Next Generation UltraFlex Solar Array for NASA's New Millennium Program Space Technology 8

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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) project to develop and flight validate a state-of-the-art solar array system. The "Next Generation UltraFlex" (NGU) system is a highly-evolved and large-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/m3), high reliability, scalability beyond 7 kW wing sizes, and operational capability for standard, high voltage, multi-A.U., and/or high temperature applications. A detailed overview of the ST8 NGU technology in-space validation program is presented. Key technology maturation activities performed (deployment kinematics, deployed dynamics, and power production / survivability) that demonstrate TRL 4+ achievement will be discussed. Completed design, development, analysis, and NGU hardware build (components, subsystems and systems), and test activities are presented. NGU hardware experimental test results will be presented and model correlations will be shown. Continued ST8 NGU technology development plans, maturation approach to increase readiness level (TRL 4+ to TRL 7/8), and planned flight experiment details are also described.

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1. 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. Follow-on Phase B and Phase C/D plans are discussed.

2. THE ABLE NGU NMP ST8 TEAM

The ABLE NGU NMP ST8 team is composed of NASA Glenn Research Center (GRC), the Jet Propulsion Laboratory (JPL), and EMCORE Photovoltaics (EPV). The ABLE team combines a wealth of solar array systems expertise, advanced technology capability, and past experience (earth-orbital, interplanetary, and planetary Lander solar array applications). As prime contractor, ABLE is responsible for executing all programmatic and technical activities, and is leading the flight experiment system design, development, analysis, build, test, model correlation, and program management. NASA GRC provides review, guidance, and direction as it relates to the development of the NGU system for earth-orbital and high voltage applications. NASA GRC also is assisting in environments development and is responsible for conducting plasma interactions validation testing of NGU hardware. JPL provides review, guidance, and direction as it relates to the development of the NGU system for interplanetary, planetary-Lander, and SEP high voltage applications. EPV is the developer of standard and ultra-lightweight high efficiency multi-junction solar cell assemblies. EPV is providing the advanced multi-junction solar cell assemblies, CIC's, and laydown for the NGU hardware.

3. NGU DESCRIPTION & TECHNOLOGY ADVANCE

The NGU solar array is an innovative technology advance that provides leapfrog performance over the state-of-the-art. NGU 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.

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.

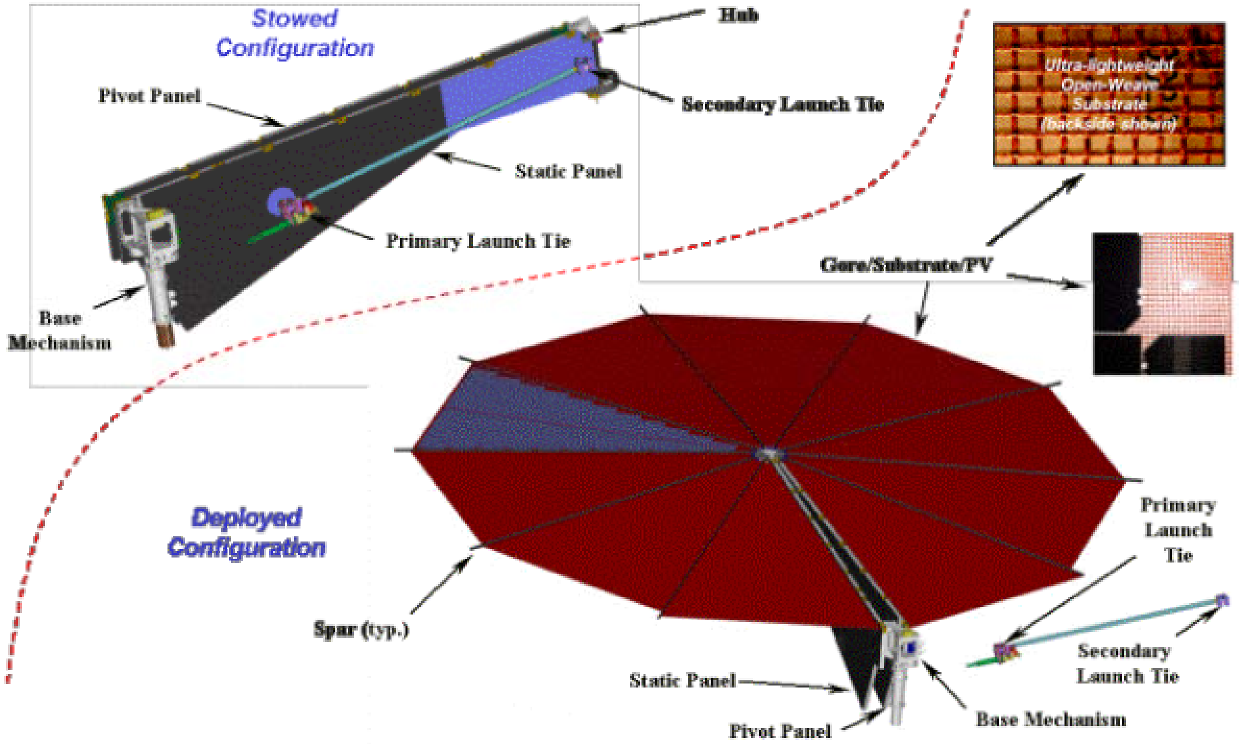

Figure 1. Major NGU Subsystem Assemblies and Nomenclature

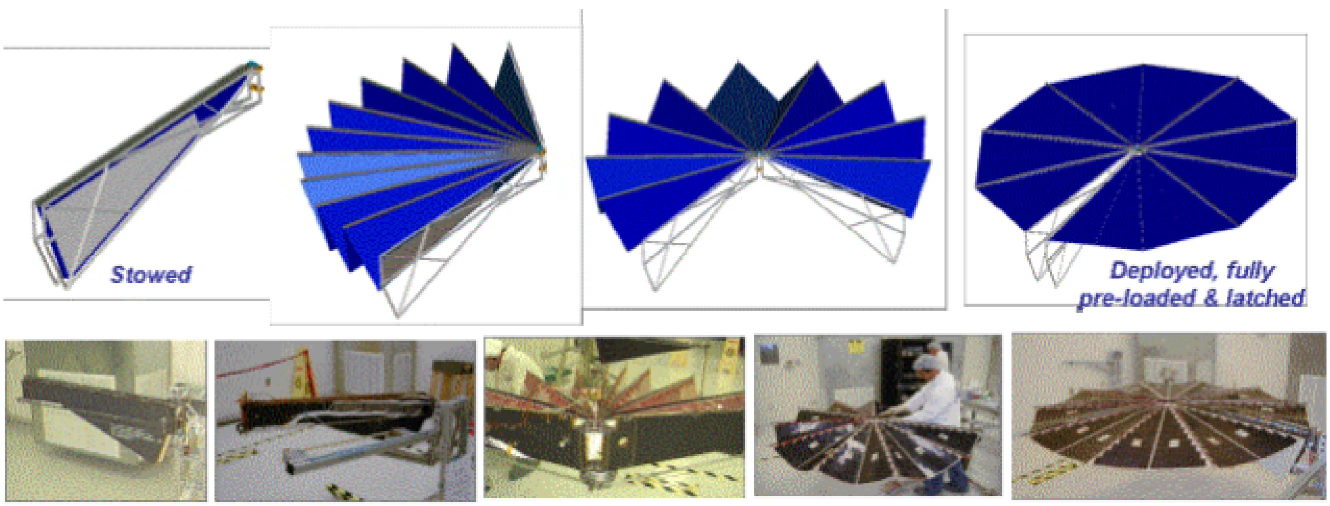

Figure 2. NGU Deployment Sequence

The NGU solar array combines structural performance and the highest available specific power with a very low stowed volume and footprint. NGU achieves its deployed strength and stiffness from lightweight radial spar members that allow tensioning of a flexible blanket populated with solar cells. This unique structural system allows the use of a flexible blanket without requiring massive secondary structure (such as a heavy mechanical or inflatable boom) to deploy and tension the wing as is common in other flexible substrate solar array systems.

The NGU is a highly evolved version of ABLE's 1st generation UltraFlex design,[1] developed for flight under ABLE IR&D and the NASA Mars 01-Lander program (MSP 01) for Lockheed Martin Space Systems Company and the Jet Propulsion Laboratory. In support of the MSP 01 program ABLE developed, built, and flight qualified two 1st generation UltraFlex flight wing systems. Each wing was populated with SHARP 17% efficient silicon PV and the entire array system (i.e., two wings) supplied almost 900 watts BOL. The (relatively small) system was designed to deploy in a 1g environment with no external off-loader. The resulting specific power of this 1st-generation UltraFlex technology for the Mars 01-Lander was 103 W/kg BOL (a factor of two increase over the NMP DS1 SCARLET concentrator array).[2], [3] Pictures of the UltraFlex Mars 01-Lander wing are shown in Figure 2, above, and in the lower right of Figure 3.

The proposed NGU baseline system offers exceptional scaled-up performance exceeding the NMP ST8 requirements, and provides many additional features desired by NASA. In addition, many breakthrough technologies are proposed to be developed/implemented within the NGU system to provide significant performance growth capability. The new electrical and mechanical subsystem features of the NGU to be implemented as part of the NMP ST8 program are shown graphically on the development road map of Figure 3. Descriptions of these new features and their rationale for implementation are provided in Table 1. The systematic maturation and implementation of the these advanced subsystem technologies will result in numerous NGU solar array system benefits, each with the potential to optimize or enable a particular spacecraft mission application. The proposed NGU technology enhancement and resulting performance growth will demonstrate the potential and flexibility of the NGU to be the standard high-performance solar array platform for future NASA, commercial and military space missions.

4. NGU PERFORMANCE VS. ST8 REQUIREMENTS

A detailed listing of predicted NGU system performance in comparison to the ST8 requirements (and other NASA needs) is shown in Table 2. The NGU technology advance provides exceptional performance (extremely lightweight, compact stowage volume, high deployed frequency, high reliability, accommodates normal spacecraft off-pointing) that exceeds the ST8 NRA requirements, and provides “road-map” performance growth for years to come.

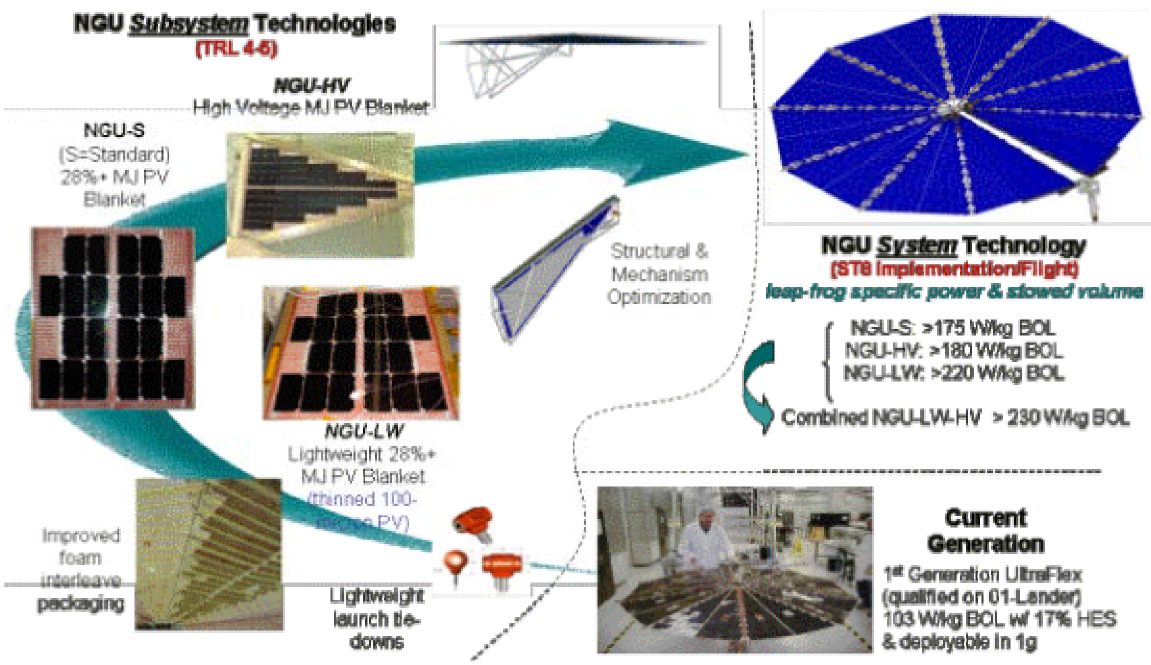

Figure 3. NGU Technology Subsystem Interdependencies and System-Level Performance

Table 1. NGU Subsystem Technologies and Rationale for Impementation

#	New Feature/Technology	Reason for Implementation and Benefit
1	Standard-thickness 28% efficient multi-junction PV (NGU-S)	Incorporating state-of-the-art cell technology increases BOL specific power to >175 W/Kg
2	Lightweight (100-micron thick) 27.5% efficient multi-junction PV (NGU-LW)	Significant reduction in cell weight increases BOL specific power to > 220 W/kg, provides performance growth path
3	High voltage (>100 VDC) PV electrical subsystem (NGU-HV)	Desirable for SEP missions. Reduction in array system harness mass and spacecraft power system mass
4	Improved foam interleave (for launch survivability) packaging	Provides an improved means of packaging foam interleave elements after array deployment, provides for lower operating temperatures and reduction in edge drag area (important for large LEO arrays)
5	Optimized structure and mechanization (spars, hub & base mechanisms, S/P panels)	Provides reduced structural mass and optimized stowed packaging load distribution (providing a more robust packaging for stowed PV during launch)
6	Ultra-lightweight launch tie-down release	Provides further weight reduction and reduces cost

Table 2. NGU Performance versus ST8 Requirements and NASA Needs

Parameter Description	ST8 Requirement and/or NASA Need	NGU Predicted Performance for a 7-kW sized wing system	Comments/Justification
BOL specific power	>175 W/kg for a 7-kW wing system	>175 W/kg for NGU-S >220 W/Kg for NGU-LW	ST8 requirement met with standard MJ PV. Much higher specific power achievable with lightweight MJ PV. The NGU platform provides "road map" growth beyond the ST8 requirement
Deployed first mode frequency	> 0.1 Hz	> 0.3 Hz	Extremely lightweight tensioned structural platform with sufficient depth provides deployed stiffness significantly higher than classical systems
Stowed specific volume	> 31.8 kW/m^3	> 33 kW/m^3	NGU occupies an extremely compact launch volume and footprint compared to classical systems
High voltage capability	> 100 VDC operation	> 100 VDC operation	NGU is inherently suited to high voltage operation because of its serpentine circuit configuration/layout and lack of conductive substrate. Conventional high voltage design solutions can be applied to NGU at lower mass than classical systems.
Multi-A.U. Operation capability	to 5 A.U.	to 5 A.U.	NGU employs use of EPV ATJ PV. These devices have undergone preliminary LILT testing and shown their suitability for multi-A.U. missions. NGU high-temp capability materials also allow for < 1.0 operation.
Scalability	7 kW wing size	to 15 kW wing size and beyond	The NGU is scalable to wing sizes beyond 7 kW with the simple optimization of spar structural elements (to optimize bending and torsional stiffness). Recent studies for advanced JPL applications have sized NGU wings as high as 12 kW.
Stowed transfer orbit power	N/S	Provides stowed transfer orbit power	NGU provides the ability to incorporate stowed transfer orbit power (need for most GEO-comsat missions), enhancing commercialization (addressed in Study Phase)
Radiation hardness	Operation in high radiation environment	Operates in high radiation environments	NGU employs proven radiation hard MJ PV technologies. Rear side and front side shielding can be applied to increase radiation hardness.
Reliability	High reliability	High reliability	NGU is a high-reliability system because of its simple and redundant mechanisms and features, and its 1st generation heritage from the UltraFlex Mars 01-Lander system
Cost	Low (Reasonable)	Low (Reasonable)	NGU has the ability to be cost-competitive with classical systems once completely developed and its significant mass benefits are included in overall mission costs. The simplicity of the mechanical design and low cost substrates should allow for NGU recurring costs to be no greater than classical systems.

5. Technology Maturation Achievement

During the 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.

ABLE's completed TRL 4+ activities (specifically analytical modeling, coupon/breadboard experiments, experimental data reduction, and model correlation activities) for the deployed dynamics, deployment kinematics, and MJ power production experiments are described in the following sections.

6. 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.

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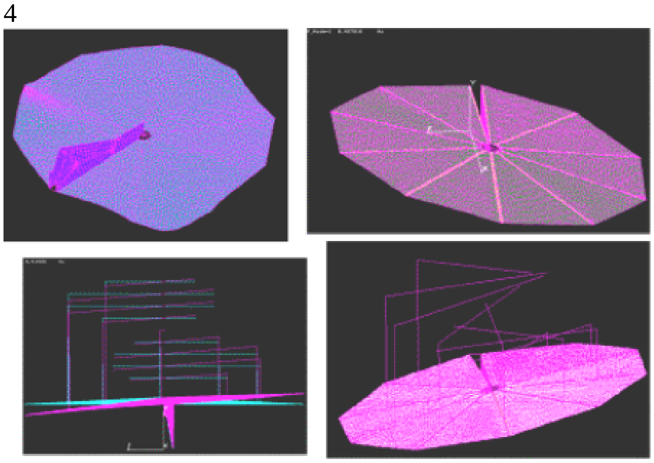


Figure 4. FEA Deployed Dynamics Model and Mode Shape

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.

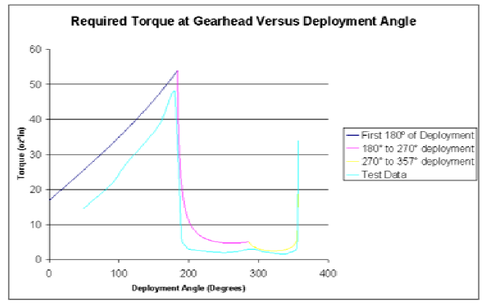


Figure 5. Torque Profile vs. Deployment Angle

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. Pictures of the various power production/survivability models are shown in Figure 6.

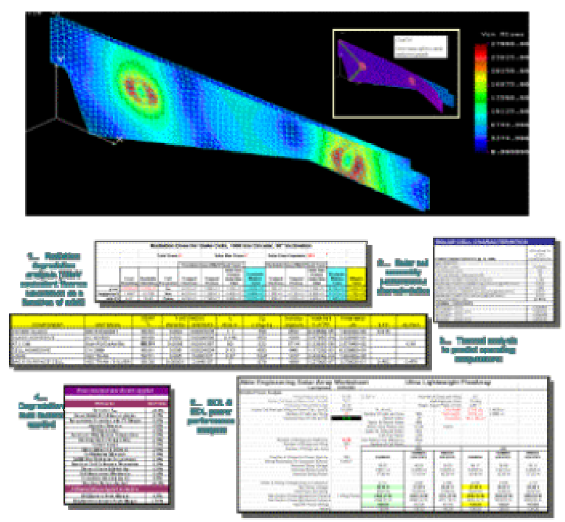


Figure 6. Various Power Production/Survivability Models

7. 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 7.

8. 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. ABLE's proven SMX measurement technique was used to validate the new video-grammetry technique being contemplated for the flight experiment. 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 8.

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. A picture depicting the deployment testing is shown in Figure 9.

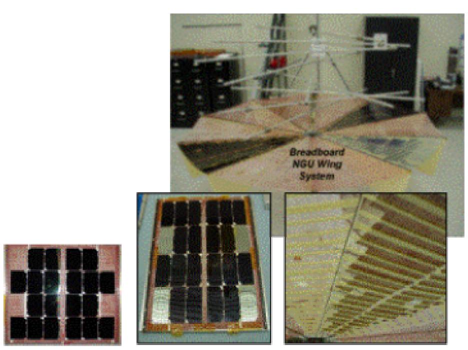


Figure 7. NGU Breadboard & Coupon Hardware

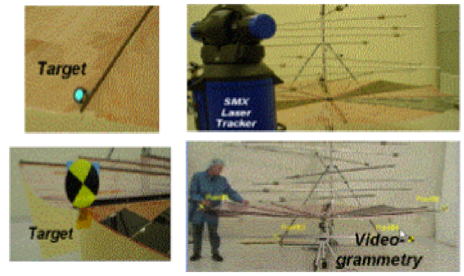


Figure 8. Deployed Dynamics Experiment/Test

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%. High and low applied stowed preload for random vibration testing was derived from the detailed stowed quasi-static analysis. 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.

Figure 9. Functional Deployment Experiment/Test

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 10.

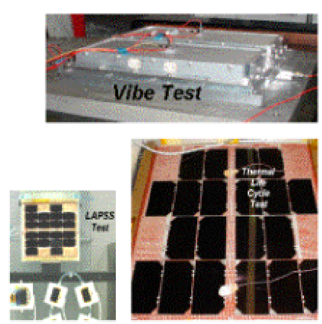


Figure 10. Vibration, Thermal Cycling & LAPSS Tests

9. 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 11. Because of their similar measurement results the more accurate "SMX Laser Tracker" measurement technique validated the "video-grammetry" method as an accurate and viable measurement process. 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.

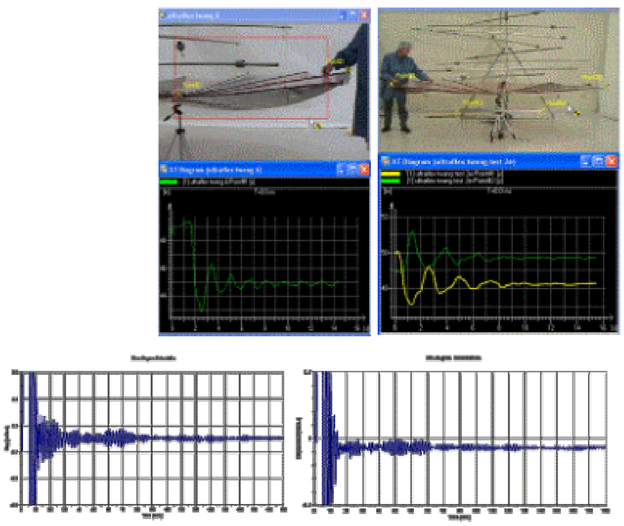
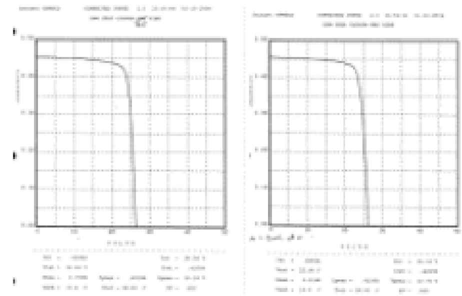


Figure 11. Deployed Dynamics Experiment/Test Data

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. Acceptable variation was observed due to motor torque characteristics and parasitic friction losses

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. Pre/post LAPSS data at various thermal cycle intervals is shown in Figure 12.



	Circuit #1, Welded		Circuit #2, Soldered	
	Pmax, Watts	%Change	(Pmax, Watts)	% Change
Baseline	9.63		9.64	
Cycle #71	9.57	-0.6*	9.51	-1.3
Cycle #600	9.58	-0.4*	9.55	-0.9
Cycle #6000	9.75	1.3	9.69	0.5
Cycle #17000	9.49	-1.4	9.48	-1.7
	* Post rework			

Figure 12. Pre/Post Thermal Cycle LAPSS Data

10. DISCUSSION & OBSERVATIONS

Deployed Dynamics: The relevant space environment for assessing the true on-orbit deployed dynamics of a large NGU wing has been identified to be zero gravity, combined with the vacuum of space. It is impossible to completely off-load the 1-G weight of a large and flexible NGU wing sufficiently to prevent structural interaction between the off-loader supports and the deployed NGU wing. The current method for off-loading a large UltraFlex wing during ground testing utilizes the "mobile"-type support structure shown in Figure 13. As shown in Figure 13, the off-loader provides vertical support via counter-balanced cables at discrete points on the wing spar elements. The offloaded NGU wing shown off-loaded is the breadboard wing system sized at 1.5-m radius. Due to the distributed weight of the cells mounted to the flexible gore segments there is a noticeable catenary-shaped "sag" in the gores at their outboard radial free edges. The off-loading of a larger NGU wing (radius >3-m) will require additional vertical support cables to prevent excessive sagging of both the gore segments and the spar elements, which will also be subject to lateral instability (buckling) as their unsupported length increases. Preliminary deployed dynamics tests performed and supporting analysis model results obtained during the Study Phase indicated a noticeable difference in the deployed response of a 1-G off-loaded wing versus a wing modeled in zero-G. Deployed dynamic models and predicted results of the NGU breadboard wing with and without the zero-G off-loader are shown in Figure 14.

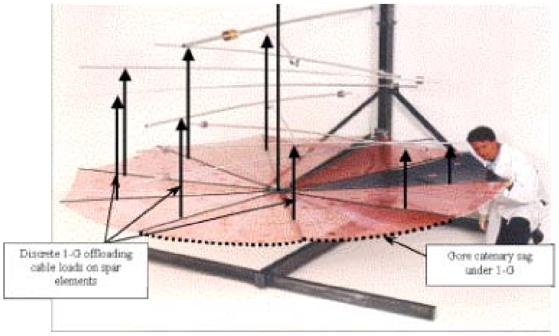


Figure 13. NGU 1-G Offloader and Design Load Orientation

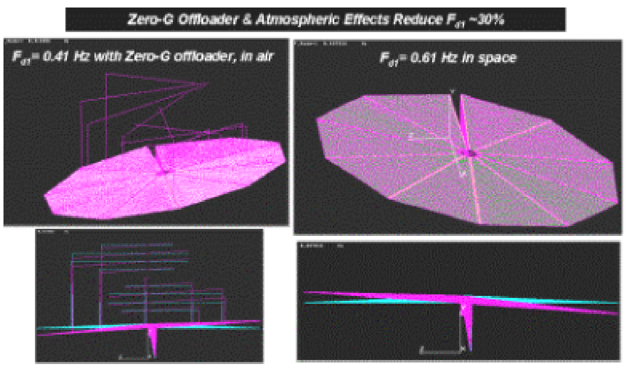


Figure 14. Deployed Dynamic FEMs and Frequency Predictions With and Without Zero-G Off-loader and Atmospheric Effects

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 also appear to change the mode shape and structural damping characteristics of the wing somewhat.

Observations made during the Mars 01 Lander UltraFlex vacuum testing indicated that the deployed dynamic response of the wing was markedly different than was observed during tests performed in one atmosphere. The (relatively small 1 meter radius) wing's higher, gore dominated modes were larger in amplitude and visually more pronounced than those observed in air (no deployed frequency measurements were made on the deployed MSP 01 wings, so only a qualitative visual assessment of the differences in deployed response could be made). It was hypothesized that air drag effects were causing the higher frequency modes to be damped out, reducing their amplitude in air. A gossamer structure such as a large NGU wing (large surface area and low areal density) will be sensitive air effects. The air will act on the structure by adding to the effective mass and increasing the damping. The added mass is the air entrained by the accelerating structure. In order for the wing to accelerate the surrounding air must accelerate as well. Any increase to the effective structural mass will mean a drop in frequency.

During the Study Phase, the breadboard NGU finite element model was run with and without an approximation for air effects included. The effective stiffness of the gores was modified to match the observed behavior of the breadboard gores during TRL 4 frequency testing (no local gore modes). The calculated added inertia due to air was represented in the model as an increase in the density of the gore elements. This gave a representative model of the breadboard wing in 1-G, with offloading in air. The first mode frequency from this model was 0.41 Hz. To represent the model for the 1-G case with off-loading in a vacuum, the added inertia was removed. The resulting first mode was 0.50 Hz. Removing the offloading structure and mass then represented the on-orbit behavior (zero-G, in vacuum). For this case the first mode was 0.61 Hz, a 32% increase from the 1-G off-loaded case in air.

<u>Deployment Kinematics / Dynamics</u>: The relevant space environment for assessing the true on-orbit deployment kinematics and dynamics of a large NGU wing has been identified to be zero gravity, combined with the vacuum of space and the space thermal environment. As is the case with the determination of fully deployed dynamics, it is not possible to completely off-load the deploying NGU wing to adequately simulate a zero-G deployment. After launch tie release, and throughout deployment, the flexible blanket gores are free to move about in a "zero-stiffness" accordion-like mode. In a 1-G deployment, the unsupported blanket segments drape down into a catenary shape as shown in Figure 15. As the wing pivot panel is rotated via a motor–driven tape reel, the cell populated gores are pulled up against gravity, introducing an additional deployment load into the system that will not be encountered in zero-G. As described previously, the 1-G off-loading of a large UltraFlex wing during deployment will require additional vertical support cables supporting the free and "sagging" gore weight. During vacuum deployments of the MSP 01-Lander UltraFlex wings, it was observed that the "accordion" oscillation of the hanging gore segments in-line with the plane of the wing was much more pronounced than those observed in air (Note that the MSP 01-Lander wings were small enough to not require 1-G offloading support of the spars or gores). A primary reason for the incorporation of a brake or rate limiter at the hub is to prevent such oscillations of the system from back-driving the deployment tape to the extent that the tape goes slack and possibly gets tangled or comes off the deployment reel. Changes in friction due to thermal and/or effects on the deployment mechanism materials can also introduce loads that may affect deployment dynamics.

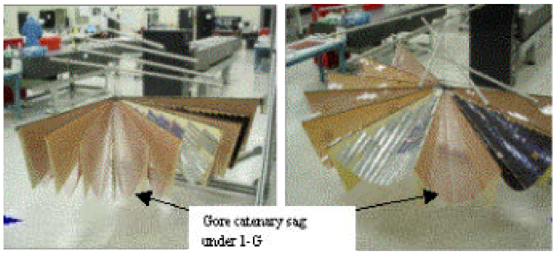


Figure 15. 1-G NGU Breadboard – Partially Deployed

MJ PV Power Production / Survivability: The implementation of standard 140-micron-thick Triple-Junction (TJ) $GaInP_2/GaAs/Ge$ PV onto the NGU gore assemblies produces a predicted specific power performance of >175 W/kg for a 7 kW-sized system. The use of advanced 100-micron thick TJ PV on the NGU platform leads to specific power performance of >220 W/kg. The relevant environments for assessing the survivability and power production of these cells when mounted in a circuit on the NGU gore mesh are: zero-G, vacuum, on-orbit thermal extremes and cycling, launch vibration, radiation (UV, e- and e+), atomic oxygen and solar illumination. Many of the power-prediction models developed to verify the survivability of the MJ cells when packaged in the NGU configuration and subjected to launch vibration have been validated in a TRL 5+ environment. The remaining TRL 5+ activity is to perform a thermal balance test of a flight-like MJ gore panel coupon and validate thermal performance/characteristics. Thermal balance testing is planned in the follow-on program phase. During this test a flight-like NGU MJ panel coupon will be mounted in a vacuum chamber under a thermal environment with steady-state solar-spectrum illumination. Temperature sensors will be mounted to the coupon cell front and back sides to determine the steady-state operating temperatures of the cells in a simulated space environment, allowing correlation / validation of the on-orbit thermal models developed.

11. FOLLOW-ON NGU ST8 TECHNOLOGY VALIDATION PLANS

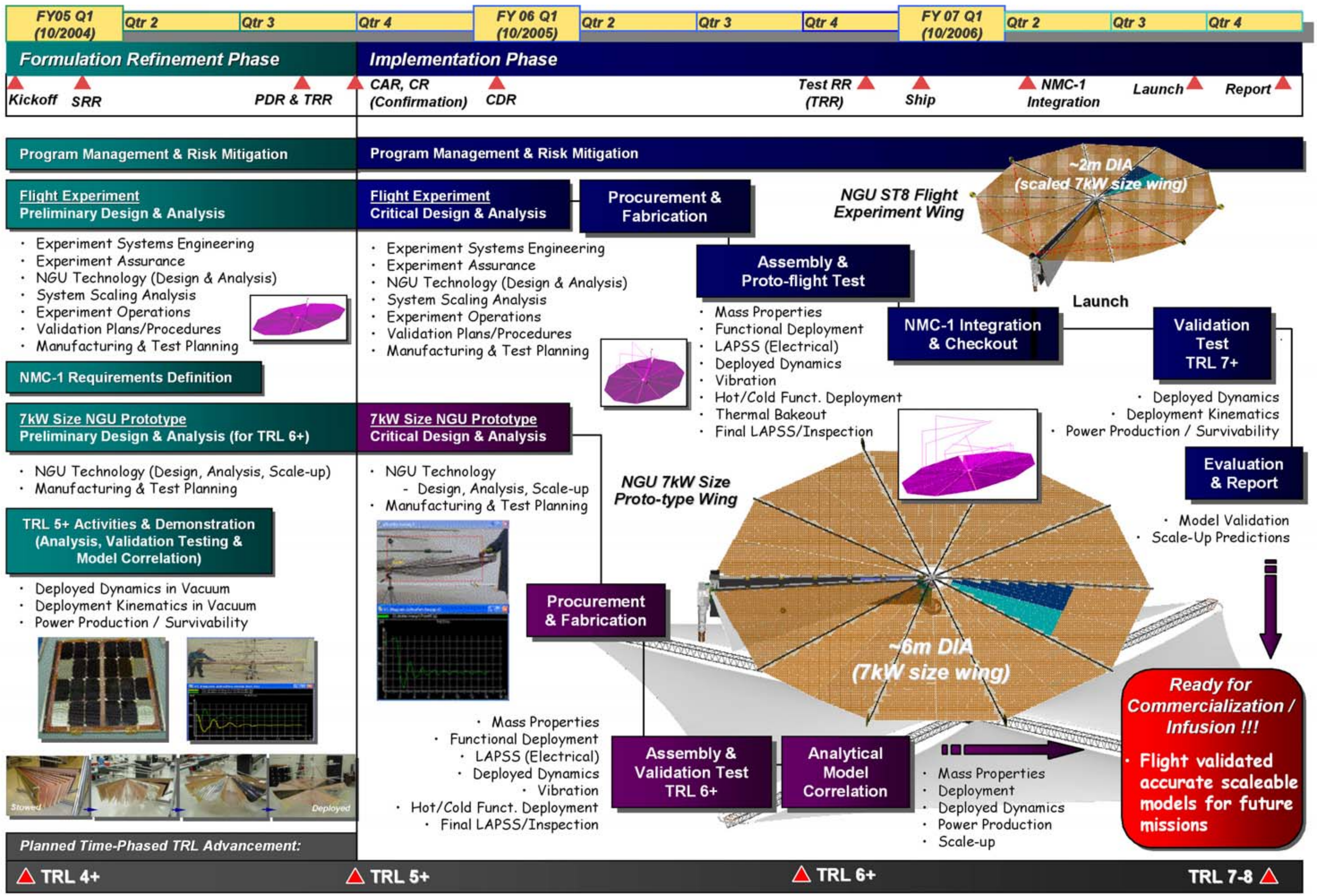
A summary of ABLE's proposed follow-on ST8 NGU technology validation and program plan is shown in Figure 16. NGU technical maturation (TRL) will be systematically and incrementally progressed by accomplishing: 1) Increased hardware fidelity via development/test (subsystem, system, prototype, and protoflight hardware) and (in parallel) 2) Increasingly refined predictive analytical models that are continuously correlated/validated with hardware experiment results. The culmination of these efforts is the ST8 NGU flight experiment and the resulting final flight-validated models.

For the follow-on Formulation Refinement Phase, the ABLE team plans to establish a TRL 5+ classification through further refined/detailed analysis, experimental test validation, and model correlation. Deployed dynamics and deployment kinematics testing in vacuum will be performed on the NGU breadboard wing system, and power production / survivability testing (vibration, thermal cycle, thermal balance, and plasma interactions) will be performed on flight-like subsystems. Multi-junction NGU cell/circuit power production / survivability testing will also be performed for NGU subsystems/components in TRL 5+ relevant environments. Analytical models will be correlated with experimental test results to produce higher fidelity modeling that better predicts performance and scale-up.

For the proposed Implementation Phase, the ABLE team plans to establish TRL 6+ and 7+ classifications for the NGU technology. A 6-m diameter, 7kW size NGU prototype wing will be designed, analyzed, built, and tested to validate analytical model predictions and scale-up capability. The 7kW size prototype wing will be tested through a sequence of "qualification-like" performance characterization and model validation tests; including deployed dynamics, deployment kinematics, and power production / survivability. A dimensionally and structurally scaled NGU flight experiment protoflight wing (scaled from the 7kW NGU design) will be designed/analyzed built/tested in this phase. The scaled flight experiment wing system (approx. 1/3 the diameter of the prototype wing) will also be subjected to similar performance/model characterization tests, as well as a full protoflight test sequence prior to spacecraft integration.

12. FLIGHT EXPERIMENT PLAN

The proposed NGU space-flight validation is comprised of three individual experiments: Deployment kinematics, deployed dynamics, and MJ power production. The NGU flight experiment wing system is shown in Figure 17. An integral digital camera (or cameras) mounted to the base of the NGU will record deployment kinematics. Motor current will be monitored during the entire deployment to verify predicted torque profiles and appropriate margins. Once complete deployment has been achieved and verified through switch telemetry, the deployed dynamics experiment can be initiated. The planned NGU excitation is to occur through a minimal spacecraft attitude control system (ACS) acceleration maneuver (nominally 0.1 to 0.3 g's), inducing sufficient response amplitude in the deployed wing for adequate measurement resolution. During and after this excitation the low-frequency accelerometers outputs are monitored/recorded, and the relative motion/displacement of the video-grammetry targets strategically positioned on the NGU wing system are monitored with the same digital camera that recorded NGU wing deployment. Data from the video-grammetry process will allow for the determination of relative NGU wing system motion versus time and validate the accelerometer data obtained to determine / validate


FY05 Q1 (10/2004)
Qtr 2
Qtr 3
Qtr 4
FY 06 Q1 (10/2005)
Qtr 2
Qtr 3
Qtr 4
FY 07 Q1 (10/2006)
Qtr 2
Qtr 3
Qtr 4
Formulation Refinement Phase
Implementation Phase
Kickoff
SRR
PDR & TRR
CAR, CR (Confirmation)
CDR
Test RR (TRR)
Ship
NMC-1 Integration
Launch
Report
Program Management & Risk Mitigation
Program Management & Risk Mitigation
Flight Experiment
Preliminary Design & Analysis
· Experiment Systems Engineering
· Experiment Assurance
· NGU Technology (Design & Analysis)
· System Scaling Analysis
· Experiment Operations
· Validation Plans/Procedures
· Manufacturing & Test Planning
NMC-1 Requirements Definition
7kW Size NGU Prototype
Preliminary Design & Analysis (for TRL 6+)
· NGU Technology (Design, Analysis, Scale-up)
· Manufacturing & Test Planning
TRL 5+ Activities & Demonstration (Analysis, Validation Testing & Model Correlation)
· Deployed Dynamics in Vacuum
· Deployment Kinematics in Vacuum
· Power Production / Survivability
Stowed
Deployed
Flight Experiment
Critical Design & Analysis
· Experiment Systems Engineering
· Experiment Assurance
· NGU Technology (Design & Analysis)
· System Scaling Analysis
· Experiment Operations
· Validation Plans/Procedures
· Manufacturing & Test Planning
Procurement & Fabrication
7kW Size NGU Prototype
Critical Design & Analysis
· NGU Technology
- Design, Analysis, Scale-up
· Manufacturing & Test Planning
Procurement & Fabrication
· Mass Properties
· Functional Deployment
· LAPSS (Electrical)
· Deployed Dynamics
· Vibration
· Hot/Cold Funct. Deployment
· Final LAPSS/Inspection
Assembly & Validation Test TRL 6+
Analytical Model Correlation
NGU ST8 Flight Experiment Wing
~2m DIA (scaled 7kW size wing)
Assembly & Proto-flight Test
· Mass Properties
· Functional Deployment
· LAPSS (Electrical)
· Deployed Dynamics
· Vibration
· Hot/Cold Funct. Deployment
· Thermal Bakeout
· Final LAPSS/Inspection
NMC-1 Integration & Checkout
Launch
Validation Test TRL 7+
· Deployed Dynamics
· Deployment Kinematics
· Power Production / Survivability
Evaluation & Report
· Model Validation
· Scale-Up Predictions
NGU 7kW Size Proto-type Wing
~6m DIA (7kW size wing)
· Mass Properties
· Deployment
· Deployed Dynamics
· Power Production
· Scale-up
Ready for Commercialization / Infusion !!!
· Flight validated accurate scaleable models for future missions
Planned Time-Phased TRL Advancement:
TRL 4+
TRL 5+
TRL 6+
TRL 7-8

deployed dynamic structural modes. After NGU deployment has been achieved the MJ power production experiment can be initiated. The power production experiment can occur before or after the deployed dynamics experiment. Power production of dedicated PV circuits will be measured through the simple periodic monitoring of current and voltage of standard Isc and Voc sensors and the circuit itself. Analytical models, continuously refined during the protoflight critical design/analysis and build/test activities, will be correlated to the in-space experiment results. Successful model correlation will result in accurate and scaleable flight-validated analytical models that can be directly applied to predict NGU performance and characteristics for all future missions. The fully developed hardware and flight-validated models will ready the NGU technology for immediate commercialization/infusion and significantly reduce user implementation risk. The proposed NGU flight experiment timeline with commands and telemetry acquisition is provided Table 3. Experiment start time can occur at any instant after Spacecraft on-orbit checkout. It is assumed that nominal ACS maneuvers to place the spacecraft in a stabilized position will occur prior to the initiation of the NGU flight experiments. After a period of inactivity on the order of 3 minutes, the first NGU experiment can be initiated (deployment). After all the desired experiments have been performed, the NGU system may be completely de-powered for the duration of the flight.

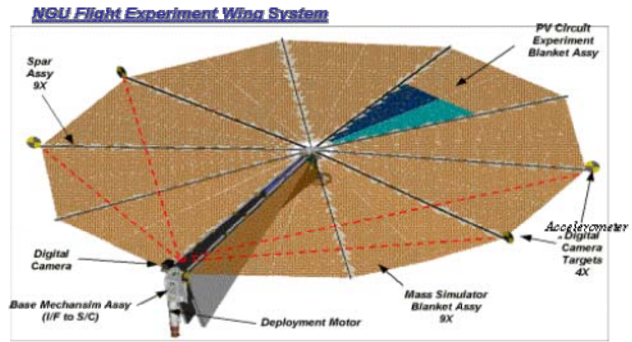


Figure 17. Proposed NGU Flight Experiment Wing System

Table 3. NGU Flight Experiment Timeline, Commands and Telemetry Acquired

Step #	Event	Command	Device Telemetry Acquired	Max. Power Required (watts)	Start Time (seconds)	Duration of Event (seconds)	Total Elapsed Time (seconds)	Camera Frame Rate (Hz)
Deployment Kinematics Experiment (Experiment #1):								
1	Pre-deployment / Full stowed wing	N/A	Stowed switch	N/A	Any time after on-orbit checkout of NMC-1	N/A	N/A	N/A
2	Launch tie release	Release	Release switch, photos	10W Release, 10W DVC	T0	120	120	15
3	Initial deployment staging complete	N/A	Position switch, motor controller current, video	10W Motor	T0 + 120	30	150	15
4	NGU deployment unfurling	Start motor	Motor controller current, video	10W Motor	T0 + 150	360	510	15
5	Full deployment complete and latched	N/A	Position switch, motor controller current, video	10W Motor	T0 + 510	N/A	510	15
Note: Deployment experiment not to be repeated								
Deployed Dynamics (Frequency) Experiment (Experiment #2):								
1	Spacecraft stabilization	ACS inputs	Accelerometer, photos	N/A	Any time after NGU deployment experiment and S/C stabilization	N/A	N/A	15
2	Nominal S/C ACS maneuver	ACS input	Accelerometer, photos	N/A	T0	1	1	15
3	Deployed frequency observation	N/A	Accelerometer, photos	10W DVC	T0 +1	300	301	15
4	Allow for NGU array settling	N/A	N/A	N/A	T0 +301	300	601	N/A
Note: Repeat deployed dynamics experiment three times over three weeks								
Power Production Experiment (Experiment #3):								
1	Spacecraft stabilization to acquire sun (off-pointing up to 45 degrees acceptable)	ACS inputs	Sun angle (off-pointing up to 45 degrees acceptable)	N/A	Any time after NGU deployment experiment and S/C stabilization	N/A	N/A	N/A
2	Illuminate PV circuit		Current, voltage, temperature	2W	T0	180	180	N/A
Note: Repeat power production experiment three times over three weeks								

13. 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, multi-A.U., and/or high temperature applications.

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-NASA, military and commercial).

14. REFERENCES

Citations given in this paper are referenced below.

[1] "A High Specific Power Solar Array for Low to Mid Power Spacecraft," P. Jones, Steve White, Jeff Harvey, & Brian Smith, 1994 SPRAT

[2] "The SCARLET Array for High Power GEO Satellites (B. Spence, Dave Murphy, P. Alan Jones, and Michael I. Eskenazi), 26th IEEE Photovoltaic Specialists Conference, September 1997

[3] "The EOS-AM Solar Array" R. Kimber & O. Regalado, 1993 IEEE Conference

15. BIOGRAPHY

Brian R. Spence, Senior Program Manager - Brian R. Spence received his B.S.M.E. from the University of California, Santa Barbara, in 1986 and has over 15 years experience in space deployable solar array and structural systems. Mr. Spence has been involved in the management, design, development, analysis, production and test of deployable structures, mechanisms, and solar array systems (rigid panel, flexible blanket, thin film blanket, and concentrator technologies) in project engineering and program management capacities. The most relevant programs/technologies to this paper include: PI for the current ST8 Next Generation UltraFlex Study Phase, Mars Dust Mitigation Development Program (under subcontract to JPL), NASA Advanced Thin Film UltraFlex, CellSaver concentrator, PowerSail/SquareRigger, HS702 AstroEdge concentrator, and the NASA SSTI AstroEdge concentrator solar array systems. Mr. Spence is a technical staff member of the ABLE solar array systems group, has authored numerous technical papers, has three awarded patents, has received a NASA Achievement Award, and is a registered professional engineer in the state of California.

Steve White, Technical Director - Steve White received his Bachelors and Masters of Science in Mechanical Engineering, with honors, from the University of California, Santa Barbara, in 1983 and 1986, respectively. Mr. White has worked solely on space deployable structures and solar array systems for the past 12 years. Mr. White has been involved in the design, development, analysis, production and test of deployable structures, mechanisms, and solar array systems in project engineering, technical director and management capacities. The most relevant programs to this paper include: Co-I for the current ST8 Next Generation UltraFlex Study Phase, the Mars Dust Mitigation Development Program (under subcontract to JPL), Mars 01 Surveyor Program Lander UltraFlex Solar Array, the GPS IIF solar array, the PUMA BSAT-2C PUMA solar array, and the PUMA INDOSTAR solar array system. Mr. White is a co-author of numerous technical papers, and has received two NASA Achievement Awards.