# Spacecraft Solar Array Technology Trends

P. Alan Jones & Brian R. Spence
AEC-Able Engineering Company, Inc.
93 Castilian Dr.
Goleta, CA 93117
805-685-2262
email: pajones@aec-able.com & bspence@aec-able.com

*Abstract*¾Photovoltaic solar array systems are the most common method for providing spacecraft power generation. The flexibility and variability of the many array types and configurations combine to accommodate a multitude of mission applications and space environments. Solar array technologies and their system configurations changed dramatically over the years as more aggressive and demanding requirements were imposed. This paper addresses the historical solar array technology trends. The evolution of solar array technologies and the key requirements responsible for driving this evolution is presented. Industry growth trends towards future systems are identified. Evolutionary technological improvements in photovoltaics, structural platforms, and deployment systems are shown. Array selection criteria for a variety of requirements, applications, and environments are presented. Solar array technologies required to meet future mission trends are shown.

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## 1. INTRODUCTION

Photovoltaic solar array systems are the most common method for providing spacecraft power generation. In a time period of less than four decades space solar arrays have grown in size from less than 1 watt to systems over 75,000 watts, such as the International Space Station Alpha (ISSA) solar array. GEO spacecraft power growth as a function of time is shown in Figure 1.

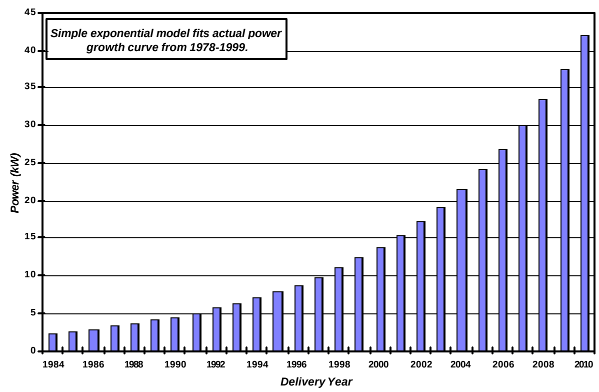



**Figure 1. GEO Spacecraft Power vs. Time**

The flexibility and variability of the many solar array types and configurations combine to accommodate a variety of mission applications and space environments. Electrical power generation by photovoltaic conversion represents a clean and environmentally safe process for providing energy to a spacecraft system. These environmentally safe features led photovoltaic means to be considered as a politically acceptable replacement for nuclear radioisotope thermal generators (RTG's) for near planetary missions.

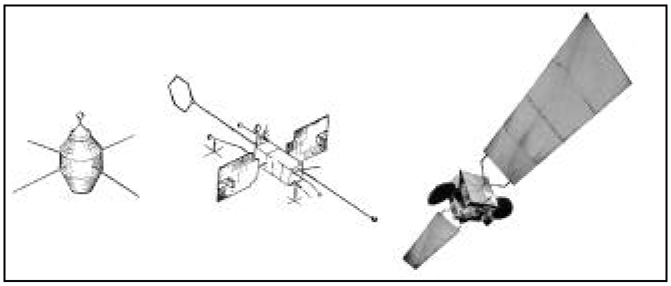
Solar array technologies changed dramatically over the years as more aggressive and demanding requirements were continuously being imposed by engineers who were creating spacecraft systems with greater capabilities. As a result of these driving requirements and unique mission applications, innovative solar array technologies were developed throughout the course of history. Primary solar array technology developments included the optimization of evolved structural platforms, lightweight substrates, innovative deployment systems, and higher efficiency photovoltaics.

The development of solar array technologies is providing the spacecraft engineer with a broad trade space of feasible solutions. The multitude of array subsystem and system level solutions is allowing the engineer a greater ability to optimize an array and specifically tailor it to a particular mission. As more exotic future mission applications arise, which will impose even more stringent requirements, the solar array trade space will undoubtedly be further broadened.

## 2. SOLAR ARRAY HISTORY

Historically, solar array technologies evolution was closely coupled with expanding spacecraft power requirements. Enhancements in spacecraft and launch vehicle systems tended to increase spacecraft capability which, in turn, drove the development of more efficient solar array technologies. This trend, when coupled with the cost pressures inherent in a commercial industry, increased the demand for more cost and mass efficient high power systems.

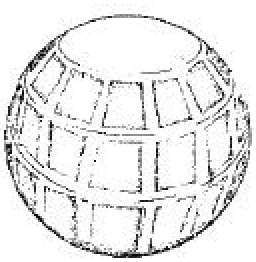
Array structural platforms evolved throughout the years from simple spacecraft body-mounted configurations, to single panel flip-out configurations, to kinematically complex multi-panel deployable systems. This array configuration evolution is depicted schematically in Figure 2.



Graphic courtesy of JPL

**Figure 2. Solar Array Configuration Evolution**

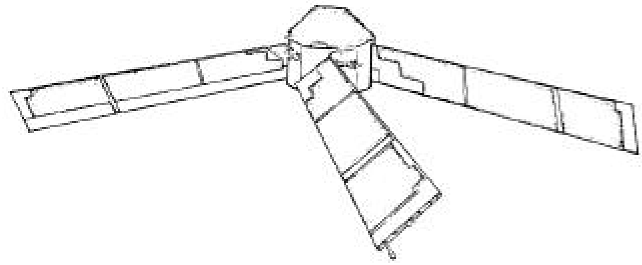
The first solar array to fly in space was launched on 17 March 1958 on the U.S. Vanguard I spacecraft[1]. The Vanguard I spacecraft is shown in Figure 3. This array consisted of six simple body-mounted panels populated with 10% efficient silicon solar cells. The total power output of this array was less than 1 watt[1]. The array on the Vanguard I spacecraft quickly ushered in the space photovoltaic solar cell age as more advanced systems were developed to meet ever-increasing power requirements.



Graphic courtesy of JPL

**Figure 3. U.S. Vanguard I Spacecraft**

Simple body-mounted solar array configurations were most prevalent in the early years. To accommodate increasing power requirements the entire exterior surface area of the spacecraft was soon utilized for mounting solar cells. As power continued to grow, spacecraft were fitted with higher efficient photovoltaics and/or solar ‘paddles’ in an effort to extend the available solar array area. An example of a spacecraft configured with ‘paddle’ type arrays is shown in Figure 4.



Graphic courtesy of JPL

**Figure 4. Spacecraft with early ‘Paddle’ Arrays**

Spacecraft designs and mission applications soon required even more powerful solar arrays than what could be provided by ‘paddles’. Solar panels attached to orientation drives provided one solution and large cylindrically shaped spacecraft (accommodating the majority of the launch vehicle volume) with body-mounted solar cells provided another. An example of a cylindrically shaped spacecraft with body-mounted solar cells is shown in Figure 5. These two solutions passivated power requirements for a short time but were limiting in power growth potential.

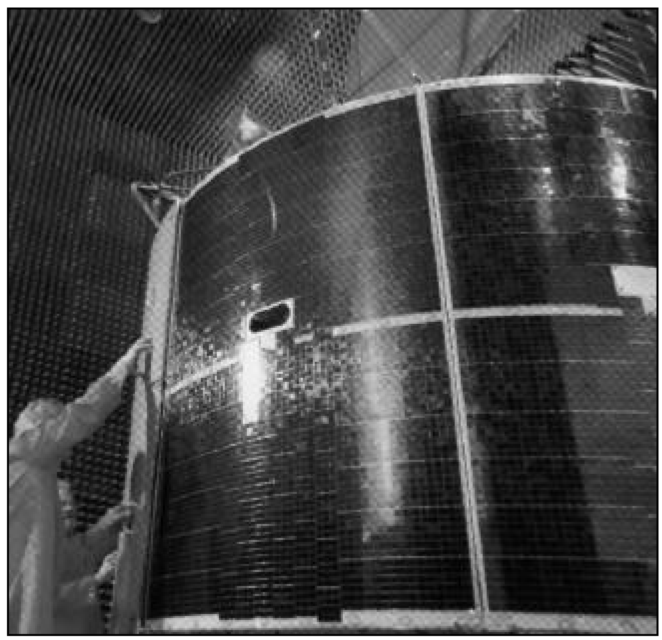


Photo courtesy of TRW

**Figure 5. Cylindrically Shaped Spacecraft with Body-Mounted Solar Cells**

Spacecraft capability and mission applications continued to require increased power. The trend was clear. As spacecraft capability and mission applications drove array technology development, increased solar array power requirements also increased to keep pace. Body-mounted array systems were limited in capacity and what the industry needed was a completely new and innovative solar array system which could provide power growth potential for future applications. This need provided the catalyst for the development of the large multi-panel sun-orientated deployable solar array. An example of a large multi-panel deployable solar array is shown in Figure 6.

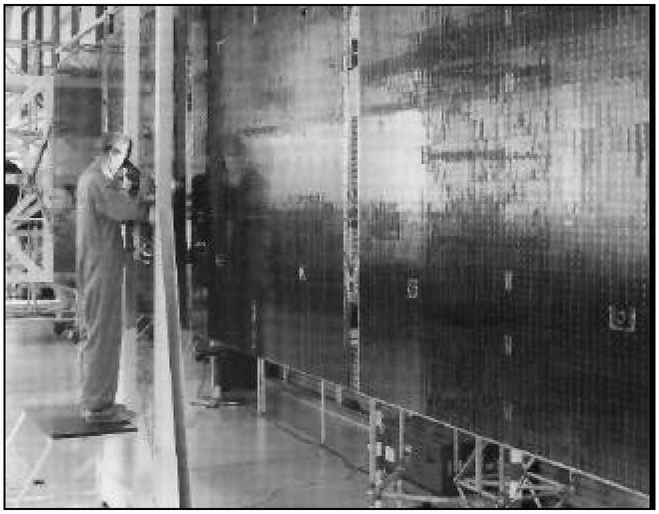


Photo courtesy of FSS

**Figure 6. Multi-Panel Deployable Solar Array**

Today, the multi-panel deployable solar array is the most common system utilized for high power applications. Its ability to provide accommodation for power growth (up to 15 kW), high reliability, competitive weight (≈45 W/kg), and low cost (<1000 $/W) led to its near-universal acceptance and high maturation.

## 3. DRIVING REQUIREMENTS

Mission requirements and objectives have historically driven the evolution of solar array technologies and array configurations. The most prominent requirements which have played key roles in evolving many array technologies have been system cost, mass, and power growth capability. Other secondary requirements which have also contributed in evolving solar array technologies have included space radiation/plasma environments, life, stowage volume, operating and survival temperatures, deployed stiffness, on-orbit accelerations, on-orbit voltage, sun tracking capabilities, transfer orbit power, deployed area, dimensional stability, and survivability from auxiliary environments.

The requirements listed above, or a combination thereof, vary with a particular mission application. The three major mission types are science, military, and commercial. Unique science, military, or commercial mission requirements combine to drive solar array technologies.

Science missions are configured for earth, interplanetary, and interplanetary surface applications. For science interplanetary and interplanetary surface missions spacecraft, weight and stowage volume is at a premium. Lightweight solar arrays which stow into compact launch volumes are attractive for these applications. The requirement for increased shielding for these applications is not as prevalent because electron and proton radiation exposure is small. Earth science applications are not as weight critical as interplanetary missions, but do require shielding from orbital electron and proton radiation. Military missions are categorized as classified and non-classified earth orbital applications. Military missions are primarily reconnaissance, intelligence, or communications in nature. These systems are designed for unique missions which generally employ state-of-the-art payloads, subsystems, and solar arrays. Many of the state-of-the-art solar array technologies employed today are a result of previous military applications. Commercial missions are primarily communications based and occupy low, medium, and geostationary earth orbits. Because of the ultra-competitive nature of the commercial business, solar array designs are primarily focused on systems which consistently reduce cost and weight. The commercial GEO market not only requires cost and mass efficiency, but also power growth potential to accommodate ever-increasing spacecraft capacities.

## 4. SOLAR ARRAY TECHNOLOGIES

Historically, the major solar array subsystem level technologies were optimized over the years to meet evolving requirements. These included innovative structural platforms, unique deployment systems, novel mechanisms, and higher efficiency photovoltaics. Improvements in each of these subsystems has led to a significant increase in operating efficiency, reduced mass, and lower cost.

Today the array engineer has many structural platforms, deployment systems, mechanisms, and photovoltaic subsystem types to choose from. This multitude of array design options enables a system to be specifically tailored to a precise mission.

### *Photovoltaics*

The first solar cell manufactured for space applications was a silicon-type solar cell with a 10% Beginning of Life (BOL) efficiency. Single-crystal-silicon photovoltaics were the standard cell type for the space industry since the 1960's, 1970's and early 1980's. Throughout this period, efficiencies for the silicon solar cell improved from approximately 10% to 17% BOL. This improvement in cell efficiency is the primary result of improved cell design (i.e., back surface reflectors, frontside light trapping structures, etc.) and manufacturing process technologies[12]. Cell thickness was reduced from a robust 12-mils to as thin as 2.5-mils though the processing of thinner wafers. This significantly reduced cell thickness provided a decrease in array system level weight.

In the late 1980's and 1990's, single-junction gallium arsenide (GaAs/Ge) based photovoltaics, with efficiencies exceeding 19%, were developed and employed. Hughes Aircraft Company pioneered the early development of GaAs/Ge photovoltaics with their Liquid Phase Epitaxy (LPE) process. Shortly after, the U.S. Air Force commenced a manufacturing technology program with Tecstar to demonstrate GaAs/Ge growth through a high volume metal-organic chemical vapor deposition (MOCVD) reactor. High volume production with the GaAs/Ge MOCVD process, or variants of, is currently being performed at Spectrolab and Tecstar. Today, single-junction GaAs/Ge solar cells account for over 50% of the total photovoltaic production. According to many solar cell vendors, the demand for single-junction GaAs/Ge will soon replace silicon for most future applications. To counter this demand for GaAs/Ge photovoltaics, various solar cell vendors developed a thin high-efficiency silicon solar cell which provides over 17% BOL efficiency. This cell is providing many commercial users with an intermediate solution between standard silicon and GaAs/Ge, as it costs less than GaAs/Ge and produces comparable array level mass characteristics.

Recently, in the late 1990's, the basic single-junction 19% GaAs/Ge cell saw considerable evolution. The major evolution of this basic cell platform was to grow additional photovoltaic active layers over the single Ga As/Ge junction. This technique led to the development of multijunction solar cells. Multijunction $GaInP_2$/GaAs/Ge solar cells, developed for the U.S. Air Force's manufacturing technology program, produced efficiencies up to 24.2% for large-area cells. The triple junction variants have yielded efficiencies over 25.5%[9]. As power requirements continue to grow, and mass and volume requirements remain constrained, the need for even higher efficiency photovoltaics will be critical. Advanced multijunction solar cells will be a critical component of future solar array power growth.

The anticipated deployment of the many proposed low-earth-orbit satellite constellations has renewed interest in low cost thin film photovoltaics. The most promising near-term thin film photovoltaics are amorphous silicon (a-Si), cadium telluride (CdTe), and copper indium gallium diselenide (CIGS)[13]. These thin films have been successfully employed in terrestrial applications but have yet to be adapted to space in high volume quantities. Although the BOL efficiencies of thin film photovoltaics are significantly less than space standard photovoltaics their costs savings potential is enormous. Transitioning this technology to the space sector will require a major mass production development effort and a thorough qualification testing program. The anticipated benefits of these technologies are promising, however they still await repeatable space demonstration and commercial viability [13].

*Structural Platforms*

Solar array structural platforms can be categorized as rigid, flexible, and concentrator systems[2]. An array platform can be configured as a deployable or non-deployable system.

Most deployable solar arrays flown to date employed rigid honeycomb panels interconnected with spring-driven hinges and electrical harnessing. These systems stow folded and attach directly to the spacecraft sidewall. A picture of a rigid panel solar array in its stowed configuration is depicted in Figure 7.

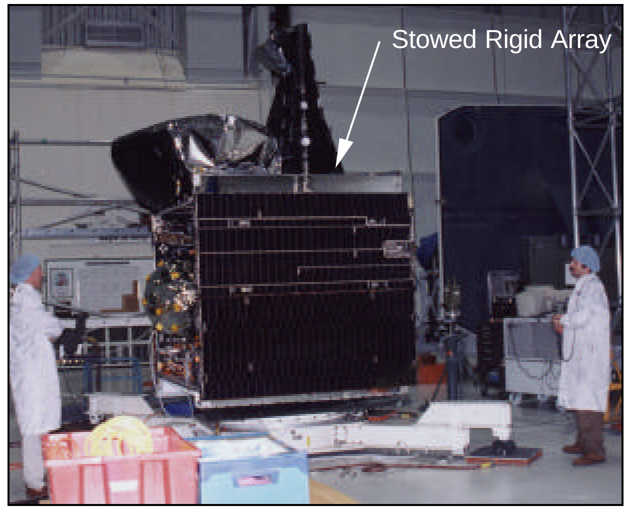



Photo courtesy of AEC-Able

**Figure 7. Rigid Panel Solar Array in its Stowed Configuration**

After release of the launch tiedowns these arrays deploy outward, in an accordion fashion, until each panel is completely flat. Deployment is, preferably, fully coordinated by synchronization mechanisms and deployment rate is governed by a damping mechanism(s). Aluminum honeycomb core and facesheet materials were the typical construction of rigid panels in early systems. Fiberglass/epoxy composite facesheets were then incorporated to reduce weight. Ply orientated Kevlar/cyanate ester and carbon/cyanate ester composite facesheets replaced the fiberglass/epoxy systems to further reduce weight and volatile outgassing. In some instances a Kapton/polyimide film was used as a facesheet material. Additionally, most fabricators now employ an adhesive reticulation technique during the construction of honeycomb panels which minimized the facesheet-to-core adhesive, further reducing weight. More advanced facesheet materials being implemented today consist of single-ply orthographically oriented open-weave materials, and extreme high-modulus, high-strength directionally oriented carbon fiber laminates. Another rigid panel construction currently under consideration is the isogrid reinforced structure. A typical rigid panel solar array with honeycomb panels is shown in Figure 8.

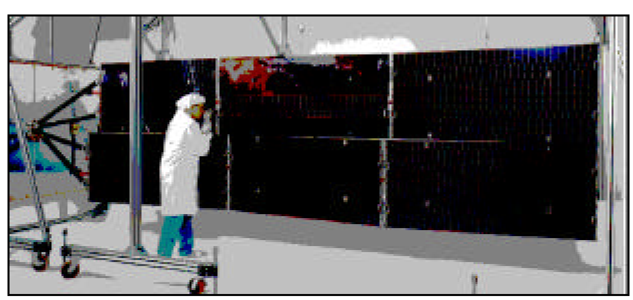
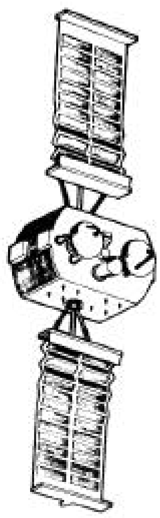


Photo courtesy of AEC-Able

**Figure 8. INDOSTAR PUMA Rigid Panel Solar Array**

Depending upon application, honeycomb panels can be a large component of the overall array system level weight. For some missions which demand reduced weight and/or improved power growth potential, honeycomb panels are being replaced in favor of a tensioned flexible blanket system. The flexible blanket solar array primarily consists of a laminated blanket assembly with photovoltaics and a structural deployment system. Blanket tensioning is achieved and maintained on-orbit by the deployment mechanism. The deployment mechanisms are generally coilable or articulated mast type systems, although tubular systems have been employed and inflatable systems have been contemplated. The first flexible blanket solar array developed was for the Communications Technology Satellite (CTS). A drawing of the CTS spacecraft with its deployable flexible blanket solar array is shown in Figure 9.



Graphic courtesy of JPL

**Figure 9. CTS Spacecraft Flexible Blanket Solar Array**

NASA's first major flexible blanket solar array, successfully flown on the Solar Array Flight Experiment (SAFE) program, employed a coilable mast deployer system. The SAFE flexible blanket solar array is shown, partially deployed, in Figure 10.

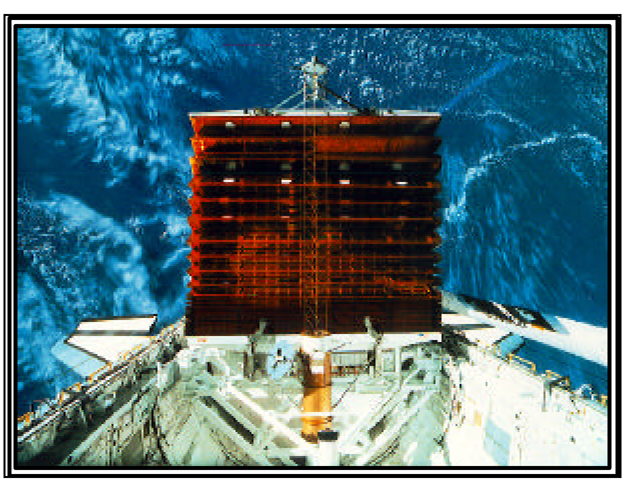
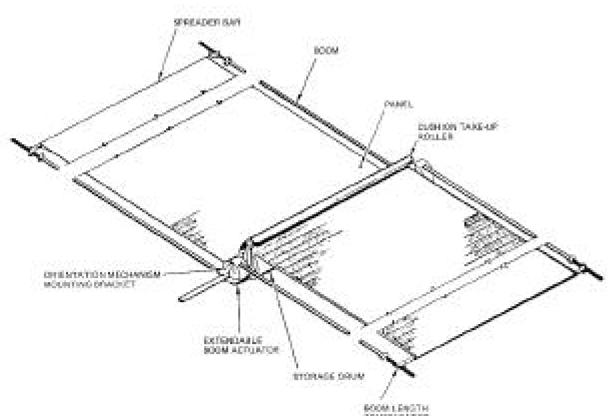


Photo courtesy of LMSC

**Figure 10. NASA SAFE Flexible Blanket Solar Array**

Flexible blanket substrates are composed of a laminated fiberglass or carbon fiber composite and Kapton/polyimide film substrate, or a single-ply composite material. As such, these substrates are very thin (>1mm) and flexible in nature. Special accommodations are required in the array packaging design to withstand the stowed launch and handling environments. Two types of stowage configurations have been implemented with flexible blanket systems. The first type is a folded blanket configuration which deploys outward in a similar accordion fashion as the rigid panel system. An open cell polyimide foam material is employed on each side of the stowed container or as an interleave material between blanket folds. When stowed, the foam is pre-loaded against the folded array to provide cushioning and protection for the delicate photovoltaic cells during launch and handling. The SAFE solar array, shown in Figure 10, is an accordion type flexible blanket system.

An alternate stowage configuration is the roll-up type in which the blanket is rolled up on a cylinder during launch and unrolled by a deployment mechanism during deployment. A picture of the Hughes FRUSA roll-up solar array is shown in Figure 11. A compliant interleave material of embossed Kapton or a separated sheet of polyimide foam is used to provide protection of the photovoltaics from the launch environment. The Hubble Space Telescope Spacecraft employed a flexible roll-up array. A picture of this array is shown in Figure 12.




Graphic courtesy of JPL

**Figure 11. Hughes FRUS A Flexible Roll-Up Solar Array**

Flexible blanket systems are becoming more popular and are being used on many spacecraft. The most notable spacecraft to implement flexible blanket solar arrays include the Milstar, the Hubble Space Telescope, Olympus, CTS and ERS-1[4]. New spacecraft which have yet to fly but will utilize thin flexible solar array technologies will include NASA's EOS-AM[5] and the International Space Station Alpha (ISSA)[6]. A picture of the EOS-AM flexible blanket solar array is shown in Figure 13. This innovative solar array produces over 7 kW BOL and is the first NASA flexible blanket array to employ single-junction GaAs/Ge photovoltaics.

Photo courtesy of NASA

**Figure 12. Hubble Space Telescope Flexible Roll-Up Solar Array**

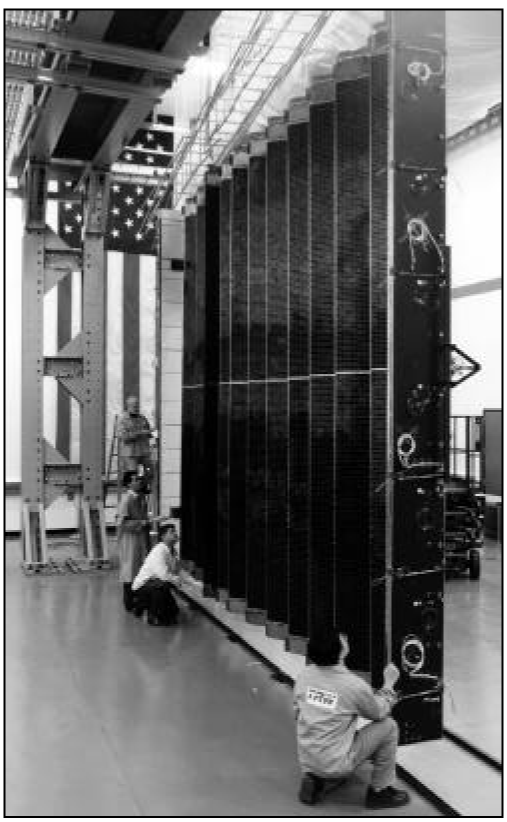


Photo courtesy of TRW

**Figure 13. EOS-AM Flexible Blanket Solar Array**

The solar arrays for the ISSA are enormous. The ISSA array consists of six wings which combine to produce a power of over 75 kW. Figure 14 depicts one half of the qualification wing for the ISSA solar array.

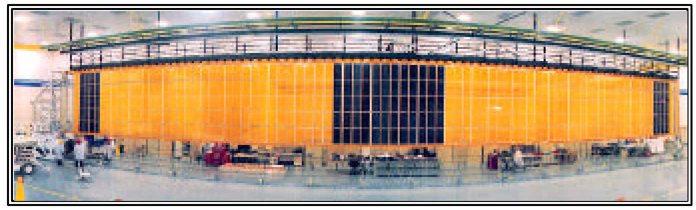


Photo courtesy of LMSC

**Figure 14. ISSA Solar Array Qualification Wing (One Half of Wing Blanket Shown)**

Flexible blanket systems with polyimide blanket composition are inherently susceptible to thermal-snap phenomena because of their relatively low thermal mass and material thermal expansion/contraction mismatches. This condition primarily occurs at eclipse exit under immediate solar illumination incidence. Thermal snap is caused by thermal expansion/contraction mismatches between the tensioned blanket system and its supporting deployment structure. As the flexible blanket system is rapidly heated it experiences an abrupt thermal mismatch between the blanket and deployment structure. The abrupt mismatch results in a significant rate of displacement along the arrays center of gravity. The abrupt change in position results in a dynamic impulse to the spacecraft which must be reacted by the attitude and control system. Thermal snap and jittering effects caused by these mismatches occur after every eclipse and can be detrimental to certain types of spacecraft that require precision pointing.

Flexible arrays are generally more mass efficient as power requirements increase. A qualitative plot, shown in Figure 15, depicts array specific power trends for rigid and flexible array technologies.

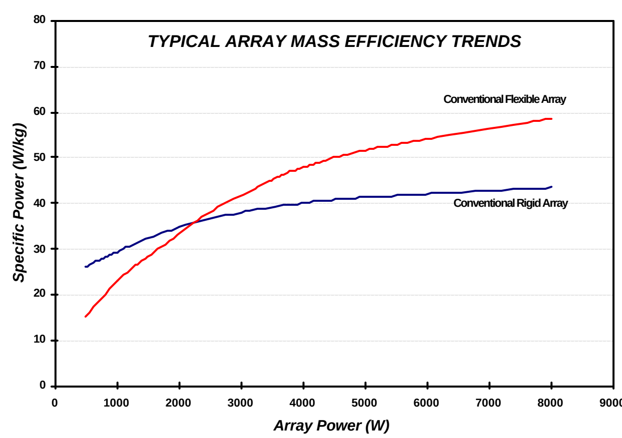



**Figure 15. Rigid & Flexible Array Specific Power Trends**

For power systems less than ~3kW, flexible blanket arrays become less weight competitive because of the large parasitic masses of their supporting deployment system and stowage container. An exception to this trend is the UltraFlex solar array, shown in Figure 16[2]. The UltraFlex incorporates an innovative antennae-like structure to tension the flexible blanket which eliminates the need for large deployment mechanisms and blanket boxes. Because of UltraFlex's low parasitic mass fraction this system provides specific powers of over 100 watt/kg for lower power arrays.

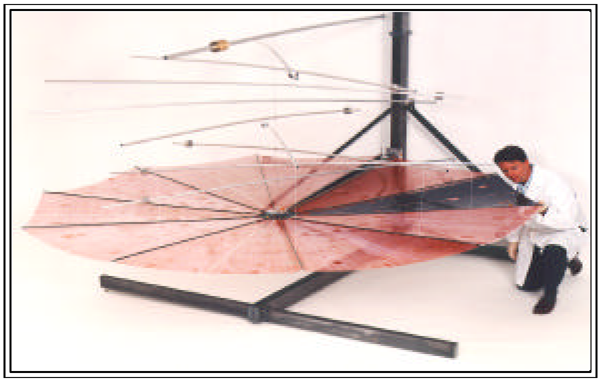
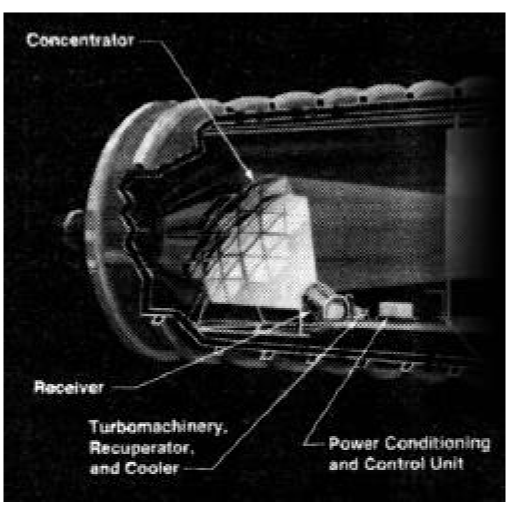


Photo courtesy of AEC-Able

**Figure 16. UltraFlex Flexible Blanket Solar Array**

Solar array platforms which concentrate sunlight onto a smaller area are being seriously considered for many next generation systems in an effort to significantly reduce cost and mass. In some applications, the cost of photovoltaics and their laydown onto substrates represents as much as 70% of the cost of a complete array system. Designs that significantly reduce the amount of active photovoltaic area represent a realistic approach for cost reduction. NASA began the development of concentrators in the early 1980's with the emphasis placed on developing a system which would provide cost benefits for high power arrays, such as the International Space Station. Early concentrator work produced designs which required very precise sun tracking/pointing tolerances ($\pm$ $0.1^0$) and precision optics, making these systems impractical for typical applications. The result of this initial concentrator work produced NASA's Solar Dynamic Array which relies on a large parabolic reflector to concentrate light onto a heat engine. A picture of NASA's solar dynamic array during a ground test is shown in Figure 17.




Graphic courtesy of NASA

**Figure 17. NASA Solar Dynamic Array**

The U.S. Department of Defense (DOD) was also interested in concentrator arrays from a natural and hostile threat survivability perspective. Their requirements drove the concentrator design to practical configurations that were simpler to integrate and matched the performance of conventional rigid panel systems. Many feasible concentrator concepts evolved from the DOD sponsored SUPER program. Under the USAF program a reflective concentrator system was developed that resembled a series of venetian blinds. This technology was developed into Phase B but then canceled. Due to the design's sensitivity to local slope errors and resultant high manufacturing cost deriving from the system's reflective optics this technology has not been taken further. Another concentrator developed in the SUPER program by TRW relied on a number of small parabolic reflective dishes integrated within each panel substrate in a mini-Cassagranian optical configuration. A picture of the TRW SUPER array is shown in Figure 18.

Photo courtesy of TRW

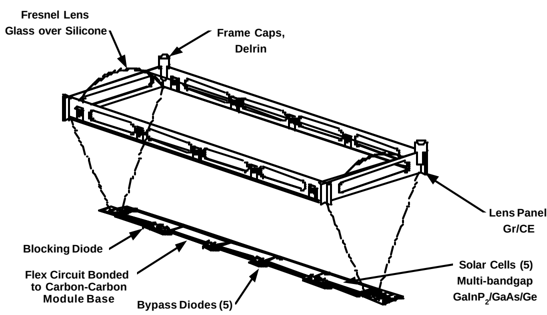
**Figure 18. TRW Super Concentrator Solar Array**

In the late 1980's and early 1990's, NASA joined BMDO to develop an entirely new mini-dome Fresnel lens light concentrating array. A test module of the mini-dome system was produced and successfully flown as part of the Air Force's PASP+ experiment, and is shown in Figure 19. The mini-dome system still required moderate alpha and beta pointing/alignment tolerances ($\pm 2^0$) and this deficiency led to the development of the SCARLET (Solar Concentrator Array with Linear Refractive Element Technology) solar array system.

Photo courtesy of NASA

**Figure 19. PASP+ Mini-Dome Concentrator Experiment**

The SCARLET array employs a linear Fresnel lens element and can accommodate generous off-pointing conditions ($\pm 3^0$ alpha and $\pm 24^0$ beta). A schematic of a SCARLET module assembly is shown in Figure 20.




Graphic courtesy of AEC-Able

**Figure 20. Schematic of SCARLET Module Assembly**

Unlike other concentrator systems, the off-pointing capability of SCARLET is compliant enough to accommodate GEO spacecraft which employ standard single axis tracking systems. SCARLET was flight qualified in 1985 for use on the METEOR spacecraft which ultimately was destroyed during a launch vehicle failure. Figure 21 depicts the SCARLET concentrator array flown on the METEOR spacecraft.

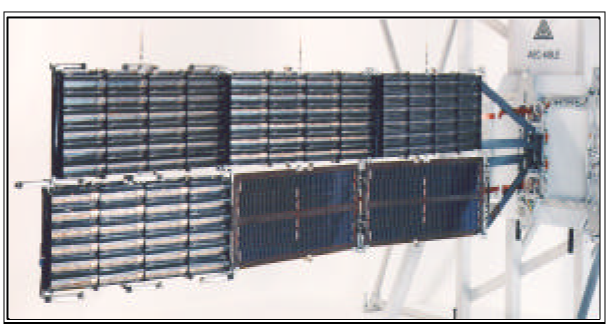


Photo courtesy of AEC Able

**Figure 21. SCARLET Solar Array for the METEOR Spacecraft**

An advanced SCARLET system is being configured for NASA's JPL New Millennium Deep Space One (DS1) spacecraft and is scheduled to launch in mid-1998. The SCARLET DS-1 New Millennium solar array is shown in Figure 22.

In parallel with the NASA/BMDO program, the U.S. Air Force Phillips Laboratory and NASA sponsored the development of a low concentration ratio (LCR) planar reflective solar array. This array was conceived in the mid-1980's by Hughes Aircraft Company, as an approach for providing hardenability from radiation and man-made environments. This concept was further developed by a number of companies since that time. The LCR reflective planar array technology is sensitive to reflective surface tolerances. When the slope errors of the reflective surfaces are not controlled properly, illumination variations occur which current-limit strings and significantly reduce power.

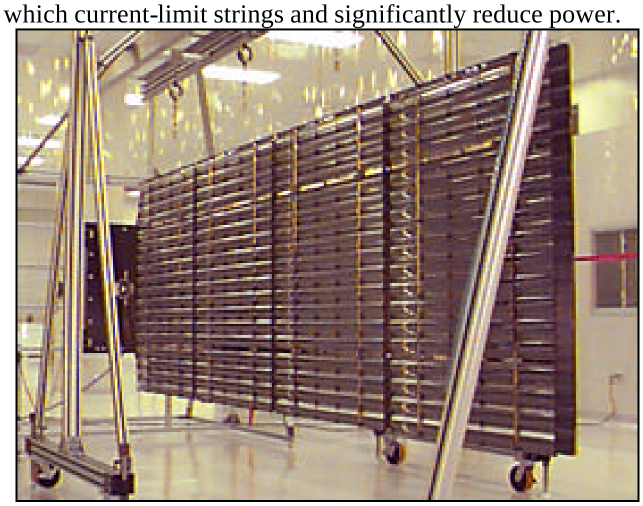
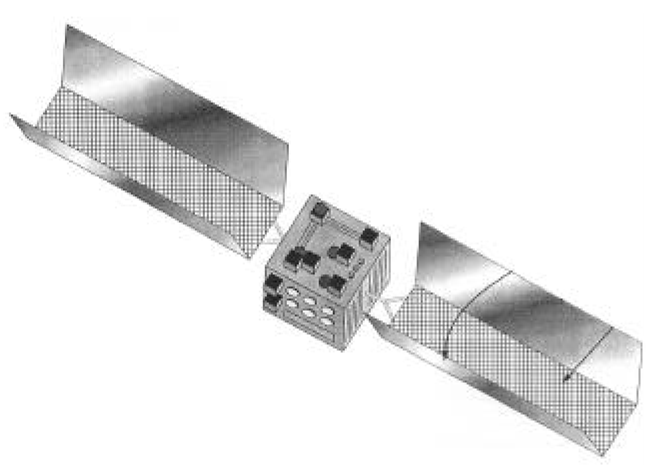


Photo courtesy of AEC Able

**Figure 22. New Millennium DS1 SCARLET Solar Array**

The cost savings potential achievable with LCR arrays is not as significant when compared with technologies that employ higher concentration levels. A LCR planar reflective panel solar array is slated to fly aboard NASA's Small Satellite Technology Initiative (SSTI) 'Clark' spacecraft. A similar LCR array concept with a concentration ratio approaching ~2.5X is being developed at the Naval Research Laboratory[3]. A picture depicting the NRL planar reflective panel concentrator solar array is shown in Figure 23.



Graphic courtesy of NRL

**Figure 23. NRL Reflective Planar Concentrator Solar Array**

Other concentrator concepts being developed include spectrum splitting using holographs to achieve up to 40% efficiency, light transmission through fiber optics to a shielded cell enclosure[7,8], and large Fresnel lens refractive systems employing inflatable structures[2]. These aforementioned systems are currently in the conceptual stages and far from development. As a result, it is difficult to predict their feasibility and the ultimate impact they will have on the spacecraft system.

*Deployment Systems*

Growing satellite power requirements have dictated the multi-panel deployable solar arrays to deploy larger area panels and a higher number of them. For rigid panel type arrays the deployment system is integral with the panel assemblies. In a rigid panel system, each panel is attached to an adjacent panel with hinges and deployment springs. The deployment force of this system is driven through a complement of primary and redundant springs along each panel hinge line. To provide a controlled and coordinated deployment each panel is generally linked to its adjacent panel with a synchronization device. The panel synchronization devices are coupled to one another and terminated at the base hinge/spacecraft interface. The rate of deployment is governed by a damping mechanism located at the base mechanism. The most common deployment synchronization method consists of cable/pulley systems or pantographically coupled panel systems. The solar array to be flown on the next generation GPS IIF spacecraft will employ a pantographic structural synchronization coupling. The GPS IIF solar array is depicted in Figure 23.


Graphic courtesy of BNA

**Figure 23. PUMA Pantographically Coupled Array for GPS IIF**

Some multi-panel rigid arrays rely on other techniques for controlling and synchronizing deployment. One technique employs individual dampers located at each panel hinge line which independently govern and control the deployment rate of each individual panel. The challenge of this system is to match the deployment rates of each individual hinge line, precisely, such that the array deploys in a predictable and safe path.

Flexible blanket arrays rely on extendible boom systems for deployment, and for providing and maintaining the correct blanket pre-load tension. The deployment system most commonly used for flexible blanket systems is the coilable mast. The coilable mast deployer was used for the SAFE, Olympus, Milstar, and EOS-AM solar arrays. These systems are extremely reliable, stow into a compact volume, have reasonable deployed stiffness, and are relatively low cost. The coilable mast system used for the EOS-AM solar array is shown in Figure 24.

For large flexible blanket solar arrays, such as the International Space Station, a mast system with a very high stiffness and strength capability is required. For these applications articulated mast deployer systems provide the needed strength and stiffness characteristics. These systems allow the structural element materials to be more appropriately tailored to requirements. The articulated mast deployer used for the International Space Station solar array is shown in Figure 25, in its stowed and deployed configurations.

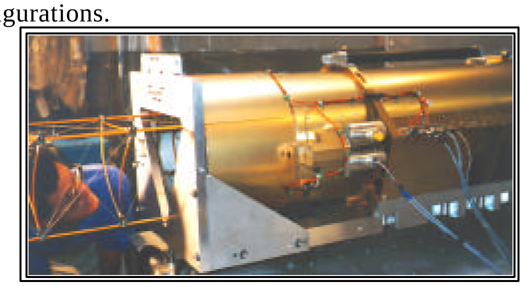
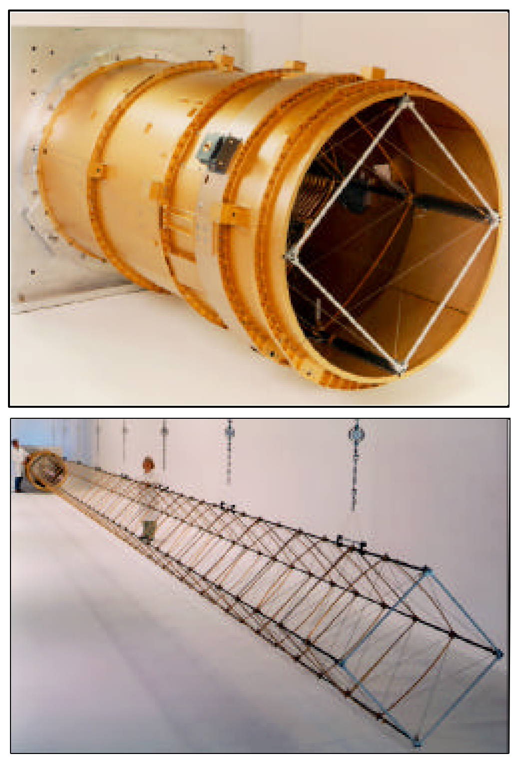


Photo courtesy of AEC Able

**Figure 24. Coilable Mast Deployer for the EOS-AM Solar Array**



Photos courtesy of AEC Able

**Figure 25. ISSA Solar Array FASTMast Deployer**

Tubular boom deployer systems have also been used in unique applications. The CTS flexible blanket solar array employed a centrally located tubular boom deployer. The Hubble Space Telescope roll-up flexible blanket array used two tubular booms running the length of each blanket, as shown in Figure 12.

Inflatable boom deployers are a technology which promises to provide systems with reduced mass and cost[14]. Although these systems have yet to be successfully tested in spaceflight solar arrays, the inflatable technology is getting considerable attention. An inflatable structure can be composed of a B-staged pre-preg composite material that can be fully cured, in its deployed configuration, with a modest exposure to heat. Once completely cured, the inflatable boom becomes rigid to offer adequate deployed strength and stiffness. These systems stow into an extremely compact launch volume, have minimal complexity and offer exceptionally low mass. The anticipated benefits of inflatable technologies are promising, however they still await repeatable space demonstration and commercial viability.

*Mechanisms*

The major mechanisms within a solar array system are integral spring/hinge assemblies (panel-to-panel assemblies and array-to-spacecraft assemblies), launch restraint/release devices, and sun-pointing orientation drive assemblies.

Most hinge assemblies are composed of pin and clevis configurations and include an integral spring along the hinge pin rotation axis. In some cases, flexible carpenter tapes are substituted for conventional hinge devices. The carpenter tape approach is unique in that it combines both hinge and spring features into one element. Flexible blanket systems employ living flexure or pin type hinges which are integral with the blanket assembly, or flexible carpenter tape type hinges/springs which are laminated within the blanket assembly.

Notable developments have occurred with launch restraint/release devices. Pyrotechnically actuated devices have historically been used to sever bolt, cable, and flexible cord tiedowns. Pyrotechnique devices have had excellent reliability, but their inherent shock loading imposed on the array upon release, and the stringent safety and quality provisions required for handling, have led to the development of non-explosive actuators (NEA).

Non-explosive actuators are desirable, for some applications, to reduce the level of shock loading upon the array during release. Non-explosive devices can be initiated with a variety of actuator mechanisms. Some non-explosive actuators, such as the Starsys high-output paraffin system, includes features which allow the device to be resettable during qualification and acceptance level testing. The advantages of these devices are that the units intended to be flown are the same ones which successfully passed acceptance testing, and no refurbishing or replacement of parts are required prior to launch. A picture of the Starsys high output paraffin actuator is shown in Figure 26.

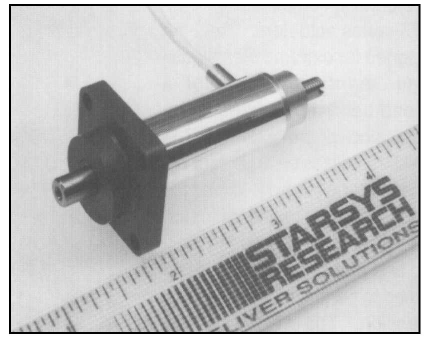
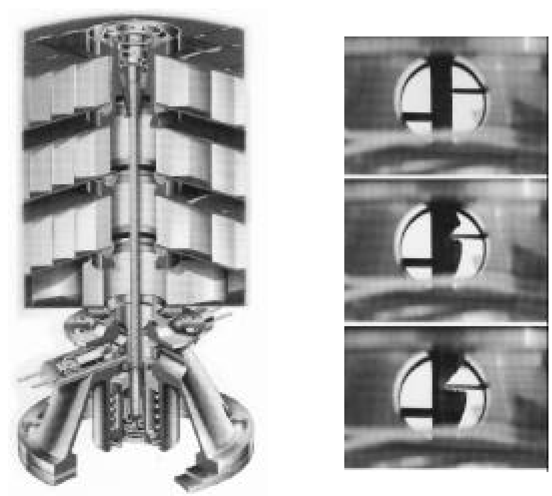



Photo courtesy of Starsys

**Figure 26. Starsys High Output Low Shock Paraffin Actuator**

Fokker Space Systems also developed a unique low shock launch restraint/release device. This system employs a thermal knife which applies heat to cut through a fibrous cord tiedown. The system is space qualified and has flown on numerous solar array systems. A picture of the Fokker thermal knife launch restraint/release device is shown in Figure 27.



Graphics courtesy of FSS

**Figure 27. Fokker Space Systems Thermal Knife Launch Restraint/Release Device**

Other NEA devices include a circumferentially burn wire initiated device produced by G&H Technologies and quick reaction Nitonol shape memory alloy devices developed initially by Lockheed Martin. These devices require replacement of components after each release. As with all NEA's, the releasing process is a slow reaction occurring over a long duration when compared with pyrotechniques. These releasing characteristics help produce very low shock loading into the array.

Orientation drive units are responsible for positioning the solar array normal to the sun for extracting maximum power. These mechanisms consist of a one- or two-axis gimbal, and a motor/controller drive system. The drive motors are configured to provide sufficient torque to autonomously track the sun during the arrays life as well as to reach a faster slew rate when desired. The gimbal mechanisms must provide the required strength and stiffness to accommodate all on-orbit array loads. Drive motors for these devices have evolved throughout the years. Initially, DC brush motors were employed in these systems. As mission life extended and electronic controllers became more powerful, reliable and miniaturized, brushless DC motors were considered as an advantageous replacement. Brushless DC motors provide enhanced controllability, longer life, and lower mechanical noise output, which are sometimes desirable characteristics for particular missions. DC stepper motors are also commonly used today for drive systems. The DC stepper motor incorporates simplistic drive electronics which generally results in a lower system cost.

## 5. FUTURE SOLAR ARRAY TECHNOLOGIES AND TRENDS

Historically, as solar array power requirements continued to grow, the demand for higher power systems that were lower in cost and weight became more crucial. To meet next generation industry needs solar array systems will also have to provide power growth potential, low cost and light weight.

Today, the transition of space from the government sector to commercial purposes is driving solar array technologies even further. Most of the commercial applications being proposed today consist of high power geostationary earth orbit (GEO) based systems, and low to medium earth orbit (LEO to MEO) constellations composed of many spacecraft. Recent projections from leading GEO spacecraft manufacturers indicate that solar array power requirements will climb from the 8 to 10 kW ranges of today to 15 to 20 kW within 5 years, and up to 30 kW within the next decade[10]. Meeting these new aggressive GEO applications will require consideration of alternative array technologies which minimize performance/cost impacts at the spacecraft system level and allow significant cost savings through economies of scale. High concentration ratio (HCR) solar arrays appear to be the best candidate for meeting the high power GEO requirements. The HCR arrays are able to significantly reduce cost while maximizing power growth potential by flying high efficient solar cells more economically than other systems. HCR arrays provide the most cost-effective platform to utilize next generation photovoltaics as they come on line. Projections from various LEO and MEO constellations indicate that within the next decade over 500 solar array systems will be required for project completion. A number of these proposed LEO and MEO applications employ large production volumes and operate in high radiation environments. These applications will demand innovative designs which deliver low system cost and employ novel radiation hardening techniques. HCR arrays which can more mass efficiently provide radiation protection and low cost, and extremely low cost thin film photovoltaics are promising candidates for emerging LEO and MEO missions. Cost and performance characteristics of various array technologies is shown in Figure 28.

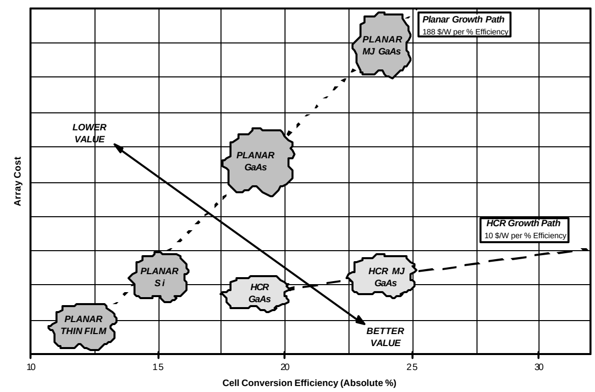



**Figure 28. Cost/Performance Landscape of Array Technologies**

Concentrator systems which employ innovative cost and mass reduction features, and can easily be adapted to a spacecraft with negligible impact, offer an attractive solution for meeting the cost and performance requirements of the future. High efficient photovoltaics will become more prominent in future systems and will provide a much needed growth potential for existing arrays. Thin film photovoltaics represent a cost-efficient technique for significantly reducing solar array cost for low power and high volume applications.

The SCARLET concentrator solar array may represent such an advanced HCR array technology for meeting future array requirements. SCARLET is currently the most mature and practical HCR array developed to date. It has been reported that a SCARLET 15-kW array system will provide over a $10M cost savings when compared to an equivalent conventional rigid panel planar array[11]. Additionally, SCARLET systems provide a marginal mass savings when compared to conventional arrays, which provides further savings at the spacecraft system level. Innovative systems which provide higher power, lower weight, and significant cost savings, such as SCARLET, will evolve solar array technologies even further.

## 6. CONCLUSIONS

As in any vibrant technical arena solar array technology evolution responds to the give and take of application requirements. A historical review illustrates how solar cell efficiencies increased by 260%, how installed power levels have grown by three orders of magnitude, and how a diverse family of structural-mechanism solutions were developed.

There now exist various technical solutions tailored for a spectrum of missions, from interplanetary to low earth orbiting applications. The available technology base is broad and proper systems optimization requires a good understanding of the relevant drivers. For some missions like interplanetary landers absolute minimum mass and stowage volume will be paramount. For other applications like multi-unit commercial communications constellations absolute minimum cost will be critical to support a viable business model.

The combined performance and low cost characteristics of HCR systems should appeal to various high power missions in the future. The transition of thin film photovoltaics to the space environment will likely be attractive to the multi-spacecraft constellation applications. And the unique requirements of interplanetary missions ought to motivate the industry to conceptualize even more unique systems than we've seen in the past.

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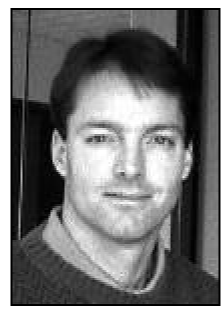
## 8. BIOGRAPHIES

P. Alan Jones:

After graduation from the University of California at Santa Barbara with a B.S.M.E. Mr. Jones performed various assignments for Able Engineering, including managing the Advanced Photovoltaic Solar Array program, the Tethered Satellite System Strengthening program, and the SUPER Solar Array program. Mr. Jones also managed the research and development effort that produced four separate solar array products for Able Engineering. Mr. Jones holds five patents in the array technology field and has authored numerous technical papers. Mr. Jones now manages the Able Solar Array Product Group and oversees the efforts in five direct programs as well as IR&D and business development matters.



Brian R. Spence:

Mr. Spence received his B.S.M.E. from the University of California, Santa Barbara, in 1986. With over 11 years experience in aerospace, Mr. Spence has been involved in the design, development and analysis of space-based deployable structures, mechanisms and solar array systems, in project engineering and management capacities. Mr. Spence's most notable projects include the ISSA Mobile Transporter, Mars Pathfinder Deployable Ramp, Phillips Laboratory/U.S. Air Force Astro-Edge solar array, NASA SSTI Astro-Edge solar array, HS702 planar reflective low concentrator solar array, and the Advanced SCARLET solar array. Mr. Spence is currently a member of the solar array systems group at AEC-ABLE Engineering, and is primarily involved in business development and advance IR&D activities. Mr. Spence has authored numerous technical papers and is a registered

professional engineer in the state of California.