NEXT GENERATION ULTRAFLEX (NGU) TECHNOLOGY MATURATION FOR NASA'S NEW MILLENNIUM PROGRAM (NMP) SPACE TECHNOLOGY 8 (ST8)

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ABSTRACT

ABLE Engineering, Inc. (ABLE), in collaboration with the NASA Glenn Research Center (GRC), Jet Propulsion Laboratory (JPL), and EMCORE Photovoltaics (EPV), has been selected for the NASA New Millennium Program (NMP) Space Technology 8 (ST8) Study Phase project to develop and potentially flight validate a state-of-the-art solar array system called: "Next Generation UltraFlex" (NGU). NGU is a highly evolved and scaled version of the previously flight qualified Mars 01-Lander UltraFlex and employs many advanced technologies. The NGU system promises very high specific power (175 W/g – 220 W/kg BOL), compact stowage volume (>33 kW/m^3), high reliability, 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 TRL 4+ achievement will be presented. NGU design, development, analysis, and hardware activities are presented. NGU subsystem and system level experimental tests/results and model correlation will be presented. NGU technology scale-up performance to 7 kW wing sizes will also be addressed.

NMP ST8 NGU PROJECT INTRODUCTION

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. The NMP ST8 has initially selected key advanced technologies to be considered for a subsystem-level flight validation experiment in the 2007-2008 time frame. ABLE's Next Generation UltraFlex (NGU) solar array system was one of these NMP ST8 technologies that was awarded a Phase A contract to increase/mature the technology readiness level (TRL) to a 4+ classification. Results of the completed Phase A program are delineated in the main body of this paper.

NGU TECHNOLOGY DESCRIPTION

The NGU solar array is an accordion fanfold flexible-blanket solar array comprised of ten primary interconnected isosceles-triangular shaped ultra-lightweight substrates. The major NGU subsystem assemblies and their nomenclature, depicted in the stowed and deployed states, are shown in Figure 1. When deploying in a rotational "fan" fashion, each interconnected triangular shaped substrate (also known as a gore) unfolds; upon full deployment the structure becomes tensioned into a rigid shallow umbrella-shaped structure. Radial spar elements attached to each substrate elastically deflect to predetermined positions when completely deployed to maintain the deployed structure in a preload and high-stiffness state.

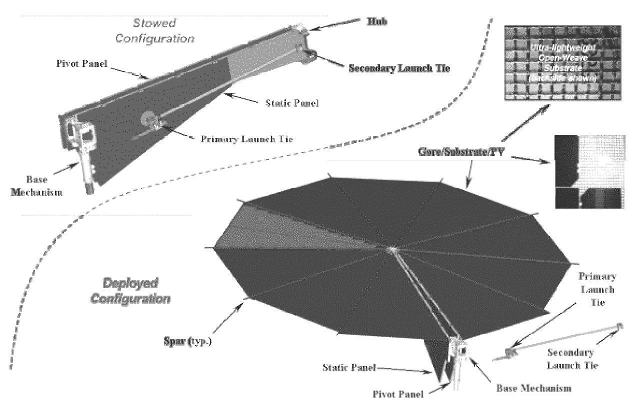

Figure 1. NGU System/Subsystems & Nomenclature

Current state-of-the-art solar arrays systems are based on rigid composite honeycomb panel construction. These existing systems are heavy, provide low deployed first mode natural frequencies, and occupy a large stowage volume. The NGU 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).

The triangular gores are the building blocks of the NGU system, consisting of an open mesh Vectran substrate to which the cell circuits are bonded using a patented ultra-lightweight process. The use of the lightweight open mesh substrate allows the NGU to have a very low non-power producing mass per unit area, and allows the cells to radiate directly from their (partially open) backsides. When stowed, the NGU array gore substrates are folded in a flat-pack accordion manner and sandwiched between two rigid panels (static and pivot panels) to produce a compact launch volume. The static and pivot panels serve as rigid platens reacting the internal cell/foam stack preload in the stowed configuration. Thin open-cell polyimide foam strips, discretely attached to the substrate backside, act as protective interleaves between each blanket fold and provide robust protection (and high damping) for the delicate PV from severe vibration environments. The entire stowed package is preloaded between the static and pivot panels by the launch restraint/release system (tie-downs).

Deployment is initiated by tie-down release. The NGU deployment sequence is a two-staged process and is shown in Figure 2. Upon tie-down release, the stowed package becomes loosely contained and begins a rotational articulation away from the spacecraft about the base mechanism to a final staging location where its position is latched and secured (staging shown is 90 degrees, but can be any angle). Once initial staging is complete, the final deployment stage is initiated through a proven motor-driven lanyard assembly. The lanyard, attached to the pivot panel, is continuously reeled onto the motor pulley; hence rotating the pivot panel and unfurling the NGU blanket nearly 360 degrees to its final deployed state. Upon final deployment, the NGU spars deflect and the blanket simultaneously tensions to produce a deployed shallow-umbrella (paraboloid) shaped structure that is a preloaded membrane having exceptionally high deployed-stiffness for its size. Further details of the UltraFlex system are provided in reference [1].

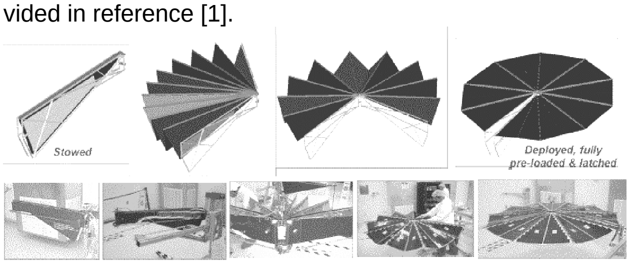

Figure 2. NGU Deployment Sequence

TECHNOLOGY MATURATION ACHIEVEMENT

During the NMP ST8 Concept Definition Phase significant NGU technology maturation was achieved to demonstrate a TRL 4+ classification. Deployed dynamics, deployment margin, and power production / survivability analytical models were created. Predicted characteristics for the NGU flight experiment wing (2-m diameter); breadboard wing (3-m diameter), and a 7kW size (6-m diameter) wing were obtained from the analytical model results. Experiments were performed in a TRL 4+ environment to determine deployed dynamics and characterize deployment torques/margins of the NGU breadboard wing, and to determine power production/survivability of NGU cell circuit coupons and components. Test results were correlated with the analytical models to demonstrate TRL 4+ achievement.

The TRL 4+ test environments supporting the Study Phase program efforts included zero-G simulation (with mobile off-loader) for deployed and deployment kinematics / dynamics; and calibrated solar illumination, ambient pressure thermal extremes for MJ power production (on-orbit operation extreme: LEO +100°C to –90°C, TRL 5 testing performed), and vibration (TRL 5 testing performed).

Multiple NGU components and a breadboard wing system were designed, built and tested in relative TRL 4 and/or 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 4 experimental results, were then used to predict the performance of the breadboard NGU wing system in the qualification environments planned for the flight ST8 NGU mission.

ANALYTICAL MODEL PREDICTIONS

Deployed dynamics: Detailed FEA models were created to predict deployed dynamics characteristics in relevant space, TRL 4, TRL 5, and qualification environments. FEA models were created for the 100-cm radius NGU flight experiment, 158-cm radius breadboard NGU, and scaled-up 7kW NGU wing system. Detailed model features included effective gore stiffness, off loader effects, gravity & atmospheric effects. Analytical results predict deployed first mode frequencies of 0.41-Hz with off loader effects, 0.61-Hz in a space environment, and 0.50-Hz in vacuum with off loader effects for the NGU breadboard wing. The predicted deployed first mode for the 7kW size NGU wing system was 0.3-Hz. All predicted 1st mode-shapes were “planar torsion about stiff panel radial axis.” Pictures of the deployed dynamics FEA models and mode shape are shown in Figure 4.

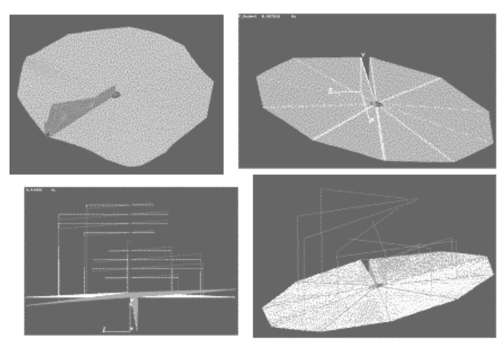
Figure 4. FEA Deployed Dynamics Model/Modes

Deployment kinematics (torques / margin): A closed-form deployment torque analysis was created to predict deployment torque profile / margins as a function of wing size and deployment position for operation in relevant space, and in TRL 4 & 5 relative environments. Model features included motor characteristics, gear-head efficiency, wing geometry & structural properties, parasitic frictions, catenary loading under 1G effects, all as a function of deployment position. The predicted torque profile vs. deployment position and resulting 64% torque margin for NGU breadboard deployment in air and with off-loader (worst case) is shown in Figure 5.

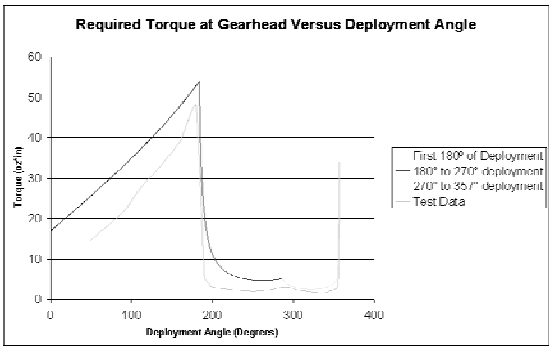

Figure 5. Torque Profile vs. Deployment Angle

PV survivability / Power production: Detailed FEA models were created for a 7kW size NGU wing (worse case) to predict stowed dynamics characteristics. Stowed 1st mode frequency for a 7kW NGU was predicted at 28-Hz. Detailed FEA models for a 7kW size NGU wing (worse case) were also created to predict stowed cell stack preload capability under quasi-static acceleration. A preload range between 0.6 psi to 0.2 psi was predicted to be required for adequate cell protection (for a 7kW NGU), and was shown to be maintained under the worst-case quasi-static loading. A closed-form power production and degradation analysis was created to predict NGU performance as a function of size. Closed form thermal analyses were performed to predict NGU operating temperature in the space environment, and a closed form mass properties analysis was created to predict NGU mass properties as a function of size. The predicted specific performance for a 7kW (6-m dia) NGU wing was >175 W/kg for NGU-S & >220 W/Kg for NGU-LW.

BREADBOARDS/COUPONS HARDWARE

Many NGU breadboards and coupons were produced and tested during the Study Phase to help validate analytical model predictions. These breadboards and coupons included: a high fidelity TRL 4+ 158-cm radius NGU wing system and off loader to simulate zero-g deployments (which originally served as ABLE's IR&D UltraFlex qualification wing), a flight-like TRL 5+ NGU MJ PV panel coupon (31-cm^2) populated with standard EPV MJ cells (2-circuits) and lightweight glassed Ge wafers (100-micron wafer thick), a flight-like TRL 5+ NGU ultra-lightweight MJ PV panel coupon (15-cm^2) populated with thinned EPV MJ cells (1-circuits of 100-micron thick cells), improved foam management system integrated to NGU breadboard wing, a flight-like high voltage coupon with solar cells at various adjacent spacing, and a flight like TRL 5+ NGU vibration coupon with complete representation of EPV MJ PV panels, mass simulators, static/pivot panels, and foam interleaves arrange in various areal coverage (50% & 100% foam coverage). A picture showing some of the breadboard and coupon hardware is shown in Figure 6.

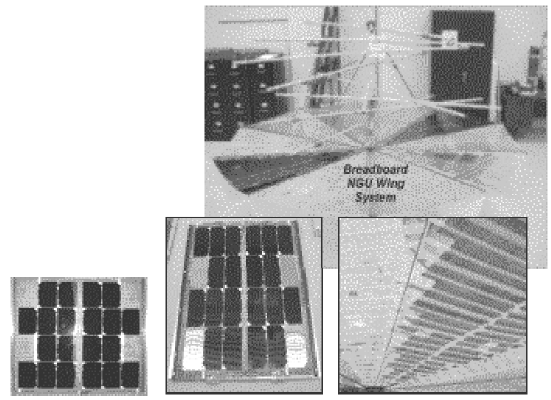

Figure 6. NGU Breadboard & Coupon Hardware

EXPERIMENTS/TESTS PERFORMED

Deployed dynamic experiments: Multiple deployed dynamics first mode frequency tests were performed in a TRL 4 lab environment with the 158-cm radius breadboard NGU wing system. Video-grammetry and SMX measurement techniques were used to record displacement as a function of time. Measurement targets were placed at high NGU wing inflection points and an in/out of-plane displacement was applied. 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 158-cm radius breadboard NGU wing system. NGU lanyard tape tension was monitored over the entire deployment sequence (tape tension is proportional to deployment torque). Deployment margin testing was also previously performed with the 104-cm radius UltraFlex Mars 01-Lander wing. The entire functional deployment sequence was videotaped to better observe kinematics.

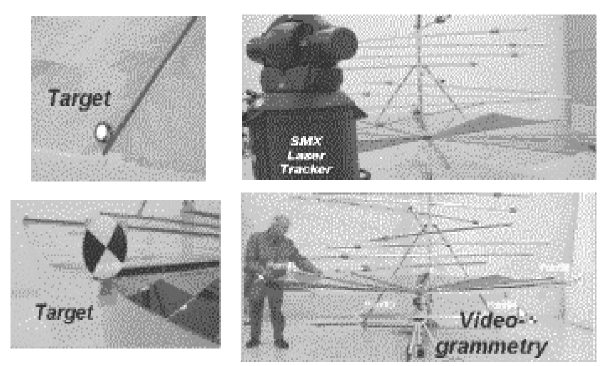

Figure 7. Deployed Dynamics Experiment/Test

Power production & PV survivability tests**:** Random vibration tests were performed with a flight-like NGU MJ PV panel coupon with standard and lightweight cells. Testing was performed with varying preload and varying protective foam areal coverage between 100%-50%. Low-earth-orbit (LEO) thermal life cycle testing was performed with a flight-like NGU MJ 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 NGU standard MJ PV panel coupon and with the flight-like NGU ultra-lightweight MJ PV (thinned PV) panel coupon. A picture depicting the random vibration, thermal life cycle, and LAPSS testing in shown in Figure 8.

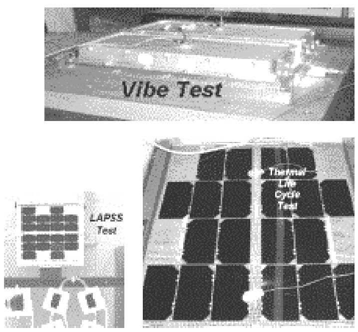

Figure 8. Vibration, Thermal Cycling & LAPSS Tests

EXPERIMENT RESULTS AND MODEL CORRELATION

Deployed dynamics: The out-of-plane deployed first mode natural frequency, measured with "video-grammetry" in a TRL 4 environment was approximately 0.58-0.69-Hz. The equivalent test, measured with ABLE's "SMX Laser Tracker", yielded a first out-of-plane first mode frequency of approximately 0.41-0.60-Hz. Test measurements/data with the "video-grammetry" and SMX techniques is shown in Figure 9.

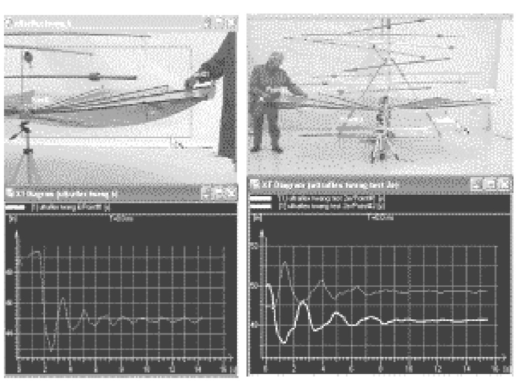

Figure 9. Deployed Dynamics Experiment/Test Data

The measured in-plane deployed first mode natural frequency with "video-grammetry" in a TRL 4 lab environment was 0.40-0.46-Hz. Analytical predictions indicate a deployed first mode frequency of 0.41-Hz in a TRL 4 environment (with off loader, in air). The first mode frequency shape of "torsion-about-the-panel-stiff -axis" was a common mode achieved through both analysis and test. The NGU analytical predictions correlate well with the TRL 4 experimental test results and validate predictive model accuracy.

Deployment torque / margin: Each test performed resulted in a successful deployment and validation of deployment torques / margins. Analytical models predicted a similar deploy torque profile with positive margin as experiment results. The TRL 4 experiments and analytical models correlate well and validate model accuracy.

Power production / PV survivability: The flight-like NGU MJ 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 NGU MJ PV survivability in a TRL 5 environment. The flight-like NGU MJ 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 MJ PV survivability in a TRL 5 environment.

CONCLUSION/SUMMARY

Key NGU technology maturation activities (deployment kinematics, deployed dynamics, and power production / survivability) performed during NASA's NMP ST8 Study Phase program have demonstrated TRL 4+ achievement. The NASA NMP ST8 program activities (design, development, analysis, breadboard and coupon hardware builds and tests) have been instrumental in reducing technical risk and validating predicted performance.

The NGU system promises very high specific power (175 W/g – 220 W/kg BOL), compact stowage volume (>33 kW/m3), high reliability, scalability beyond 7 kW wing sizes, and operational capability for standard, high voltage, and/or multi-AU missions. Continued NGU technology development and in-space flight experiment under the proposed NMP ST8 follow-on 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] "A High Specific Power Solar Array for Low to Mid Power Spacecraft," P. Jones,A.U., and/or high temperature applications.