Self Deploying, Thin-Film PV Solar Array Structure

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Abstract. Spacecraft solar array systems require launch restraint hardware, array-stiffening structures to meet minimum natural frequency and provide protection during integration and test, as well as mechanisms necessary to reliably deploy the arrays. Conventional structures, mechanisms and rigid space solar cells add undue mass, cost and complexity. Current minimum solar array system costs are $1000/Watt and maximum specific power is 106 Watts/Kg at beginning of life (BOL). Mass and cost reductions are needed to meet the demanding requirements of present and future DoD, AFRL, NASA and commercial spacecraft solar arrays.

New satellite programs are looking beyond state-of-the-art (SOA) power subsystems, to thin-film photovoltaics (TFPV) that are lighter and more robust than current rigid cells. Conventional approaches to TFPV array design require a separate boom, or structure to tension the array for meeting a natural frequency requirement. Tensioning a TFPV array introduces many issues with structural integrity, complexity and also significantly increases the cost and mass of the system.

MSI has developed a technology innovation that extends the bounds of SOA space PV systems by eliminating conventional rigid structures and mechanisms to take full advantage of the lightweight and low volume characteristics of TFPV. This technology uses multifunctional, foldable components with stored energy to provide deployment force and deployed stiffness for meeting the demanding mass, cost and power requirements of future spacecraft programs.

MSI's TFPV enabling technology, economies of scale, non-recurring engineering, constant efficiency improvements, as well as developments in multi-junction and polyimide substrate TFPV result in a MSI PV system cost of less than $200/watt, a stowed volumetric power of greater than 90 Kw/m^3, and specific power of greater than 600 watt/kg.

This paper will address the characteristics of MSI's solar array system and demonstrate the cost, mass and stowage volume benefits that will become available to satellite manufacturers in the next few years.

Description And Significance Of The Problem

Mass, stowage volume and cost reductions are needed to meet the demanding requirements of present and future DoD, NASA and commercial spacecraft solar arrays. Spacecraft solar array systems require launch restraint hardware, array-stiffening structures to meet a minimum natural frequency, and mechanisms necessary to reliably deploy the arrays and provide protection during integration and test. State-of-the-art (SOA) structures, mechanisms and rigid pace solar cells add undue mass, cost and complexity reaching their limitations in minimum system costs of $1000/Watt and maximum specific power of 106 Watts/Kg, beginning-of-life (BOL). Programs like AFRL's PowerSail and TS21 are looking beyond SOA photovoltaics (PV) to thin-film PV (TFPV) that are lighter and more robust than SOA rigid cells. Conventional approaches to TFPV array design require a separate boom, or structure, to stiffen or tension the array for meeting a natural frequency requirement. Tensioning a TFPV array introduces many problems with structural integrity, complexity and also significantly increases the cost and mass of the system.

MSI introduces a foldable, integrated, thin-film stiffened (FITS) array for flexible TFPV, providing the solution to achieving lower cost and stowage volume, as well as higher specific power for space solar arrays.

Benefits of FITS Technology

- Enables Flexible Thin-film PV for Space
- Low Cost
- High Specific and Volumetric Power

Figure 1 illustrates the FITS concept that integrates the following technologies:

Enabling Technologies For FITS

- Thin-film PV
- Foldable Integrated Stiffeners
- Living Hinge

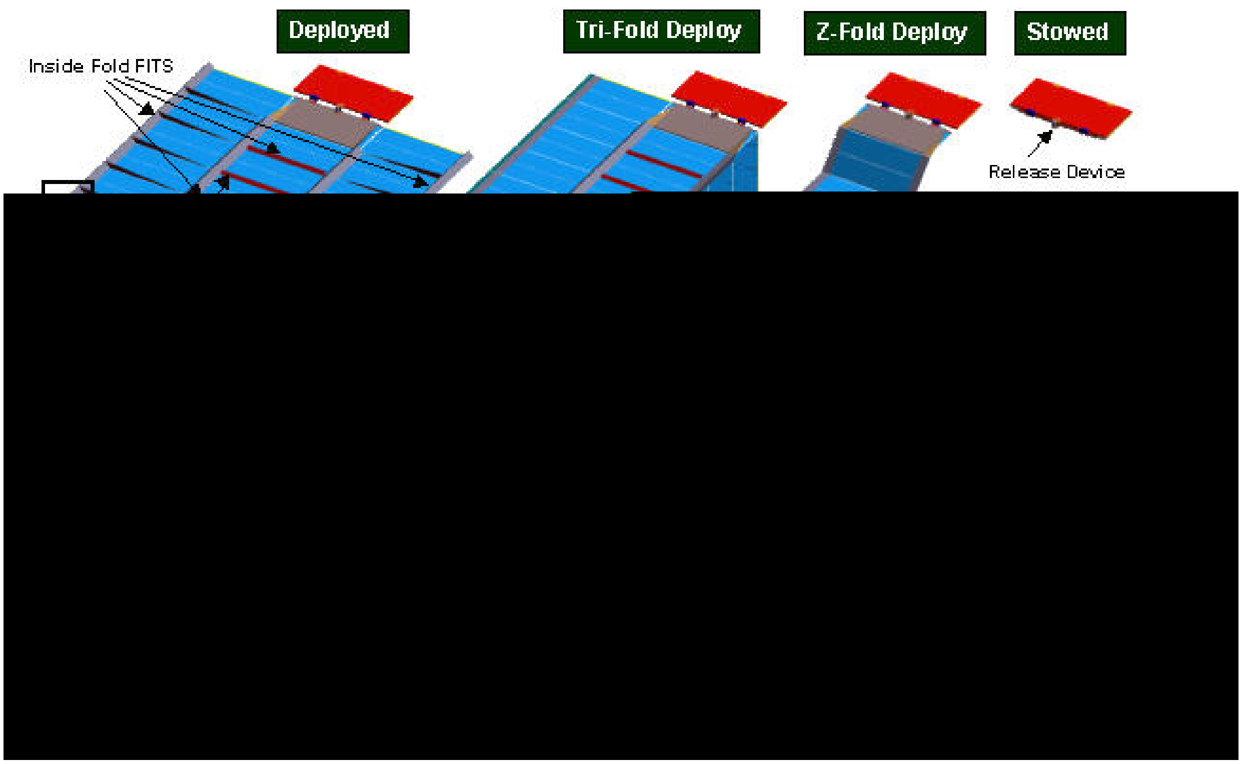

Figure 1. MSI's Revolutionary FITS is a Lightweight, Compact Solar Array Designed Specifically for Flexible Photovoltaics

MSI's FITS Philosophy

The FITS design was conceived using the following objectives to enable the most efficient use of TFPV:

1) Optimize thin-film array stiffening with minimum mass (High specific power in W/Kg)

2) Utilize multifunctional components to minimize mass and complexity

In order to meet these objectives, MSI believes that TFPV is the only viable means to meet the high specific power requirements. The TFPV material is lightweight and flexible, offering innovative ways to stow, deploy and stiffen the array, while minimizing mass. Copper, indium, gallium and diselenide (CIGS) PV is in production at Global Solar Energy (GSE), and has some flight heritage on an NRL experiment. Interconnect, Electrostatic Discharge (ESD) mitigation, and thermal coating technologies were developed for the GSE CIGS by ITN Energy Systems Inc. (ITN). Amorphous silicon (aSi) technology is produced commercially for terrestrial markets by Uni-Solar, and has flown in an experiment on the Soviet MIR station. TFPV material will be flown by MSI on NASA Starshine 6, to gain flight heritage in 2004. Air Force Research Lab (AFRL) Dual Use Science and Technology (DUS&T) program is making large strides in the advancement of TFPV technologies for space qualification, and will gain flight heritage from their PowerSail program.

PowerSail is an AFRL program commissioned to develop large space solar arrays using TFPV in the 2001 to 2004 timeframe. The goals of this program are as follows:

BOL Specific Power > 275 W/Kg

Cost = 100 to 200 $/W in 2010

Stowage Volume > 75KW/m^3

PowerSail will benefit from the innovative FITS concepts for stiffening and deploying as well as the methods developed for analyzing FITS and TFPV arrays. Figure 2 shows a concept of FITS used as a PowerSail.

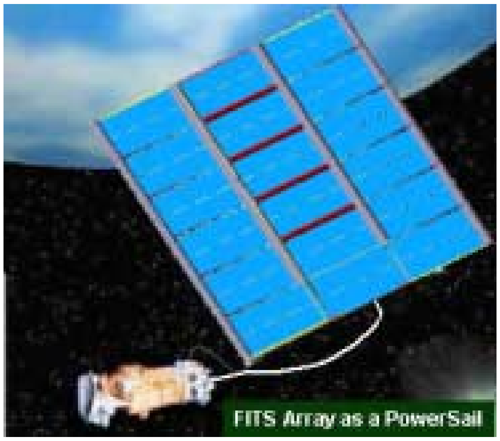

Figure 2. FITS as a PowerSail

TS21 is an experimental spacecraft funded through AFRL in partnership with MSI (Figure 3). MSI is proposing to optimize, build and test the FITS design for space environments, develop the necessary analysis techniques to aid in future designs, and secure a position on TS21 flight experiment. The array has been designed to the TS21 requirements in order to obtain FITS flight heritage as soon as possible.

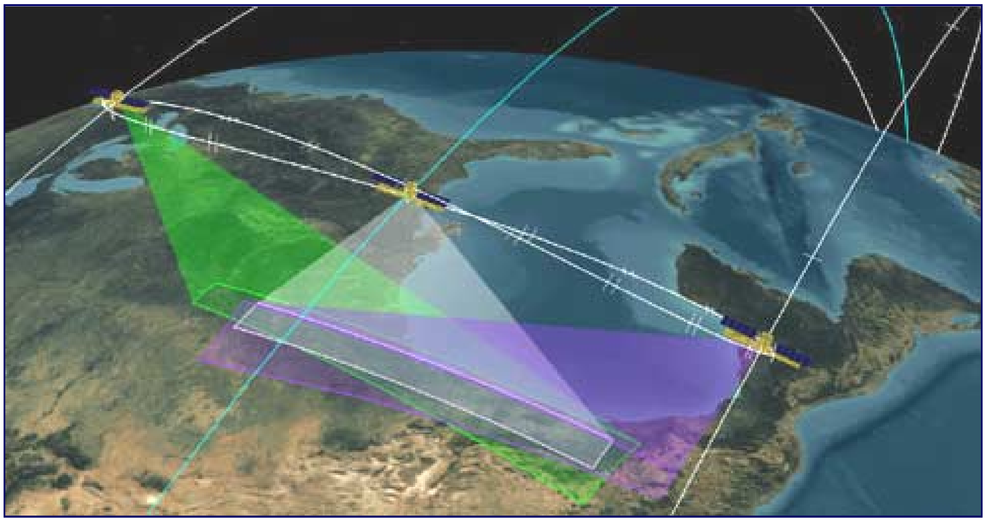

Figure 3. Virtual Satellite: TechSat 21 Autonomous Formation Flying

In concert with the TS21 philosophy of developing and flying "breakthrough" technologies to reduce cost and mass of future satellites, MSI has funded the TFPV developments necessary to fly a solar array system with very high specific power and lower costs than ever before seen in the aerospace Industry. The progress of these developments has strengthened the rationale to use the Global Solar Energy (GSE) TFPV material, ITN Energy System's space cell and module, and the MSI array designs as the baseline solar array system for TS21. These studies have validated the FITS design as a revolutionary concept in thin-film array deployment and stiffening.

The goal of each component designed in FITS is to have multiple functions in order to eliminate mass associated with non-multifunctional constituents.

FITS Configuration

In keeping with the philosophy described above, MSI proposes its concept of the FITS, as shown in Figure 4. A section of the array is shown in detail to illustrate the folding scheme and the different types of FITS stiffeners needed for outside, inside and double-folded joints. A test article is also seen in Figure 4 to further illustrate the FITS geometry and operation. Figure 5, also illustrates and demonstrates the inside and outside folded FITS stiffeners.

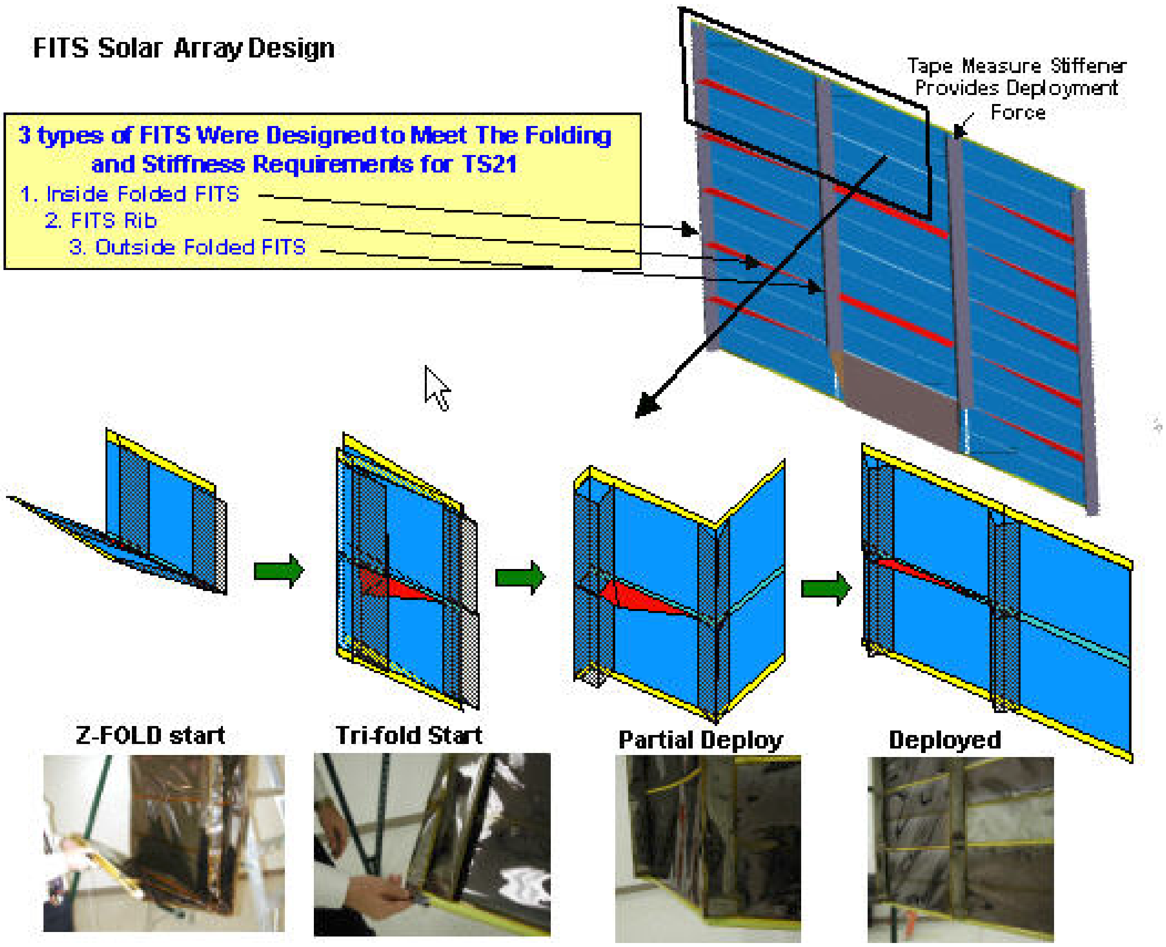

Figure 4. FITS Configuration and Deployment Sequence

Conventional methods of solar array deployment involve structure and deployment mechanisms. Thin-film arrays provide a challenge to deploy and stiffen while preserving mass savings. Two methods for stiffening are tensioning the blanket, or adding stiffening components to the blanket. The tensioning method involves complex and heavy mechanisms to provide deployment of the blanket and forces to maintain a constant tension throughout the mission. The FITS design uses the stiffening method with thin-film multifunctional deployable components, to increase the blanket moment of inertia, while minimizing mass & maximizing the utility of the lightweight thin-film arrays. The Z-folded joints have a stored energy to provide deployment forces using "living" hinges, resembling ligaments that have no moving parts. The Tri-fold joints complete the FITS deployment using forces from the tape hinge integrated into the end stiffeners, which also serve to lock the FITS stiffeners open. The completed deployment offers an increased array moment of inertia to meet a 0.5 Hz natural frequency requirement of the FITS array.

Mission Adaptability

FITS was conceived with the intent of satisfying a wide range of spacecraft power requirements. Design and analysis have been accomplished for 1000 Watt, 6 Kwatt and 15 Kwatt systems. The design also can accommodate a gimbal and is designed in a modular fashion for maintainability and scalability for programs other than TS21 and PowerSail.

Thin-Film PV Blanket Design

Thin-film PV blanket designs are driven by spacecraft requirements and cell loss data. Figure 5 shows the relationships of requirements to design for the TS21 application. One PV cell produces a voltage dictated by its particular chemistry, which is independent of cell area. Series connection of these cells increases the voltage by the number of cells to obtain the necessary spacecraft bus voltage required. The number of cells to attain this voltage at EOL is calculated by the predicted voltage losses of the cell, and is called a string. These strings are then connected in parallel, increasing the current and subsequently the array power, to obtain the necessary spacecraft power.

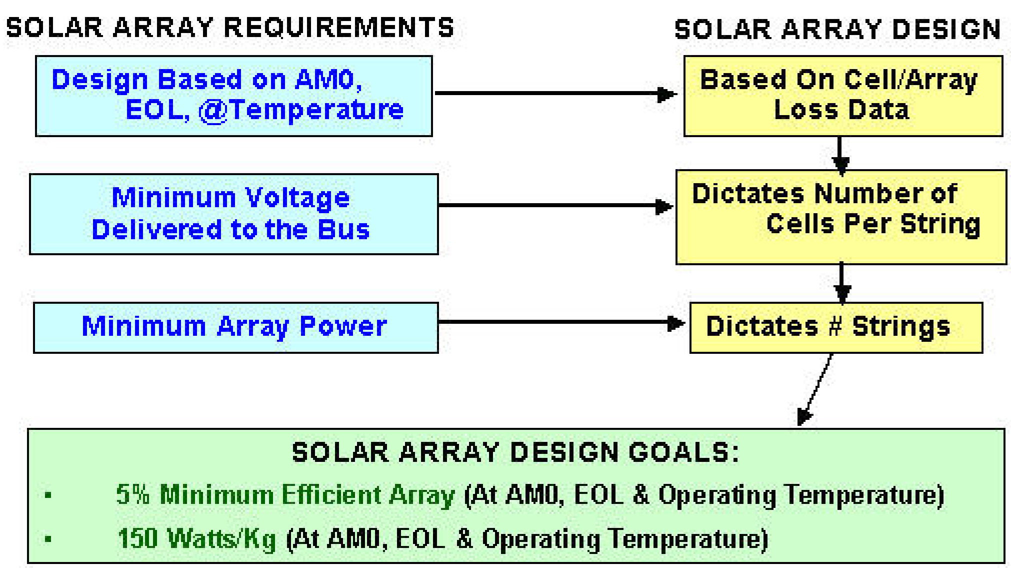

Figure 5. PV Blanket Design Process

Using state-of-the art efficiencies, voltage, currents and conservative knockdowns for GSE CIGS material, we optimized the cell and module size for the TS21 stowage envelope. Array area was sized to meet the power requirement at worst-case temperature and EOL, resulting in a near-square, 2-wing, 10 m^2 array configuration. The folding scheme was then created to fit in the stowed envelope, and fold locations were optimized for deployment.

A blanket configuration using GSE/ITN cells was created to address integration into the TS21 design. The module size was designed to stay within the stowage envelope and allow for an easily deployable folding scheme. Figure 6 shows the two-wing blanket design with 12 strings to meet the power requirements, each consisting of three modules.

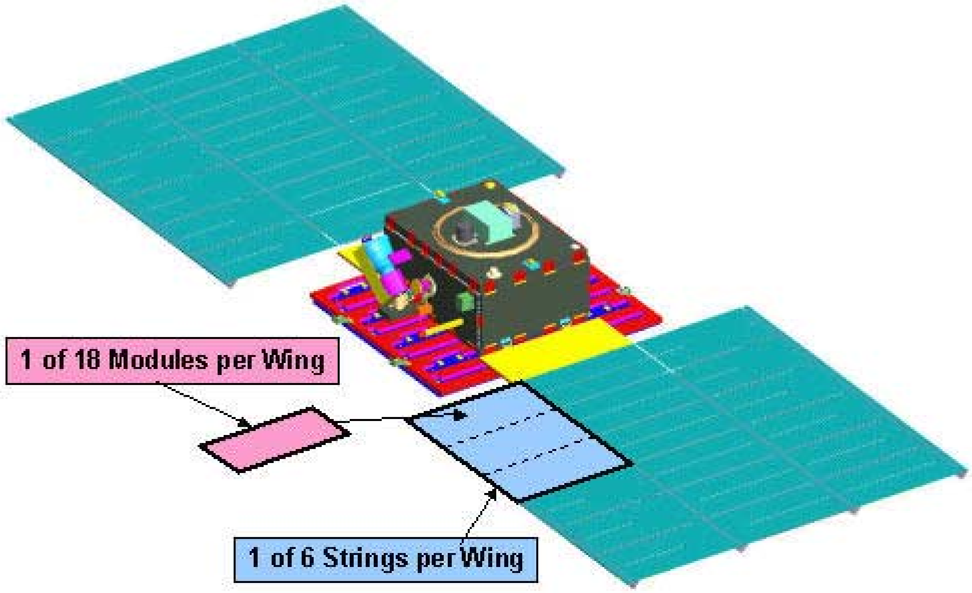

Figure 6. FITS Blanket configuration Developed for TS21

FITS Parametrics

The major parameters that are important in choosing a solar array subsystem are; specific power in (W/Kg), cost ($/W), and stowage volume in (KW/m^3). MSI's FITS design was created to achieve optimal parameters using the TS21 mission requirements, current TFPV capabilities and conservative assumptions. The following parametrics show the enormous advantages of FITS structure:

BOL Specific Power = 150 W/Kg

Cost = $500/W

Stowage Volume = 45 KW/m^3

Parametric assumptions are as follows; 0.5 Hz minimum natural frequency, 8.5% CIGS Stainless steel substrate TFPV, all mechanisms, restraint hardware, gimbal yoke and electrical cabling included in mass calculations, non-recurring engineering included in cost

Reducing frequency requirement below 0.5 Hz, increasing TFPV efficiencies, improvements in multi-junction and polyimide substrate TFPV and further optimization of FITS materials as well as economies of scale will produce the following near-term parametrics:

BOL Specific Power > 600 W/Kg

Cost < $200/W

Stowage Volume > 90 KW/m^3

Thin-Film FITS Array Analysis

Spacecraft solar arrays have traditionally been designed to have a first mode natural frequency well above the control loop frequency of the attitude control system (ACS). This separation in frequency prevents adverse coupling between the two systems. Thin-film solar arrays inherently have very low fundamental frequencies due to the blanket modes associated with their thin cross sections. These low frequencies do not meet the stiffness requirements imposed on traditional designs. MSI believes that thin-film solar arrays can be designed with low fundamental natural frequencies without adversely affecting the ACS. This belief is predicated on the fact that the effective mass participating in the low frequency modes is not significant enough to drive the spacecraft. MSI, in cooperation with Advanced Solutions Inc, (ASI), has accomplished studies that validate this belief, shown in Figure 7.

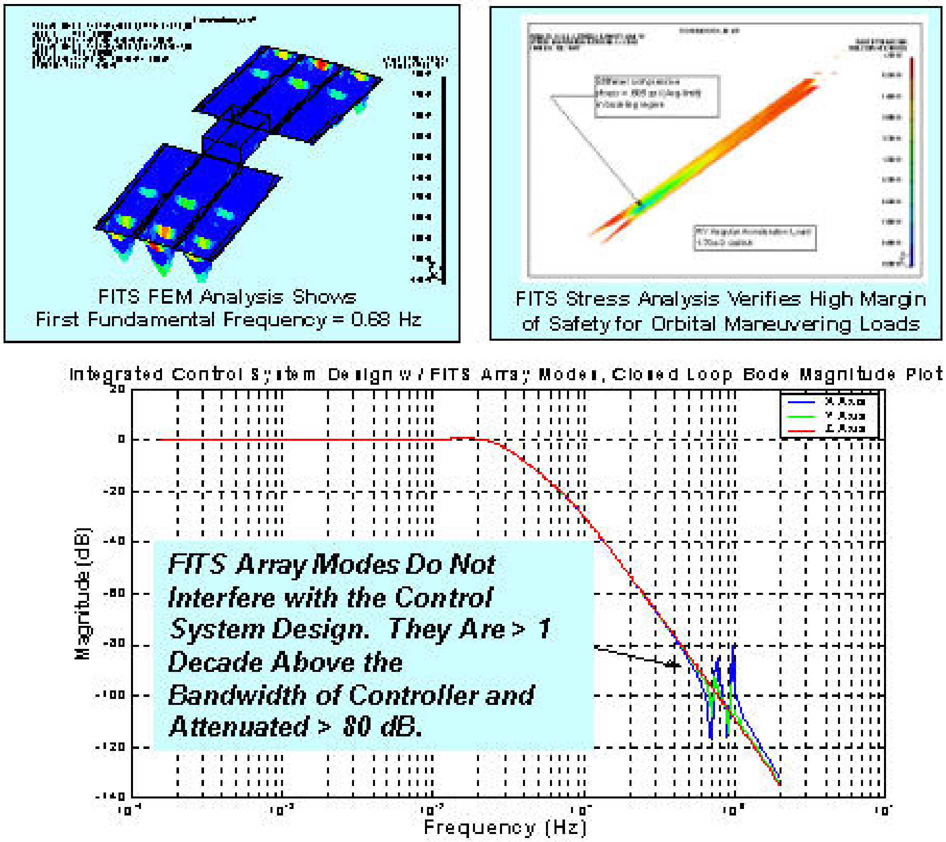

Figure 7. FITS FEM Analysis

Allowing low fundamental frequencies in thin-film arrays means greater mass savings and simpler restraint and deployment mechanisms, because the amount of tension stiffening or the number of integrated stiffeners is reduced. Low fundamental natural frequencies can be correlated to structural stability of thin-film arrays. Structures with low natural frequencies also tend to have low buckling and crippling strength. Deployed thin-film solar arrays have to be designed to be structurally stable against all on-orbit inertia loads. Minor buckling of the blanket itself is allowed, but buckling of integral stiffeners is detrimental to the performance of the solar array. There is a delicate balance to be met in thin-film solar array design between frequency and the interaction with the ACS and structural stability.

There are two ways of meeting both the frequency and stability requirements for thin-film solar arrays:

1. Add structure and mass to increase array fundamental frequencies and structural stability or
2. Develop of verifiable spacecraft flexible body/controls system interaction analysis methods that accommodate low frequency, low mass modes and develop simple structural analysis techniques to predict the structural stability of the thin-film solar arrays subject to on-orbit inertia loads.

To minimize thin-film solar array mass and reduce their design complexity and iterations, MSI is furthering the development of a method for thin-film solar array design. This involves developing a dynamic model of the FITS array, quantitatively analyzing the effects of the ACS system, and providing a system trade for FITS design configuration optimization.

These analysis methods will be validated using ground-based testing of frequencies and dampening as a function of blanket stiffening. The test program and TS21 flight experiment will validate the flexible body dynamics and ACS interaction. All programs investigating thin-film arrays, such as AFRL's PowerSail, TS21, DUS&T and future spacecraft designs will benefit from development of this analysis.

Summary And Conclusion

MSI's FITS design, analysis and strategic plan for implementation into spacecraft market demonstrates the feasibility to make FITS the next generation solar array subsystem structure. It will enable the use of TFPV, create very high specific power, low cost and low stowage volume for future spacecraft industry needs. FITS has the near-term capability of providing the following parametrics for spacecraft power sub-systems:

BOL Specific Power > 600 W/Kg

Cost < $200/W

Stowage Volume > 90 KW/m^3

Acknowledgements

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