter of a Radio Telescope", Journal of the British Interplanetary Society, Vol. 47, pp. 67−70, 1994.

Sail Grand Unified Requirements

Sail Configuration		Non−rotating circular inflatable body sail.
Sail Dimensions	m	1786 diameter
Sail Area	m^2	$2.5x10^6$
Sail Film Thickness	µm	0.053 reflector, 0.029 minimum for dark side skin.
Sail & Structure Mass	kg	5342
Sail Areal Density	g/m^2	2.14
S/C+Payload Mass	kg	1000
Total Mass	kg	6342
Total Areal Density	g/m^2	2.54
Acceleration at 1 A.U.	mm/s^2	3.41
Launch Mass	kg	
Storage Volume	m^3	
Launch Vehicle		
Trip Time	years	5.5
Sail Temp Max/Min	°C	2003 reflector, 1641 back side, 583 at payload.
Other Environmental		
Spin Rate	deg/s	0
Front Optical Reflect.		
Front Optical Absorb.		
Front IR Emissivity		
Back IR Emissivity		
Upper Stage Maneuvers		
Station Keeping Man'vrs		Reflective flaps attached to edge.
Trajectory Maneuvers		Included.
Science Maneuvers		Included.
Miscellaneous		
Preparer and Date:		Benjamin L. Diedrich, July 26 1999 (Using Strobl data)

Sail or Mission Name:	Earth Polar Observer − Mission A

Sail and Mission Description:

Solar sail stations a payload high above the north pole at the summer solstice at an artificial Lagrange point on the day side of the Earth. Use for low resolution polar imaging, high lattitude communications or possibly a solar physics platform with a single ground station.

1. Polar Distance 3.8 million km (596 Earth radii) − minimises required sail loading.

2. Minimum mission with a 50 kg payload and relatively poor sail + structure areal density.

3. Sail has front side reflectivity of 0.9 and a rear emissivity of 0.64 (Chromium backing).

References:

McInnes, C.R.: 'Artificial Lagrange Points for a Non−Perfect Solar Sail', Journal of Guidance, Control and Dynamics, Vol. 22, No. 1, pp. 185−187, 1999.

McInnes, C.R.: 'The POLAR OBSERVER Mission: Initial Definition − Consultants report to NOAA/OSD', NOAA NE−EK1000−7−00813, February 1999.

Sail Grand Unified Requirements

Sail Configuration		Square sail with inflatable booms
Sail Dimensions	m	86 x 86
Sail Area	m^2	7,340
Sail Film Thickness	µm	TBD
Sail & Structure Mass	kg	73.4
Sail Areal Density	g/m^2	10
S/C+Payload Mass	kg	50
Total Mass	kg	123.4
Total Areal Density	g/m^2	16.8
Acceleration at 1 A.U.	mm/s^2	0.54
Launch Mass	kg	123.4
Storage Volume	m^3	TBD
Launch Vehicle		Pegasus XL/Star27
Trip Time	years	TBD
Sail Temp Max/Min	°C	−50.6
Other Environmental		TBD
Spin Rate	deg/s	0
Front Optical Reflect.		0.9
Front Optical Absorb.		TBD
Front IR Emissivity		TBD
Back IR Emissivity		0.64
Upper Stage Maneuvers		Delivery of stowed sail to C3>=0 Earth escape trajectory
Station Keeping Man'vrs		Sail control to achieve stability when on station
Trajectory Maneuvers		Sprial from Earth escape to station
Science Maneuvers		None
Miscellaneous		Sail pitch angle 48 deg to Sun−line on station

Preparer and Date:	Colin R McInnes, 27 July 1999

Sail or Mission Name:	Earth Polar Observer − Mission B

Sail and Mission Description:

Solar sail stations a payload high above the north pole at the summer solstice at an artificial Lagrange point on the day side of the Earth. Use for low resolution polar imaging, high lattitude communications or possibly a solar physics platform with a single ground station.

1. Polar Distance 3.8 million km (596 Earth radii) − minimises required sail loading.

2. Larger mission with a 150 kg payload and good sail + structure areal density.

3. Sail has front side reflectivity of 0.9 and a rear emissivity of 0.64 (Chromium backing).

References:

McInnes, C.R.: 'Artificial Lagrange Points for a Non−Perfect Solar Sail', Journal of Guidance, Control and Dynamics, Vol. 22, No. 1, pp. 185−187, 1999.

McInnes, C.R.: 'The POLAR OBSERVER Mission: Initial Definition − Consultants report to NOAA/OSD', NOAA NE−EK1000−7−00813, February 1999.

Sail Grand Unified Requirements		
Sail Configuration		Square sail with CFRP booms
Sail Dimensions	m	113 x 113
Sail Area	m^2	12,703
Sail Film Thickness	µm	TBD
Sail & Structure Mass	kg	63.5
Sail Areal Density	g/m^2	5
S/C+Payload Mass	kg	150
Total Mass	kg	213.5
Total Areal Density	g/m^2	16.8
Acceleration at 1 A.U.	mm/s^2	0.54
Launch Mass	kg	213.5
Storage Volume	m^3	TBD
Launch Vehicle		Taurus/Star27
Trip Time	years	TBD
Sail Temp Max/Min	°C	−50.6
Other Environmental		TBD
Spin Rate	deg/s	0
Front Optical Reflect.		0.9
Front Optical Absorb.		TBD
Front IR Emissivity		TBD
Back IR Emissivity		0.64
Upper Stage Maneuvers		Delivery of stowed sail to C3>=0 Earth escape trajectory
Station Keeping Man'vrs		Sail control to achieve stability when on station
Trajectory Maneuvers		Sprial from Earth escape to station
Science Maneuvers		None
Miscellaneous		Sail pitch angle 48 deg to Sun−line on station
Preparer and Date:	Colin R McInnes, 27 July 1999	

Sail or Mission Name:	Earth Polar Observer − Mission C

Sail and Mission Description:

Solar sail stations a payload high above the north pole at the summer solstice at an artificial Lagrange point on the day side of the Earth. Use for low resolution polar imaging, high lattitude communications or possibly a solar physics platform with a single ground station.

1. Polar Distance 2.5 million km (392 Earth radii) − requires good sail performance.

2. Close mission with a 150 kg payload and good sail + structure areal density.

3. Sail has front side reflectivity of 0.9 and a rear emissivity of 0.64 (Chromium backing).

References:

McInnes, C.R.: 'Artificial Lagrange Points for a Non−Perfect Solar Sail', Journal of Guidance, Control and Dynamics, Vol. 22, No. 1, pp. 185−187, 1999.

McInnes, C.R.: 'The POLAR OBSERVER Mission: Initial Definition − Consultants report to NOAA/OSD', NOAA NE−EK1000−7−00813, February 1999.

Sail Grand Unified Requirements		
Sail Configuration		Square sail with CFRP booms
Sail Dimensions	m	199 x 199
Sail Area	m^2	39,621
Sail Film Thickness	µm	TBD
Sail & Structure Mass	kg	198.1
Sail Areal Density	g/m^2	5
S/C+Payload Mass	kg	150
Total Mass	kg	348.1
Total Areal Density	g/m^2	8.8
Acceleration at 1 A.U.	mm/s^2	1.04
Launch Mass	kg	194.2
Storage Volume	m^3	TBD
Launch Vehicle		Taurus/Star27
Trip Time	years	TBD
Sail Temp Max/Min	°C	−75.26
Other Environmental		TBD
Spin Rate	deg/s	0
Front Optical Reflect.		0.9
Front Optical Absorb.		TBD
Front IR Emissivity		TBD
Back IR Emissivity		0.64
Upper Stage Maneuvers		Delivery of stowed sail to C3>=0 Earth escape trajectory
Station Keeping Man'vrs		Sail control to achieve stability when on station
Trajectory Maneuvers		Sprial from Earth escape to station
Science Maneuvers		None
Miscellaneous		Sail pitch angle 65 deg to Sun−line on station
Preparer and Date:		Colin R McInnes, 27 July 1999

Sail or Mission Name:	Sub L1 Solar Storm Warning − Mission A

Sail and Mission Description:

Solar sail stations a payload sunward of the classical L1 interior Lagrange point in the Sun−Earth system. The payload is also stationed off the Sun−Earth line to avoid the solar radio disk, as viewed from Earth. Use to provide early warning of Earth bound coronal mass ejections with warining time significantly better than that available from the classical L1 point (ACE mission).

1. Solar distance 0.98 AU, 0.002 AU from Sun−line (Geostorm/ST−5 baseline).

2. Minimum mission with a 50 kg payload and relatively poor sail + structure areal density.

3. Sail has front side reflectivity of 0.9 and a rear emissivity of 0.64 (Chromium backing).

References:

West, J.L.: 'NOAA/DoD/NASA Geostorm Warning Mission', JPL D−13986, October 1996.

McInnes, C.R.: 'Solar Sail Force Model and Up−Dated Performance Requirements for the GEOSTORM Warning Mission − Consultants report to NASA/JPL', NOAA NE−EK1000−7−00813, March 1998 (University of Glasgow, Department of Aerospace Engineering Report 9805).

Sail Grand Unified Requirements

Sail Configuration		Square sail with inflatable booms
Sail Dimensions	m	52 x 52
Sail Area	m^2	2,753
Sail Film Thickness	µm	TBD
Sail & Structure Mass	kg	27.5
Sail Areal Density	g/m^2	10
S/C+Payload Mass	kg	50
Total Mass	kg	77.5
Total Areal Density	g/m^2	28.16
Acceleration at 1 A.U.	mm/s^2	0.32
Launch Mass	kg	77.5
Storage Volume	m^3	TBD
Launch Vehicle		Pegasus XL/Star27
Trip Time	years	TBD
Sail Temp Max/Min	°C	−25.7
Other Environmental		TBD
Spin Rate	deg/s	0
Front Optical Reflect.		0.9
Front Optical Absorb.		TBD
Front IR Emissivity		TBD
Back IR Emissivity		0.64
Upper Stage Maneuvers		Delivery of stowed sail to C3>=0 Earth escape trajectory
Station Keeping Man'vrs		Sail control to achieve stability when on station
Trajectory Maneuvers		Sprial from Earth escape to station
Science Maneuvers		None
Miscellaneous		Sail pitch angle 0.8 deg to Sun−line on station
Preparer and Date:	Colin R McInnes, 28 July 1999	

Sail or Mission Name:	Sub L1 Solar Storm Warning − Mission B

Sail and Mission Description:

Solar sail stations a payload sunward of the classical L1 interior Lagrange point in the Sun−Earth system. The payload is also stationed off the Sun−Earth line to avoid the solar radio disk, as viewed from Earth. Use to provide early warning of Earth bound coronal mass ejections with warining time significantly better than that available from the classical L1 point (ACE mission).

1. Solar distance 0.95 AU, 0.005 AU from Sun−line (< Geostorm/ST−5 baseline).

2. Follow−on mission with a 50 kg payload and good sail + structure areal density.

3. Sail has front side reflectivity of 0.9 and a rear emissivity of 0.64 (Chromium backing).

References:

West, J.L.: 'NOAA/DoD/NASA Geostorm Warning Mission', JPL D−13986, October 1996.

McInnes, C.R.: 'Solar Sail Force Model and Up−Dated Performance Requirements for the GEOSTORM Warning Mission − Consultants report to NASA/JPL', NOAA NE−EK1000−7−00813, March 1998 (University of Glasgow, Department of Aerospace Engineering Report 9805).

Sail Grand Unified Requirements

Sail Configuration		Square sail with CFRP booms
Sail Dimensions	m	97 x 97
Sail Area	m^2	9,493
Sail Film Thickness	µm	TBD
Sail & Structure Mass	kg	47.5
Sail Areal Density	g/m^2	5
S/C+Payload Mass	kg	50
Total Mass	kg	97.5
Total Areal Density	g/m^2	10.3
Acceleration at 1 A.U.	mm/s^2	0.89
Launch Mass	kg	97.5
Storage Volume	m^3	TBD
Launch Vehicle		Pegasus XL/Star27
Trip Time	years	TBD
Sail Temp Max/Min	°C	−21.8
Other Environmental		TBD
Spin Rate	deg/s	0
Front Optical Reflect.		0.9
Front Optical Absorb.		TBD
Front IR Emissivity		TBD
Back IR Emissivity		0.64
Upper Stage Maneuvers		Delivery of stowed sail to C3>=0 Earth escape trajectory
Station Keeping Man'vrs		Sail control to achieve stability when on station
Trajectory Maneuvers		Sprial from Earth escape to station
Science Maneuvers		None
Miscellaneous		Sail pitch angle <0.1 deg to Sun−line on station

Preparer and Date:	Colin R McInnes, 28 July 1999

Sail or Mission Name:	Sub L1 Solar Storm Warning − Mission C

Sail and Mission Description:

Solar sail stations a payload sunward of the classical L1 interior Lagrange point in the Sun−Earth system. The payload is also stationed off the Sun−Earth line to avoid the solar radio disk, as viewed from Earth. Use to provide early warning of Earth bound coronal mass ejections with warining time significantly better than that available from the classical L1 point (ACE mission).

1. Solar distance 0.90 AU, 0.009 AU from Sun−line (<< Geostorm/ST−5 baseline).

2. Advanced mission with a 50 kg payload and low sail + structure areal density.

3. Sail has front side reflectivity of 0.9 and a rear emissivity of 0.64 (Chromium backing).

References:

West, J.L.: 'NOAA/DoD/NASA Geostorm Warning Mission', JPL D−13986, October 1996.

McInnes, C.R.: 'Solar Sail Force Model and Up−Dated Performance Requirements for the GEOSTORM Warning Mission − Consultants report to NASA/JPL', NOAA NE−EK1000−7−00813, March 1998 (University of Glasgow, Department of Aerospace Engineering Report 9805).

Sail Grand Unified Requirements

Sail Configuration		Square sail with CFRP booms
Sail Dimensions	m	145 x 145
Sail Area	m^2	21,115
Sail Film Thickness	µm	TBD
Sail & Structure Mass	kg	63.3
Sail Areal Density	g/m^2	3
S/C+Payload Mass	kg	50
Total Mass	kg	113.3
Total Areal Density	g/m^2	5.4
Acceleration at 1 A.U.	mm/s^2	1.70
Launch Mass	kg	113.3
Storage Volume	m^3	TBD
Launch Vehicle		Pegasus XL/Star27
Trip Time	years	TBD
Sail Temp Max/Min	°C	−15.0
Other Environmental		TBD
Spin Rate	deg/s	0
Front Optical Reflect.		0.9
Front Optical Absorb.		TBD
Front IR Emissivity		TBD
Back IR Emissivity		0.64
Upper Stage Maneuvers		Delivery of stowed sail to C3>=0 Earth escape trajectory
Station Keeping Man'vrs		Sail control to achieve stability when on station
Trajectory Maneuvers		Sprial from Earth escape to station
Science Maneuvers		None
Miscellaneous		Sail pitch angle <0.1 deg to Sun−line on station

Preparer and Date:	Colin R McInnes, 28 July 1999

Sail or Mission Name:	Sun−Centred Non−Keplerian Orbit − Mission A

Sail and Mission Description:

Solar sail stations a payload on a circular, Sun−centred orbit displaced high above, and parallel to, the ecliptic plane with a 1 year orbit period. Use for 3D solar physics, imaging Earth bound coronal mass ejections against dark sky, searching for near Earth asteroids with ideal phase angle and possibly communications with spacecraft in conjunction with Earth on other side of the Sun.

1. 0.5 AU radius orbit, displaced 0.5 AU above the ecliptic plane.

2. Minimum mission with a 50 kg payload and very low sail + structure areal density.

3. Sail has front side reflectivity of 0.9 and a rear emissivity of 0.64 (Chromium backing).

References:

McInnes, C.R.: 'Mission Applications for High Performance Solar Sails', IAF−ST−W.1.05, 3rd IAA Conference on Low Cost Planetary Missions, California Institute of Technology, Pasadena, 27th April − 1st May 1998.

McInnes, C.R.: 'Passive Control for Displaced Solar Sail Orbits', Journal of Guidance, Control and Dynamics, Vol. 21, No. 6, pp. 975−982, 1998.

Sail Grand Unified Requirements

Sail Configuration		Spinning disc sail
Sail Dimensions	m	158 (radius)
Sail Area	m^2	78,040
Sail Film Thickness	µm	TBD
Sail & Structure Mass	kg	78
Sail Areal Density	g/m^2	1
S/C+Payload Mass	kg	50
Total Mass	kg	128.0
Total Areal Density	g/m^2	1.64
Acceleration at 1 A.U.	mm/s^2	5.6
Launch Mass	kg	128.0
Storage Volume	m^3	TBD
Launch Vehicle		Pegasus XL/Star27
Trip Time	years	TBD
Sail Temp Max/Min	°C	19.7
Other Environmental		TBD
Spin Rate	deg/s	TBD
Front Optical Reflect.		0.9
Front Optical Absorb.		TBD
Front IR Emissivity		TBD
Back IR Emissivity		0.64
Upper Stage Maneuvers		Delivery of stowed sail to C3>=0 Earth escape trajectory
Station Keeping Man'vrs		Sail control to achieve stability when on orbit
Trajectory Maneuvers		Sprial from Earth escape to displaced orbit
Science Maneuvers		None
Miscellaneous		Sail pitch angle 13 deg to Sun−line on orbit

Preparer and Date:	Colin R McInnes, 27 July 1999

Sail or Mission Name:	Sun−Centred Non−Keplerian Orbit − Mission B

Sail and Mission Description:

Solar sail stations a payload on a circular, Sun−centred orbit displaced high above, and parallel to, the ecliptic plane with a 1 year orbit period. Use for 3D solar physics, imaging Earth bound coronal mass ejections against dark sky, searching for near Earth asteroids with ideal phase angle and possibly communications with spacecraft in conjunction with Earth on other side of the Sun.

1. 0.2 AU radius orbit, displaced 0.2 AU above the ecliptic plane.

2. Close mission with a 50 kg payload and very low sail + structure areal density.

3. Sail has front side reflectivity of 0.9 and a rear emissivity of 0.64 (Chromium backing).

References:

McInnes, C.R.: 'Mission Applications for High Performance Solar Sails', IAF−ST−W.1.05, 3rd IAA Conference on Low Cost Planetary Missions, California Institute of Technology, Pasadena, 27th April − 1st May 1998.

McInnes, C.R.: 'Passive Control for Displaced Solar Sail Orbits', Journal of Guidance, Control and Dynamics, Vol. 21, No. 6, pp. 975−982, 1998.

Sail Grand Unified Requirements

Sail Configuration		Spinning disc sail
Sail Dimensions	m	184 (radius)
Sail Area	m^2	106,593
Sail Film Thickness	µm	TBD
Sail & Structure Mass	kg	106.6
Sail Areal Density	g/m^2	1
S/C+Payload Mass	kg	50
Total Mass	kg	156.6
Total Areal Density	g/m^2	1.47
Acceleration at 1 A.U.	mm/s^2	6.2
Launch Mass	kg	156.6
Storage Volume	m^3	TBD
Launch Vehicle		Taurus/Star27
Trip Time	years	TBD
Sail Temp Max/Min	°C	192.8
Other Environmental		TBD
Spin Rate	deg/s	TBD
Front Optical Reflect.		0.9
Front Optical Absorb.		TBD
Front IR Emissivity		TBD
Back IR Emissivity		0.64
Upper Stage Maneuvers		Delivery of stowed sail to C3>=0 Earth escape trajectory
Station Keeping Man'vrs		Sail control to achieve stability when on orbit
Trajectory Maneuvers		Sprial from Earth escape to displaced orbit
Science Maneuvers		None
Miscellaneous		Sail pitch angle 0.7 deg to Sun−line on orbit

Preparer and Date:	Colin R McInnes, 27 July 1999

Sail or Mission Name:	Sun−Centred Non−Keplerian Orbit − Mission C

Sail and Mission Description:

Solar sail stations a payload on a circular, Sun−centred orbit displaced high above, and parallel to, the ecliptic plane with a 1 year orbit period. Use for 3D solar physics, imaging Earth bound coronal mass ejections against dark sky, searching for near Earth asteroids with ideal phase angle and possibly communications with spacecraft in conjunction with Earth on other side of the Sun.

1. 0.5 AU radius orbit, displaced 0.5 AU above the ecliptic plane.

2. Advanced mission with a 150 kg payload and ultra low sail + structure areal density.

3. Sail has front side reflectivity of 0.9 and a rear emissivity of 0.64 (Chromium backing).

References:

McInnes, C.R.: 'Mission Applications for High Performance Solar Sails', IAF−ST−W.1.05, 3rd IAA Conference on Low Cost Planetary Missions, California Institute of Technology, Pasadena, 27th April − 1st May 1998.

McInnes, C.R.: 'Passive Control for Displaced Solar Sail Orbits', Journal of Guidance, Control and Dynamics, Vol. 21, No. 6, pp. 975−982, 1998.

Sail Grand Unified Requirements

Sail Configuration		Spinning disc sail
Sail Dimensions	m	176 (radius)
Sail Area	m^2	97,314
Sail Film Thickness	µm	TBD
Sail & Structure Mass	kg	9.7
Sail Areal Density	g/m^2	0.1
S/C+Payload Mass	kg	150
Total Mass	kg	159.7
Total Areal Density	g/m^2	1.64
Acceleration at 1 A.U.	mm/s^2	5.6
Launch Mass	kg	159.7
Storage Volume	m^3	TBD
Launch Vehicle		Taurus/Star27
Trip Time	years	TBD
Sail Temp Max/Min	°C	19.7
Other Environmental		TBD
Spin Rate	deg/s	TBD
Front Optical Reflect.		0.9
Front Optical Absorb.		TBD
Front IR Emissivity		TBD
Back IR Emissivity		0.64
Upper Stage Maneuvers		Delivery of stowed sail to C3>=0 Earth escape trajectory
Station Keeping Man'vrs		Sail control to achieve stability when on orbit
Trajectory Maneuvers		Sprial from Earth escape to displaced orbit
Science Maneuvers		None
Miscellaneous		Sail pitch angle 13 deg to Sun−line on orbit

Preparer and Date:	Colin R McInnes, 27 July 1999