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ABSTRACT

This paper summarizes in-space structural validation plans for a proposed Space Shuttle-based flight experiment. The test article is an innovative, lightweight solar array concept that uses pop-up, refractive stretched-lens concentrators to achieve a power/mass density of at least 175 W/kg, which is more than three times greater than current capabilities. The flight experiment will validate this new technology to retire the risk associated with its first use in space. The experiment includes structural diagnostic instrumentation to measure the deployment dynamics, static shape, and modes of vibration of the 8m-long solar array and several of its lenses. These data will be obtained by photogrammetry using the Shuttle payload-bay video cameras and miniature video cameras on the array. Six accelerometers are also included in the experiment to measure base excitations and small-amplitude tip motions.

INTRODUCTION

The power-generation subsystem on most spacecraft constitutes a substantial fraction of the total spacecraft mass. Currently, the maximum power density (power per unit mass) for space solar arrays is about 50 W/kg, represented by the SCARLET arrays on the Deep Space 1 spacecraft [Ref. 1]. Future space science missions, especially those using electric propulsion systems, will require a factor-of-three increase beyond the SCARLET capability. To address this need, the NASA Space Technology 6 New Millennium Program solicited proposals to develop and demonstrate the required technology in space by 2004.

In response, a team led by AEC-Able Engineering Company conducted a concept definition study in February-August 2001 entitled "Lightweight High-Voltage Stretched-Lens Concentrator Solar Array Experiment." This paper discusses results from the study. Other team members are Entech, Inc., Auburn University's Space Power Institute, and three NASA Centers (Langley Research Center, Glenn Research Center, and Marshall Space Flight Center). The proposed solar array concept is a descendent of the SCARLET array with much lighter flexible concentrator lenses and support structures in addition to advanced (30% efficient) triple-junction solar cells. It is referred to as the Stretched Lens Array (SLA) [Refs. 2-4].

NASA Langley Research Center is responsible for developing the in-space structural measurement/validation approach and data analysis techniques for the flight experiment [Ref. 5]. In this paper, the phrase "in-space structural validation" specifically refers to measuring the following three structural characteristics in space: 1) deployment dynamics, 2) static shape, and 3) modes of vibration. Each characteristic will be measured globally (overall structure) and locally (individual lenses). These data will be acquired primarily using photogrammetry.

Photogrammetry generates three-dimensional object coordinates from two-dimensional image coordinates [Refs. 6-7]. It has been used successfully on several Space Shuttle missions to measure large flexible structures. Previous missions using photogrammetry include the Solar Array Flight Experiment (SAFE) on STS-41D in 1984, the Photogrammetric Appendage Structural Dynamics Experiment (PASDE) on STS-74 in 1995, the Hubble Space Telescope repair mission on STS-103 in 1999, and the International Space Station solar array deployment on STS-97 in 2000 [Refs. 8-10].

The next section of the paper provides a general description of the solar array structure and some details of the proposed flight experiment. The following two sections give additional details of the in-space measurement approach and the data processing plans. The paper closes by showing experimental and analytical vibration data for a 1m-long stretched-lens test article used to develop a local lens measurement approach with miniature video cameras.

FLIGHT EXPERIMENT OVERVIEW

Solar array structure: Figures 1 through 3 illustrate the geometry of the SLA structure. The array will mount on the roof of a SpaceHab module and will unfold accordion-style from a stowed configuration that is less than 0.25m in height. It consists of eight 1m x 3m lightweight, composite support panels that deploy (and retract) synchronously using torsional springs on the hinges (and cables for retraction). This deployment approach has considerable space flight heritage. The panels support the flexible concentrator lenses and solar cells and also serve as heat radiators. The solar array will be launched with its panels oriented parallel to the longitudinal axis of the Shuttle. Once deployed, it can rotate 360 degrees for sun-tracking power measurements. Structural photogrammetry measurements can be obtained at various rotation angles, depending on the types of cameras available in the payload bay and existing lighting conditions.

Figure 3 shows the layout of the flexible concentrator lenses on the front side of the array. There are 35 side-by-side lenses per panel, each spanning the 1m width of the panel. All 280 lenses on the array deploy (and retract) synchronously in concert with the support panels. The fully populated, operational SLA weighs approximately 1.6 kg per square meter of surface area.

Stretched-lens concentrators: Figure 4 shows details of the flexible, stretched-lens solar concentrators. They are silicone-rubber, linear Fresnel lenses that focus parallel rays of light from the sun onto a narrow line of solar cells. With an 8.5X solar concentration ratio, they require only 12% of the solar cell area of traditional spacecraft solar arrays. This significantly reduces array cost and weight. The patented refractive Fresnel lens design has a unique arch shape that provides much greater tolerance to slope errors than either reflective solar concentrators or conventional flat Fresnel lenses [Ref. 2].

The lenses fold down against the radiator for launch, and then unfold and are tensioned by spring-loaded end support arches. Adjacent support arches are riveted together so that all 35 individual lenses on each panel deploy in unison. The lenses at the ends of each panel are somewhat more prone than the others to unwanted shape errors because they have a free edge. Nylon chord-strings will be placed at three or more locations along the length of these lenses to help maintain the proper arch shape.

Shuttle cameras and photogrammetry targets: Figure 5 shows the locations and nomenclature of five video cameras located in the Space Shuttle payload bay that are potentially available for photogrammetry of the SLA. The four corner cameras fly on every mission, but there are two different kinds of cameras, one of which is preferable for structural measurements. Specifically, each corner location contains either a color television camera (CTVC) or a black-and-white, intensified television camera (ITVC) for low-light operations. Experience shows that the CTVC is better for photogrammetry. On most Shuttle flights there is one ITVC and three CTVC's in the corner positions, but the location of the ITVC varies with top-level mission requirements, which are not yet known. The elbow camera on the remote manipulator arm is also useful for photogrammetry of the SLA when the arm is docked at the side of the payload bay. (Undocked, the arm has excessive vibration for photogrammetry use.) However, the remote manipulator arm does not fly on every mission, again depending on overall mission requirements. The elbow camera is usually a CTVC.

Photogrammetry requires distinguishable features ("targets") on the structure that are seen by two or more cameras simultaneously. Moderate measurement accuracy is possible using natural features of the structure as photogrammetry targets, such as the corners of panels that are visible against the black background of space. However, for the highest accuracy, precision circular targets should be mounted on the structure at known locations. For global SLA measurements, a rectangular grid of 25-40 targets will probably be installed on the back side of the array. The targets will be circles 10-15 cm in diameter with black and white concentric rings. This design improves photogrammetric accuracy over a range of camera focal-length (zoom) settings.

Dynamic excitation approach: Modes of vibration of the structure will be excited by programmed firings of the Shuttle reaction control system (RCS) jets. Figure 6 shows the jet locations and thrust magnitudes. Each jet is permanently fixed to fire in a general direction: up, down, left, right, forward, or aft. The RCS is used primarily for on-orbit rotational maneuvers (pitch, yaw, or roll). Small velocity changes along the orbiter axes are also possible.

Automatic sequences of jet firings are controlled by the digital autopilot and will be pre-programmed for the experiment based on analytical predictions of array structural dynamics. The pilot initiates each excitation

sequence on cue. The minimum jet-firing duration is 80 milliseconds, and the maximum duration is 125 secs for the vernier jets and 150 secs for the primary jets. Jet firings will induce transient dynamic responses on the order of a few inches of tip motion. Vibration data for modal-parameter identification purposes will be recorded during subsequent free-decay periods. Some practical aspects of this type of structural dynamics testing are documented in the literature [Ref. 11].

Pre-flight photogrammetric simulations: A working relationship has been established with the Graphical Research and Analysis Facility (GRAF Lab) and the Image Science and Analysis Group at Johnson Space Center to support pre-flight simulations and to ensure optimal use of the Shuttle video camera system for photogrammetry of the SLA. Figure 7 shows typical simulated camera views generated by the GRAF Lab of the solar array in its initial orientation (i.e., oriented with its surface parallel to the longitudinal X-axis of the Shuttle). Photogrammetry software can analyze these images just as if they were actual flight recordings. This capability allows high confidence to be obtained in the selected set of camera settings and experiment operations.

Many factors affect photogrammetric accuracy. The most significant ones are: 1) the camera geometry relative to the structure, 2) camera-to-structure distances, 3) accuracy with which targets can be located in the images, 4) image resolution, and 5) how accurately the photogrammetric numerical solution establishes the absolute object coordinate system. Of these factors, the first two are the predominant variables controlling the suitability of various payload-bay video cameras for this experiment.

One of the most basic calculations for experiment planning is the intersection angle of light rays from pairs of cameras that view a particular point on the solar array. Table 1 shows an example of intersection-angle calculations. Angles less than approximately 40 degrees or greater than approximately 140 degrees should be avoided. Note that results are given for two different orientations and mounting locations of the array. Orientation choices are either parallel or perpendicular to the Shuttle X-axis. When the solar array is mounted on the SpaceHab roof, it must be offset to one side or the other for adequate clearance with the payload-bay doors. Therefore, there are also two options for the array mounting location: on the port side or starboard side of SpaceHab. Based on these intersection-angle results,

camera pairs (B, Elbow) and (C, D) are best when the array is located on the port side of SpaceHab and pairs (A, B) and (B, Elbow) are best when it is on the starboard side of SpaceHab. In both cases, orienting the array parallel with the X-axis is preferred.

IN-SPACE MEASUREMENT PLANS

How data will improve analytical model and test key model assumptions: Spaceflight history contains many instances of unexpected structural dynamics problems with new components and spacecraft [Ref. 12]. This is the first time that stretched-silicone membrane lenses have flown in space, and structural analytical models and modeling techniques for both the lenses and the solar array subsystem require in-space validation. The analytical models contain several modeling, tensioning, friction, stiffness, packaging, and deployment assumptions that cannot be fully validated in ground tests. The flight data (deployment dynamics, static shape, and modes of vibration) will be compared with structural model predictions using both numerical and graphical correlation procedures.

Structural characteristics to be validated: Table 2 lists the three structural characteristics to be validated in space and the measurement approach and rationale/justification for each. Each characteristic will be measured globally (overall structure) and locally (individual lenses). Photogrammetry is preferable to traditional accelerometers for measuring the overall solar array because it avoids the significant mass penalty and packaging complexity of a set of accelerometers and it can measure the static shape of the structure as well as its dynamics. Space Shuttle payload-bay video cameras (SC) will provide cost-effective photogrammetric data for the overall structure with good accuracy but would provide only fair to poor measurement accuracy for individual lenses because of the distances and geometry involved.

High-accuracy lens measurements require miniature video cameras (MC) mounted behind the lenses (on the radiator and facing the lens) that track targets or patterns placed on the membrane surface. These measurements are desired for the following reason. Natural frequencies of the stretched silicone membranes are a strong function of the magnitude and distribution of in-plane tension forces and only a weak function of basic material properties that can be measured on the ground. In space, unexpected tension variations can arise from several sources, including space environmental effects (especially

temperature), imperfections in the deployed shape of the lens (e.g., due to sticking), and absence of gravity (compared with ground measurements). Approximately five of the 1m-long membrane lenses will be measured this way to assess the variability of their structural characteristics in space. These units will not have active solar cells.

Array deployment dynamics and modes of vibration will also be sensed with six accelerometers on the array (AA) (three at the base and three at the tip), providing natural frequency and damping information but not corresponding mode shape information, which requires distributed measurements.

Data acquisition approach: Data will be collected in space during the eight periods listed in Table 3. Video recordings will start approximately 30 seconds before and end approximately 3 minutes after pre-scheduled mission events. A wide variety of flight conditions are desired to measure the predictability and variability of the solar array and lens structural characteristics in space. Data will be collected multiple times for some of the collection periods. For example, periods 4 and 5 will be repeated for different combinations and sequences of reaction control system jet firings in order to excite various modes of interest.

Shuttle video will be recorded on mini-DVCAM digital cassettes using established Shuttle procedures. Video data from the mini-cameras behind the lenses will be transferred (probably with wireless links) to Video Data Acquisition equipment (VDAQ) located in the SpaceHab module. The VDAQ will have high-volume data storage devices, a laptop computer for control and video recording, camera selector switch, and power and network interfaces. SpaceHab will provide the recording system for the six accelerometers on the array. All data will be time coded with a standard mission time signal and stored for post-flight analysis.

One realtime video downlink channel is desirable periodically to ensure adequate illumination and dynamic response amplitudes on-orbit so that test conditions can be varied accordingly. Realtime downlink of accelerometer signals during each test is also desirable.

Accelerometers: Figure 8 shows the accelerometers included in the experiment. They are precision servo accelerometers with a resolution of approximately one micro-g. The three tip sensors will provide natural

frequency and damping estimates of the solar array modes with higher signal-to-noise ratio than the photogrammetry data (i.e., the dynamic range of these measurements is significantly higher). The three base accelerometers will measure the input disturbances to the solar array in all three orbiter axes. These base excitation data are required for calculating the modal mass of each identified mode for correlation with corresponding analysis results.

DATA PROCESSING

Data reduction: All video data will be recorded during the experiment and reduced on the ground. The objective is to calculate 3D coordinates as a function of time of specific targets and distinguishable features in the images that appear in two or more camera views. Photogrammetry has four principal steps:

1) Image registration, which uses the known coordinates and/or separation distances of several stationary points (perhaps in the payload bay or on the array) to calculate or confirm the pointing angles and other properties of the cameras,
2) Target tracking, which creates X and Y image-plane time histories of each target in each image,
3) Referencing, which matches each target in one image with the corresponding target in other images (can be done automatically in some cases),
4) Intersection, which computes 3D motion time histories in a least-squares sense (Bundle adjustment) using two or more sets of X,Y image-plane data and the camera parameters.

Data validation: Maximum photogrammetric accuracy requires pre-flight and some in-flight calibration of the cameras and several known coordinates and/or separation distances of stationary points in the images (control points). Data accuracy can be validated by calculating the coordinates of known points in the images that are not used in the control set and comparing the photogrammetric results with the known coordinates of these points.

Data analysis: Data analysis for the Deployment Dynamics and Static Shape tests consists of direct comparisons of the experimental and analytical predictions for each measurement point. For the Modes of Vibration tests, transient free-decay vibration responses will be recorded and analyzed using time-domain modal identification techniques such as the Eigensystem Realization Algorithm (ERA) [Ref. 13]. ERA calculates

structural modal parameters (natural frequencies, damping factors, mode shapes) from the transient time histories, which are then compared with corresponding analytical results.

1-METER-LONG LENS TEST ARTICLE

To support development of the lens video measurement system, NASA Langley perfomed structural dynamics tests and analyses in the study phase on a 1m-long stretched-lens test article. Figures 9(a)-(c) show the test article, one of the two miniature video cameras for stereo photogrammetry of the vibrating membrane, and the test configuration using an electrodynamic shaker. Figure 9(d) shows a typical video camera image. Synchronized image sequences were processed by photogrammetric intersection to obtain 3D coordinates versus time of 40 circular targets placed on the lens surface. Corroborative vibration measurements were also made with a scanning laser vibrometer system.

Both finite-element (FE) and partial-differential-equation (PDE) structural analytical models of the 1m lens were also created [Ref. 14]. Figure 9(e) shows the PDE-predicted first torsional mode at 3.0 Hz. This mode, which occurs at about the same frequency as the first bending mode, is of primary concern because twisting can degrade the solar concentration effectiveness of the lens. Figure 9(f) shows predicted natural frequencies of all modes under 7 Hz versus lens longitudinal strain level, with corresponding experimental frequencies marked by triangles. The test article had 2% strain. Reduced strains (which can occur in space if there is unexpected slackening of end support boundary conditions) will lower natural frequencies and cause the lenses to be more susceptible to vibration. The experimental first bending mode at 2.4 Hz is 20 percent lower than predicted, probably due to air mass loading. In the future, additional vibration tests of lenses will be conducted in a vacuum chamber to eliminate unwanted aerodynamic mass and damping effects.

CONCLUSIONS

This paper summarized in-space structural validation plans for a proposed Space Shuttle-based flight experiment. The test article is an innovative, lightweight solar array concept with 280 pop-up, refractive stretched-lens concentrators. The flight experiment will validate this new technology to retire the risk associated with its first use in space. The experiment includes structural diagnostic instrumentation to measure the deployment dynamics, static shape, and modes of vibration of the solar array and several of its lenses. These data will be obtained by photogrammetry using Shuttle payload-bay cameras and miniature cameras on the array. Six accelerometers are also included in the experiment to measure base excitations and small-amplitude tip motions.

The concept definition study for the flight experiment has been completed. If approved for continued development, the experiment will fly on a Space Shuttle research mission in May 2004. Successful completion of the experiment will validate a promising new space solar array design concept that is applicable to all future spacecraft seeking an inexpensive, high-efficiency, lightweight, compactly stowed power source.

ACKNOWLEDGEMENTS

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Table 1 – Basic Camera Suitability Assessment for Global Photogrammetry of SLA

Camera Pair		*Intersection Angle (in Degrees) to a Point on the Axis of Rotation at the:*		
		Base of Array	*Middle of Array*	*Top of Array*
WITH ARRAY LOCATED ON THE PORT SIDE OF SPACEHAB				
With Array Parallel to Shuttle X Axis				
A	B	158.2	111.5	80.1
B	Elbow	131.6	73.3	45.7
C	D	138.8	106.6	78.4
With Array Perpendicular to Shuttle X Axis				
A	D	17.1	15.6	13.2
B	C	40.1	30.5	21.4
D	Elbow	44.4	46.2	39.1
WITH ARRAY LOCATED ON THE STARBOARD SIDE OF SPACEHAB				
With Array Parallel to Shuttle X Axis				
A	B	138.8	106.6	78.4
B	Elbow	100.9	67.6	44.3
C	D	158.2	111.5	80.1
With Array Perpendicular to Shuttle X Axis				
A	D	17.1	15.6	13.2
B	C	40.1	30.5	21.4
D	Elbow	55.3	49.8	40.3

Shaded values are <40° or >140° (not recommended for photogrammetry)

Table 2 – In-Space Structural Validation Objectives

	Function To Be Validated	**Measurement Techniques**		**Rationale/Justification For Validation**
		Global (Array)	**Local (Lenses)**	
1	Deployment Dynamics	SC, AA	SC, MC	Unanticipated motions may damage array or lenses
2	Static Shape	SC	SC, MC	Shape deviations may affect solar energy concentration
3	Modes of Vibration	SC, AA	SC, MC	Validation of structural analytical model and modeling techniques (mass, stiffness, and damping properties of array and lenses)

SC=Shuttle Payload-Bay Video Cameras, AA=Array Accelerometers, MC=Miniature Video Cameras Behind Lenses

Table 3 – Data Collection Periods

Period	**Event**
1	Camera calibration
2	Array deployment
3	Array rotation
4	Daytime with scheduled Shuttle RCS jet firings
5	Nighttime with scheduled Shuttle RCS jet firings (with artificial illumination)
6	Day/night transitions
7	Solar tracking
8	Array retraction
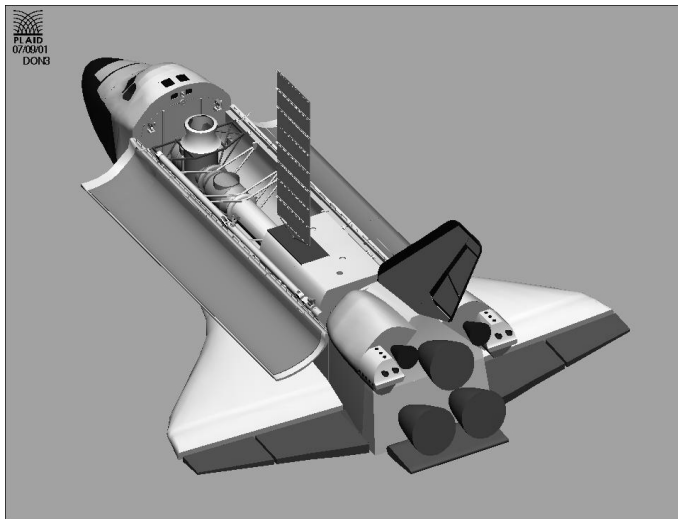
(a) Initial Array Orientation
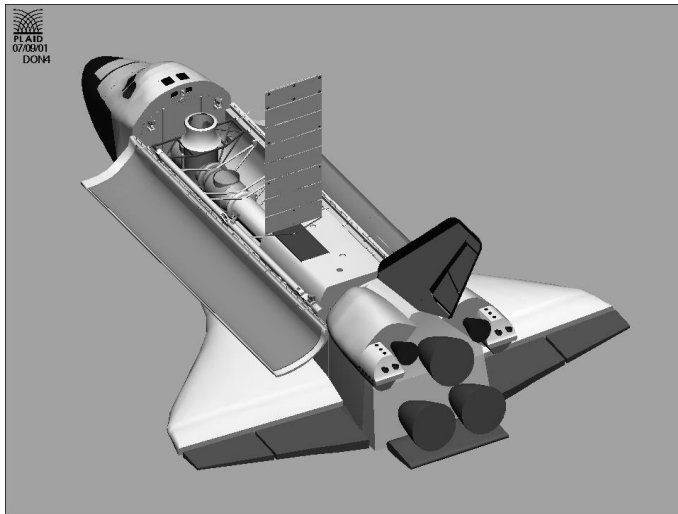
(b) Array Rotated 90 Degrees

Figure 1 – Experiment Configuration
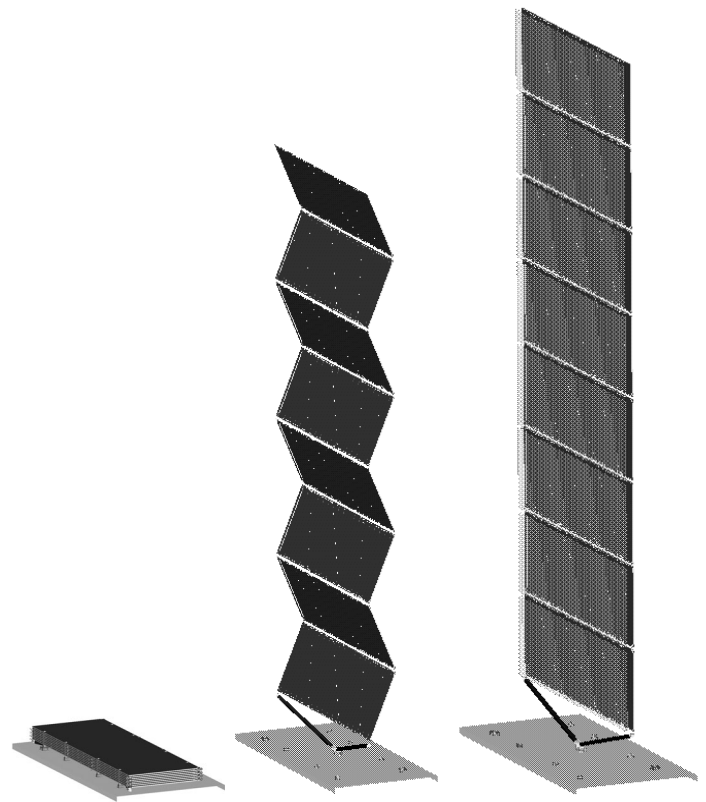
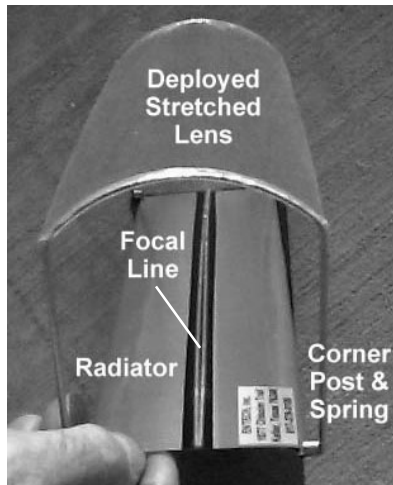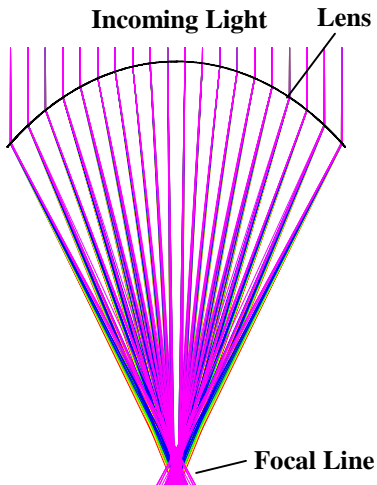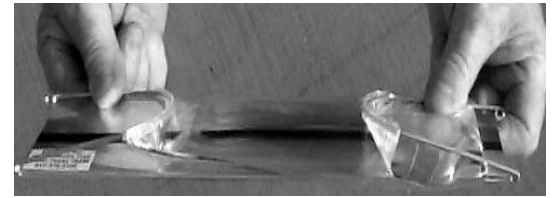Figure 2 – Deployment Sequence

8m

3m
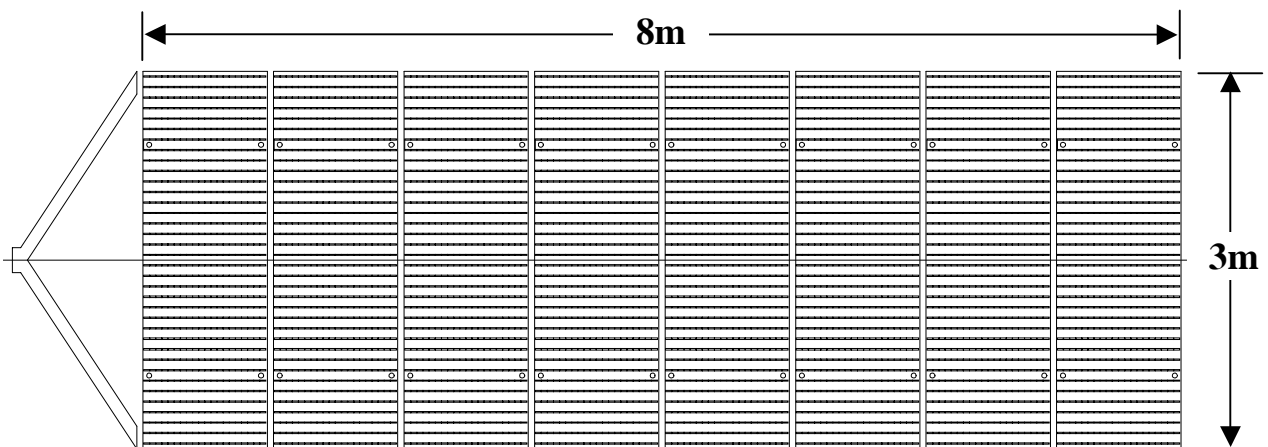
Figure 3 – Arrangement of the 280 Pop-Up Stretched-Lens Solar Concentrators on Front of Array
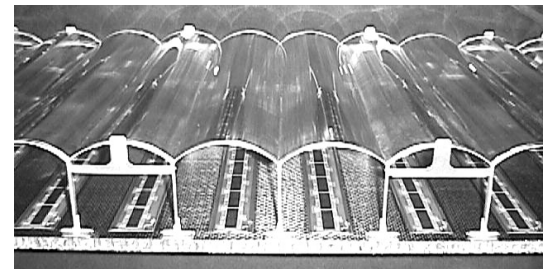
(a) Components

(b) Ray Trace Diagram

(c) Stowed Against Radiator

(d) Assembly
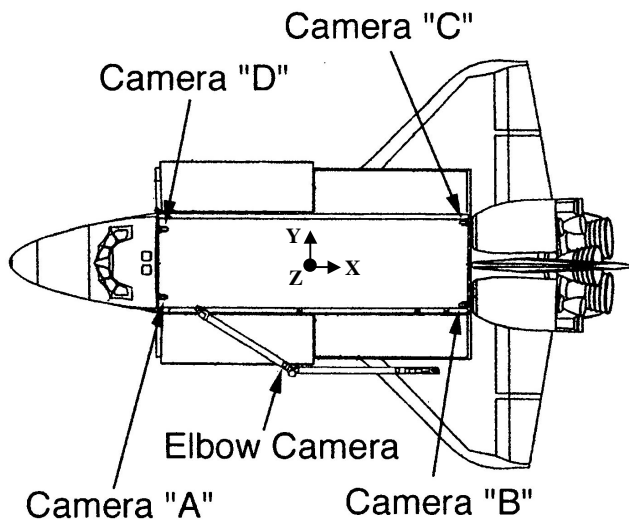
Figure 4 – Stretched-Lens Solar Concentrators

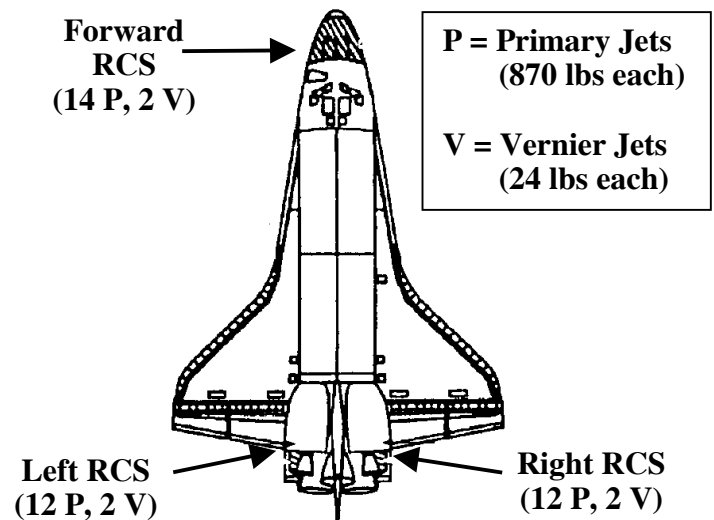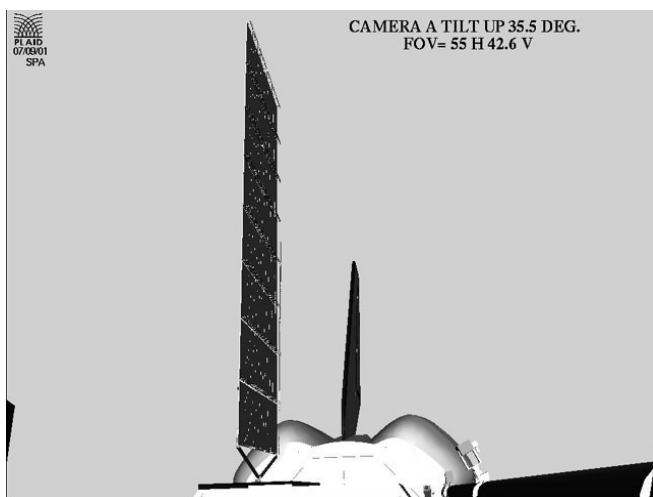Figure 5 – Payload-Bay Video Cameras
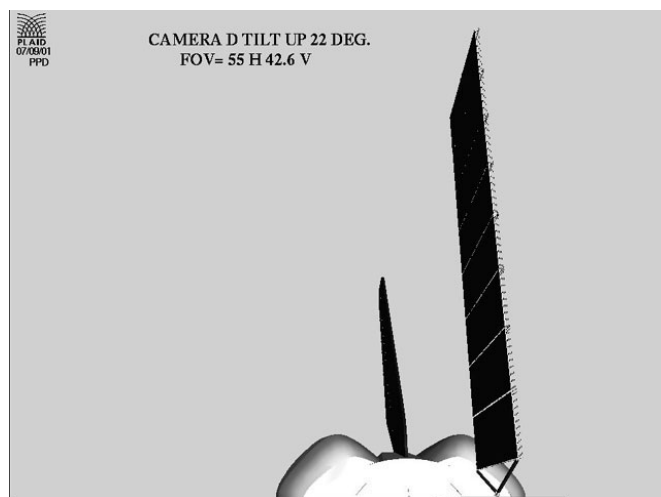Available for Photogrammetry

Figure 6 – Reaction Control System (RCS) Jets
Available for Dynamic Excitation of Solar Array

(a) Front-Port Camera View (Camera A)

(b) Front-Starboard Camera View (Camera D)

(c) Rear-Port Camera View (Camera B)
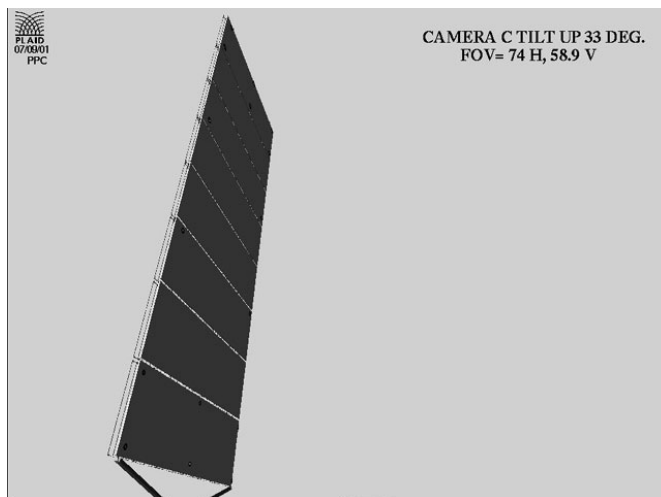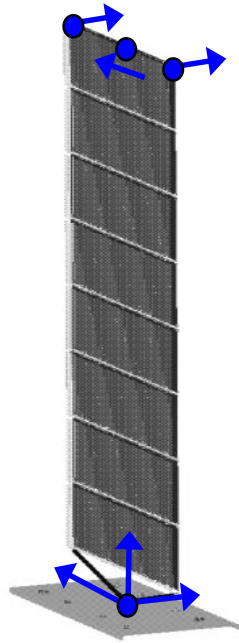
(d) Rear-Starboard Camera View (Camera C)
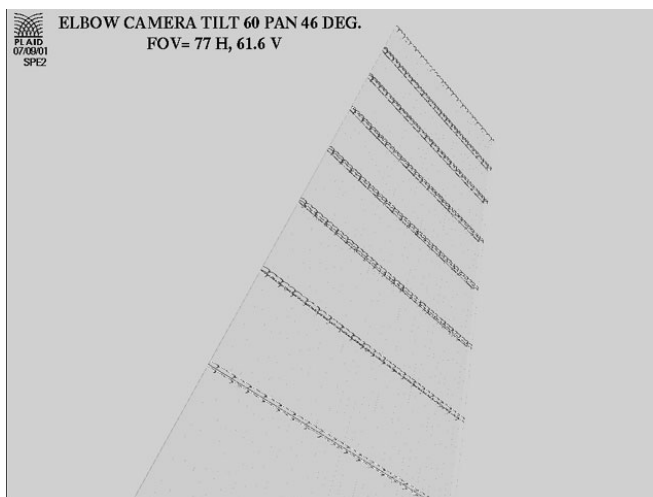
(e) Elbow Camera View
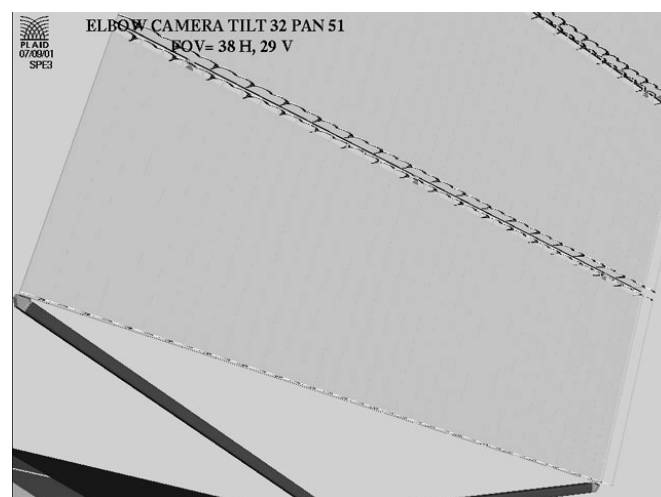
(f) Elbow Camera Close-Up View of Lower Panel

Figure 7 – Simulated Space Shuttle Camera Images of the Deployed Solar Array
(For Pre-Flight Photogrammetry Simulations)

10

- 3 accelerometers at tip of array:
  X direction at ends (out-of-plane and torsion)
  Y direction at center (in-plane)

- 3 accelerometers at base of array:
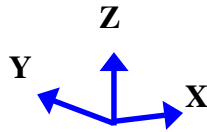 X, Y, Z directions near attachment location
  (base input acceleration)
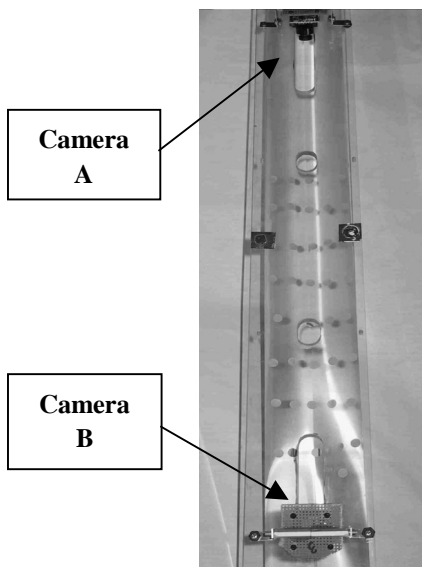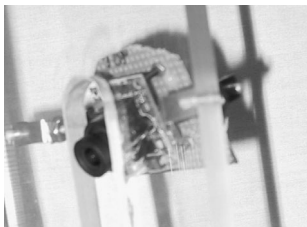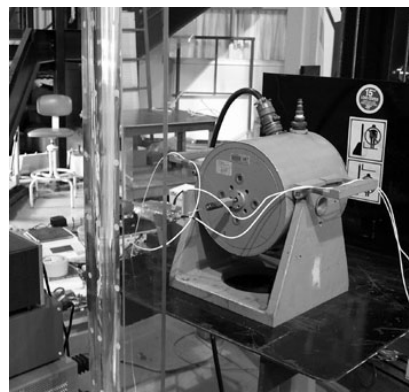
- Data recorded in SpaceHab module

Figure 8 – Array Accelerometer Locations
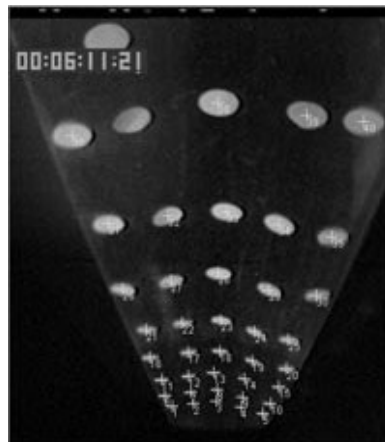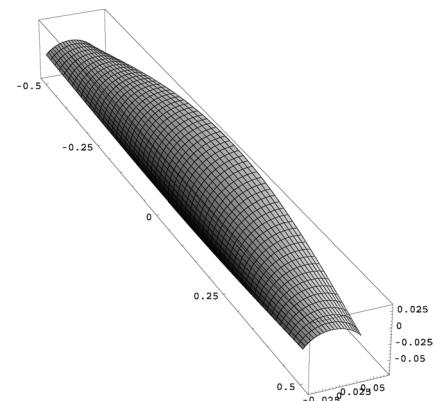

Camera A

Camera B

(a) 1m-Long Lens with 40 Optical Targets

(b) Camera A Close-Up

(c) Vibration Test Configuration

(d) Camera Image

(e) Predicted 1st Torsion Mode (3.0 Hz)

Lines represent all modes below 7 Hz
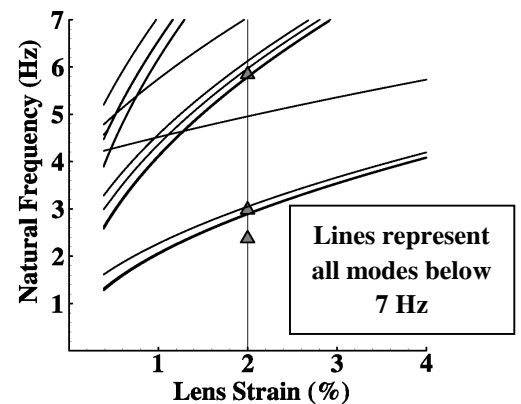
(f) Predicted Natural Frequencies and 3 Test Results (Triangles)

Figure 9 – Laboratory Demonstration of Stretched-Lens Photogrammetry Using Two Miniature Video Cameras

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REPORT DOCUMENTATION PAGE

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13. ABSTRACT (Maximum 200 words)

This paper summarizes in-space structural validation plans for a proposed Space Shuttle-based flight experiment. The test article is an innovative, lightweight solar array concept that uses pop-up, refractive stretched-lens concentrators to achieve a power/mass density of at least 175 W/kg, which is more than three times greater than current capabilities. The flight experiment will validate this new technology to retire the risk associated with its first use in space. The experiment includes structural diagnostic instrumentation to measure the deployment dynamics, static shape, and modes of vibration of the 8m-long solar array and several of its lenses. These data will be obtained by photogrammetry using the Shuttle payload-bay video cameras and miniature video cameras on the array. Six accelerometers are also included in the experiment to measure base excitations and small-amplitude tip motions.

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