ULTRAFLEX-175 ON SPACE TECHNOLOGY 8 (ST8) – VALIDATING THE NEXT-GENERATION IN LIGHTWEIGHT SOLAR ARRAYS

Steve White, Brian Spence, Thomas Trautt, Paul Cronin
ATK Space Systems, Goleta, CA 93117

ABSTRACT

ATK Space Systems, Goleta (ATK) in collaboration with the Jet Propulsion Laboratory (JPL), NASA Glenn Research Center (GRC), and EMCORE Photovoltaics (EPV), is executing NASA's New Millennium Program (NMP) Space Technology 8 (ST8) Project Implementation Phase to develop and validate through spaceflight a next-generation solar array system called UltraFlex-175. UltraFlex-175 is an advanced (and much larger) version of the previously flight-qualified Mars Phoenix UltraFlex, and employs several unique, next-generation technologies to facilitate scale-up and maximize performance. The UltraFlex-175 system provides exceptional specific power (175 W/g – 220 W/kg BOL), compact stowage volume (>33 kW/m^3), very high deployed stiffness, scalability beyond 7 kW wing sizes, and operational capability for standard, high voltage, multi-A.U., and/or high temperature applications. Key technology maturation activities performed (deployment kinematics, deployed dynamics, and power production / survivability) that demonstrate high Technology Maturity Level (TRL) will be presented. Subsystem and system level design, development, experimental hardware builds, conducted testing and results, and analytical model development / correlation activities performed on ST8 are summarized. The UltraFlex-175 ST8 flight experiment details and UltraFlex scale-up performance to 7 kW wing sizes will also be presented.

INTRODUCTION & TECHNOLOGY DESCRIPTION

The goal of NASA's New Millennium Program (NMP) Space Technology 8 (ST8) is to validate, through spaceflight, breakthrough technologies that show distinct promise of being able to minimize risk of first use and reduce cost for future space science and exploration missions [1].

Validation of UltraFlex-175 advanced solar array technology by ST 8 will radically reduce the mass, and thereby the cost, of future high-priority, medium-to-high power space and earth science missions, including those that use Solar Electric Propulsion (SEP) or space radars. The availability of very lightweight solar arrays having specific powers ≥ 175 W/kg allow these missions to be performed cost effectively, by reducing the mass of their solar arrays by as much as a factor of three compared to today's state of the art. This mass reduction can be used to reduce the demands on the launch vehicle or may permit the inclusion of additional science instruments. Not only is the UltraFlex 175 considerably lighter than conventional solar array designs, but it is, when deployed, substantially stiffer and stronger as well. This higher deployed stiffness and strength simplifies the design of the spacecraft control system, reducing design complexity and mission risk. Additionally, UltraFlex 175 packages into 1/4th the stowed volume of a state-of-the-art rigid array when stowed for launch, providing the spacecraft designer significantly more flexibility and space for including additional science instruments on a given mission.

The UltraFlex-175 solar array, shown in Figure 1 in its stowed and deployed configurations, is an accordion fanfold flexible-blanket solar array comprised of ten primary interconnected triangular shaped ultra-lightweight substrates. During deployment, which is actuated by a simple stepper motor-driven / lanyard system, each interconnected triangular substrate (or gore) unfolds in a rotational "fan" fashion. Upon full deployment, the structure becomes tensioned into a rigid shallow umbrella-shaped structure. Lightweight composite radial spar elements attached to each substrate provide structural support for the gores during deployment and in the deployed state. When fully deployed, the UltraFlex gores are maintained in a preloaded and tensioned state via the elastic deflection of in-plane spring flexures, forming a high-stiffness structural platform for the solar cells. The deployment sequence of UltraFlex is shown in Figure 2.

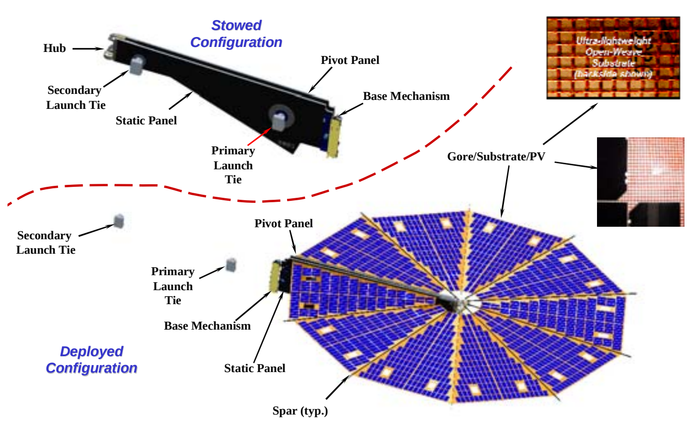

Figure 1. UltraFlex-175 System & Nomenclature

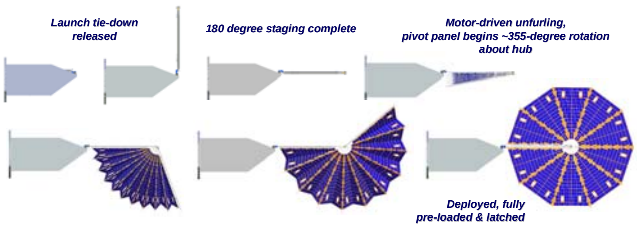

Figure 2. UltraFlex-175 Deployment Sequence

Current state-of-the-art solar arrays systems are based on rigid composite honeycomb panel construction. These existing systems are relatively heavy, provide low deployed first mode natural frequencies, and occupy a large stowage volume. The UltraFlex-175 system achieves break-through performance through an innovative technology advance composed of a flexible-blanket accordion-folded lightweight membrane that is deployed to a tensioned and rigid pre-loaded structure (similar to a shallow umbrella structure). Mission performance benefits of implementing UltraFlex versus a state-of-the-art rigid array are shown graphically in Figure 3. General details of the UltraFlex solar array technology are provided in the listed references [1,2,3].

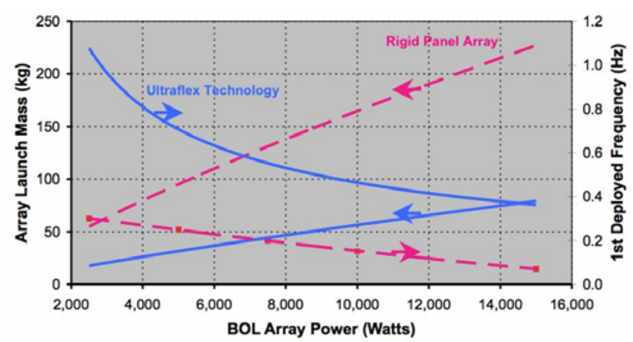

Figure 3. UltraFlex Mass / Structural Benefits

TECHNOLOGY MATURATION ACHIEVEMENT

During the NMP ST8 program, significant UltraFlex-175 technology maturation has been achieved to demonstrate a TRL 5-6 classification. The technology maturation efforts mirrored the three fundamental UltraFlex-175 technology advance areas to be validated in the ST8 flight experiment: deployment kinematics, deployed dynamics and photovoltaic power production / survivability. Detailed scalable deployed dynamics, deployment torque, and power production / survivability analytical models were created. Predicted characteristics for the UltraFlex-175 flight experiment wing (3-m diameter); breadboard wing (3.2-m diameter), and a 7kW size (5.5-m diameter) wing were obtained from the analytical model results. In the formulation refinement phase, experiments were performed in TRL 5+ environments to determine deployed dynamics and characterize deployment torques/margins of the UltraFlex-175 breadboard wing, and to determine power production/survivability of UltraFlex-175 cell circuit coupons and components. Test results were correlated with the analytical models to demonstrate TRL 5+ achievement.

The TRL 5+ test environments supporting the Formulation Phase program efforts included zero-G simulation (with off-loader), hot/cold vacuum, calibrated solar illumination, ambient pressure thermal extremes (on-orbit operation extremes: LEO +100°C to –90°C), and launch vibration. Multiple UltraFlex-175 components and a breadboard wing system were designed, built, and tested in the relative TRL 5+ environments. Analytical models of key technology advance performance characteristics were created and their results replicated / correlated to the test data. The detailed analytical models, correlated with the TRL 5 experimental results, were then used to predict the performance of the UltraFlex-175 wing system in the qualification and on-orbit environments planned for the flight ST8 UltraFlex-175 experiment. During the implementation phase, the models developed were instrumental to the design maturation, and were used to perform design configuration trades, component sizing, weight optimization and structural stiffness / strength assessment for the ST8 UltraFlex-175 flight hardware.

The detailed design of a scaled-up 5.5-meter diameter prototype wing system has been completed, and fabrication / testing of this hardware is planned to occur after delivery of the flight experiment hardware. Testing of this large scaled-up system will allow flight-experiment and ground based correlation of the scalable models developed in prior phases to achieve TRL 6-7 for a large UltraFlex.

ANALYTICAL MODEL PREDICTIONS

Deployed dynamics: Highly detailed non-linear FEA models were created to predict deployed dynamics characteristics in relevant space, TRL 5, and qualification environments. Deployed FEA models were created for the 3-m DIA UltraFlex-175 flight experiment, 3.2-m DIA UltraFlex-175 breadboard wing, and scaled-up (5.5-m DIA) UltraFlex-175 wing system. Model trade studies were performed and FEA features were included for: effective gore stiffness, detailed non-linear simulation of gore tensioning, off loader effects, gravity and atmospheric effects. Analytical results predicted UltraFlex-175 breadboard wing deployed first mode frequencies of 0.76-Hz with off loader effects in a laboratory environment, and 0.93-Hz in vacuum with off loader effects. These predictions correlated within 5% to the breadboard frequencies measured in relevant environments during TRL 5 dynamics tests. The predicted deployed first mode for the 3-m DIA flight UltraFlex-175 wing system is 0.70-Hz. All predicted 1st mode-shapes were "planar torsion about stiff panel radial axis." Pictures of the flight ST8 UltraFlex deployed dynamics FEA model and first mode shape are shown in Figure 4.

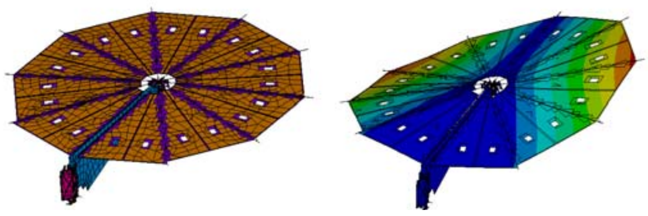

Figure 4. Deployed Dynamics FEA Model / 1st Mode

Deployment kinematics (torques / margin): A detailed closed-form deployment torque analysis was created in MathCAD to predict deployment torque profile / margins as a function of wing size and deployment position for operation in relevant TRL 5+ test and space environments. Model features included motor characteristics, gear-head efficiency, wing geometry and structural properties, parasitic frictions, harness torque effects, catenary loading under 1G effect, and atmospheric effects; all as a function of deployment position. These predictions correlated within 15% to the breadboard torques measured in relevant environments during TRL 5 deployment tests. The TRL 5 test-measured torque profiles vs. deployment position for the UltraFlex-175 breadboard deployment in air and vacuum are shown in Figure 5.

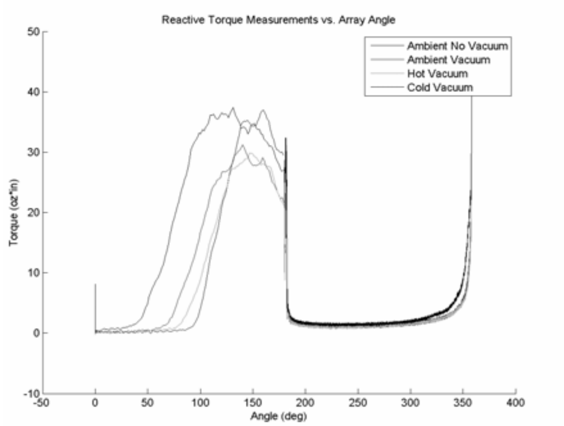

Figure 5. Torque Profile vs. Deployment Angle

The correlated deployment torque model was subsequently used to size the deployment motor / gearhead for the ST8 flight UltraFlex-175 design.

PV survivability / Power production: When UltraFlex is stowed, the folded cell stack is interleaved with foam layers and tightly compressed between the two rigid triangular honeycomb panels to effectively protect the solar cells from the launch vibration environment. Detailed FEA models were created for a 7kW size (5.5-m DIA) UltraFlex-175 wing to predict worst-case stowed dynamics characteristics. Stowed 1st mode frequency for a 7kW UltraFlex-175 was predicted to be 28-Hz. Detailed FEA models for a 7kW size UltraFlex-175 wing were also created to predict stowed cell stack preload capability under worst-case random vibration and quasi-static acceleration. A minimum preload range between 0.2-psi to 0.4-psi was predicted to be sufficient for cell protection (for a 7kW UltraFlex-175), using the criteria of no cell "gapping" under the worst-case loads. These results were subsequently validated during coupon-level vibration testing. A closed-form power production and degradation analysis was created to predict UltraFlex-175 performance as a function of size. Closed form and Thermal Desktop thermal analyses were performed to predict UltraFlex-175 operating temperature in the space environment, and a detailed mass properties analysis, based on solid model geometry, was created to predict UltraFlex-175 mass properties as a function of size. The predicted specific performance for a 7kW UltraFlex-175 wing is >175 W/kg for UltraFlex-175 with standard (150 micron thick) TJ PV, and >220 W/Kg for UltraFlex-175 with thinned (100 micron thick) TJ PV.

BREADBOARDS/COUPONS HARDWARE

Many UltraFlex-175 breadboards and coupons have been produced and tested during the ST8 program to help validate analytical model predictions. These include: a high fidelity 3.2-m DIA UltraFlex-175 breadboard wing system and off loader to simulate zero-g deployment and deployed dynamics, a flight-like TRL 5+ UltraFlex-175 TJ PV panel coupon (31-cm^2) populated with standard EPV TJ cells (2-circuits), a flight-like TRL 5+ UltraFlex-175 ultra-lightweight MJ PV panel coupon (15-cm^2) populated with thinned EPV TJ cells (1-circuit of 100-micron thick cells), improved foam management system integrated to the UltraFlex-175 breadboard wing, a flight-like high voltage ESD coupon with solar cells at various adjacent spacing, and a flight like TRL 5+ UltraFlex-175 vibration coupon with complete representation of TJ PV panels, mass simulators, static/pivot panels, and foam interleaves arranged in various areal coverage (50% & 100% foam coverage). A picture showing some of the breadboard and coupon hardware is shown in Figure 6.

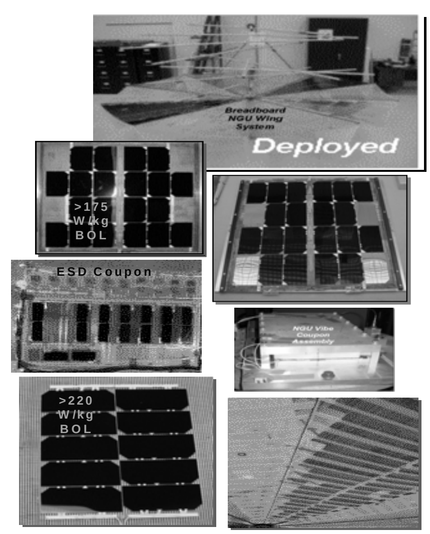

Figure 6. UltraFlex-175 Breadboard & Coupon Hardware

EXPERIMENTS/TESTS PERFORMED

Deployed dynamic experiments: Multiple deployed dynamics first mode frequency tests were performed in a TRL 5+ vacuum environment with the 3.2-m DIA breadboard UltraFlex-175 wing system. Accelerometers strategically placed on the wing surface/structure were used to record data to determine modal frequencies. Excitation was applied as a twang-displacement, and as a sinusoidal vibration input at the wing's base. Dynamic response was then measured as a function of time. A picture depicting the deployed dynamics experiment is shown in Figure 7.

Deployment kinematics / dynamic experiments: Deployment torque testing was performed with the 3.2-m DIA breadboard UltraFlex-175 wing system in a TRL 5+ vacuum environment at hot/cold temperature extremes. UltraFlex-175 lanyard tape tension and motor torque was monitored over the entire deployment sequence (tape tension is proportional to deployment torque and accounts for parasitic torques/losses). Deployment margin testing was also previously performed with the 2-m DIA flight UltraFlex Mars 01-Lander and Phoenix wing systems. The entire functional deployment sequence was videotaped to observe kinematics and gore dynamic behavior.

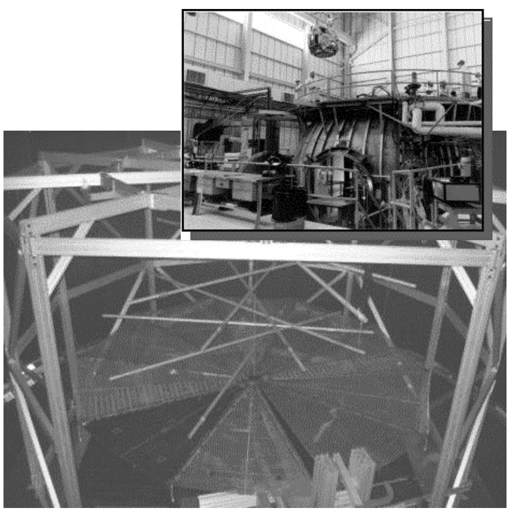

Figure 7. Deployed Dynamics Experiment/Test

Power production and PV survivability tests**:** Random vibration tests were performed with a flight-like UltraFlex-175 TJ PV panel coupon populated with standard and lightweight cells. Testing was performed with varying preload and varying protective foam areal coverage between 100%-50% over a range of vibration levels that enveloped all major launch vehicles. Low-earth-orbit (LEO) thermal life cycle testing was performed with a flight-like UltraFlex-175 TJ PV panel coupon. Testing was comprised of 17,000 cycles between –90°C and +100°C. Circuit continuity was monitored continuously throughout the test sequence.

Multiple power production electrical tests (LAPSS) were performed with the flight-like UltraFlex-175 standard TJ PV panel coupon and with the flight-like UltraFlex-175 ultra-lightweight TJ PV (thinned PV) panel coupon. A picture depicting the random vibration, thermal life cycle, and LAPSS testing is shown in Figure 8.

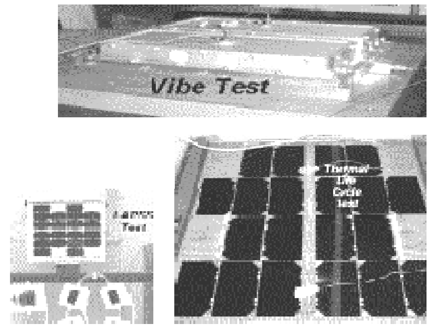

Figure 8. Vibration, Thermal Cycling & LAPSS Tests

Electrostatic discharge (ESD) testing was performed with a representative UltraFlex panel coupon with TJ PV to determine arcing voltage threshold, susceptibility to sustained arcing, and damage mechanisms. ESD testing was performed at NASA Glenn Research Center in a simulated LEO plasma environment. A picture of the ESD coupon and testing is shown in Figure 9.

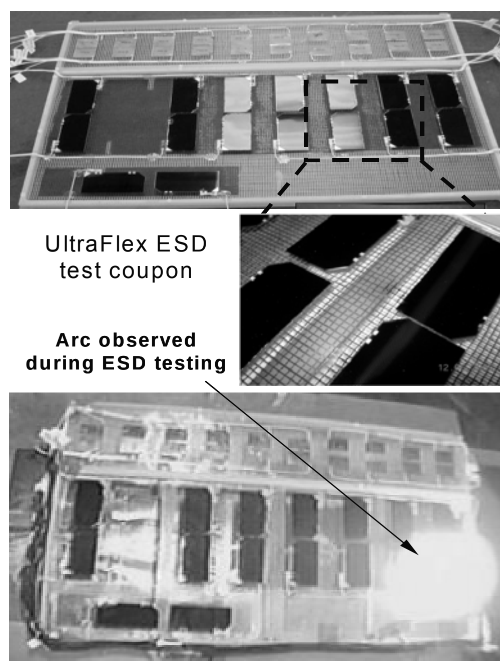

Figure 9. ESD Panel Coupon and Testing

EXPERIMENT RESULTS AND MODEL CORRELATION

Deployed dynamics: The out-of-plane deployed first mode natural frequency of the 3.2 m DIA breadboard UltraFlex, measured in a TRL 5 vacuum environment with off-loader, was approximately 0.92-Hz. The measured natural frequency in the laboratory (ambient air) environment with off-loader was approximately 0.73-Hz. The test set-up and measurements/data obtained are shown in Figure 10.

The first mode frequency shape of "torsion-about-the-panel-stiff -axis" was a common mode achieved through both analysis and test (refer to Figure 4). The UltraFlex-175 analytical predictions correlated well (within 15 %) with the TRL 5+ experimental test results and validated model accuracy.

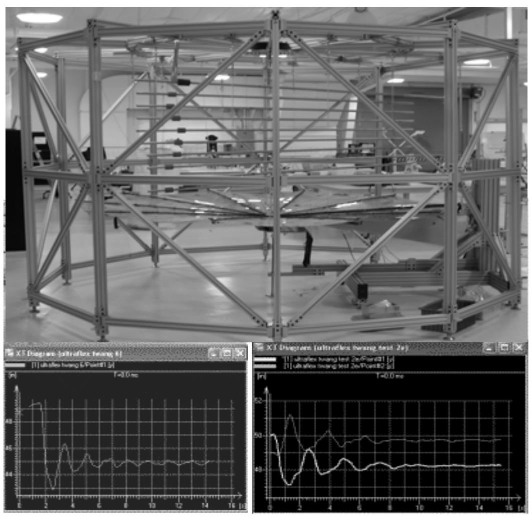

Figure 10. Deployed Dynamics Experiment/Test Data

Deployment torque / margin: Each test performed resulted in a successful deployment and validation of deployment torques / margins in the hot and cold vacuum TRL 5+ environment. Analytical models predicted a similar deploy torque profile with positive margin as experiment results. The TRL 5 experiments and analytical models correlate well and validate model accuracy.

Power production / PV survivability: The flight-like UltraFlex-175 TJ PV panel coupon survived the vibration environment (worst case accelerations) under an applied preload range of 0.2-psi to 0.6-psi. No power production degradation, cracked cells or coverslides were observed after the vibration testing sequences. Vibration test results validate UltraFlex-175 TJ PV survivability in a TRL 5 environment. The flight-like UltraFlex-175 TJ PV panel coupon survived the LEO thermal life cycle testing (17,000 cycles). No visual anomalies and no cracked/damaged cells or coverslides were observed. Good cell/substrate adhesion and continuous continuity was maintained throughout the test. Pre and post electrical performance tests indicated no power production degradation. Thermal cycle test results validate TJ PV survivability in a TRL 5+ environment. ESD test results indicate that no arcing below 200V bias at 18°C or 500V at 84°C occurs. Sustained arcing was not observed up to maximum tested array voltage of 200V and 2 Amps. Trigger (bias) arc damage was determined minimal. The successful ESD testing performed proved that UltraFlex-175 ESD-risk is minimal for operation in LEO under 150V.

5.5M DIA ULTRAFLEX-175 SCALE-UP HARDWARE

A 5.5-m DIA UltraFlex-175 wing system, shown in Figure 11, has been designed and is planned to be built and tested after delivery of the flight ST8 UltraFlex-175. The 5.5-m DIA wing will validate scale-up capability of the UltraFlex-175 technology for wing sizes within the 7kW class/range. The projected specific power performance of the 5.5-m DIA UltraFlex-175 wing system is greater than 175 W/kg BOL, based on the detailed scalable sizing models developed on ST8. The planned test sequence will validate functional deployment at temperature extremes (hot/cold), LAPSS / electrical performance, deployed dynamics performance, strength/stiffness performance, vibration survivability, and mass properties verification.

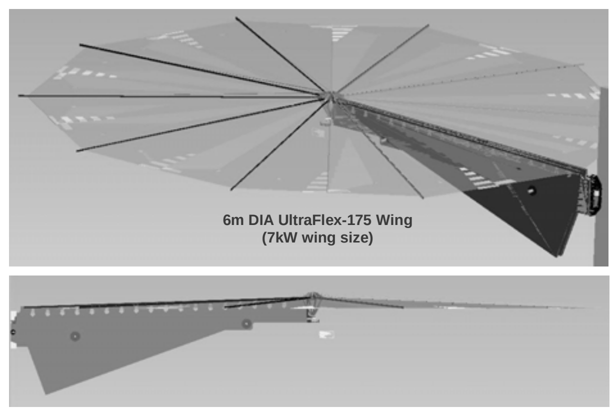

Figure 11. 5.5m DIA UltraFlex-175 Wing System (7kW)

ULTRAFLEX-175 ST8 FLIGHT EXPERIMENTS

The NMP ST8 spacecraft and the UltraFlex-175 flight experiment is currently planned be launched on a Pegasus expendable launch vehicle. Due to the Pegasus launch volume constraints, and the associated small ST8 spacecraft bus size the largest UltraFlex-175 size that can be integrated within the available envelope is approximately a 3-m DIA size. A picture of the UltraFlex-175 flight experiment configuration is shown in Figure 12.

The UltraFlex-175 flight experiment will provide a thorough investigation of the fundamental attributes of the ultra-lightweight tensioned blanket solar array structure, with the objectives of validating and completing the technical maturation of the three UltraFlex-175 fundamental technology advance areas:

- Deployment kinematics / dynamics
- Deployed structural behavior
- Survivability and space electrical power production of MJ (Multi Junction) photovoltaics when mounted onto the UltraFlex-175 platform

The ST8 flight experiment is based on the rationale that the advanced UltraFlex-175 solar array cannot be completely characterized (sufficient for implementation into a future mission) by ground testing alone (due to 1-G off-loading and air-drag effects on deployment and fully deployed dynamics, and lack of space-validated thermal / electrical performance data). The information obtained from the flight experiment will provide critical model validations, mitigating the risks seen by potential users associated with predicting the on-orbit performance of UltraFlex-175 arrays of various sizes. Three experiments, corresponding to the TRL advance areas currently being investigated / validated, are planned to be conducted on the 3m DIA UltraFlex-175 wing system: Deployment, deployed dynamics, and power production.

Flight validation of the UltraFlex-175 deployment will characterize all effects associated with the space relevant environment of zero gravity, combined with the vacuum of space and the space thermal environment, via successful wing deployment and concurrent on-orbit measurement of deployment torques. The measured torque profile will be compared to equivalent deployment profiles obtained from 1-G offloaded ground testing in air and vacuum to validate scalable UltraFlex-175 deployment kinematics models.

In the deployed dynamics flight experiment, the deployed wing will be sinusoidally excited at the base using a motor-driven actuator. The response accelerations of the wing at various locations will be measured versus time to determine the first fundamental deployed frequency, mode shape and associated transfer function. Accelerometers will be located on the wing in sufficient locations to determine the wing frequencies and mode shapes. Additionally, digital video will be taken of the deployed wing motion during base excitation.

Preliminary deployed dynamics tests performed and supporting analysis model results indicate a noticeable difference in the deployed response of a 1-G off-loaded wing versus a wing modeled in zero-G. As predicted by these models, the zero-G off-loader inertia reduces the deployed first mode frequency by over 15% when compared to the space environment. Zero-G off-loader effects reduce the first-mode frequency when compared to the space environment, and also appear to change the mode shape and structural damping characteristics of the wing. Additionally, a gossamer structure such as a large UltraFlex-175 wing (large surface area and low areal density) will be sensitive to the effects of the air when tested on the ground. The air will act on the structure by adding to the effective mass and increasing the damping. Any increase to the effective structural mass will mean a drop in ground-test measured frequency versus that observed in space vacuum. The flight data obtained from the relevant in-space UltraFlex-175 wing deployed frequency response measurements will be used for complete validation of analytically modeled dynamics of the deployed wing, allowing accurate predictions for future applications.

The rationale for the Electrical Power Production measurement is that system-level space validation of cell and circuit performance is required to properly verify cell survivability after launch, cell performance, loss factor, thermal and degradation modeling assumptions for the industry standard and next generation MJ GaAs cells when mounted in the unique open-backside flex blanket UltraFlex configuration. The design and performance of MJ-cell circuits specific to the unique UltraFlex-175 mounting configuration have been characterized for electrical power production through analysis and ground testing during previous ST8 phases. Similar MJ cell circuits will be mounted to the flight experiment UltraFlex-175 wing and instrumented to allow model correlation data to be obtained for cell operating temperature and in-space I-V performance. The objectives of the Electrical Power Production Measurements are to: 1) Determine the UltraFlex-175-mounted MJ cell-operating temperature when exposed to the representative space environment and 2) Determine UltraFlex-175-mounted MJ cell operating I-V characteristics when exposed to in-flight solar incidence.

One string of Advanced Triple Junction (ATJ) solar cells and one string of Next Generation Triple Junction (BTJ) solar cell technologies will be mounted to the flight ST8 UltraFlex-175 wing and instrumented to allow model correlation data to be obtained for cell operating temperature and in-space I-V performance. Each circuit will have fully functional and flight-qualified cells, coverslides, adhesives, interconnects, weld/solder joints, diodes and wiring. The primary measurements will be to monitor the cell operating temperature via multiple RTD's mounted to the cell backsides, and to determine the cell strings short-circuit current (Isc), open-circuit voltage (Voc) and current/voltage at a load point near the maximum power point.

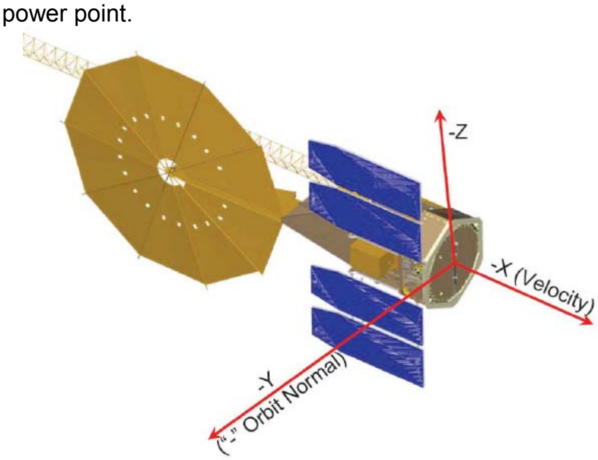

Figure 12. UltraFlex-175 Flight Experiment

CONCLUSION/SUMMARY

Key UltraFlex-175 technology maturation activities (deployment kinematics, deployed dynamics, and power production / survivability) performed during NASA's NMP ST8 program have demonstrated TRL 5-6 achievement. The NASA NMP ST8 program activities (detailed design, analytical model development, analysis predictions, breadboard and coupon hardware builds and tests) have been instrumental in reducing technical risk, greatly enhancing the UltraFlex platform design and validating predicted performance for all sizes.

The UltraFlex-175 ST8 flight experiment will provide a thorough investigation of the fundamental attributes of the ultra-lightweight tensioned blanket solar array structure, with the objectives of fully validating in space, and completing the technical maturation of, the three UltraFlex-175 fundamental technology advance areas.

The UltraFlex-175 system promises very high specific power (175 W/g – 220 W/kg BOL), compact stowage volume (>33 kW/m3), exceptional deployed structural performance, high reliability, scalability beyond 7 kW wing sizes, and operational capability for standard, high voltage, and/or multi-AU missions. Continued UltraFlex-175 technology development and the planned in-space flight experiment under the NMP ST8 program will significantly advance the state-of-the-art for solar arrays and will enable this breakthrough technology to be applied at a high TRL to all missions (LEO, MEO, GEO, and interplanetary) and all market-segments (civilian, military and commercial).

REFERENCES

Citations given in this paper are referenced below.

[1] "Next Generation UltraFlex (ULTRAFLEX-175) Technology Maturation for NASA's New Millennium Program (NMP) Space Technology 8 (ST8)", B.R. Spence et. all, 31st IEEE PVSC Conference, January 2005.

[2] "Next Generation UltraFlex Solar Array for NASA's New Millennium Program Space Technology 8", B.R. Spence et. all, 2005 IEEE Aerospace Conference, March 2005.

[3] "A High Specific Power Solar Array for Low to Mid Power Spacecraft," P. Jones, et. all, SPRAT Conference, 1992.