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Next Generation Solar Array Technologies for Small Satellites

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Abstract

Recent advances in Shape Memory Alloy (SMA), Elastic Memory Composites (EMC), and ultra-light composites along with thin-film Copper-Indium-Diselinide (CIS) photovoltaics have offered the potential to provide solar array systems for small satellites that are significantly lighter than the current state of the practice. The Air Force Research Laboratory (AFRL), National Aeronautics and Space Administration (NASA) Langley, Defense Advanced Research Projects Agency (DARPA), and Lockheed Martin are jointly sponsoring an effort that will develop and, in partnership with AeroAstro, demonstrate advanced technologies for solar array applications. These technologies will result in advances that include cost, weight, risk, reliability, and power. Conventional state-of-the-practice solar arrays utilize rigid honeycomb panels to provide the structural support for the crystalline Silicon (Si) or Gallium Arsenide (GaAs) solar cells. Rigid composite panel structural and manufacturing methods have placed a practical producible limit on the power to weight efficiency of today's solar panels. This limit is about 60 Watts per kilogram (W/kg). New technologies are needed to break this power to weight barrier and meet future DOD and NASA space power requirements.

A potential solution to this problem, are the technologies that are being developed under the Lightweight Flexible Solar Array (LFSA) program. The LFSA will demonstrate key technologies on four space flights. The first space opportunity consisted of a flight experiment of a Shape Memory Alloy (SMA) deployment hinge that was demonstrated on the Space Shuttle Columbia (STS-93) in July 1999. The second flight opportunity consisted of a sub-scale two-panel solar array that was demonstrated on NASA's Earth Observing-1 spacecraft in November 2000. The third and fourth flight opportunities will transition thin-film solar arrays into

operational spacecraft systems, specifically on the AeroAstro/Astronautic Technology Sdn. Bhd. (ATSB) Small Payload ORbit Transfer (SPORT™) vehicle in 2003 and the Team Encounter solar sail in 2004. The synergistic merging of the new, innovative technologies into an advanced lightweight thin-film solar array will meet the requirements of the emerging next generation of small satellites. The implementation of these new technologies directed at lightweight solar arrays will result in significant weight and volume reductions over current satellite systems. The SMA devices will provide a controlled shock-less deployment of the solar array and improved testability due to mechanism re-set capability. Additionally, the SMA actuators will eliminate or minimize deployment motors, mechanisms, and part count. The LFSA program is a pathfinder for next generation rollout arrays that increase specific power densities to >200 W/kg.

Introduction

Existing spacecraft technologies may not be able to meet requirements for future spacecraft programs. The mission of the Air Force Research Laboratory Space Vehicles Directorate (AFRL/VS) is to develop and transition high payoff space technologies to support the warfighter while leveraging commercial, civil, and other government space capabilities to ensure America's advantage. In the development of new innovative space technologies to support the warfighter, there are several common technology goals that benefit both the military and commercial sectors. Some of these common goals include reducing the cost, size, volume, and part count of spacecraft components, while streamlining and improving integration and safety procedures, and increasing performance and reliability. One of the high payoff spacecraft technology areas that benefit both the military and commercial sector is the development of solar array technologies. The AFRL/VS has several ongoing joint programs with industry to develop and demonstrate innovative solar array technologies to support future military and commercial requirements. This paper summarizes several technology programs at the AFRL/VS that could potentially revolutionize the efficiency of spacecraft solar arrays. The difficulty in transferring new technology is reluctance of program managers to use radically new technology. These program managers must answer for success or failure of multi-million dollar spacecraft, the risks associated with new technology far outweighs the potential reward. The AFRL/VS has taken the responsibility of reducing this risk by proving new technologies with flight experiments designed to fully demonstrate a variety of new technologies. Several flight experiments to demonstrate key subcomponent technologies have already occurred with several other key technology demonstrations planned in the upcoming years.

Solar Cell Developments

Current on-orbit satellite electrical power system demands are doubling every five years, forcing the spacecraft designer to look for options to solve the power availability problem. The need for high performance solar arrays for space applications continues to increase, as the energy budget of satellites becomes ever higher, and power systems become constrained by either total mass or stowed volume. The Advanced Space Power Generation Team at the AFRL/VS has stepped up to this challenge by developing, with industry, new innovative cell designs that will increase the state-of-the-practice cell efficiencies. Two approaches are being pursued to enable higher power levels on satellites systems. The first approach is to increase the efficiency of the solar cells used on state-of-the-art flat panel solar arrays thereby increasing the total power delivered to the payload for a given array size. The second approach is to utilize thin-film solar cells that can be efficiently stowed, possess greater radiation hardness, and are lightweight and less costly. Solar cell efficiency is the most significant parameter to optimize in order to achieve minimum mass and volume of the solar cell power system. Figure 1 shows how solar array designers take advantage of increased solar cell efficiencies to provide increasing power to the spacecraft.

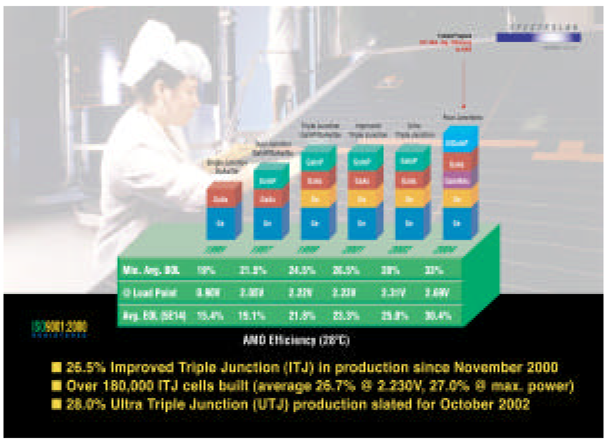

Figure 1. Impact of Solar Cell Efficiency on Solar Array Power (Spectrolab Cell Efficiency Technology Roadmap).

Monolithic Rigid Crystalline Solar Cells

Flat panel arrays have traditionally utilized monolithic crystalline solar cells. The AFRL/VS has established programs with Emcore Corp. and Spectrolab, Inc. to increase the efficiency of these solar cells. These programs have brought great rewards; the efficiency has increased at about 1% per year since achieving 7% in 1970. Solar cell designs have increased in complexity since single junction silicon cells were in service; today's cells (Figure 2.) have accomplished a better match to the air mass zero (space) solar spectrum by stacking several junctions on top of each other monolithically grown as a single crystal.

Figure 2. Typical Commercial Solar Cell. (Cell picture Courtesy of Spectrolab).

The operation of a multi-junction can be understood by the depiction in Figure 3., where incident light is incident on the multiple junctions of the solar cell. The upper junction absorbs the higher energy photons and transmits the remainder to the second junction, etc. Further complexities of the cell include an uppermost cover glass with antireflective coatings to trap light and shield the cell from radiation, window layers on top of emitter sections to passify emitter surfaces to minimize surface recombination velocities (reduce shunting), tunnel junctions that act as sub-cell connectors with high bandgaps to transmit most of the light to the next cell below, and back contacts. Additionally, complications result when the cell is fine-tuned to reduce power losses over the life of the cell resulting from radiation damage.

Features such as grading junctions and dopants to slightly alter bandgaps have been introduced to level off power produced by the cell for time spans as long as fifteen years. In spite of the complexity and cost of monolithic crystalline multi-junction solar cells, the arrays built using these cells have achieved prominence in the community as a result of the robustness of operation and simplicity of the design of the arrays. The cost and mass of the arrays does leave room for higher efficiency cells improvement.

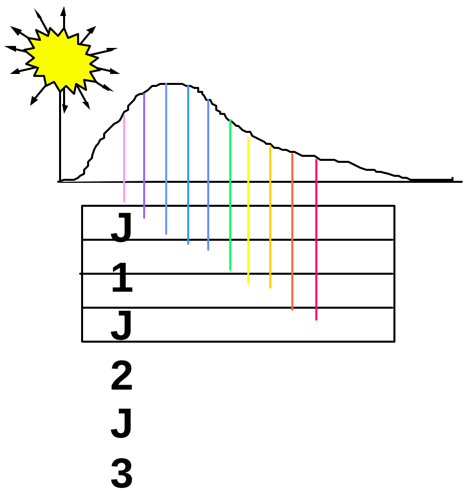

Figure 3. The Multi-junction Solar Cell Concept.

Flexible Thin-film Solar Cells

Conventional flat plate arrays are simple, rugged, and can be very large. Their configurations have not changed substantially over the years, consisting of solar cells mounted on a honeycomb structure for rigidity and thermal control. This limits the amount of total power that can be obtained from such an array either by the mass of the array or by the volume constraints of the fairing of the launch vehicle since flat plate arrays can only be folded. In order to meet future Air Force and the National Aeronautics and Space Administration (NASA) power requirements, new solar array designs are required that could substantially alleviate both constraints.

One of the most promising approaches that could provide dramatic increases in the solar array power densities is flexible thin-film solar cells (Figure 4). The advantages of thin-film technology include large stowed volume power densities, very high specific powers, and an inherent high radiation tolerance. The high radiation tolerance owes itself to the thin solar cell and the fact that thin-film photovoltaics is polycrystalline material and defect density is high, therefore the radiation-induced defects are a smaller percent change as compared with the high quality monolithic crystalline solar cells. The disadvantage of thin-film solar cells is that state-of-the-art efficiencies are fairly low (~10%). The great advantages of these thin-film photovoltaics are that they can be compressed tightly to achieve very high stowed volume densities, three times as high as crystalline arrays have been projected, as well as being 3-5 times lighter and three times cheaper than crystalline arrays. The one main disadvantage is the area of the array is three times larger in area as a direct result of the reduced efficiency.

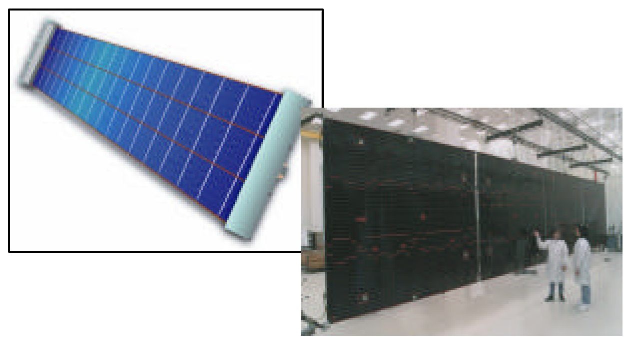

Figure 4. Flexible Thin-film Photovoltaic Array Versus Flat Panel Array. (Flat Panel Array Figure Courtesy of Spectrolab).

Solar Array Concentrators

Another promising solar array technology that is approaching maturity is the refractive concentrator system. The present configuration of the refractive lens concentrator system (Figure 5) is encompassed in the Stretched Lens Array (SLA) developed by Entech Inc. The design utilizes a unique arched Fresnel lens that spreads the colors over the active area of the solar cell and does not utilize any support for the thin-film lens other than the edge tensioners. The lens focuses the intercepted light onto a thin line of high efficiency solar cells. This design has led to high operating voltages in a plasma environment (400 V, greatly impacts bus harness mass), an 80% savings in the most expensive cost element (the solar cells), and substantial improvement in areal power density. The main disadvantages of the SLA are the pointing requirements (impacts the fuel requirements) and the optical transmission efficiencies.

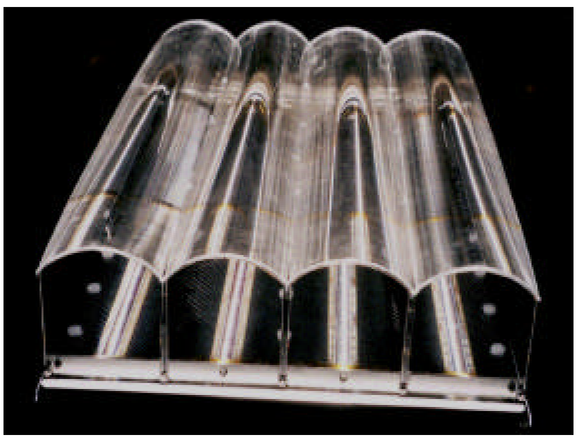

Figure 5. Basic Configuration of the Stretched Lens Array

Multi-Functional Structures (MFS)

Current state-of-the-practice on aerospace vehicle electronic configurations use heavy cumbersome cabling and large connectors. These components compose a significant portion of the gross mass of the aerospace vehicle, require a large amount of touch labor to manufacture, have a limited test/monitoring capability, are difficult to install in the vehicle, and require a significant mass of support brackets and such due to their high mass. The AFRL, Missile Defense Agency, Defense Advanced Research Projects Agency (DARPA), and Lockheed Martin have been developing an innovative technology called MFS. This new technology is a revolutionary way to package and configure cabling that can reduce cabling volume, mass, and touch labor by >80%, > 75%, and >50% respectively[1]. The MFS technology is a new design paradigm that seeks to integrate the load carrying capability of traditional structures with the cabling requirements of aerospace vehicles. The basic approach of the MFS program is to reconfigure the cabling to improve the way they integrate with the aerospace vehicle structure, minimize mass and volume requirements, in addition to simplifying the manufacturing process for the cabling[2]. For example, a cable manufactured using the MFS techniques looks very different from a cable manufactured using conventional techniques (Figure 6). The conventionally manufactured cable is composed of a bundle of individual wires bound together with mechanical bindings, attached to the aerospace vehicle structure with various high-strength mechanical brackets and tie-downs, and finished on each end with complex and expensive connectors. Additionally, conventional cabling is heavy and requires substantial touch labor by technicians to manufacture and install in the aerospace vehicle. A MFS cable is a flat matrix of polyimide film that lays out the various "wires" side-by-side. This flexible electrical insulation material has outstanding thermal, mechanical, and chemical properties. This configuration results in a very low mass structure that does not require the heavy bundling and tie-down hardware. The MFS cable has such low mass that it can be tacked down with adhesive directly to the vehicle structure without complex brackets. The MFS cable is finished on each end with low-mass interconnects.

A major benefit of the MFS technology is that these components can be cheaply mass-produced. Conventionally configured cabling require significant touch labor to manufacture. Once a MFS cable design is coded into a

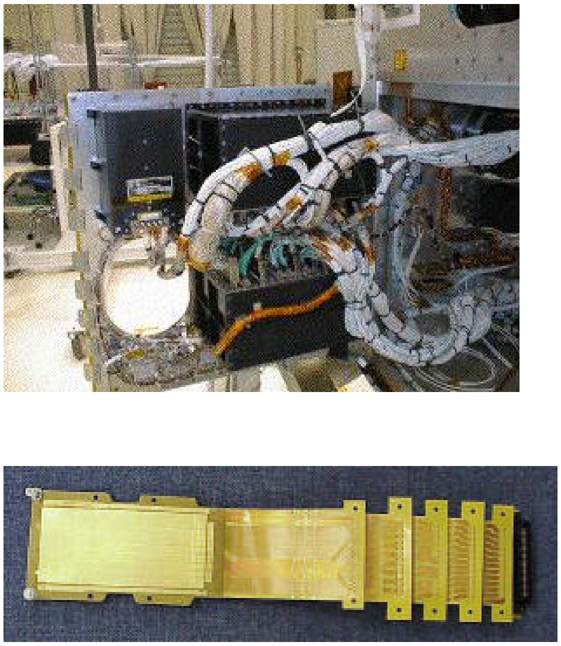

Figure 6: Conventional and MFS Cable

computer; the cable can be easily and cheaply manufactured by machine. Nearly all of the touch labor associated with manufacturing the cable is eliminated, and at least 90% of the touch labor associated with installation of the cable is also eliminated. This reduction in manpower costs has obvious benefits during depot-related retrofit actions to existing aerospace vehicles. Using the MFS configured cables represents one method to achieve significant reductions in the cost of accomplishing some depot maintenance such as cable retrofits by reducing the cost of the replacement cables and the labor to install them. An additional benefit of the MFS concept is that the configuration facilitates significant test and verification capability. It is extremely easy to incorporate simple test nodes into the MFS cabling that allow for a full system test/monitoring capability without the need to break the flight-ready configuration. This capability can be incorporated into a standard MFS cable for only a few grams of added mass at almost no cost delta (the test capability is designed into the cable for machine manufacture). The low mass and volume that is achievable using the MFS technology has obvious benefits for new aerospace vehicles. In addition, the MFS configured cabling allows more compact packaging because the MFS cabling is capable of tighter radii than conventional cabling. A MFS configured aerospace vehicle allows for significant life-cycle cost savings from several different efficiencies. First, the lighter mass and smaller volume of a MFS cabling allows for reductions in overall aerospace vehicle mass and volume requirements. This effect can be used to reduce overall cost of procuring the vehicle (less is cheaper) or can be used to allow the vehicle greater performance than possible otherwise. The second efficiency is that the cost of the MFS is significantly less than current cabling due to lower manufacturing and installation labor costs. The final efficiency results in the reduced labor to maintain the aerospace vehicle fleet because of significant test/monitoring capability that can be built into the initial design and the ease of the "drop-in" replacement of failed MFS components. The MFS hardware testing has demonstrated an inherent robustness of flexible circuitry designs. The MFS designs substantially reduce part counts and facilitate automated fabrication, which reduce technician touch labor during assembly and rework operations. Compared to round wire cabling where each electrical wire must be soldered into position, the MFS circuit connectivity is accomplished in an automated fashion, reducing the possibility of technician error or inefficiencies. All this lends itself to increased reliability and reduced cost.

Lightweight Hinge Development

Spacecraft require a variety of mechanisms to accomplish mission-related functions such as deployment, articulation, and positioning. Current technologies for these mechanisms include pyrotechnics, high output parafin and electric motors. These technologies are sufficient for the moment, but have drawbacks that make them unsuitable for the more restrictive environments of future spacecraft. These drawbacks include generation of shock and contaminants that may adversely affect nearby instruments, short lifespan due to use of expendable materials such as lubricants, and low efficiency in terms of both weight and size. The AFRL/VS is developing innovative technologies for new mechanisms that avoid the drawbacks in current devices. The goal of this program is to develop technologies that will improve the state-of-the-art and state-of-the-practice in spacecraft mechanisms. Pyrotechnic bolts are currently used for these tasks, but their presence on a spacecraft has several negative impacts. Recent advances in Shape Memory Alloy (SMA) and Elastic Memory Composite (EMC) devices have shown the potential of providing solar array deployment systems that are significantly lighter than the current state-of-the-practice. The key advantages of such hinges (Figure 7) over other hinges include a controlled low shock deployment of the solar array and improved testability due to mechanism reset capability, fewer parts, lighter weight, higher reliability, and ease of production and assembly.

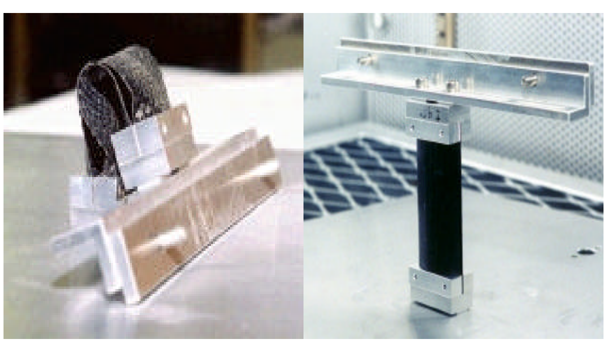

Figure 7. EMC Hinge Deploying

Solar Array Technologies Flight Demonstrations

There have been various programs at the AFRL/VS that have focused on characterizing new innovative technologies and validating their performance in ground and space flight demonstrations. One of these programs, "The Lightweight Flexible Solar Array (LFSA)," focused on the development of new, emerging solar array technologies. The LFSA program was a joint AFRL, NASA Langley, DARPA, and Lockheed Martin effort to develop and demonstrate advanced technologies for solar array applications that will result in lower cost, reduced weight, less risk, more reliability, and more available power.

Conventional state-of-practice solar arrays utilize rigid honeycomb substrates to provide the launch stowage and deployed structural support of rigid crystalline Si or GaAs cells. Rigid panel composite facesheet thicknesses (~0.010 inch) and honeycomb densities (1.6 kg/m3) have reached the practical producible limits, limiting rigid panel solar array technology to a specific power of ~60 Watts per kilogram (W/kg). A revolutionary solar array approach is required to meet the evolving DOD and NASA specific power (>100W/kg), packaging, and stowage requirements.

Recent advances in SMA devices, ultra-light composites, thin-film photovoltaics, and MFS have shown the potential of providing solar array systems that produce > 100 W/kg. The LFSA program will demonstrate key solar array technologies on four space flights. The first space opportunity consisted of a flight experiment of a six SMA deployment hinge that was demonstrated on the Space Shuttle Columbia (STS-93) in July 1999. The second flight consisted of a sub-scale two-panel solar array that was demonstrated on NASA's Earth Observing-1 (EO-1) spacecraft of the third

New Millennium Program technology demonstration flight in November 2000. The third and fourth flight opportunities are full-scale arrays that will be demonstrated on AeroAstro's Small Payload ORbit Transfer (SPORT) and Team Encounter spacecraft in 2004. The LFSA program on the SPORT and Team Encounter spacecrafts will qualify and fly the world's first full-scale solar array using thin-film solar cells. The solar arrays will be designed, fabricated, and tested by Lockheed Martin.

Space Shuttle Columbia (STS-93) Experiment

A critical component of solar array development is the successful development and demonstration of the SMA deployment hinges. Hinges are the primary mechanism used to deploy spacecraft solar arrays that are folded together for launch. Once on-orbit, these solar array systems are deployed, or unfolded and used to generate power for the spacecraft. The key advantages of SMA hinges over other hinges include low-shock controlled deployment, fewer parts, lighter weight, higher reliability, and ease of production and assembly. In July 1999, an experiment consisting of six SMA hinges were successfully demonstrated on the Space Shuttle Columbia (STS-93). The STS-93 experiment (Figure 8) provided a way to test the SMA hinges in a weightless environment prior to being applied to a future spacecraft design. Flight demonstration of the hinges provided an opportunity to evaluate various hinges in a realistic environment and allowed investigators to verify the mechanical design data and evaluate the dynamic properties of the hinges. The hinge operations for the experiment were reported by the crew as nominal. No downlink was available to observe the data, but the mission specialist

Figure 8. STS-93 Shuttle Flight Experiment

reported a good deployment on all 6 hinges. The experiment was integrated and flown under the direction of the DOD Space Test Program office at NASA Johnson Space Center in Houston, TX.

NASA's Earth Observing-1 (EO-1) Spacecraft

In November 2000, on NASA's EO-1 spacecraft, a subscale thin-film solar array (20cm X 50 cm) panel consisting of MFS cabling, SMA hinges, and thin-film photovoltaic solar cells was successfully demonstrated. The two-panel array (Figure 9) consists of very lightweight composite, window frame-like structures, SMA deployment hinges, MFS, and thin-film photovoltaic solar cells. The objective of this experiment was to demonstrate and validate the performance of thin-film solar cells and the flexible SMA deployment mechanism.

SPORT

The final step for the application of the technologies developed from the LFSA program was a full-scale demonstration on a spacecraft where the array is a secondary source of power. The LFSA array is being base-lined into the AeroAstro/ATSB commercial SPORT spacecraft that will be

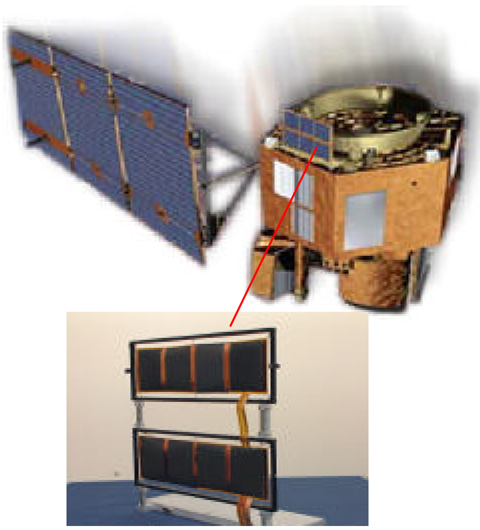

Figure 9. Sub-scale two-panel Array on NASA's EO-1 Spacecraft.

launched in FY04. While the LFSA will be used as a secondary power source on the first SPORT flight, subsequent flights will use the proven array for primary power. The SPORT spacecraft has a power requirement of approximately 50 Watts. The SPORT is an orbital transfer vehicle that will save commercial customers approximately $10M per mission by enabling the deployment of their spacecraft to a relatively inexpensive Geosynchronous Transfer Orbit (GTO) deployment, then utilizing the SPORT to transfer that orbit to a much more useful Low Earth Orbit (LEO).

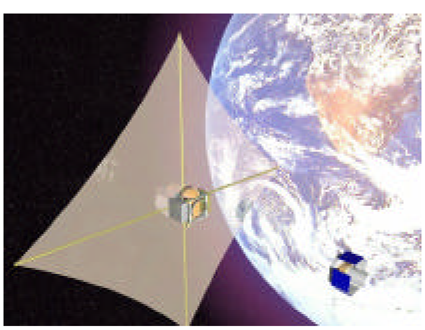

Figure 10. AeroAstro's SPORT Spacecraft

Encounter

The next transition of the LFSA technology into a commercial spacecraft is on the Team Encounter spacecraft being built by AeroAstro (Figure 11) being developed by Encounter 2001, AeroAstro and L'Garde. The LFSA array will be the primary power source for the commercial team encounter the into the commercial Team Encounter solar sailcraft that will be launched on an Ariane V in FY04. The Team Encounter spacecraft is a commercially funded entertainment mission that will transport the DNA and messages of 4-5 million participants into deep space. The LFSA technologies will save the mission approximately 20% mass and 40% volume at the spacecraft system level; this translates directly to additional payload carrying capability. The Encounter spacecraft has a power requirement of approximately 200 Watts at 1AU to provide the required 15 Watts when it reaches 4AU at the end of its 1 year of active operation.

Figure 11. The Team Encounter Spacecraft In Development at AeroAstro

Conclusion

The AFRL will continue in its efforts to tranisition innovative solar array technologies from the laboratory to the users. The AFRL realizes that for soalr array technologies, there is large return in terms of mass, volume, and increased power densities that translate directly to lower launch costs and enhanced satellite performance. Additionally, we recognize that this technology is critical for micro and nano satellite development. New solar array technologies are constantly being pursued, and the AFRL welcomes ideas from both industry and government organizations in regards to the next development effort. The AFRL and its partners are committed not only to development and test, but also to mission integration, to ensure that this new technology obtains the flight heritage and industry recognition needed to support further development and applications. The flight demonstrations on the STS-93, EO-1, SPORT, and Team Encounter spacecraft were major milestones in providing flight heritage to help transition and transfer this technology to other users. The AFRL/VS goal is to develop these micro-satellite enabling technologies for operational systems, both military and commercial. Implementation of these efforts will translate into decreased operational costs for the space community.

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