JOURNAL OF PROPULSION AND POWER
Vol. 12, No. 5, September–October 1996

Linear Refractive Photovoltaic Concentrator Solar Array Flight Experiment

P. Alan Jones* and David M. Murphy†
AEC–Able Engineering Co., Inc., Goleta, California 93117

Concentrator arrays deliver a number of generic benefits for space, including high array efficiency, protection from space radiation effects, and minimized plasma interactions. The line-focus concentrator concept delivers two added advantages: 1) low-cost mass production of the lens material and 2) relaxation of precise array tracking requirements to only a single axis. Current array designs emphasize lightweight, high stiffness, stowability, and ease of manufacture and assembly. The linear refractive concentrator can be designed to provide an essentially flat response over a wide range of longitudinal pointing errors for satellites having only single-axis tracking capability. In this article we describe the solar concentrator array with refractive linear element technology–multiple experiments to Earth orbit and return (SCARLET)–(METEOR) flight experimental hardware as well as the status of the current SCARLET linear concentrator program. After a vigorous six-month design, fabrication, and qualification test phase, the flight experiment was delivered for spacecraft integration onto the METEOR spacecraft. Despite the failure of the Conestoga launch vehicle and, hence, the loss of spaceflight data, the program succeeded in validating system-level concentrator array component integration and alignment issues.

Introduction

PAYLOAD capability for next-generation satellite systems will continue to grow as economic pressures drive demand for greater return on investment measured, in the commercial arena, as transponder revenue and, in the government sector, as either scientific return or payload capability. In some cases an increase in payload capability requires a like increase in available spacecraft electrical power. Spacecraft trade studies often indicate the use of a high-efficiency solar array system to accomplish this design requirement. If standard silicon cell rigid array technologies are employed, array mass, stowed volume, and deployed area may quickly erode the desirability of the enhanced payload. Standard bus designs were developed with silicon cell technologies for standard launch vehicles with standard fairing shroud sizes. When power levels are roughly doubled, the twice-as-big solar array on such a standard bus seriously erodes launch vehicle mass and volume margins. This trend will serve to limit spacecraft power levels. To maintain reasonable array sizes and therefore standard spacecraft sizes, systems (attitude control system, station-keeping fuel usage, etc.), and manufacturing facilities, higher cell photovoltaic conversion efficiency is required.

High-performance, sunlight-concentrating solar arrays offer spacecraft users cost and performance benefits, especially when high-efficiency solar cells are indicated by system-level trades. The solar concentrator array with refractive linear element technology (SCARLET) system is the first concentrator array with sufficient practicality to reasonably provide such benefits. To quantify and verify these benefits via in-orbit performance measurement, an aggressive, six-month development and flight validation program was undertaken. In this article, we introduce the basic SCARLET technology and its benefits to users, examine previous experimental work, and describe the SCARLET–multiple experiments to Earth orbit and return (METEOR) flight demonstration/validation program.

Received Oct. 16, 1995; revision received June 4, 1996; accepted for publication June 7, 1996.

*Director, Advanced Programs, 93 Castilian Drive.
†Senior Engineer, Advanced Programs, 93 Castilian Drive.

Simply stated, concentrator technology, by definition, enables arrays to operate with much lower cell active area for a given power level. For instance, a concentrator array with a 15:1 geometric concentration ratio requires about 7% of the active solar cell area of a traditional planar array. This equates to a direct 93% reduction in solar cell material costs that are a large component of total array costs. Additionally, since only 7% of the total area needs to be populated, high-efficiency multijunction cells can be more economically employed to field a reduced-area array, which limits aerodynamic drag and relaxes attitude-control-system requirements. The indirect system-level life-cyle cost benefits of such high-cell-efficiency reduced-area arrays vs low-cell-efficiency large-area arrays are well-documented by Ralph.[1] These generic cost benefits will, of course, favorably impact all mission types.

For some missions, medium orbital height Earth orbits (MEO) are desired for their favorable payload fields of view vs radiated power requirements. The main technical barrier to employing satellites in such high-radiation environments is degradation of cell energy conversion efficiency as a result of electron and proton impingement. In a planar array, compensating for this cell degradation requires the use of larger, more costly arrays [i.e., a high beginning of life (BOL) to end of life (EOL) power ratio]. Alternately, system costs are driven by unreasonably massive radiation protection over the entire cell area, frontside and backside. For such missions, the SCARLET array will provide significant mass savings because only 7% of the array's area requires radiation protection with mass shielding. This mass savings can technically and financially enable certain missions, such as MEO communication constellations or a geosynchronous mission employing spiral-out electric propulsion orbit raising.

SCARLET technology can also partially mitigate the debilitating effects of interplanetary distances on solar cell absolute efficiency. These low-intensity, low-temperature (LILT) effects increase the size and cost of a solar array for a multi-astronomical unit (AU) (Mars and beyond) spacecraft. Although LILT effects can be minimized by cell design, concentrator technology offers a less expensive method of addressing the issue using current cell technologies. For instance, at 4 AU the sunlight intensity is approximately 1/16th of that at 1 AU. A 15:1 SCARLET array will concentrate the sunlight intensity received at the solar cell receiver back to a level approaching

1-AU intensity. The photovoltaic cell would then operate at its near 1-AU absolute efficiency rather than the reduced efficiency associated with the diminished 4-AU light intensity. Even though the total array area will still only receive the reduced 4-AU intensity, the cell will not suffer the low intensity (LI) component of LILT-induced photoconversion efficiency degradation. The combination of concentrator arrays and LILT-capable cells may enable deep interplanetary missions that might otherwise require nonphotovoltaic power sources.

Technical Basis and Design Description

The application of concentrator arrays has historically been limited by their waning power response to an off-pointed solar vector. From a risk point of view, the reliance on such tight pointing accuracies is unacceptable. The SCARLET array technology utilizes pointing error tolerant refractive Fresnel optics to achieve a 15:1 concentration of the incoming sunlight onto photovoltaic solar cells. The SCARLET design, utilizing the innate error tolerance of Fresnel optics, is a highly practical concentrator solar array because it accommodates the combination of manufacturing tolerances, thermal distortions, and jitter, as well as the inevitable off-angle errors caused by positioning knowledge and command errors.

Optics System

To avoid the problems encountered by previous reflective-optics-based concentrator arrays the choice of Fresnel refractive optics is driven by its relatively large tolerance to local slope errors. The arched linear Fresnel lens tolerance to local slope errors is 300× better than reflective approaches because of the self-correcting nature of its symmetrical design [half the required light turning angle occurs at the outer surface with the remaining half occurring at the inner surface (Fig. 1)]. This feature reduces manufacturing costs and favorably impacts spacecraft operational concerns. Unlike reflective optics, refractive optics do not require the high-surface smoothness required to prevent scattering losses. Such a surface is costly to manufacture and difficult to protect from on-orbit environmental effects. The len's shape error tolerance eliminates potential problems caused by deflections, distortions, or thermal expansion/contraction effects, which have plagued other types of photovoltaic concentrator systems (especially parabolic trough reflector systems).

A light ray trace drawing for a typical optics configuration is shown in Fig. 2. Note the secondary concentrator at the focus of the Fresnel lens primary concentrator. The secondary reflects rays onto the underlying cell by total internal reflection (TIR), and thus requires no metallic reflector surface.

The linear Fresnel system has different sensitivities to sun vector off-pointing in the two principal axes, α and β shown in Fig. 3. Sensitivity to errors about the lateral axis α are greater than to errors about the longitudinal axis β as shown in Fig. 4. This feature can be employed to provide optics for missions planning only a one-axis array tracking mechanism. Longitudinal sun-pointing errors of up to 23.5 deg can easily be accommodated. The data for the particular lens design plot-

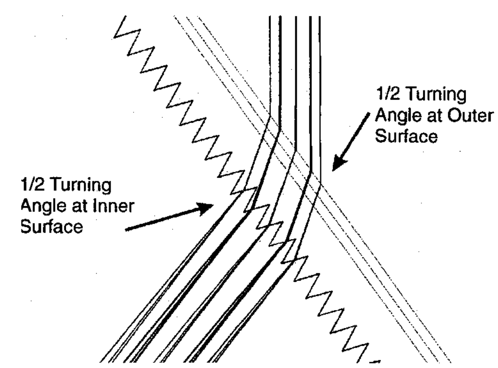

Fig. 1 SCARLET refractive optics; close-up of Fresnel showing ray turning.

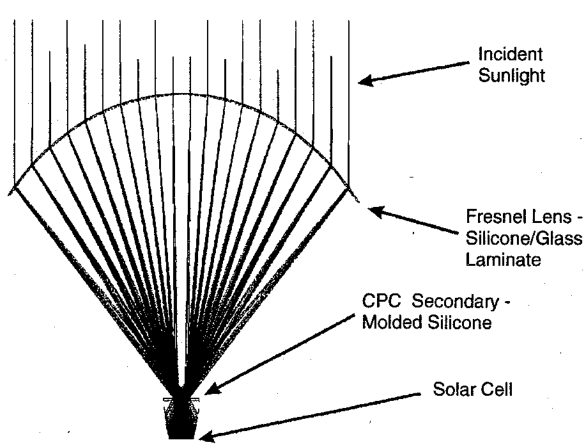

Fig. 2 SCARLET optics light ray trace; side view of Fresnel optics train showing ray trace.

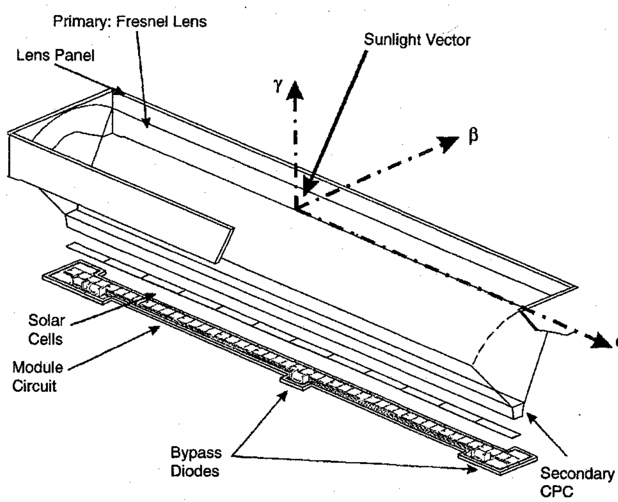

Fig. 3 SCARLET module design; drawing of Fresnel optics integrated into module unit.

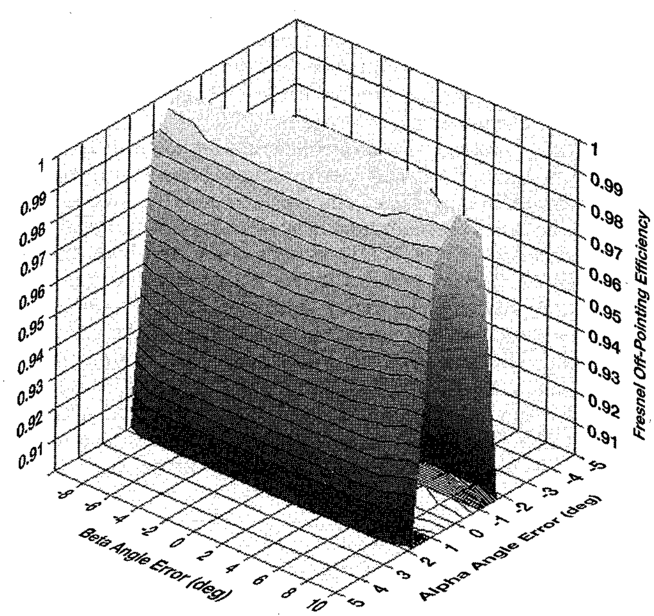

Fig. 4 Optical off-pointing efficiency; three-dimensional chart showing alpha and beta off-pointing tolerance of lens efficiency.

ted in Fig. 4 show a 0.5% factor at a 10-deg longitudinal pointing error and a 10% factor at a 2-deg lateral pointing error. In practice, the desired lateral and longitudinal tracking tolerances are traded against overall light concentration ratio in the system design process.

Cell Module

To meet the program's cost objectives the cell module design (Fig. 3) is oriented toward cost-effective mass production techniques. Small concentrator solar cells (1.3 by 3.2 cm) are attached to a high thermal conductivity base. An automated ultrasonic wire welding step completes the cell series interconnection with a Kapton flex circuit attached to the base. Mesa-type bypass diodes are assembled on the module with surface mount techniques. One blocking diode per string is similarly attached to the first of the modules in a circuit string.

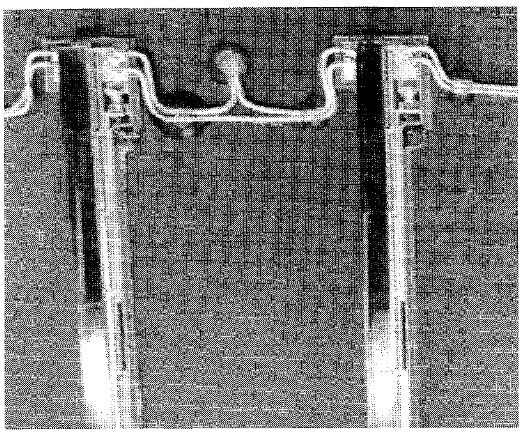

Fig. 5 SCARLET-METEOR modules; close-up of two SCARLET 1 cell modules.

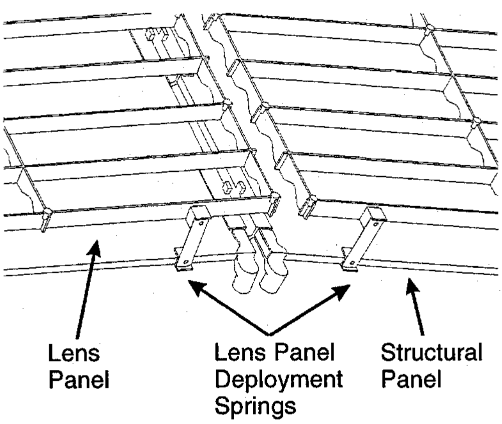

Fig. 6 Fresnel lens deployment; drawing showing means of deployment of Fresnel lens from structural panel.

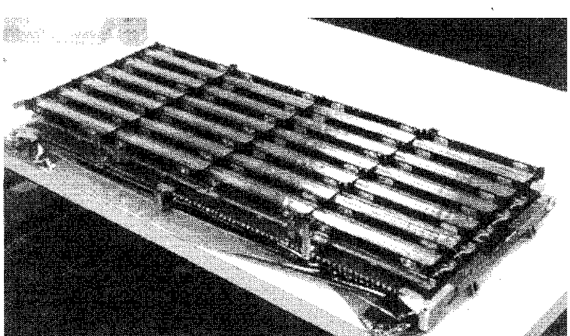

Fig. 7 SCARLET panel with deployed optics; finished SCARLET panel on workbench.

Such a cell placement, attachment, and interconnection approach is amenable to commercial pick and place electronic assembly operations. Typical module subassemblies contain 6–12 solar cells and are about 20 cm long.

If required, compound parabolic curvature (CPC) secondary optics are molded as a single unit the length of a module so that only a single bonding operation is performed rather than a separate bond operation for each cell. A close-up photograph of two SCARLET–METEOR flight modules mounted onto the substrate is shown in Fig. 5. The gallium arsenide on germanium (GaAs/Ge) cells can be seen through the CPC optics.

Deployable Optics

A critical feature of the SCARLET design is the maintenance of reasonable stowed volumes. Concentrator optics require a finite focal length ($\approx$3.0 in. or $\approx$7.6 cm) that historically has defined the array's required stowed thickness and, hence, volume. These volumes are typically too large for most missions. The SCARLET system utilizes a deployable optics system to maintain a small stowage volume. Two patented approaches for lens deployment have been defined. One utilizes a system of lenticular springs to deploy the Fresnel lenses (Fig. 6). The other uses a precision linkage system to articulate the lenses into position. The former design was implemented in the SCARLET–METEOR flight demonstration hardware shown in Fig. 7 with its primary optics deployed above the populated substrate panel. The stowed SCARLET–METEOR wing is shown in Fig. 8.

System Performance

Various design and analytical trade studies were performed to assess the performance of the SCARLET technology. The

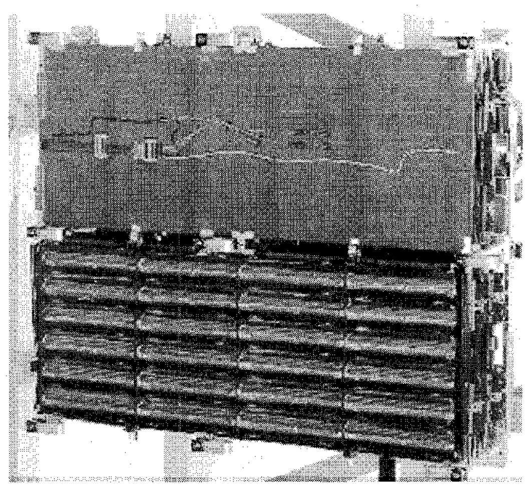

Fig. 8 Stowed SCARLET wing; photograph of stowed SCARLET I wing.

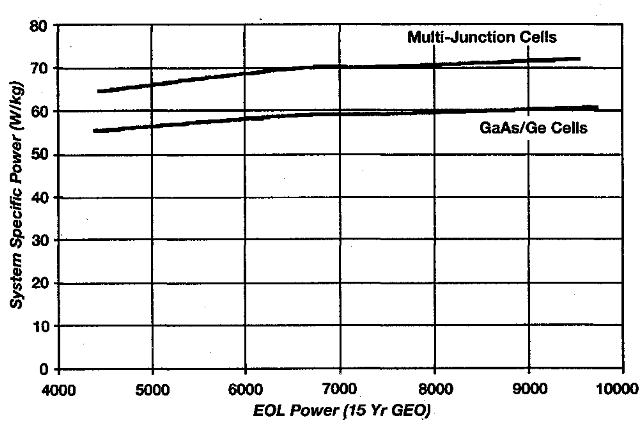

Fig. 9 GEO EOL specific power performance; specific power performance (W/kg) vs array power.

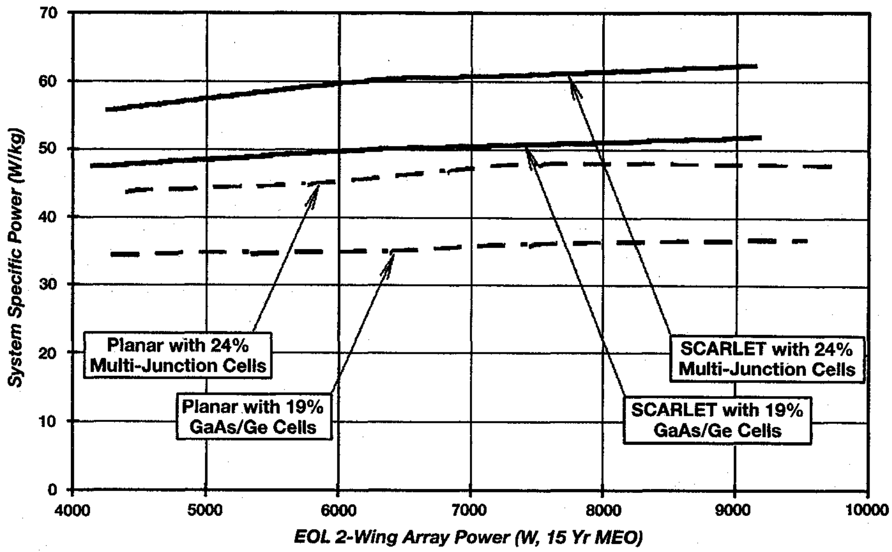

Fig. 10 MEO EOL specific power performance; specific power performance (W/kg) vs array power.

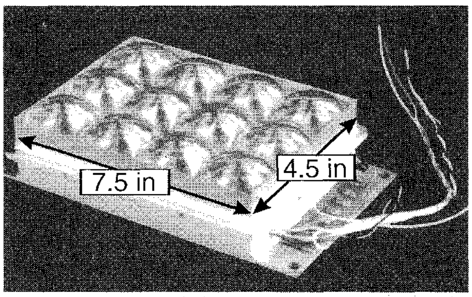

Fig. 11 PASP+ concentrator experiment module; photograph of PASP+ 12 module test article.

results, which incorporate thermal, optical, and radiation analyses, are in keeping with the initial technology assessments put forward by Caveny[2] and Piszczor.[3] SCARLET EOL specific power trends for two solar cell assumptions are depicted in Fig. 9 for a nominal 15-year geostationary (GEO) mission. Figure 10 depicts the same data for a 15-year high-radiation MEO mission, and clearly illustrates the gain in specific power achievable using SCARLET technology, regardless of the type of solar cell used.

Developmental and Flight History

Early Hardware Development

Development of the arched/domed Fresnel lens concentrator concept for space began in 1986 under a small business innovation research (SBIR) contract.[4] This space concept evolved directly from the large linear Fresnel concentrator systems developed for terrestrial applications. Now in their fourth generation of technology development, these multikilowatt terrestrial systems have provided years of experience and validation of the performance of this refractive concentrator approach, demonstrating high overall system efficiencies.

The early space work focused on development of the minidome concentrator, a point-focus version of the concentrator element used by the current SCARLET design. Under government funding, a number of prototype modules were built. These early units emphasized lens fabrication and lens/cell performance. In 1989, this work was integrated with the use of a high-efficiency gallium arsenide/gallium antimonide (GaAs/GaSb) tandem cell structure.[5]

One of the most important concerns early in the program was the long-term stability of the concentrator lens material in the space environment. While terrestrial-based testing provided significant information, the synergistic effects of the space en-

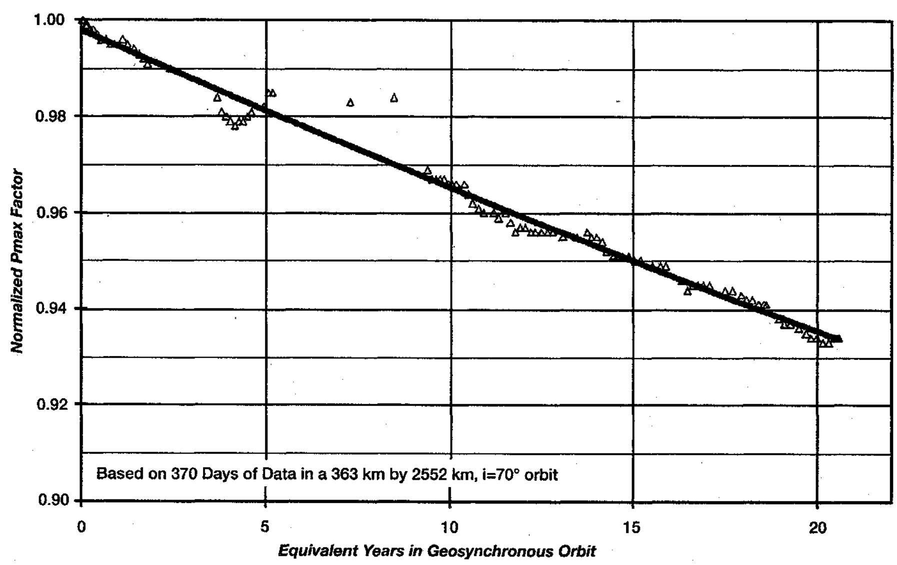

Fig. 12 PASP+ concentrator experimental data; PASP+ power vs equivalent years at GEO.

vironment made actual space-flight data extremely important. The early minidome lens design used a self-supporting, space-qualified silicone (DC 93-500) with a multilayer coating to protect the silicone from the effects of atomic oxygen erosion and uv darkening. A number of passive Shuttle experiments (LDCE 4-5, EOIM-3, and wake shield) were conducted to support lens material characterization and evaluation. These early tests culminated with the fabrication of an active photovoltaic module for PASP Plus.

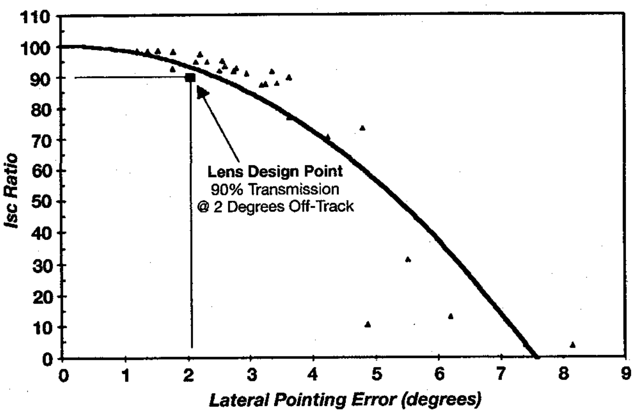

Fig. 13 PASP+ concentrator off-track data; PASP+ power vs sunlight off-pointing vector.

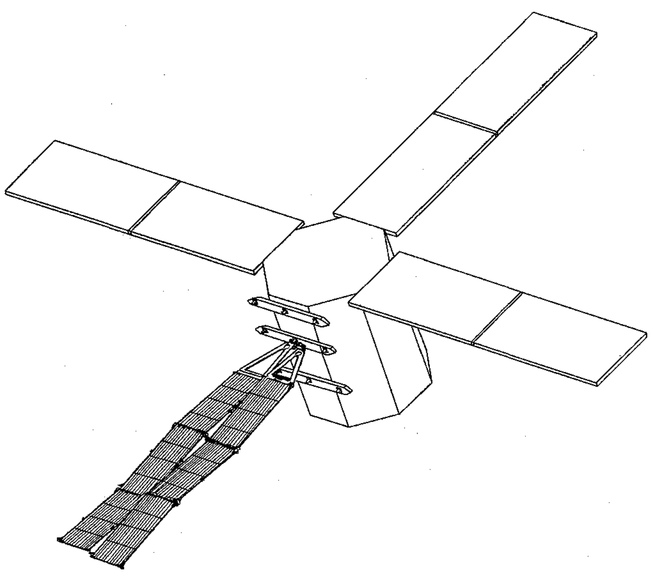

Fig. 14 METEOR spacecraft; drawing of METEOR spacecraft showing SCARLET experimental array.

PASP Plus Flight Experiment

On Aug. 3, 1994, the photovoltaic array space power plus diagnostics (PASP Plus) experiment carried 12 different photovoltaic experiments into a 2552 by 363 km orbit (70-deg inclination). The objective of the experiment was to test a variety of solar array/cell types under different environmental conditions. The highly elliptical orbit subjected the experiments to a proton-dominated, high-radiation environment, as well as wide variations in space plasma densities. In an effort to study the effects of space plasma on high-voltage arrays, a number of the experiments were biased at voltages from −75 to +500 V. With over one year in orbit, PASP Plus has supplied a wealth of information, specifically on the performance of refractive concentrator technology and its interactions with the space environment. The refractive concentrator experiment is a 12-element, point-focus, minidome-Fresnel lens concentrator module with GaAs/GaSb tandem cells and optical secondaries to increase tracking error tolerance. The concentrator portion of the PASP+ experiment is well described by Piszczor et al.[6] The lens is made of DC 93-500 silicone with a multilayer uv reflecting/atomic oxygen protection coating. While the PASP Plus experimental module is a point-focus design, the general concept and use of lens materials is identical to the line-focus concept and directly applicable to SCARLET. A photograph of this module is shown in Fig. 11.

The data from PASP Plus have been extremely encouraging.[7] After one year in orbit, with 3537 thermal cycles (eclipses) and a relatively high radiation dose of 9.7 E14 equivalent 1-MeV electrons, the minidome concentrator has degraded the least of all the experiments. The module performance as a function of time is shown in Fig. 12 with a linear curve fit. It is important to note that the short circuit current, a direct measure of lens optical efficiency and durability, showed minimal changes over the first 200 days. This indicates that contamination of the optical surface (a significant problem for previous reflective concentrator experiments) was a negligible concern and verified that the lens works well in space as designed. The off-tracking data points obtained were also consistent with predictions (Fig. 13). Analysis of the current–voltage curves does not indicate any nonuniformity over the 12 element module, leading to the conclusion that most of the minimal degradation observed in the module is because of the radiation damage to the photovoltaic cell itself[8] and, thus, that the UVR coating is doing a good job protecting the silicone optic materials from uv darkening and atomic oxygen (AO) degradation.

Another very important aspect of concentrator technology demonstrated by PASP Plus is its inherent resistance to the effects of plasma interactions. Consistent with ground-based testing prior to flight, the concentrator module exhibited minimal leakage current during positive biasing and minimal arcing during negative biasing at voltages up to 500 V. This is an extremely important attribute when incorporated with cer-

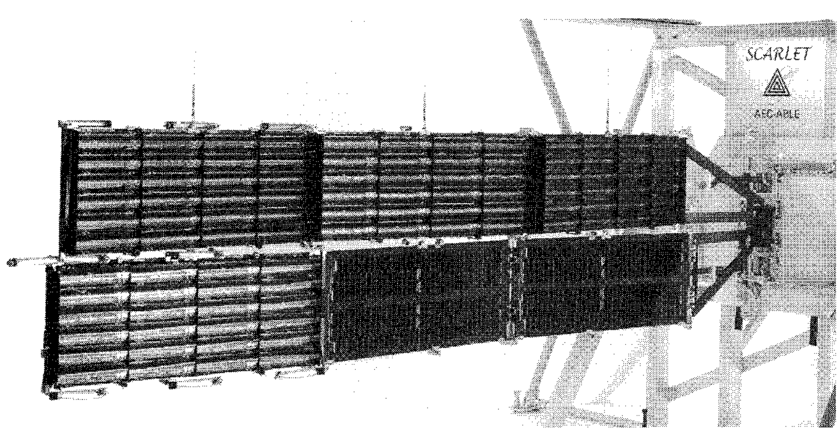

Fig. 15 SCARLET/METEOR flight demonstration wing; photograph of the deployed SCARLET experimental array.

tain aspects of electric propulsion, where advantages may be gained by running the thrusters at high voltages directly off the photovoltaic power system.

SCARLET-METEOR Flight Experiment

In early 1995, an opportunity arose to fly SCARLET technology at the array level on the METEOR spacecraft. The SCARLET/METEOR flight validation program was awarded to the contractor team in January of 1995 and the first-generation wing was delivered for integration to the NASA METEOR spacecraft in July 1995 (Fig. 14). The single-wing, six-panel deployable array demonstrated the first-generation implementation of SCARLET and first use of concentrator technology at the operational array level. The SCARLET–METEOR demonstrator was designed to replace one of the four existing silicon cell planar wings. The METEOR spacecraft was to fly in a nadir orientation most of the time and periodically would have slewed the spacecraft into a solar-inertial orientation with sun-pointing solar arrays, for data acquisition from the array experiment. The SCARLET wing (Fig. 15) was composed of four concentrator panels and two silicon cell planar panels. The two planar panels were required to maintain energy balance when the spacecraft is in the nadir mode as all the wings are nongimbaled. The array used the PUMA deployable structure (previously qualified as a planar array deployment system) with deployable concentrator lens panels to decrease the stowage volume of the array as described in the previous section. The structural panels were populated with GaAs/Ge concentrator cell receivers that used secondary CPC lenses to increase tracking error tolerance along the critical lateral axis and provide additional protection in high-radiation environments.

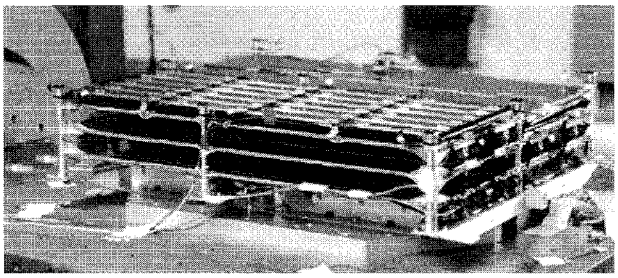

Fig. 16 SCARLET/METEOR random vibration test setup; photograph showing *y*-axis SCARLET vibration test.

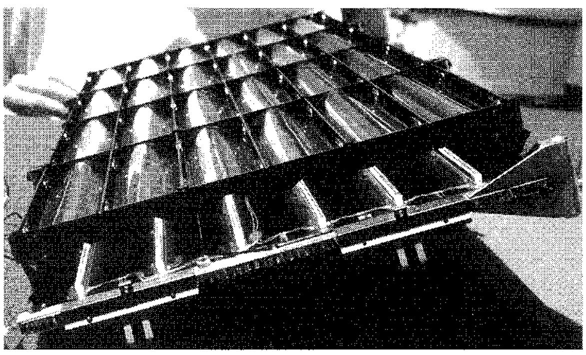

Fig. 17 SCARLET/METEOR air mass 1.5 power testing; photograph showing SCARLET panel-level air mass 1.5 direct power verification test.

The time constraints associated with this opportunity required the prime contractor to go from concept definition and prototype hardware to a flight-qualified array in a period of six months. Despite the schedule driven nature of this challenge, the hardware development and qualification program was a complete success. The array was successfully qualified through acoustic, random vibration, thermal vacuum, deployed stiffness and strength, thermal ambient-environment deployment, and performance testing. Figure 16 depicts the stowed SCARLET array mounted to a shake-table for random vibration testing (lateral in-plane accelerations, 12 g-rms).

Power verification testing was performed at the cell, module, and panel levels. Cell-, module-, and panel-level tests were conducted using a standard large area pulsed solar simulator (LAPSS) with the test article located at a position that provided the same average light intensity as the Fresnel primary lens. The panel-level testing that was done in sunlight at air mass 1.5 (AM1.5) is depicted in Fig. 17. A comparison of LAPSS-based testing with AM1.5 testing is made in Fig. 18. The test data are shown extrapolated to the panel-level air mass zero (AM0) 28°C basis. The test data indicate a correlation within 10% between analytical predictions, LAPSS AM0 tests, and AM1.5 panel-level testing. This correlation is considered good given that the SCARLET/METEOR demonstrator panels were prototypical in nature and subject to numerous manufacturing inconsistencies as assembly processes were evolved within the program's six-month time frame.

Figure 19 depicts the METEOR spacecraft during integration activities. Unfortunately, the loss of the Conestoga launch vehicle on Oct. 23, 1995, prevented SCARLET–METEOR from generating useful spaceflight data.

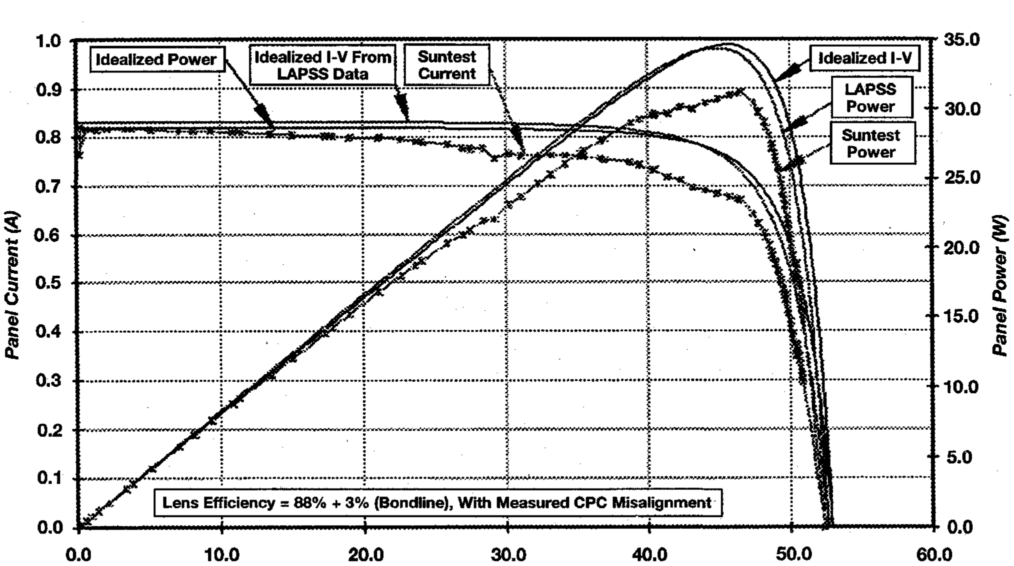

Fig. 18 METEOR AM1.5 power test results; chart of SCARLET power verification test results.

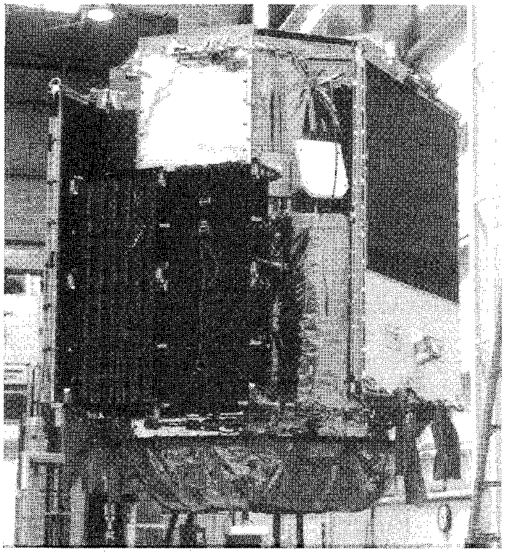

Fig. 19 SCARLET/METEOR spacecraft; photograph showing the SCARLET array integrated to the METEOR spacecraft.

Follow-On SCARLET Activity

Moving beyond the 1/4-kW SCARLET/METEOR experiment, a 2.6-kW SCARLET array is being assembled for use on NASA's first New Millennium deep space mission, DS-1 (Ref. 9). The array will power all of the DS-1 spacecraft's subsystems, including the NSTAR electric propulsion system. The DS-1 SCARLET array uses 24% $GaInP_2$/GaAs/Ge cells, four bar linkages to deploy the concentrator lens panels, a 100-V array bus, and a lightweight flat panel structural design to achieve high performance and low system cost. SCARLET/DS-1 will be launched in the summer of 1998 for a mission of two or more years.

Conclusions

The SCARLET concentrator technology offers unique capabilities to both commercial and government spacecraft users. These include solar array cost reduction, especially when high-performance multijunction cells are employed; mass reduction over traditional planar arrays, especially in high radiation missions MEO and electric powered LEO-to-GEO orbit raising missions; and potentially reduced drag area. The SCARLET technology is ready for near-term application as it has been fully proven in both terrestrial applications and long-duration space experiments (PASP+) and has been qualified at the array level during the COMET/METEOR program.

Acknowledgments

The authors gratefully acknowledge the support of the Ballistic Missile Defense Organization, the AEC–Able Engineering Company, NASA Lewis Research Center, and the U.S. Air Force Phillips Laboratory.

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