# Deployment Optimization of a Boom for FalconSAT-3 Using Elastic Memory Composite Material

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**Rationale for the inclusion of deployable structures onboard small satellites is ever increasing. For example, replacing traditional mass-expulsion control thrusters with micro-propulsion ion thrusters on extendible booms can significantly reduce fuel mass requirements for attitude control systems. However, current flight-heritage booms are rendered inadequate when held to the stringent mass and mechanical requirements necessary to justify such a change. To address the deficiencies of existing boom technologies, a new generation of deployable structures must be developed. Paramount in this endeavor will be the ability to incorporate new materials into the design of next-generation deployable space structures. One promising new material/ technology for longeron members of deployable booms is TEMBO™ Elastic Memory Composite (EMC). EMC retains the structural properties of traditional fiber reinforced composites, i.e. high stiffness to mass ratio, while possessing the ability to behave as a shape memory material. These characteristics enable the primary structural component of a boom to additionally function as the primary deployment mechanism. This paper will focus on the developmental efforts encountered while advancing EMC from a material concept to a viable boom technology. In particular, this paper will introduce a family of deployable EMC booms and then outline the down select process employed during the development of the baseline United States Air Force Academy FalconSat-3 microsat boom.**

## Nomenclature

| | | |
|---|---|---|
| *ACS* | = | Attitude Control System |
| *AFRL* | = | Air Force Research Laboratory |
| *CTD* | = | Composite Technology Development, Inc. |
| *EMC* | = | Elastic Memory Composite |
| $f$ | = | natural frequency of the deployable structure |
| $f_b$ | = | natural frequency of the deployable structure in bending |
| $f_{pitch}$ | = | pitch libration frequency of the spacecraft |
| $f_t$ | = | natural frequency of the deployable structure in torsion |
| *FEA* | = | Finite Element Analysis |
| $I_{pitch}$ | = | mass moment of inertia of spacecraft in pitch |
| $I_{roll}$ | = | mass moment of inertia of spacecraft in roll |

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|---|---|---|
| $I_{yaw}$ | = | mass moment of inertia of spacecraft in yaw |
| *MEC* | = | Mass-Expulsion Control |
| *MPACS* | = | Micro-Propulsion Attitude Control System |
| $P_{orb}$ | = | orbital period |
| *SEM* | = | Structural Engineering Model |
| *SRC* | = | Starsys Research Corporation |
| *STEM* | = | Storable Tubular Extendible Member |
| *USAFA* | = | United States Air Force Academy |
| $\Delta$ | = | dynamic magnification factor |
| $\zeta$ | = | damping factor |
| $\Omega$ | = | excitation frequency |

## I. Introduction

Small satellites can realize significantly improved mission capability through the addition of deployable booms which can carry a variety of tip payloads. For example, replacing traditional mass-expulsion control (MEC) thrusters with micro-propulsion ion thrusters on the end of an extendible boom can significantly reduce fuel mass requirements for the attitude control system. However, fully realizing these potential mass savings requires a new generation of lightweight, extendible booms that increase the moment arm of the thruster (from the satellite's center of mass) by one or two orders of magnitude.[1] To address this technical need, new deployable booms must be developed that overcome significant deficiencies in current flight-heritage booms. In particular, next generation boom designs must be developed that are *both* mechanically simple *and* mass efficient.

A recent innovation that promises to revolutionize the design of deployable booms is the development of shape memory materials and their introduction into the design of deployment mechanisms. Shape memory "mechanisms" can eliminate the need for traditional highly complex mechanical deployment devices, massive launch canisters, and independent deployment-control systems. In addition, these shape memory mechanisms can lead to dramatically simpler boom designs that include fewer "parasitic" (i.e., non-structural) parts and are therefore much lighter in weight. Elastic Memory Composite (EMC) materials are a relatively new addition to the family of shape memory materials. The key advantages of EMC materials over shape memory alloys and shape memory ceramics are their substantially lower densities, higher strain capacities, and higher damping. Hence, EMC materials exhibit many favorable qualities for deployable space structures and have piqued a broad interest within the deployable space structures industry.

The present paper introduces a family of innovative, highly-efficient, next-generation deployable booms. This family utilizes Composite Technology Development's (CTD's) class of TEMBO™ EMC materials as the basic foundation to deployable boom design. The TEMBO™ line of EMC materials are "heat activated", meaning that this particular line of EMC material exploits a transition in the mechanical properties of the material that occur at a critical laminate temperature. Venturing above this critical temperature will result in a "rubbery" composite structure, which allows high levels of strain to be achieved. Laminate properties below this critical temperature are comparable to traditional "rigid" composite structures. This allows for strain energy to be "frozen" into an EMC structure by cooling a deformed laminate below the critical temperature. Conversely, deployment of a packaged laminate can be triggered by applying enough heat to raise the "frozen" laminate above this critical temperature.

The TEMBO™ EMC family of booms has been designed around a central common element, EMC longerons with embedded heaters. These EMC longerons are *both* the primary deployment mechanism *and* the principal structural members of the boom. The EMC longerons provide a uniquely versatile platform from which a variety of boom designs can be arranged. In the case of the United States Air Force Academy FalconSat-3 microsat mission, two designs from the TEMBO™ EMC family of booms were identified as potential candidates. These candidates included a three-longeron truss configuration and two-longeron "tubular" design. A design exercise employed 3D CAD modeling to conform each of these conceptual EMC boom configurations to meet the FalconSat-3 mission constraints and requirements. These CAD models were used to assess the mission requirements vs. the attributes of the two candidate designs. From this, a baseline boom configuration was identified. A trade study then compared alternate variations within the baseline design, identifying two viable contingency designs.

## II. Background

### A. Attitude Control System

Typical three-axis high stability Attitude Control Systems (ACS) employ the use of thrusters in conjunction with reaction wheels to steady the gentle rocking motion of a spacecraft (see Fig. 1).[2] The reaction wheels eliminate gravity gradient rocking motion and allow for precise control of the vehicle, thus, providing a steady platform from which imaging and data transfer can take place. Thrusters assist in spacecraft control, but they also perform critical momentum desaturation maneuvers that are required due to reaction wheel drag. While effective, this method of attitude control does necessitate significant mass allotments for the storage of thruster propellant. For this reason, great effort has been poured into the development of micro-propulsion ion thrusters. Theoretically, utilizing ion micro thrusters over the current MEC thruster technology could dramatically reduce the propellant mass and/or extend the life of the spacecraft. However, as the thruster output force decreases, a correspondingly linear separation in thruster distance from the center of mass of the spacecraft is required. This separation is accomplished by extending the micro thruster away from the spacecraft through the use of a deployable boom. Being an integral part of the attitude control system, great care needs to be exercised during the selection process of this boom.

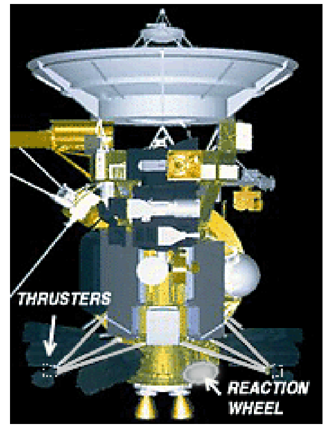
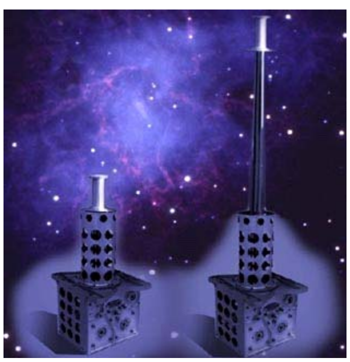



**Figure 1: Typical 3-Axis Attitude Control System.**

### B. Current State of the Art Deployable Boom Technology

All currently available deployable spacecraft booms are based on designs that have been in existence for more than 30 years. In general, these heritage boom designs can be divided into two classes: 1) tubular, extendible booms (see Fig. 2),[3] which are mechanically simple but mass inefficient, and collapsible truss booms (see Fig. 3),[4] which are mechanically complex but mass efficient. For example, the Storable Tubular Extendible Member ((STEM), Fig 2a) is one of the oldest tubular boom designs, having been first flown in 1962. However, STEM's tend to be heavy due to their use of either beryllium copper or stainless steel, and STEM's are limited in size to a maximum diameter of about 2" due to their high stored strain energy in the launch package. Similarly, the STACER boom design (Fig. 2b), which is currently flown on many microsatellites, dates back to the 1960's and suffers from high packaged strain energy and low deployed stiffness and strength.



a) Astro Aerospace STEM Boom

b) Surrey STACER Boom

**Figure 2: State-of-the-art tubular, extendible booms.**

a) Astro Aerospace Aestromast

b) SRTM Mission Articulated Mast

**Figure 3: State-of-the-art collapsible truss booms.**

By contrast, collapsible truss booms (Fig. 3) are inherently more mass efficient than tubular, extendible booms, but they involve mechanically complex designs and mass penalties associated with launch-containment canisters and deployment-control systems. For example, coilable-longeron booms (e.g., AstroMast, Fig. 3a) are twisted into a tight helix during packaging. This packaging scheme results in very high strain energy being stored in the coilable longerons of these booms, which necessitates the use of massive launch-containment canisters. In order to reduce stored strain energy, articulated-longeron boom designs (Fig. 3(b)) have been developed and flown. However, most articulated-longeron booms require some type of heavy deployment mechanism to drive and control their deployment.

## III. EMC Boom Design

### C. Family of EMC Booms

To combat the deficiencies in existing technology, Composite Technology Development (CTD) is developing a family of next-generation deployable booms that can be characterized by an innovative, high-efficiency TEMBO™ EMC longeron. Commonality within this family takes the form of these single tape EMC longerons, which are arranged to form an assortment of boom configurations. Examples of these configurations include several variations of the truss and of the "cylindrical" tubular boom classes that were described in the previous section. Packaging strain energy is stored and released through the use of discretely embedded heaters within each longeron (see Fig. 4). These heaters provide localized heating at pre-determined hinge locations. Altering the heater dimensions, the cross section of the longeron, and/or the architecture of the composite laminate allows for a variety of boom layouts to be explored within any a given class (for example, multiple design variations of the "tubular" classification are evaluated later in this paper). This flexibility enables a deployable structure to be developed which specifically and efficiently meets the mission requirements.

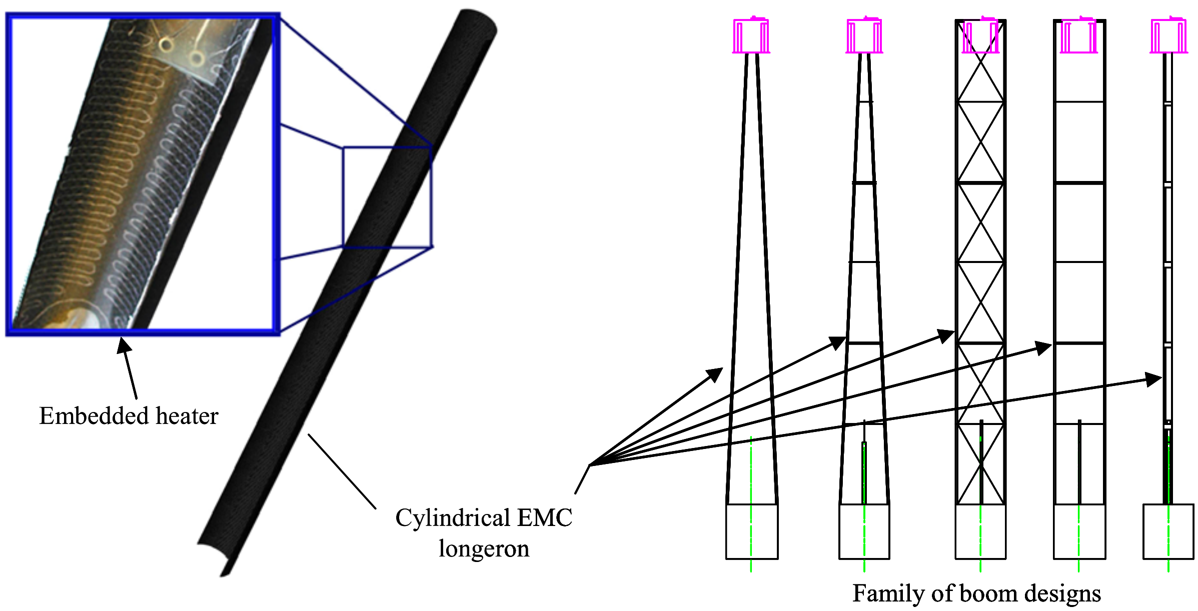



**Figure 4: Family of EMC boom configurations that share common EMC longeron components.**

These booms demonstrate mechanical simplicity *and* mass efficiency as the TEMBO™ EMC longerons have essentially no parasitic (i.e., non-structural) mechanical components or mechanical interfaces through which structural performance can degrade. A typical longeron is multi-functional in that it provides deployment force and dampening, while additionally functioning as the principal load bearing element of the deployed boom. Consequently, the boom design is simplified as this attribute eliminates the need for secondary deployment drive mechanisms.

In addition to dampening, further deployment control can be gained through the sequencing of the previously mentioned embedded heaters. This coordinates boom deployment, and can eliminate the mass of a secondary mechanical synchronization device.

### D. United States Air Force Academy FalconSat-3 Mission Requirements

The Air Force Research Laboratory (AFRL) is currently funding the development of a lightweight Micro-Propulsion Attitude Control System (MPACS) that is set to be flown on the upcoming United States Air Force Academy (USAFA) FalconSat-3 mission (see Fig. 5).

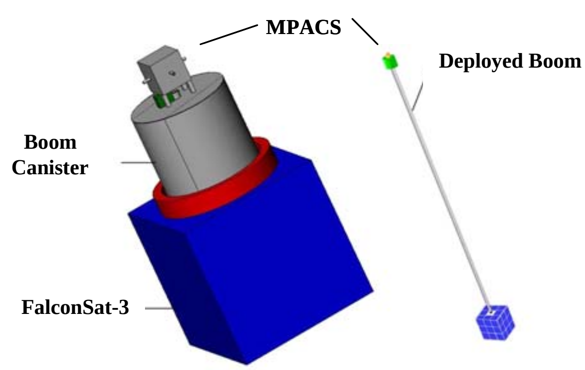



**Figure 5: Spacecraft layout and deployed boom.**

*1. Physical Constraints*

As previously discussed, justification for MPACS is realized once the micro thruster has been placed far enough from the spacecraft to allow for attitude control to occur with a propellant mass reduction eclipsing the additional mass of the boom. Beyond the deployment of the MPACS payload, the deployable boom for the FalconSat-3 mission is additionally required to provide passive gravity gradient stability for the spacecraft. These requirements, and constraints stemming from the size of the launch vehicle, have given rise to the envelope requirements illustrated in Fig. 6.

Mass requirements for the FlaconSat-3 boom are derived from the gravity gradient requirement of the boom and are as follows:

- Tip Mass = 7.8 kg.
- Total boom system mass shall not exceed 9.0 kg.

*2. Derived Frequency Requirements*

For structures that must react to harmonic loading, it is important that the frequency of the structure be adequately separated from the frequency of loading in order to avoid significant dynamic magnification. According to Thomson, the magnification factor, $\Delta$, can be expressed in the form of equation (1).[5]

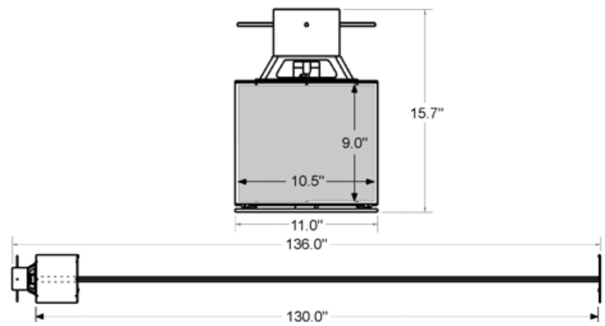



**Figure 6: Packaging volume and deployed length.**

$$\Delta = \left| \frac{1}{\sqrt{\left[1-\left(\frac{\Omega}{f}\right)^2\right]^2 + \left(2\zeta\frac{\Omega}{f}\right)^2}} \right| \quad (1)$$

Where $\Omega$ is the frequency of the excitation load, $f$ is the natural frequency of the structure, and $\zeta$ is the damping factor. If damping is neglected, the dynamic magnification factor reduces to equation (2).

$$\Delta = \left| \frac{1}{1-(\Omega / f)^2} \right| \quad (2)$$

According to equation (2), if significant dynamic magnification (i.e., $\Delta > 1.0$) is to be avoided, the natural frequency of the boom system must be either one order of magnitude greater than, or a factor of 1.41 less than, the excitation frequency.

In the case of the FalconSat-3 boom, there are two harmonic load conditions that must be taken into consideration. The first load condition is defined by the pitch/roll libration oscillation of the spacecraft and boom system in the gravity gradient field. Gravity gradient libration frequency is very low, so in the design of gravity gradient boom systems it is common for the fundamental vibration frequency of the boom to be one order of magnitude greater than the pitch libration frequency of the spacecraft.[6] Equation (3) gives an approximate value for the pitch libration frequency, $f_{pitch}$.

$$f_{pitch} = \frac{1}{P_{orb}}\sqrt{\frac{3(I_{roll}-I_{yaw})}{I_{pitch}}} \approx \frac{\sqrt{3}}{P_{orb}} \quad (3)$$

The Falconsat-3 spacecraft will fly in a low-earth orbit with an approximate orbital period, $P_{orb}$ = 90 minutes. Thus, minimum bending and torsional frequencies, $f_b$ and $f_t$, respectively, are:

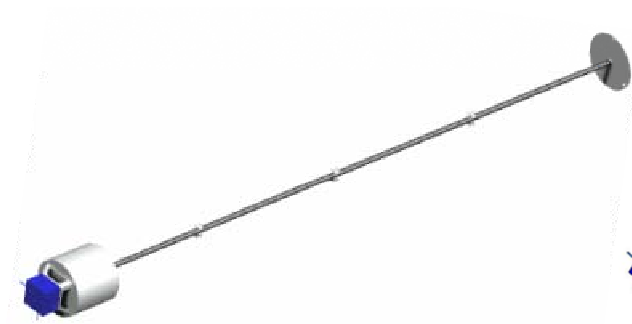
$$f_b, f_t > \frac{10\sqrt{3}}{P_{orb}} > 0.0032\text{Hz} \quad (4)$$

The second harmonic loading condition is the 2Hz pulse firing frequency of the MPACS thruster. To avoid significant dynamic amplification of the MPACS thruster loading it is desirable for the deployed frequency of the boom to be either an order of magnitude greater than this operating frequency, or at least a factor of 1.41 below. Due to the low mass budget, the target deployed frequency of the boom was chosen to be a factor of 1.41 below the MPACS thruster excitation frequency. Hence, considering both gravity gradient libration and MPACS operational frequency, the acceptable ranges for the vibration frequencies of the deployed boom system is given by equation (5).

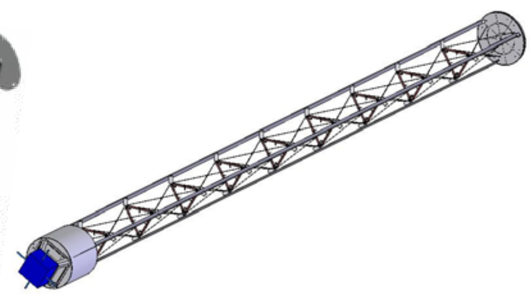
$$1.41\text{Hz} > f_b, f_t > \frac{10\sqrt{3}}{P_{orb}} > 0.0032\text{Hz} \qquad (5)$$

### E. Selection of Candidate Booms

Two configurations from the TEMBO™ EMC family of booms were chosen as possible candidates for the FalconSat-3 mission. The first candidate was made of two semi-cylindrical EMC longerons that upon deployment formed a centrally split "tubular" boom design. The second configuration was a three-longeron truss configuration (see Fig. 7). Starsys Research Corporation (SRC) provided expertise in the area of mechanical flight hardware design for both of these structures.



a) Two-Longeron Cylindrical Configuration



b) Three-Longeron Truss Configuration

**Figure 7: TEMBO™ EMC Candidate Boom Configurations**

Detailed 3D CAD models took the conceptual candidate booms and merged fundamentals of mechanical flight system design and design fundamentals of TEMBO™ EMC into the packaging envelope, deployed length, and system mass parameters of the FalconSat-3 mission (see Figs. 8 and 9). This exercise allowed for representative comparisons between candidate boom designs. Feasibility of each design was further validated through "proof of concept" tabletop models that were capable of simplified packaging and deployment tests (see Fig. 10). The models were full scale replicas which represented two bays of the truss and a single bay of the cylindrical boom configurations. Preliminary deployment tests were conducted in order to verify design feasibility. Minor problems were uncovered during the deployment of the test models. The Two-Longeron cylindrical design stalled due to batten rotation around the guide rod, while the rigid fiberglass diagonal members on the Three-Longeron model were difficult to tie down. However, these issues should be able to be addressed and both concepts have been deemed feasible.

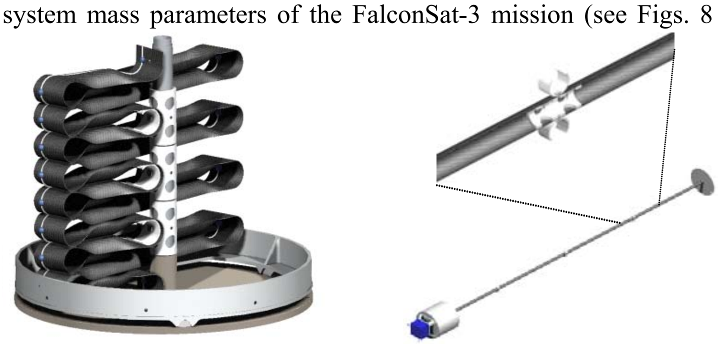


**Figure 8: Proposed FalconSat-3 Two-Longeron EMC Boom.**

Stiffness calculations have revealed a slight infringement of the Three-Longeron truss configuration beyond the previously described "safe" upper frequency limitation (see Table 1). However, this theoretical deviation was minor, and it has been assumed that sufficient alterations could be made to effectively drop the boom within compliance. The Two-Longeron cylindrical configuration complied with all frequency requirements.

The higher bending and torsional stiffness of the truss design imply that it will attain a greater level of deployment precision. However, due to the current model limitations, tests to verify this assumption have yet to be conducted. The truss design does benefit from a more efficient EMC packaging scheme, as the folding path of each longeron is unobstructed by the corresponding deployment guide rod. Thus, a simple two dimensional in-plane packaging scheme can be exploited.

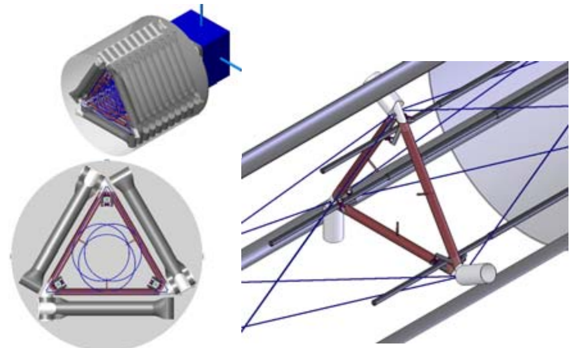
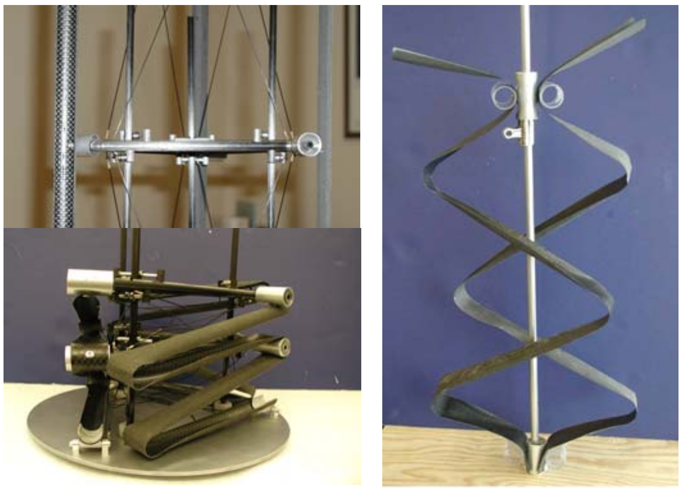


**Figure 9: Proposed FalconSat-3 EMC Truss Boom**

Meanwhile, the Two-Longeron cylindrical boom showcases a lower part count, and an overall more simplistic mechanical design. In conjunction with the lower part count, the Two-Longeron system benefits from a slightly lower mass than the truss design.



a) Three-Longeron Truss b) Two-Longeron System

**Figure 10: Proof of concept models.**

Concerns have been raised on the deployment reliability of the current Two-Longeron system. The out-of-plane folding scheme requires multiple unrestrained hinges. These hinges “float” between the restrained hinges, which tie into the batten fittings. Further testing will be conducted to study the kinematics of the longerons at these uncontrolled hinges. These tests will assess potential risks of this packaging scheme.

It is important to note that mass calculations for both designs are primarily based upon CAD models. These values include a 20% contingency margin for all components.

Ultimately, simplistic mechanical design proved most attractive for USAFA, thus the two-longeron cylindrical boom was selected as the baseline system for the FalconSat-3 mission.

| | **Two-Longeron Cylindrical Configuration** | **Three-Longeron Truss Configuration** |
|---|---|---|
| **Frequency in Bending - $f_b$** | 0.24 Hz | 1.5 Hz |
| **Frequency in Torsion - $f_t$** | 0.10 Hz | 1.7 Hz |
| **System Mass Including MPACS** | 7.45 kg | 8.54 kg |
| **Mass of Heated TEMBO™ EMC Material** | 0.10 kg | 0.10 kg |
| **Normalized Part Count*** | 1.0 | 20.6 |

*Longerons, Batten Fittings and Diagonal Members

**Table 1: Comparison of Candidate Boom Configurations.**

### F. Baseline Design Progression

With the baseline boom configuration established, two areas of focus were identified as priority during the next phase of development. The first area was the design and fabrication of a Structural Engineering Model (SEM) of a cylindrical EMC boom. This model would empirically validate the stowed frequencies of the baseline configuration while bolted onto the FalconSat-3 spacecraft. Finite Element Analysis (FEA) was employed by SRC to validate the analytical design of the SEM (see Fig. 11). Meanwhile, AFRL-Kirtland provided the resources necessary to fabricate the model (see Fig. 12). Fabrication of the SEM is complete; however, results from the integration tests being conducted by USAFA cadets were not available for this report.

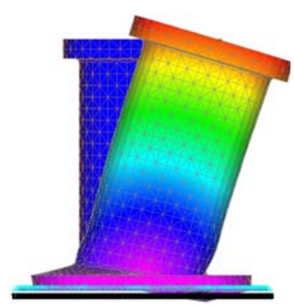


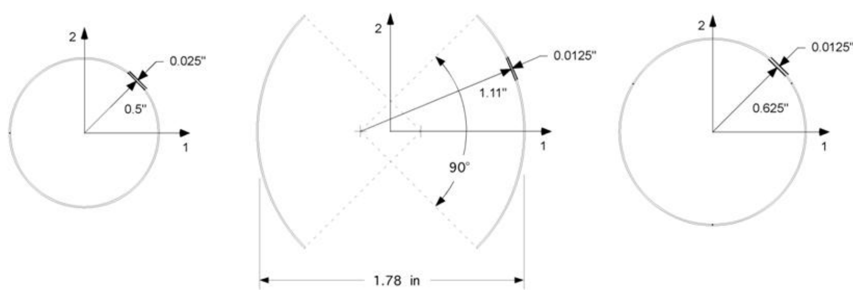
**Figure 11: FEA of SEM.**

**Figure 12: SEM Fabrication at AFRL.**

The other area of development focused on a trade study conducted to identify variations on the packaging arrangement and/or to the longerons. The purpose of this study was to satisfy the possibility that a variation on the existing cylindrical boom might appear more attractive than the baseline as development progressed, particularly if testing validated concerns over the use of the baseline out-of-plane EMC longeron packaging scheme. If variations were to materialize, they could be carried as contingencies on the baseline.

One of the design parameters for this trade study assumed that bending stiffness needed to match that of the baseline arrangement. Other requirements maintained the level of laminate strain, the deployed length, and the packaging envelope.

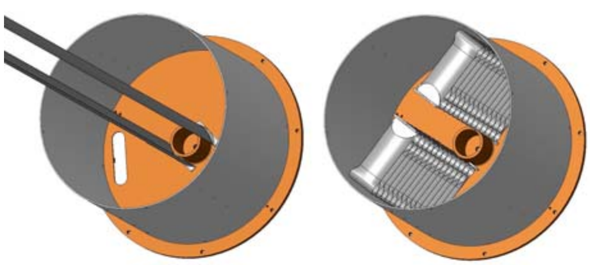
Two alternatives emerged from this study. The first alternative utilized a thinner laminate than the baseline. The cross section of this alternative was comprised of quarter-circles (90°) as opposed to the baseline semicircles (180°), and the individual longerons had a radius of 1.11 inches (see Fig. 13). In order to match the frequency in bending, the separation between longerons was increased by more than ¾ of an inch. This resulted in a boom that did not "close" upon itself when deployed. Packaged and deployed CAD models of this alternative have been generated to validate the conformance with the FalconSat-3 packaging envelope (see Fig. 14).




a) Baseline Design b) Alternative 1 c) Alternative 2

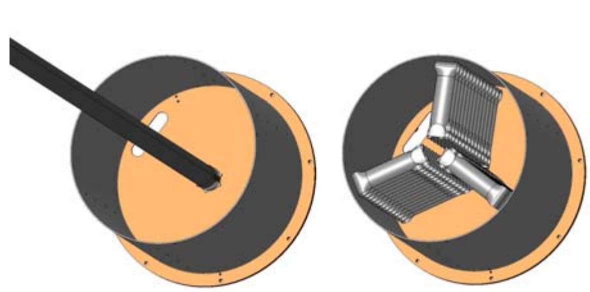
**Figure 13: Cross Sections Investigated in Design Trade Study.**

The second alternative consisted of three independent longerons. The cross section of each longeron constituted 1/3rd of a circle (120°). Upon deployment, these longerons joined to form a "closed" cylindrical boom. Packaging was achieved by arranging the longeron "stacks" radially at 120° angles of each other (see Fig.15). A tighter bending radius was necessary to package a full length boom into this packaging schematic. In order to comply with laminate strain limitations, the tighter bending radius required a laminate thickness half that of the baseline design. Due to the thinner laminate, a deployed "tubular" radius of 0.625" was required for the cylindrical boom to maintain equivalent bending stiffness (see Fig. 13).



a) Deployed. b) Packaged.

**Figure 14: Design Trade Study Alternative 1.**



a) Deployed. b) Packaged.

**Figure 15: Design Trade Study Alternative 2.**

Both of these alternatives can be packaged within the specified envelope. Additionally, both alternatives meet the deployed frequency and length requirements. Table 2 compares the alternative design with the baseline design.

All values within this table have been normalized with respect to the baseline configuration. Based upon these calculations, the current baseline Two-Longeron boom arrangement does appear to be the most attractive design.

| | Baseline Configuration | Alternative 1 | Alternative 2 |
|---|---|---|---|
| **Frequency in Bending - $f_b$** | **1.0** (0.24 Hz) | **1.0** | **1.0** |
| **Frequency in Torsion - $f_t$** | **1.0** (0.10 Hz) | **0.37** | **0.40** |
| **Deployed Length** | **1.0** (130 in) | **1.0** | **1.0** |
| **Mass of Heated TEMBO™ EMC Material** | **1.0** (0.10 kg) | **0.80** | **0.80** |
| **Laminate Strain** | **1.0** (5.0%) | **1.0** | **1.0** |
| **Normalized Part Count*** | **1.0** (6) | **2.5** | **2.67** |

*Longerons, Batten Fittings and Diagonal Members

**Table 2: Comparison of Alternative Boom.**

## IV. Conclusions and Future Efforts

This program began with the intent to present and advance the family of TEMBO™ EMC booms as a viable next generation deployable boom alternative. These efforts were justified by the deployable structure requirements of the AFRL micro-propulsion ion thruster experiment, which is slated to fly on the USAFA FalconSat-3 microsat mission.

During the course of this program two EMC boom configurations were identified as candidates for further developmental efforts. Each candidate merged the proprietary CTD TEMBO™ line of elastic memory composites into longerons that were capable of forming a well defined boom system. From these designs, table top models were fabricated to verify packaging and deployment "proof of concepts". A series of analytical calculations compared the two candidate systems, and from these results a Two-Longeron cylindrical boom was chosen as the baseline boom for the FalconSat-3 flight experiment. As development progressed, two variations on the baseline cylindrical boom configuration were created as contingency designs.

Based upon the current status of this program it would be premature to declare that a proven "next generation" boom design has been developed. However, the advancement of this technology has already revealed the feasibility of such a design. Furthermore, future efforts are in progress that will empirically correlate the output force of a boom system with such variables as the laminate cross section, the composite ply architecture, and the packaging strains. Meanwhile, AFRL is in the process of fabricating a longeron test fixture, and a gravity offload system, which will be capable of qualifying both of the original candidate boom configurations that were identified within the present study.

Due to the aggressive nature of the CTD and the AFRL test programs, it is within reason to say that qualification of a TEMBO™ EMC FalconSat-3 boom is on schedule to meet all critical milestones currently scheduled before launch. Additionally, by leveraging knowledge learned during the development of the EMC longerons for the baseline FalconSat-3 boom, the TEMBO™ EMC family of booms will be well positioned as a viable "next generation" deployable boom technology.

## Acknowledgments

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