

Developments in Nano-Satellite Structural Subsystem Design at NASA-GSFC

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Abstract. The NASA-GSFC Nano-satellite Technology Development Program will enable flying constellations of tens to hundreds of nano-satellites for future NASA Space and Earth Science missions. Advanced technology components must be developed to make these future spacecraft compact, lightweight, low-power, low-cost, and survivable to a radiation environment over a two-year mission lifetime.

This paper describes the efforts underway to develop lightweight, low cost and multi-functional structures, serviceable designs, and robust mechanisms. As designs shrink, the integration of various subsystems becomes a vital necessity. This paper also addresses structurally integrated electrical power, attitude control, and thermal systems. These innovations bring associated fabrication, integration, and test challenges.

Candidate structural materials and processes are examined and the merits of each are discussed. Design and fabrication processes include flat stock composite construction, cast aluminum-beryllium alloy, and an injection molded fiber-reinforced plastic.

A viable constellation deployment scenario is described as well as a Phase-A Nano-satellite Pathfinder study.

Introduction

Nano-satellites¹ are inherently suited for large constellation missions by virtue of their size. The spacecraft (S/C) shown in Figure 1a is 30 cm in diameter, 10 cm high, and weighs less than 10 kg, consistent with the true definition of a nano-satellite. The scientific benefit of a constellation lies in widely dispersed sensing instruments. The more S/C placed in orbit, the higher the scientific return. Due to present day NASA mission cost caps, all spacecraft of a constellation are to be deployed with one launch vehicle. This presents interesting challenges, and the particular need to

miniaturize spacecraft down to the nano-satellite class. The first NASA-GSFC constellation mission using up to 100 nano-satellites is the Magnetospheric Constellation mission, presently scheduled for launch in 2010. The long lead-time implies significant technological development. The evolution of state-of-the-art materials, processes, and designs will benefit this advanced technology program as it responds to developments in the other subsystem areas.

Figure 1b shows the S/C in exploded view. This is a fully functional S/C that supports

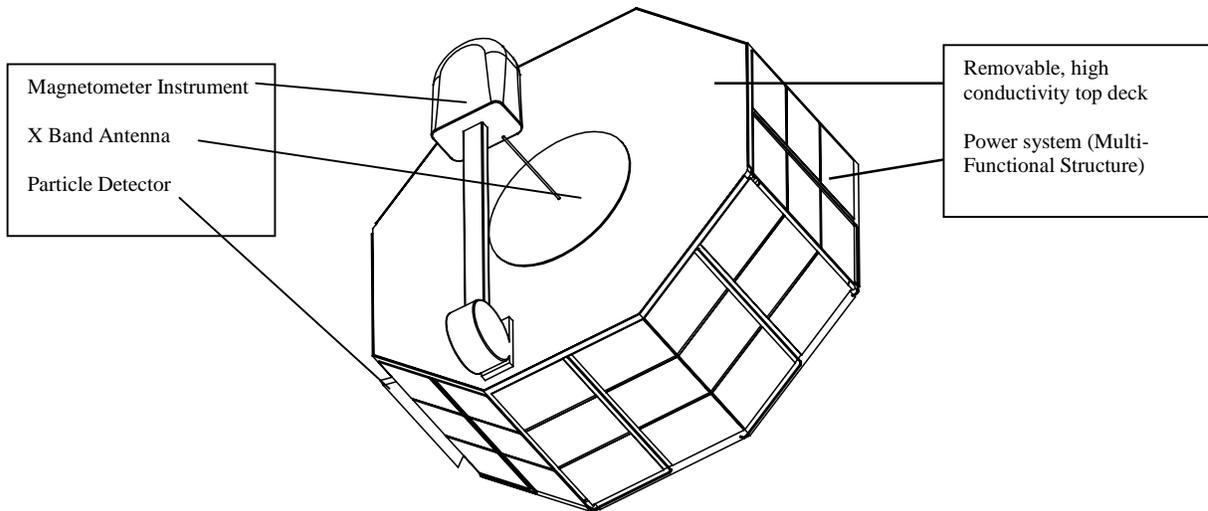


Figure 1a. Nano-satellite Current Configuration

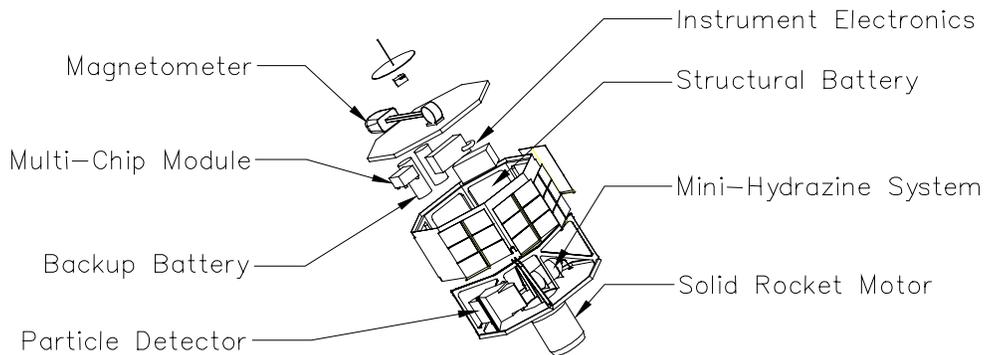


Figure 1b. Exploded view of Nano-satellite

constellation operations with an instrument complement, active orbital adjustments, and attitude control maintenance.

The major structural/mechanical system design drivers for the nano-satellite are:

- The nano-satellite requires spin-stabilization;
- High radiation environment;
- Medium-class (e.g. Delta II) launch vehicle;
- Size and cost constraints.

This paper will focus on the mechanical issues involved in producing and deploying a nano-satellite (Nanosat) constellation. The main structural/ mechanical design topics are:

1. The basic spacecraft structural bus;
2. The Deployer Ship structure, which is in itself a separate space-faring vehicle;
3. Reliable mechanisms to support and deploy satellites from the Deployer Ship;
4. The Nano-satellite Pathfinder study

Due to the nano-satellite constellation mission launch date considerably distant from today, the figures here represent detailed design concepts incorporating a compromise between the current state of development and what is envisioned for the future. The results thus far are valuable and applicable to a broad class of missions.

I. Structure

This section treats the structural design (including fabrication strategies), thermal design, multifunctional structures, integration and test (I&T) issues, and new technology infusion into the GSFC Nano-satellite Program.

Structure Description

The structural subsystem shown in Figure 2 is composed of top and bottom decks to which components are mounted, joined by an octagonal shell sidewall. The octagonal prism was chosen because it minimized voltage fluctuations from the body-mounted solar arrays and was more straightforward to fabricate than a cylinder. The S/C spins about

its Z-axis, keeping the solar arrays facing the Sun.

The decks are made of high-thermal conductivity material. They spread and radiate heat generated by the components (except the Solid Rocket Motor, which is isolated as much as possible). The top deck supports most of the high heat-generating components, while the bottom deck holds the more massive solid rocket motor, electrical power module, and propellant tank. The bottom deck is reinforced with a stiffening spine that holds embedded release mechanism fittings. The release mechanism is a technology development item discussed in the Mechanisms section. The solid rocket motor fits inside the spine.

The intervening sidewall structure supports the thermally isolated solar cells and integrated electrical power system. Figure 2 shows internal recesses for the power storage and conditioning modules. An inner facesheet closes out the modules and stiffens the sidewall.

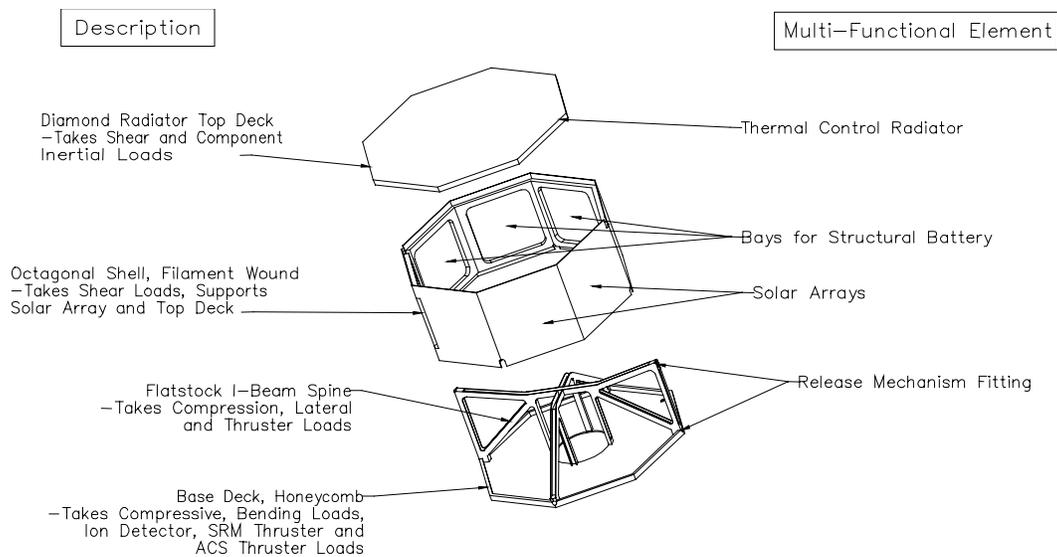


Figure 2. Nano-satellite Composite Multi-Functional Structure Details

Load Path

Fittings embedded in diametrically opposite vertices, which serve as the release mechanism interface, restrain the S/C in the Deployer Ship. Three translational and two rotational loads are reacted at the bottom pair; the secondary top pair takes out the remaining rotation. Optionally, a single fitting on the bottom deck at the 90° vertex could take out the last rotation; however, it could be difficult to implement, as it would be obscured when mounted in the Deployer Ship.

The bottom deck is the primary load-bearing member. Its spine has a structurally efficient cross-section. The sidewalls support some in-plane tension and compression due to loads axial to the S/C and in-plane shear due to lateral loads on the top deck and through the upper, secondary release mechanism fitting. The top deck reacts bending and shear from its supported components.

Design Options and Anticipated Evolution

State-of-the-art for the decks is either a honeycomb sandwich construction with composite facesheets, or a single facesheet with stiffening ribs. Components, though miniaturized, are in separate enclosures that are fastened or bonded to the facesheet. With near-term technological advances, the facesheets are anticipated to be synthetic monolithic diamond with miniaturized, combined subsystems in partially integrated, molded housings. Later on, the decks will have fully integrated electronics and other components such as conduits for data, power and propellant. The decks will have radiation shielding as part of the structural laminate.

The sidewall is a relatively low-load structure, which supports the electrical power system, and transmits top deck loads to the bottom

deck. The most straightforward solution is a thin octagonal shell. A thermal insulating layer isolates the solar array on its own substrate from the rest of the structure, with the power storage modules inside the shell.

Alternatively, a truss forms the sidewall, and the solar cells are easily isolated thermally by mounting them at discrete points, minimizing the thermal path area. The power conditioning and storage modules are easily integrated to enclosures in the interior of the truss. This structure could be built up of flat stock composite parts (like the spine) or an investment casting.

Investment casting has been promoted as a complete structural bus option, though its advantage lies more in truss structures than in deck spans. Nevertheless, a deck of another material could span a cast truss that forms the sidewall support structure. A key challenge is to compensate for thermal mismatch.

Thermal Design

The close packing and miniaturization of the Nanosats create a thermal design challenge. A spinning requirement alleviates this a great deal. The thermal analysis investigated various design concepts, and found that, with certain state-of-the-art technologies, a passive design will suffice.

The temperature of a spinning spacecraft is generally 20-30 °C in sunlight, provided component heat is rejected from surfaces that do not face the Sun. During eclipse periods, the Sun-facing surfaces become heat radiating, causing temperatures of interior components to drop. For our spin-stabilized Nanosat, the body-mounted solar arrays face the Sun and the top and bottom decks reject heat.

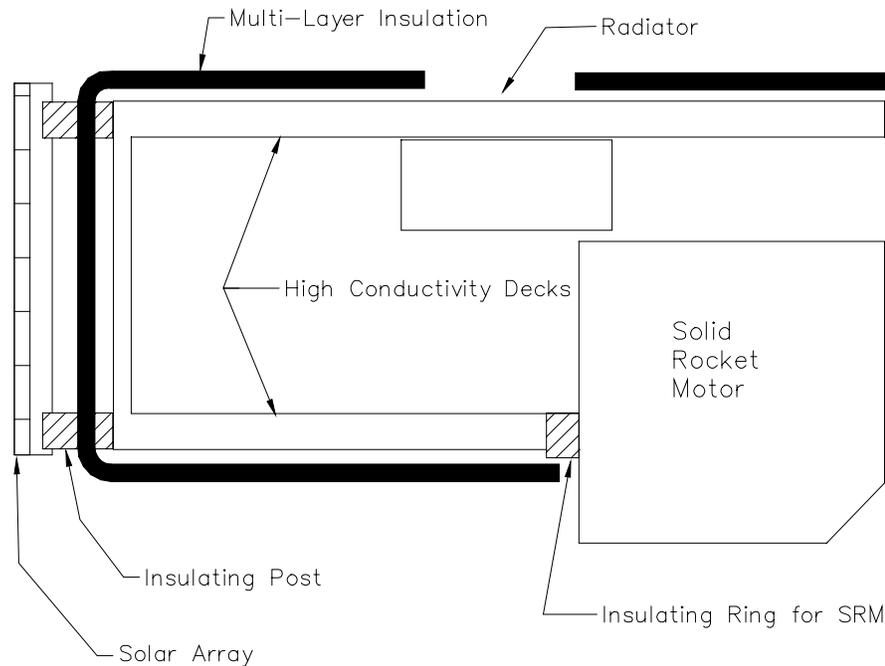


Figure 3. Nano-satellite Thermal Design

The thermal design shown in Figure 3 insulates the solar arrays (sun-facing surfaces) completely from the rest of the S/C, and applies Multi-Layer Insulation (MLI) Blankets to selected areas of the decks. Thus the solar arrays lose little, and the decks lose only a moderate amount of heat during long eclipse periods. The success of this design depends on the S/C low power consumption.

The structural radiator concept has been demonstrated effectively of late with the advent of high-thermal conductivity graphite fibers such as K1100. Ordinarily a low conductor, these new graphite fibers demonstrate adequate strength as well as thermal properties matching or exceeding aluminum.

Fabrication and Integration & Test Issues

The nano-satellite design is driven by:

- Mass & cost

- Multifunctionality
- User-friendliness (I&T)
- Manufacturability (directly tied to cost)

Great cost-savings are realized in the manufacture of 100 identical spacecraft structures. The application of economies-of-scale brings the per-unit cost down significantly. Cost and mass are also driven by the materials and fabrication strategy selected for the structure.

User-friendliness is achieved by the removable top deck, and by providing copies of the structure to selected subsystem disciplines for separate qualification testing. Low per-unit cost makes this feasible. Prior to S/C integration and test, several engineering test units will be used to prove out qualification and acceptance strategies. This will be essentially a dry-run of the I&T sequence.

The following types of materials are under consideration:

1. Graphite Composite Based
2. Cast Aluminum
3. Alternate Composite

While the Graphite Composite technique is the lightest, and has improved greatly in terms of production cost, its recurring labor cost erodes the mass benefits. Re-melt fabrication

techniques such as investment casting may prove less expensive. The casting process easily reuses tooling, such as molds, and has a low recurring skilled labor cost.

There are advances yet to be made in all production areas. The benefits and trade-offs of each strategy are assessed in Table 1 according to the four criteria for overall system design previously listed.

Table 1. Nano-satellite Material Assessment

Material	Pro	Con	Comments
Graphite Composite	Lightweight and stiff	Not a good radiation shield	Spot-shielding for radiation required even with Aluminum
	Enables MFS through room-temperature bond cure		Laminates must be cured separately at elevated temperatures
	Established Flight Heritage	High material and recurring labor cost	Modifications and repair are becoming standard practice, reducing scrap
Cast	Moderate Initial & Low Recurring Cost	Heavy	
	Provides radiation shielding	Does not form panel or deck surfaces well	
	Handles Complex Features	Difficult to modify After Fabrication	
Alternate Composite (fiber-reinforced polymer)	Lightweight	New Technology in this Application	
	Very low Recurring cost	Structural, Vacuum performance/ stability	Medium Multi-Functionality due to elevated cure temperature

New Thermal Technology

As the S/C power requirements increase, or the S/C becomes even more compact, the design becomes more complex. This scenario will possibly require active heat management, such as the use of a miniature heat transport system (mini-HTS). Another exciting thermal technology is the use of monolithic, Chemical Vapor Deposited (CVD) Diamond for use as a heat transport device and as a substrate for electronic circuits. CVD Diamond has over four times the conductivity of copper, while remaining a good electrical insulator. These items are currently under development at GSFC, for use in three-axis-stabilized Nanosats.

Multi-Functional Structures

The need to minimize mass has created the interest in Multi-Functional Structures (MFS). However the structure is not so tightly integrated that it precludes any type of

servicing. Of critical importance is being user-friendly to the rest of the S/C, enabling, not hindering, servicing functions during integration and test. While the I&T phases of development are expected to be very different for hundreds of identically produced S/C than for one or two, there will inevitably be a need to switch out parts and components.

Essential structural elements exhibit multi-functionality as described in Figures 2 – 4. The release mechanisms are embedded in the structure, with loads taken primarily through the decks. The decks contain conduits for power, data and propellant, and also act as thermal spreaders and radiators. The octagon shell contains bays in which the battery cells supply stiffness to the structure. The internal spine and deck edges contain pathways for electrical harness, propellant lines, and other conduits as needed.

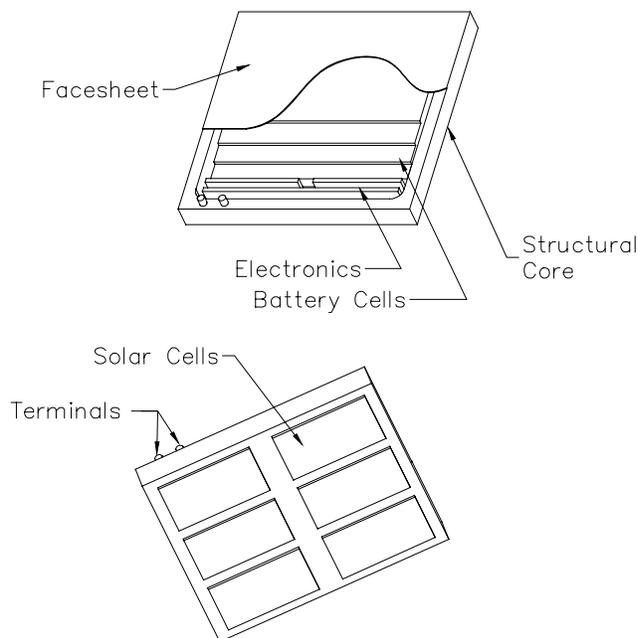


Figure 4. Multi-Functional Structure Example

Electrical Power System (EPS)

The Electrical Power System (EPS) is shown in Figure 4. It is a completely integral module and is thus a new concept in the S/C arena. It is composed of a sandwich panel on which one side has solar cells; the core is composed of a flat-cell battery and miniaturized conditioning electronics. In operation, it provides conditioned power to the rest of the S/C. The notion of a Structural EPS is the next logical step, which integrates the power and structure functions, saving volume and mass.

Propulsion

By a similar procedure, pressure vessels, propellant lines, and valve bodies are integrated into a structure. High rigidity is obtained from an array of filament-wound pressure tanks. Structural fittings that tie corners together form valve bodies and nozzle assemblies. Propellant lines run through otherwise unused spaces inside struts and edge stiffeners.

Electronics

As long as the sandwich panel sees low stress, an embedded electronics card on a flexible substrate replaces the core. Located near the neutral axis, the card only takes low compressive and tensile loads; bending loads are reacted mainly in the facesheets.

Harness

Diamond's electrical insulation properties allow conductive traces to be inscribed in its surface, thus eliminating electrical harness entirely. Alternatively, the electrical harness occupies unused structural space in the same way as propellant lines.

Radiation Shielding

Radiation shielding is critical when orbits pass through the radiation belts in the near-Earth

environment. Radiation shielding is accomplished by laminating high "Z" material such as tungsten into the composite. In addition, the fabrication techniques lend themselves to integrating what was formerly known as the "electronics box" into the structure. This allows a box- and component-level approach, while reducing mass.

Philosophy

As previously mentioned, there is a tension between MFS and modularity. A modular and necessarily large S/C such as the Hubble Space Telescope is easily serviced, yet a compact S/C such as a Nanosat is considered almost like a piece of consumer electronics. If a problem cannot be diagnosed and repaired quickly, the entire unit is scrapped.

The key to effectively combining disparate disciplines into a tightly integrated S/C is the concurrent engineering team approach. This is a management subject of high interest, as there are barriers beyond technology that must be broached before achieving success. The traditional distinct spacecraft disciplines are not expected to disappear. Rather, each discipline engineer will actually become more of a "systems level" engineer, much more cognizant of the concerns of the other disciplines, in order to make optimum gains in integration.

II. Deployer Ship

In-depth studies^{2, 3} have proven the feasibility of deploying one hundred Nanosats from a single medium-class (e.g., Delta II) launch vehicle (LV) and Deployer Ship (DS) to meet the requirements of a Magnetospheric Constellation mission. Never in civil space history have so many fully functional, separate S/C been deployed at once. The resulting concept is shown in Figure 5a.



Figure 5a. Deployer Ship Concept

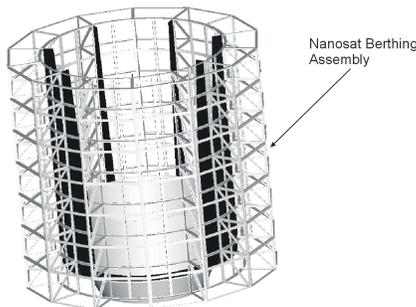


Figure 5b. Deployer Ship Berthing Assembly

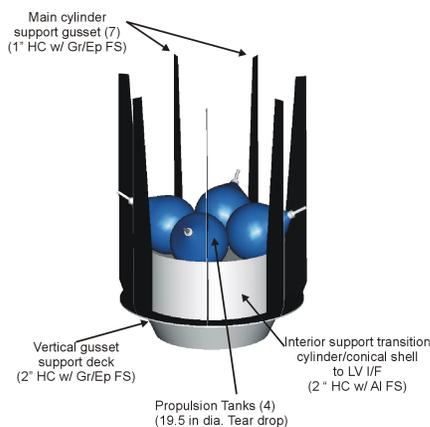


Figure 5c. Deployer Ship Structural Core

The first step was to maximize the number of Nanosats carried to their required orbits without limits on the Nanosat on-board propulsion. This parametric analysis made simplified, rule-of-thumb assumptions for DS subsystems such as propulsion dry mass (30%

of wet mass) and structure mass (15% of total supported mass). The parameters studied included DS initial and final orbit perigee and apogee, Delta rocket insertion parameters, and Nanosat propellant mass. Various orbit strategies were found to meet the requirements.

The second step was a preliminary DS system-level design that verified the previous assumptions. It was based on the most generic, acceptable orbit strategy, and came in well within prior, approximate assumptions. In this generic orbit strategy, the DS attains an orbit with an average apogee, from which Nanosats are then released and fire their on-board motors either posi- or retrograde to their final orbit. Nanosat propellant mass is less than 1 kg in this scenario.

Mission Scenario

In the strategy chosen, a Delta II launched from Florida separates the DS in a 185 km by 20 Re orbit. The DS immediately assumes a power-positive attitude (spin-axis perpendicular to the sun line) and returns to this attitude after every other maneuver (easy to do in a spinner). The DS fires its 100 lb bi-propellant orbit change engine twice to raise perigee to 3.0 Re and lower inclination to $\sim 7.5^\circ$ to the equator. The DS then uses its 5 lb bi-propellant attitude control thrusters to maintain the proper Nanosat release attitude and spin rate at perigee, and power-positive attitude at other times. The S/C are deployed radially, with or without additional spin, from individual bays. Assuming the DS is able to release ten Nanosats per 2.25-day orbit after orbit-adjust and checkout, the entire DS mission is complete in under two months.

DS Description

The LV interface is at the bottom of the inverted cone, shown in Figure 5c. The vertical gussets, support deck, and transition cylinder mount to the top of this cone. Other

DS bus components are located on the support deck. The gussets support the “birdcage” Nanosat berthing assembly in Figure 5b. The Nanosats are held by release mechanisms contained in the berthing assembly members.

The DS uses a passive thermal design, with blankets closing out the top opening and separating each bay, to minimize reflections. The Nanosats are powered off during ascent to minimize heat input to the DS.

The propulsion module, except for the 5 lb thrusters, is integral to the interior support cylinder. The structural core is sent out to the propulsion vendor for integration and qualification of the propulsion system as a unit. The four 5 lb thrusters are attached later. This modularity reduces cost dramatically. There are two 5 lb thrusters for attitude and precession control (one is redundant) and two for DS spin rate maintenance. These small thrusters are remotely located to increase their effective moment arm to the DS center-of-gravity (CG), and reduce plume impingement on the rest of the structure.

Figure 6 shows a finite-element model (FEM) deformed plot of the DS first bending mode. The cylinder diameter and number of gussets were increased to bring the frequency up to 15 HZ, an LV requirement.

One trade has been between a stiff structure, which carries all ground handling, launch, and operational loads, and a relatively more flexible one, in which some of the loads are taken through the Nanosats. The traditional approach has been the former. Yet with tough new compliant release mechanisms, the load-sharing enables a lighter, more efficient DS structure.

Systems Issues

The DS uses a spin-stabilized Attitude Control System (ACS) strategy for reasons of simplicity and easier deployment of a spinning Nanosat. The stacked ring approach was most efficient for space, inertia ratio, and deployment. Bi-propellant is an optimal solution for its high specific impulse, ability to re-start the orbit-adjust engine, as well as its suitability for attitude control. Originally, the

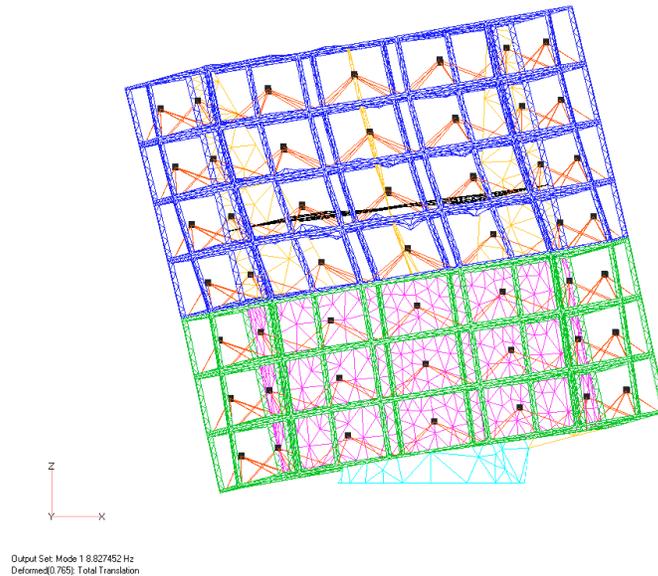


Figure 6. Deployer Ship First Bending Mode

DS was to be a simple mechanism. However, it soon became clear that it required a fair amount of on-board intelligence to perform orbit, communications, power and Nanosat release activities. The DS is a mission single-point failure, and as a result, must have low risk, using well-established, reliable components.

III. Mechanisms

The mechanism requirements for a constellation of S/C lie primarily in the ability to restrain the S/C in the DS during launch, and provide for orderly and reliable deployment. Figure 6, while showing exaggerated deformations, still indicates the need to have such a robust mechanism design. Such a mechanism is compliant in selected Degrees-of-Freedom (DOF), protecting the Nanosat from loads in certain directions, while making full use of inherent Nanosat strength to stiffen the DS structure. It takes up strains and passes on loads as needed.

The classic clamp-band device is not feasible because it does not allow spinning release without a costly spin-up table. It also imparts a high shock environment upon actuation, which would be in close proximity to sensitive components on such a small S/C.

Three general concepts for multiple S/C release are Rear-Tension Member, "Frisbee" and Clamp-member, as shown in Figure 7. The Rear-Tension Member device shown in Figure 7a, pulls the Nanosat radially inward at the rear vertex. The S/C is retained at the two primary vertices by kinematic snubbers that allow thermal expansion and DS deformation while stowed. On deployment, the rear connection to the DS is severed, and the S/C is pushed radially out by compression springs at all 3 vertices. The disadvantage of this design is the rear tension member, which must be accessed manually from the exterior or interior of the DS. The snubbers are located

diagonally across the bay, lending stiffness to the DS structure.

The Frisbee approach restrains the S/C only at two opposite edges. Holding top and bottom vertices in the proper DOF at these edges prevents rotations and contributes to DS stiffness. Upon deployment, the S/C pivots about one edge, while a rotating arm pushes the other edge out away from the DS.

The Clamp-Member Mechanism is a combination of the aforementioned designs. The rear tension member is replaced by an over-center clamping device activated by the radial push of S/C installation. Snubbers at the vertices 90° away act passively with static or spring-loaded restraints. Actuation is provided at the rear mechanism. The advantage of this design is that the rear mechanism may be surface mounted to the DS berthing ring or cylinder, and requires no further manual attention when the S/C is installed. This design allows for easy S/C integration to the DS because it is self-aligning, and self-tensioning.

IV. Pathfinder Mission

GSFC has recently completed a series of studies aimed at reducing the risks of a Nanosat constellation mission. This has culminated in a Phase A proposal⁴ to NASA's New Millennium Program to produce a small constellation of micro-satellites for the Space Technology 5 (ST5) mission, presently scheduled for a 2003 launch. This project envisions an S/C with technologies scalable to Nanosat proportions by 2010. The proposed micro-satellite (<20 kg) is approximately double the size and weight of the proposed Nanosat for the Magnetospheric Constellation mission. The ST5 concept consists of a constellation of three S/C flying as a secondary payload to a GTO orbit.

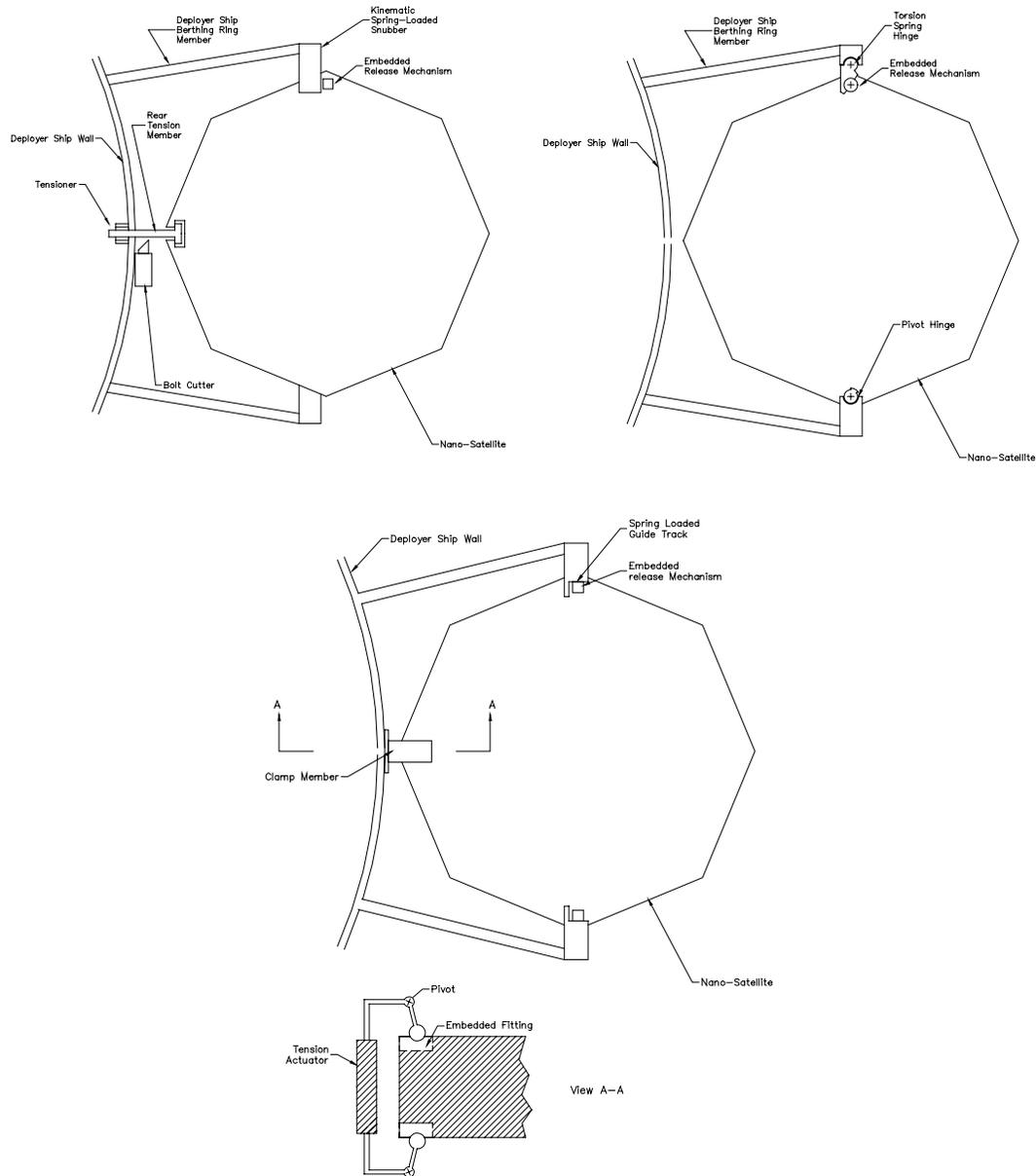


Figure 7. Release Mechanisms. a) Rear Tension Member b) Frisbee c) Clamp-type

The structure is similar to the current state-of-the-art described in section I. An octagonal shell joins honeycomb decks that have high-thermal conductivity composite facesheets. The structurally embedded release mechanisms are mounted at diametrically opposite vertices. There is no solid rocket motor or structural EPS due to cost constraints. Figure 8 shows the ST5 layout and Table 2 lists calculated mass properties.

Instead of a DS, ST5 mounts to a deployer structure attached to the secondary payload deck of a medium-class LV as shown in Figure 9. This structure duplicates an individual DS bay with embedded release mechanisms that mate to the S/C fittings. The frisbee strategy is used for deployment.

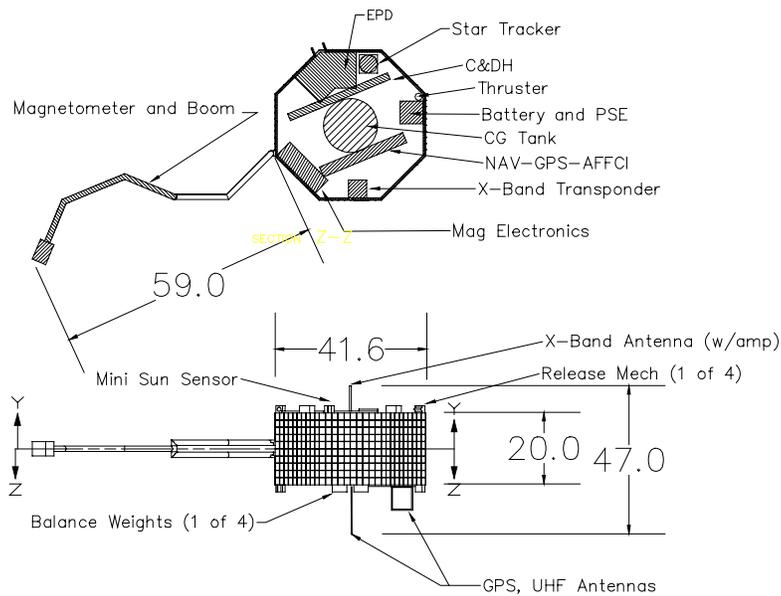


Figure 8. ST5 Nanosat Pathfinder Internal Layout

Table 2. ST5 Mass Properties

Mass	18.1 kg
Principal Moments of Inertia	0.26, 0.64, 0.78 kg-m ²
Structure Flat-to-Flat Dimension	41.6 cm
Structure Height	20.0 cm
Overall Dimensions (Boom and Antenna Deployed)	104.0 x 47.0 x 45.0 cm

ST5 is a structural/mechanical pathfinder in the following areas:

- SC bus design and fabrications strategies
- Release Mechanisms (inside deployer structure)
- I&T practices (e.g., spin-balance by placement of components)
- Design for radiation shielding

V. Conclusion

This paper has addressed three critical areas of a spin-stabilized Nanosat mechanical design.

A dependable, lightweight and multifunctional structure is essential in successfully developing a nano-satellite. The baseline structural concept has been presented, along with a discussion of fabrication techniques and issues relating to S/C integration and test. A feasible DS design has been presented. An efficient methodology for Nanosat deployment into orbit has been addressed. Three release mechanism designs were illustrated.

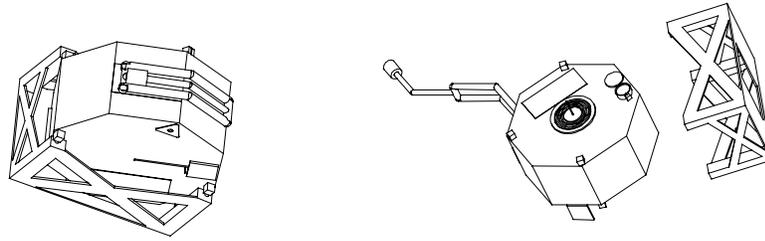


Figure 9. ST5 Nanosat Pathfinder with Deployer Structure

GSFC performs on-going research and development in micro- and nano-satellite systems and components. This includes the development of new hardware and software prototypes, new innovative approaches and techniques for systems integration and testing, manufacturing processes, and constellation management. GSFC collaborates with other NASA centers, other government agencies, aerospace industry partners, and academic institutions in order to achieve its objectives.

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