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SMART SPACE TECHNOLOGY

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Team Encounter Solar Sails

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TEAM ENCOUNTER SOLAR SAILS

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Abstract

The Team Encounter solar sail, scheduled for launch late 2006, will escape the solar system with 3 kilograms of commercial payload. The payload will include messages, drawings, photographs, and biological signatures submitted by up to 4.5 million participants. Large logos will also be painted on the sail surface. The sailcraft will be 4900 m^2, utilizing the thinnest material available, 0.9 µm Mylar. Configuration is square, with 15.4 g/m inflatable-rigidizable beams as the structural members. The vehicle will use beam tip vanes for 3-axis attitude stabilization & control. After launch on Ariane 5 as a micro-ASAP payload, conventional propulsion will be used to escape Earth orbit. The sailcraft will then be deployed, and fly out of the solar system on its own, without gravity assists. The areal density, including payload, will be 3.63 g/m^2, giving a characteristic acceleration of 2.26 mm/sec^2. Solar escape velocity will be achieved in 3.75 years at 11.6 AU. Fabrication is getting under way on Flight One, the 2005 precursor to the solar escape mission. Flight One will test sail deployment, sailcraft structural integrity, and the functionality of the sailcraft attitude control system (ACS). After the tests, NOAA may use the sail to fly into a non-Keplerian pole sitter orbit. The Flight One sail will be a 625 m^2 segment of the solar escape design, with a characteristic acceleration of 0.42 mm/sec^2, including payloads. L'Garde, Inc. is building the sailcraft, and Microsat Systems is building the sailcraft ACS and carrier. There has been much progress to date, including deployment and structural tests on a 7.6 m boom at L'Garde, as well as deployment and dynamics tests in Langley's 16 m vacuum chamber. A 3 m X 3 m and a 5.7 m X 5.7 m sail quadrant, both 0.9 µm thick, have been fabricated and deployed at L'Garde. Radiation tests have been conducted on the material.

This paper details the design, progress to date, and future plans for this high-performing sailcraft.

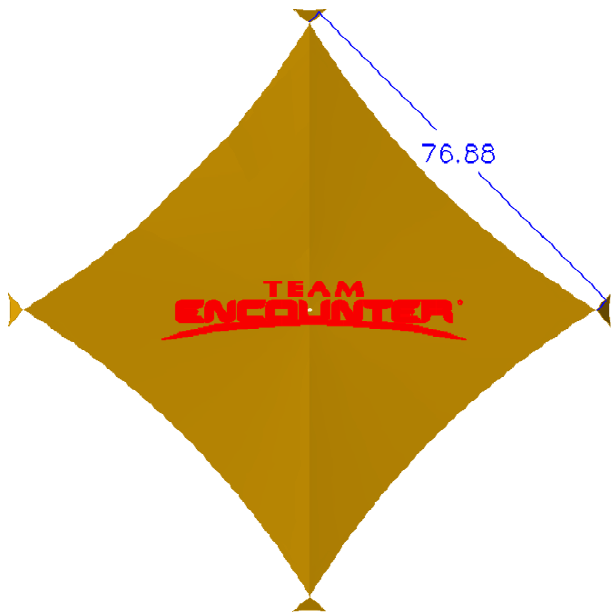

Figure 1. 4900 m^2 Solar Escape "Starship"

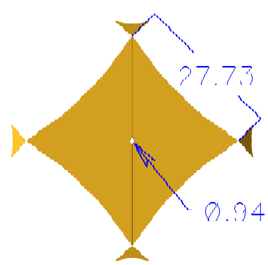

Figure 2. 625 m^2 Flight One Sailcraft

Three Technical Requirements

Team Encounter has a "revenue-driven" approach to the design of this mission vehicle. A very simple set of technical requirements were presented:

3 kg payload
solar escape velocity
Ariane 5 µASAP secondary

There were some immediate implications. First of all, since the primary Ariane payload would have priority, launch date could not be guaranteed, so planetary flyby's were out of the question. Without flyby's, and with the 120 kg Ariane µASAP launch mass limit, chemical and electric propulsion were not feasible. Thus the idea was borne to try a solar sail.

A small carrier spacecraft would be required to orient and command the sail for deployment, and to bear launch loads. This carrier mass has to be jettisoned after sail deployment in order to make it to solar escape. With it are jettisoned the support systems for sailcraft deployment, primarily the inflation system.

Cameras were placed on the carrier to provide live streaming video over the internet of the sail pulling away from the jettisoned carrier. Large sponsor logos were also added to the sail. Finally, an EPROM was put onboard the sailcraft for last-minute uploading of messages prior to release from the carrier. These all provide additional commercial revenue streams.

It was clear that spiraling out of Earth orbit using a solar sail would be difficult the first time out. Reasonably lightweight chemical motors could provide Earth escape velocity, then be jettisoned with the carrier. However, the motor would easily be the largest component in the tiny Ariane µASAP slot (60 cm X 60 cm X 71 cm). Fortunately, L'Garde's beam design allows the stiff beam footprint to be collapsed for storage, forming a table-shaped packaging envelope. The motor could be fit "under the table", along with the other carrier components.

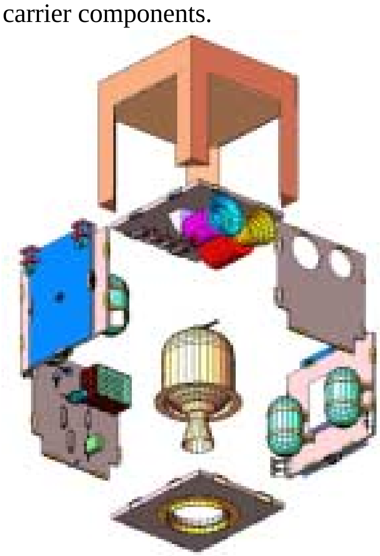

Figure 3. Carrier Packages Under the Sail "Table"

In order to achieve solar escape with its inert 3 kg payload, only the bare necessities could be brought along with the sailcraft. The sailcraft was required to achieve solar escape velocity, but it could do so in any direction. Direct validation was not required either, so long as it could be shown the sail would escape with reasonable certainty. Therefore, no navigation or communications systems were necessary.

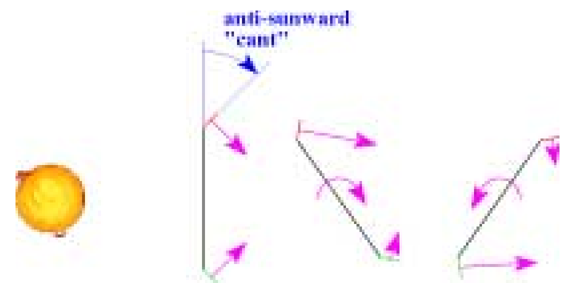

Figure 4. Passive Stabilization due to Canted Vanes

Passive attitude stabilization is provided in two axes by virtue of the four beam tip vanes, which are "Canted" anti-sunward. Analysis has shown that sailcraft structural damping will result in rigid-body damping of the vehicle. Therefore, with vanes, the sail could be held normal to the sun-sail line without the mass of a sailcraft attitude control system (or its solar arrays). However, a lightness factor (force due to solar pressure ÷ solar gravity) of ≥ 0.5 would be required to escape, and the best lightness factor that could be accomplished would be perhaps 0.4. Therefore, the sail will have to be flown with its normal at some "Sun Incidence" angle to the sun-sail line, at least early in the trajectory. As it is not possible to passively stabilize "Top" rotation about the sun-sail line, active Top angle stabilization is necessary, in order to keep the sail from deviating out of the plane of the ecliptic when its Sun Incidence angle is non-zero. This is done by by differentially "Twirling" the port and starboard vanes about their boom axis. A star tracker, controller, vane actuators, and solar arrays are necessary.

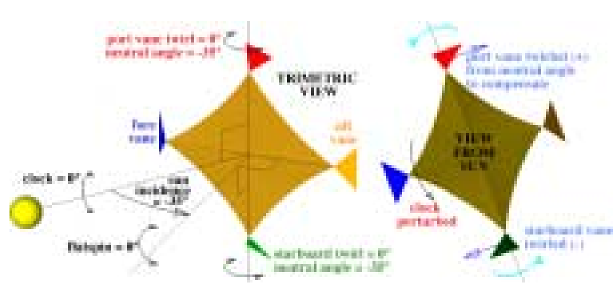

Figure 5. Active Top Angle Stabilization via Vanes

Optimum Sun Incidence angle is approximately -35° early in the trajectory, but drops to 0° after about a year, when the sail is at 3.8 AU, and is essentially flying radially away from the sun. This is fortunate, as operation of an active control system beyond 4 AU begins to require solar arrays of unreasonable mass. Therefore, timers will be used to vary the Cant angles of the fore and aft vanes, retrimming the passively stable sailcraft Sun Incidence angle from an initial value of -35° down to 0° after one year. This is called the "tack" phase. During this time, the Top angle stabilization system will actively maintain 0° about the sun-sail line. After a year, the sailcraft will power down and fly normal to the sun-sail line (0° Sun Incidence), passively stable, until it achieves and exceeds local solar escape velocity (the "terminal" phase). Top is allowed to vary in the terminal phase.

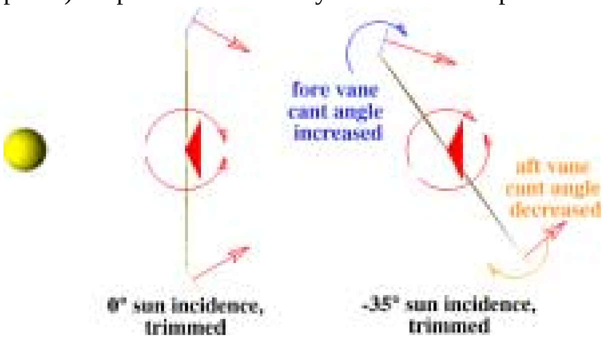

Figure 6. Retrim of Sun Incidence Angle

Extra performance could be gained by using a "solar slingshot". The sailcraft would initially be brought closer to the sun to pick up extra speed. However, this would increase the load in the sailcraft beams, as the increased thrust must be transferred to the central mass. Structural integrity at 1 AU will be easy to verify via the carrier cameras, but not structural safety factor. As no structure even close to the necessary lightness and size has ever been flown, it was decided not to add the uncertainty of a solar slingshot, at least not for the first couple of flights.

The more time a sail is allowed to reach solar escape velocity, the more mass can be carried. However, after five to ten years, not much can be gained even with long extensions to life. Passive stability is therefore designed to hold a terminal phase sun-staring attitude to ten years, and sail materials have successfully been tested to withstand the ten-year trajectory environment.

Given this thrust vector control scheme, the sailcraft must have an areal density no more than 3.8 g/m^2 in order to achieve solar escape. The areal density of the thinnest available sail material, 0.9 µm Mylar, is already 41% of that (metallized); 47% with seams and other sail features. It was obvious we had to use the thinnest material available. The challenge was to develop techniques to handle, assemble, and deploy such a fragile film. L'Garde has since demonstrated these capabilities.

L'Garde determined that it could package a controllably deployable 4900 m^2 sail into the little µASAP slot. This was enabled primarily by L'Garde's telescopic boom packaging and beam footprint collapsing techniques, as well as by the thin 0.9 µm sail material.

For a 4900 m^2 sail, the payload alone takes up another 18% of the maximum mass that could be carried to solar escape. Lightweight customized sailcraft ACS, vanes, and solar arrays were devised, which took up another 13%. The remaining mass, the beams, have to be less than 16 g/m. L'Garde has designed, deployed, and tested components of 15.4 g/m beams.

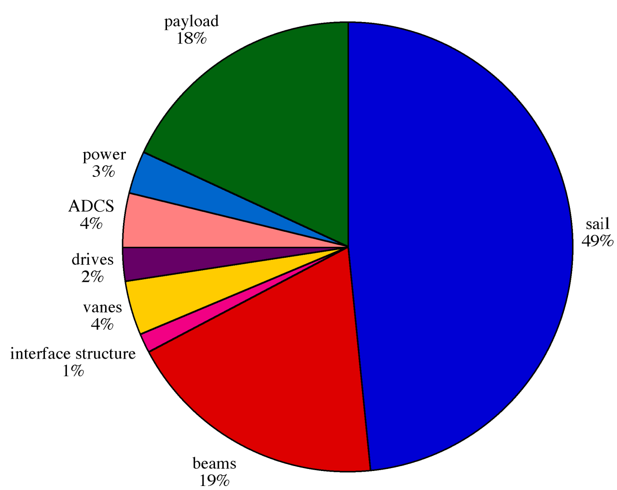

Figure 7. Operational Mass Components

From three simple revenue-driven technical requirements, quite a lot of the design has been derived. Having such a simple, focused set has allowed designers to find ways to make this rather difficult mission possible.

<u>Mission Timeline & Propulsive Performance</u>

After launch on Ariane 5 as a secondary µASAP payload, and dwell in GTO for up to 90 days, the Earth escape motor will be fired, at perigee. Twenty minutes later, the sensible atmosphere will be cleared, and sail deployment can begin. After jettisoning a protective sail canister, the carrier will orient the sail normal to the sun-sail line, with the carrier on the sun side. Sail deployment and boom rigidization will take 1 to 1.5 hours. Last minute messages will be uploaded to the sailcraft EPROM. The sail will then be released, at approximately 24,000 km altitude. For one hour, cameras onboard the carrier will image the departing sailcraft, as well as large sponsor logos painted on the sail, streaming the video live over the internet.

For 1 to 5 days, the "initial phase", the sail will remain at 0° Sun Incidence, and if viewing geometry is favorable, the sail will be the brightest object in the night sky besides the moon, at visual magnitude -6 (Venus will be the closest at -4.4 max).

The sailcraft will then be retrimmed to -35° Sun Incidence, and the tack phase begins. The orbit of Mars will be crossed in 114 days. After one year, the sail, now at 3.8 AU and 0° Sun Incidence, will be powered down, starting the terminal phase. Jupiter's orbit will be passed less than 19 months after deployment.

Finally, 3.75 years after deployment, 2 AU past the orbit of Saturn, Humanity's First Starship, with its 3 kg of payload (plus EPROM messages), will achieve the local solar escape velocity of 12.4 km/sec, never to return. Pluto's orbit will be passed 17.5 years after deployment. Heliopause will be reached in 38 to 57 years.

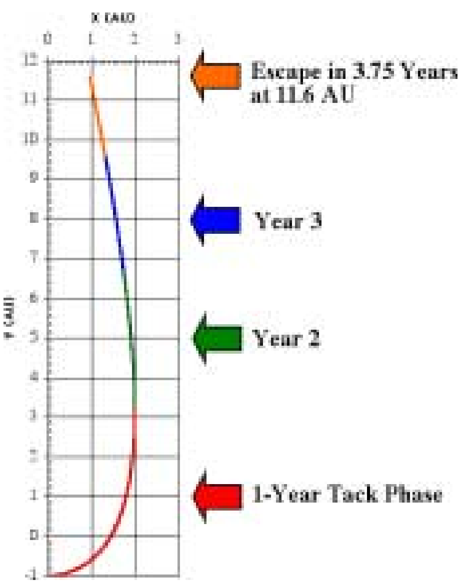

Figure 8. Escape Trajectory & Flight Phases

Generic sail performance can be stated in terms of areal density, 3.63 g/m^2, or characteristic acceleration, 2.26 mm/sec^2. For performance at off-normal attitudes, a polar plot of 1AU accelerations vs thrust angle is presented (Figure 9). Polar plots are commonly used to specify performance of racing sailboats, whose speed vary with course. Maximum circumferential thrust (acceleration 0.8 mm/sec^2) is achieved at a vehicle Sun Incidence angle of 35°. The maximum thrust angle of 57.7° is realized at 70° attitude. The luff limit of the sail is 84.3°.

Figure 9. Polar Plot of Acceleration vs Thrust Angle (Sun is to the Left)

Sail propulsive performance can be compared to chemical and electric propulsion using effective specific impulse, as defined in Ref. 1, p. 18:

$$Isp = a\,T / [g \ln(1/R)]$$

The payload mass fraction "R" is calculated as if the sail were jettisoned at the destination orbit (for transfer missions), or at end of useful life (for ferries or for stationkept orbits such as the 1 AU non-Keplerian Geostorm, Solar Sentinel, or Polesitter). R = 0.18 for the Encounter sail. For the Geostorm mission at 0.855 AU, acceleration would be 3.1 mm/sec^2.

It can be seen that Isp is linearly dependent on sail time in use "T". The Team Encounter solar sail uses no life-limiting expendables - the vanes are used to dump momentum in all axes, including the sail normal. Long-lived spacecraft components have flown before, and L'Garde's beam materials have been tested for long life. The Mylar sail material can degrade most of its structural properties, and still carry solar pressure. This is because it is so lightly loaded, and because there are no stress concentrations with our striped suspension, discussed below. L'Garde has successfully tested metallized 0.9 µm Mylar against a 10 year solar escape trajectory. The potential is there for a long-lived sail. Effective Isp would be very high:

T, years	**Isp, sec**
5	29,124
10	58,248
20	116,497
40	232,994

Packaging Performance

The cost of an Ariane µASAP launch is \$3M - \$4M, perhaps another \$1M for the Earth escape kick motor. Another commonly proposed launcher for solar sails is the Delta II, at least an order of magnitude higher in cost at \$40M - \$50M. Discussion of the propulsive performance of a sail cannot go without an evaluation of the propulsion needed to launch it, which comes down to packaging volume, as gossamer structures will generally be volume-limited, rather than mass-limited for launch.

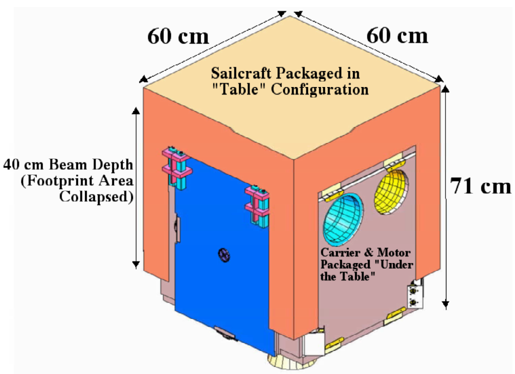

Figure 10. Sail, Carrier, & Motor in Ariane µASAP

The driver in sailcraft packaging turns out to be the length and cross-section area of the packaged beams. L'Garde's beams have a length contraction ratio of 175:1 A large deployed cross-section is necessary for structures, but would easily swallow up most of the packaging volume if not collapsed somehow. L'Garde's beams have a cross section area contraction ratio of 7:1 Packaged beam volume is 0.08% of deployed volume. Moreover, much of the packaged beam volume is located at the vertical edges of the envelope, forming "legs", so the volume "under the table" is available for hard-to-reconfigure items like the kick motor. The packaged sailcraft occupies 23% of the µASAP envelope, still volume limited at 0.37 g/cc.

Enabling Design Elements

Nine key technologies make possible this high performance sailcraft:

1. 0.9 µm Mylar sail material & fabrication
2. Striped sail suspension
3. Periodically loaded, "proa" beam structure
4. Lightweight semi-monocoque boom
5. Sub-Tg rigidization
6. Telescopic boom packaging & deployment
7. Segmented sail deployment
8. Passive stability with Sun Incidence retrim
9. Nanosat-mass Top angle control

0.9µm Mylar Sail Material & Fabrication

One-meter wide 0.9 µm Mylar was successfully metallized with aluminum on the frontside, black chromium on the backside. Measured backside emissivity is 0.4, giving a 1AU temperature of 2°C. For future missions which may utilize a solar slingshot, or for missions to Mercury, a high emissivity Germanium backside coating would keep the Mylar below tolerable temperatures [Ref 4].

L'Garde tested metallized 0.9 µm Mylar at Brookhaven against the Encounter solar escape trajectory (4MeV protons, 10^9 rads). Tensile strength degraded from 110 MPa (16 kpsi) to 90 MPa (13 kpsi). In a normal application, structural material is utilized to a high proportion of its strength, so only maybe 30% degradation is acceptable. However, this is anything but a normal application. The stress the sail will see will be four orders of magnitude less than Mylar's BOL capability. Additionally, the striped suspension has no corner stress concentrations to act as weak links.

Given acceptable thermal and radiation performance, Mylar becomes a clear winner considering its cost and availability in 0.9 µm thickness, 1 m wide. Mylar is inexpensive because of its commercial application, capacitors. The investment in manufacturing facilities has already been made by DuPont. Also, since Mylar melts, unlike polyimides, high production roll-to-roll processes can be applied, as opposed to short-run solvent casting, so the material is available in quantity. Further, as Mylar is a well-characterized commercial product, we can comfortably carry lower mass margin on the substrate, which is 35% of total mass, lowering risk on the other sailcraft components.

Figure 11. 12,500 m^2 (3.1 acres) 1 m Wide 0.9 µm Mylar: $4,554; 4 Month Delivery

L'Garde has developed the techniques to assemble, handle, and deploy 0.9 µm Mylar. Extrapolation to ultra thin material was not easy. For example, it took us several months to make a 0.9 µm sail, while we made and deployed an identical 6.4 µm sail in a single day. Our fabrication technique allows us to use a long, narrow building instead of a facility with excessive lengths and widths. This gives a huge cost savings.

Figure 12. 5.7mX5.7m 0.9µm Sail Post-Deploy 3mX3m Sail Inset

The gore joint uses a seam tape and adhesive. L'Garde has extensive experience with adhesives for both Mylar and Kapton. If a polyimide sail is desired for future missions, and the material available, we will be able to quickly adapt our methods.

The metallized 0.9 µm sail film weighs 1.53 g/m^2; the seams, adhesives, ripstop, and grounding straps add less than 0.17 g/m^2, and the sail-boom connection system adds less than 0.06 g/m^2.

Striped Sail Suspension

Striped suspension results in one-half the total boom compression of its nearest alternative, 5-point suspension; one-third to one-fifteenth the loads in a quadrant sail with outboard catenaries [Fig 5 & Table 1 of Ref 2]. A lighter structure can be used to carry these lower loads.

As a striped sail is attached periodically along the beam length, corner stress concentrations are avoided. This extends the life of the sail, as stress concentrations represent weak links.

Beam load also depends on the amount of billow in the sail. The greater the camber ratio (billow), the lower the load, but a more billowed shape is poorer for propulsion. The Encounter billow design is fairly flat, giving minimal loss of propulsion due to shape.

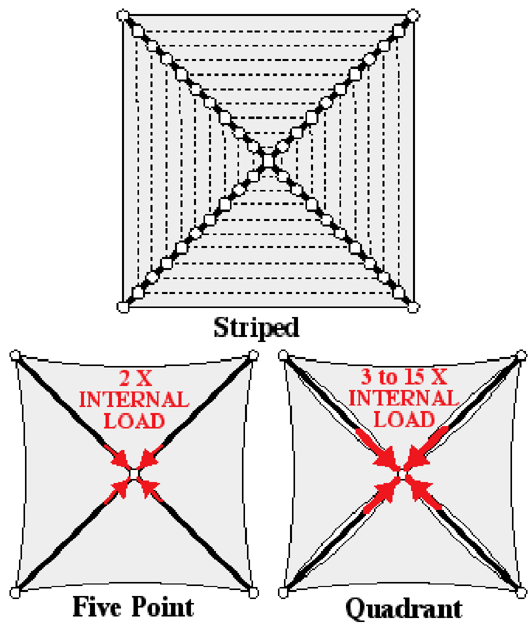

Figure 13. Suspension Architectures

Periodically Loaded, "Proa" Beam Structure

A "proa" sailboat differs from a catamaran in that it has only one main hull, to which is mounted the mast, with a smaller outrigger used by the crew to counter roll. It is only sailed with the wind coming over the outrigger, the main hull on the leeward side. The main hull has a bow at either end to allow tacking. The wind direction known, a lighter, faster rig can be designed.

Similar advantage can be taken for a solar sail, as the sunlight always strikes the reflective side of the sail. L'Garde's beam consists of a single compressive boom, with a high modulus tensile spreader system on the sun side, for which no parasitic pretensioning is necessary. The result is a 15.4 g/m beam with safety factor > 4.

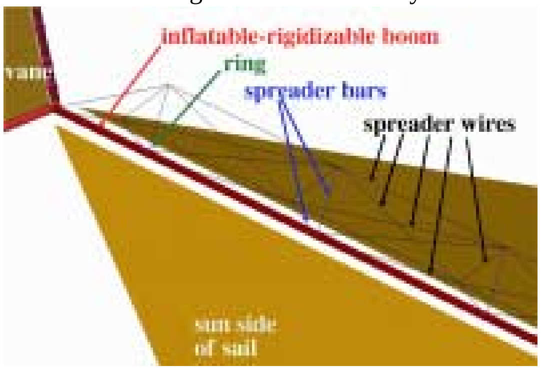

Figure 14. "Proa" Beam Architecture

A proa approach cannot be considered for conventional spacecraft, which do not possess passive stability nor high mass moment of inertia, thus can quickly get flipped, and must carry provisions (and mass) to withstand a flip and recover from it. A solar sail, on the other hand, can handily avoid a flip, even with hard failures of the vane drives and attitude control system. The Encounter sail has sufficient passive stability that in the extreme event of sudden anomalous rotation of the fore and aft vanes to stops in the initial-to-tack phase maneuver, the sail would not approach the luff limit, even with a dead ACS. Further protection can be gained using hardwired watchdogs observing vane angles and vehicle attitudes and rates.

The sail is attached to the beam periodically along its length. This is a benefit to the beam, improving its global buckling capability by a factor as great as (the number of attachments)^2 (Ref 3). The extent to which this is realized is evident in the beam's low linear density. It greatly enhances scalability.

Another trade of structural mass vs propulsive sail shape is available in the beam design. To a point, beam out-of-plane stiffness can be lowered to reduce beam mass, but the more bent beam means a more curved sail shape and poorer propulsion. The Encounter beams are rather stiff; 1AU deflections are small.

Lightweight Semi-Monocoque Boom

A monocoque boom of even the thinnest available composite would be excessively heavy and structurally overdesigned for this sail. L'Garde has developed and tested a 9 g/m boom of semi-monocoque construction to meet the need. It is filament wound, thus can withstand greater than 140 kPa (20 psi) pressure before burst. This means that a positive, controllable deployment force greater than 240 N (50 lbf) could be applied to assure deployment.

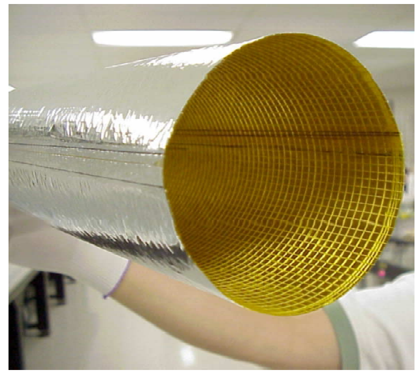

Figure 15. Semi-Monocoque Boom

Sub-Tg Rigidization

The boom wall is warm and flexible for deployment, allowing it to extend from its packaged state. Once deployed, an insulation tube about the boom will bring it well below the –40°C glass-transition temperature (Tg) of its composite matrix, to –70°C. The boom is thus passively rigidized - no chemical reactions are involved. On the ground, the flight boom can be rigidized and structurally tested, then repackaged for flight.

L'Garde's sub-Tg resins have been developed for and tested against high radiation environments.

For future missions that may involve closer solar approaches, the Tg of the resin can be increased to be rigid in the hottest thermal environment.

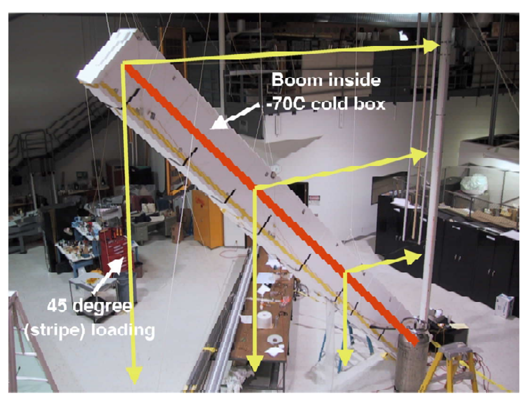

Figure 16. Cold , Unpressurized Test of 7.6 m Boom

Telescopic Boom Packaging & Deployment

The booms are tapered along their length. They can then be folded in along themselves, in a manner resembling a telescopic rod. As pressure is introduced, the base fold of the stack begins to peel away. The still-packaged boom travels outboard. This repeats for the next fold, always base first, in a controlled manner. The deployed segment of the boom is pressure stabilized during deployment.

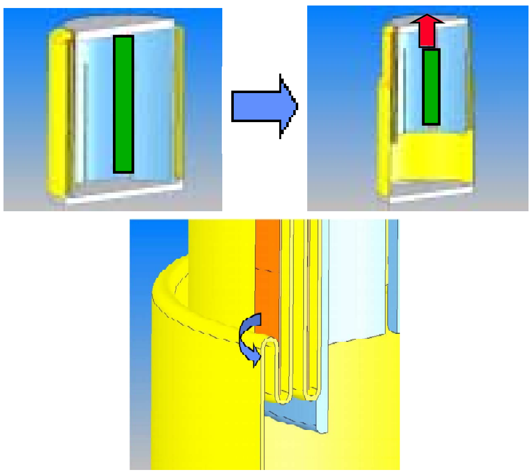

Figure 17. Telescopic Deployment

Note that deployment is linear, and a ring can be mounted to the outboard end of each fold, to which can be tied a stripe of the sail. Telescopic boom packaging makes periodic attachment physically possible, allowing the low load striped architecture and helping to stabilize the beam. It also makes possible segmented deployment of the sail, to be discussed.

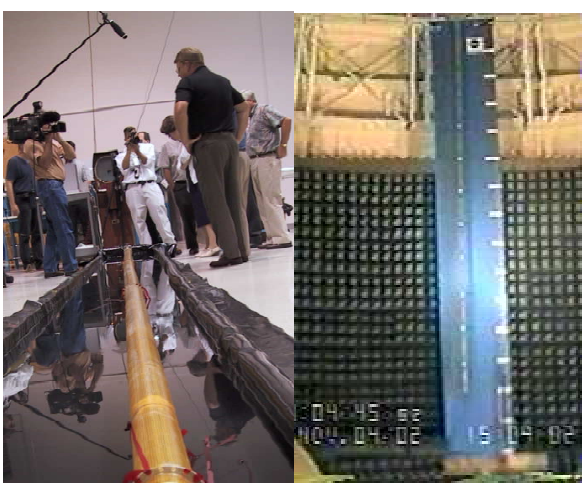

Figure 18. Water Trough and Langley Vacuum Deployment of 7.6 m Telescopic Boom

Once the boom is deployed, the now parasitic mass of the spent inflation system, boom heaters, and length sensors are jettisoned.

Segmented Sail Deployment

The sail is attached periodically to the boom, so boom deployment drives and controls sail deployment. All four beams deploy simultaneously, and the sail quadrants deploy with them. The sail is folded and deployed stripe by stripe, segmented like the boom packaging. During deployment, the inboard sections of sail and beam are fully deployed, taking solar load. The boom is pressure stabilized. Only the outboard stripe is deploying at any time, limiting the amount of free edge and potential sail-beam snag. This technique has been tested successfully at L'Garde.

A 0.9 µm sail experiences nearly 2000 times the gravitational load as it will see in space under solar pressure. Offloading devices will inevitably be limited and directionally biased. Further, only subscale sails can be tested in vacuum. Beam deployment, on the other hand, can handily be tested full scale, and is not nearly as affected by atmosphere. Limiting the regions of unfolding sail material, folding such that folds are sequentially released, and the complete lack of mechanisms or slipstitches or any relative sail-beam movement, reduce the risk of in-space sailcraft deployment at least as importantly as controlled beam deployment.

Outboard stripes will scallop to allow full pullout of neighboring inboard stripes. The final stripe is permanently scalloped to allow full sail deployment.

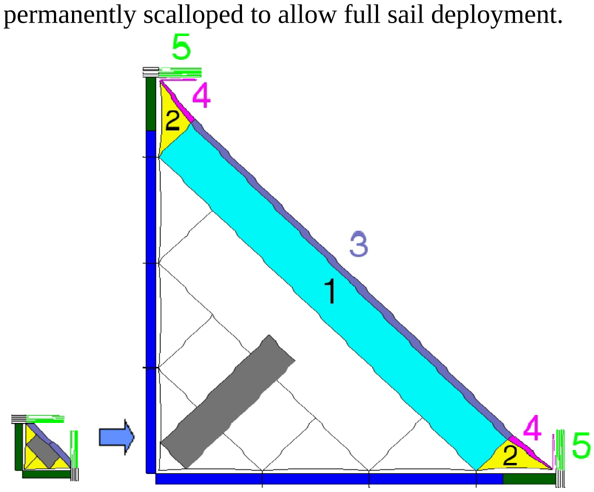

Figure 19. Sail Folding Regions

Passive Stability with Sun Incidence Retrim

All sails with the center of mass forward of the center of pressure experience some passive stability about the two in-plane axes due to the solar "drag" force of an imperfectly reflecting sail, and sail billow imparts more stability due to the effective shuttlecock angle. Stability and trim in two axes could be gained by placing the payload forward on the tip a long articulated boom, but this setup could not dump momentum about the sail normal. Momentum wheels and life-limiting expendables (cold gas for thrusters) would be needed. Instead, the Encounter sail uses beam tip vanes Canted antisunward for passive stability and trim (Fig 4). Vanes dump momentum in all axes, and the vane mass is not parasitic - the vane fields contribute appreciably to propulsion.

By varying the Cant angles of the fore and aft vanes, the Sun Incidence trim angle can be changed (Fig 6). The port and starboard vanes are fixed at 30° anti-sunward Cant. When a new Sun Incidence trim is set, the active Top stabilization system will also reset the neutral Twirl angle of the port and starboard vanes to the Sun Incidence angle. These vanes will then passively stabilize the port-starboard axis normal to the sun-sail line. This stability, coupled with the Sun Incidence angle stability due to the fore and aft vanes, will stabilize the sail Flatspin angle to zero, but this coupling will only occur only when the Sun Incidence angle is non-zero. The greater the Sun Incidence, the greater the Flatspin stability. At zero Sun Incidence, the sail normal is coincident with the sun-sail line, Flatspin and Top are one and the same, and there is no passive Flatspin stability. Active stability is available, but none is needed at Sun Incidence 0°. Zero Flatspin at non-zero Sun Incidence is desirable, as variations in Flatspin will alter the asymmetric sail shape somewhat, affecting propulsion. By always flying "fore beam into the wind", propulsion is made more repeatable.

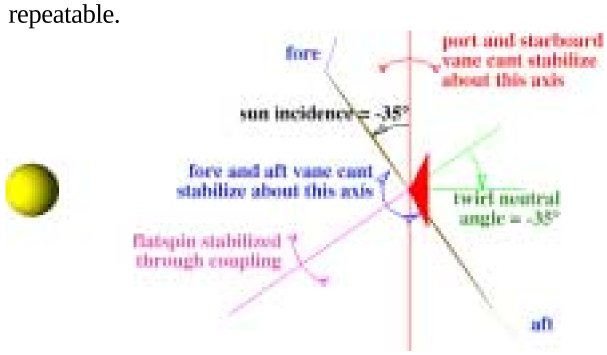

Figure 20. Flatspin Angle Stabilization

Nanosat-Mass Top Angle Control

Rotation about the sun-sail line cannot be passively stabilized. A star camera is used to determine Top angle, and a controller varies the differential Twirl of the port-starboard vanes to actively stabilize Top angle at 0° (Fig 5). This control system could rotate the sail to non-zero Top angles if it were desired to maneuver out of the plane of the ecliptic, as to reach and maintain a polesitter equilibrium point. This sailcraft thus has full control authority for other missions, using "yank and bank" style maneuvers.

Typical full-functioned star cameras and controllers are impracticably heavy for this mission. Instead, MSI will utilize the "MicroNode" controller, and a star camera developed for nanosats.

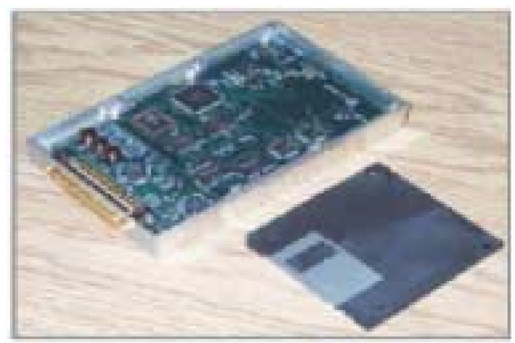

Figure 21. MicroNode Controller

Passive stabilization and active control will not be perfect; performance margin based on analysis is carried for +/- 3° error in all axes.

Summary

Three simple requirements were presented for the Team Encounter Starship:

3 kg payload
solar escape velocity
Ariane 5 µASAP secondary

It quickly became evident that a high performance solar sail was the way to go. Nine key technologies were brought to bear on the problem:

1. 0.9 µm Mylar sail material & fabrication
2. Striped sail suspension
3. Periodically loaded, "proa" beam structure
4. Lightweight semi-monocoque boom
5. Sub-Tg rigidization
6. Telescopic boom packaging & deployment
7. Segmented sail deployment
8. Passive stability with Sun Incidence retrim
9. Nanosat-mass Top angle control

After a great deal of development and test, the design is nearly ready to go forward to flight. The 625 m^2 Flight One sailcraft will launch in 2005, testing deployment, structural integrity, and attitude control. NOAA may then fly it to a polesitter position. Late in 2006, Humanity's First Starship will be launched and deployed. 3.75 years later, at 11.6 AU, this 4900 m^2 sailcraft, with its 3 kg payload of messages, drawings, photographs, and biological signatures submitted by up to 4.5 million participants, will achieve solar escape velocity. At 3.63 g/m^2, including payload, this is the highest performance sail project currently being undertaken.

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