AAS 01-352

DESIGN AND SYSTEM IDENTIFICATION OF A NANOSATELLITE STRUCTURE

Craig L. Stevens*, Jana L. Schwartz†, and Christopher D. Hall‡

The Virginia Tech Ionospheric Scintillation Measurement Mission, known as HokieSat, is a 40 lb nanosatellite being designed and built by graduate and undergraduate students. The satellite is part of the Ionospheric Observation Nanosatellite Formation (ION-F) which will perform ionospheric measurements and conduct formation flying experiments. In this paper we describe the design of the primary satellite structure, the analysis used to arrive at the design, and the experimentation used to verify the analysis. We also describe the internal and external configurations of the spacecraft and how we estimate the mass, mass center, and moments of inertia.

INTRODUCTION

The Virginia Tech Ionospheric Scintillation Measurement Mission, hereafter known as HokieSat, is part of a satellite formation known as the ION-F mission. ION-F is comprised of three nanosatellites designed and built by students at the University of Washington, Utah State University, and Virginia Tech. The ION-F mission is part of the Air Force Research Laboratory/DARPA/NASA University Nanosatellite Program. The University Nanosatellite Program involves 9 university-built nanosatellites planned to launch on two launches on the space shuttle in 2003. The program provides technology demonstration for future high risk, low cost nanosatellite formation missions such as TechSat21[1].

The three satellites, University of Washington's Dawgstar, Utah State's USUSat, and Virginia Tech's HokieSat, are all hexagonal prisms massing between 33 and 44 lbs. The configuration of HokieSat is 18 inches in major diameter, and approximately

*Graduate Research Assistant, Aerospace and Ocean Engineering, Virginia Polytechnic Institute and State University, Blacksburg, Virginia, 24061. email: cls@vt.edu

†National Science Foundation Fellow, Aerospace and Ocean Engineering, Virginia Polytechnic Institute and State University, Blacksburg, Virginia, 24061. email: jana@vt.edu

‡Associate Professor, Aerospace and Ocean Engineering, Virginia Polytechnic Institute and State University, Blacksburg, Virginia 24061. Associate Fellow AIAA. Member AAS. email: cdhall@vt.edu

12 inches in height. In this paper, we discuss the design of the spacecraft configuration, and the analysis and experimentation that define the satellite structural and mass properties.

SYSTEM DESIGN

Satellites typically have unique designs that are based on their respective missions. The structural design of HokieSat is based on several design goals. These goals include integration compatibility, simplicity of fabrication, and structural and mass optimization.

Integration compatibility of the multiple spacecraft system is an integral part of the spacecraft design. As stated above, HokieSat is part of the three-satellite formation flying experiment ION-F. The formation flying mission requirements dictate that the three spacecraft have nearly identical initial conditions [1]. Therefore, the formation must be launched aboard the same launch vehicle. The launch vehicle chosen for this mission is the Shuttle Hitchhiker Experiment Launch System (SHELS), via the Space Shuttle. Due to safety issues and tracking limitations, NASA prohibits the nanosatellites from deploying separately from the Shuttle Orbiter Payload Bay. The solution to the safety issues is the Multiple Satellite Deployment System (MSDS) designed by AFRL (see Figure 1). The MSDS is a platform that supports two groups of three nanosatellites in a stack configuration aboard the SHELS [2]. The two stacks are comprised of two University Nanosatellite formation flying constellations, ION-F and 3 CornerSat. The mission profile calls for the MSDS to deploy from the SHELS with the stacks mounted to the platform. Once a specified time has elapsed, the two stacks are ejected from the MSDS. Finally, the ION-F nanosatellites separate from each other and begin the formation flying mission. The large number of organizations involved in the mission created a necessity for emphasis on integration control early in the design phase of the project. In order to minimize the inherent complications of integration, all satellites are designed as hexagonal cylinders with dimensions resembling the figures stated for HokieSat above.

Another factor in the design of the nanosatellite is the simplicity of fabrication and assembly. Several materials are used in satellite fabrication, such as aluminum, titanium, graphite composite, and composite sandwich panels. These materials vary in cost, manufacturing time, mass, strength, durability, and required craftsmanship. Aluminum 6061 T-651 was selected as the primary material in the spacecraft structure for several reasons. The material is relatively abundant and economically feasible for a low budget program. It has a density of approximately 0.1 lb/in^3 which is roughly one third the density of steel and other metals used in manufacturing. Finally, aluminum is simple to manufacture and has relatively good workability [3]. Good workability is an important advantage to consider for a small budget program, which must minimize cost by using university machine shops, and relatively inexperienced

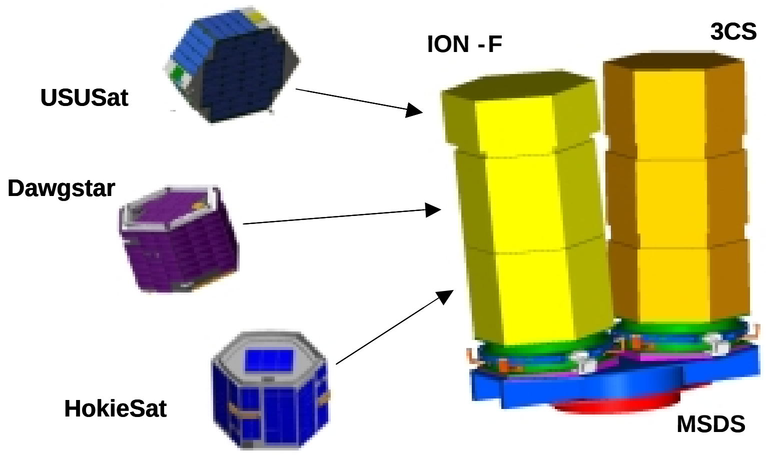

Figure 1 University Nanosat launch configuration

students to perform the majority of the machine work.

The final consideration in the design process is optimizing the structural and mass properties of the spacecraft. The optimal mass reducing design chosen for HokieSat is isogrid. Isogrid, illustrated in Figure 2, uses an array of equilateral triangles to increase the structural performance of a flat sheet of material. Ideally, machining an isogrid pattern reduces the mass of the original plate by approximately 75% and reduces the strength of the plate by approximately 25%. Nominally, this procedure may produce a 200% increase in strength per weight compared to the original flat plate [4]. Another advantage to machining the triangle array is that the plate remains isotropic [5]. Therefore, it exhibits similar strength in all directions, and locations of stress concentrations are minimized.

Figure 2 Photograph of HokieSat structure

The HokieSat structural configuration is designed to accommodate all of the components used to perform the mission (see Figure 3 and Figure 4). The isogrid pattern is designed to have two inch spacing between each node, or connection point. This pattern allows for convenient mounting of components while increasing the structural performance.

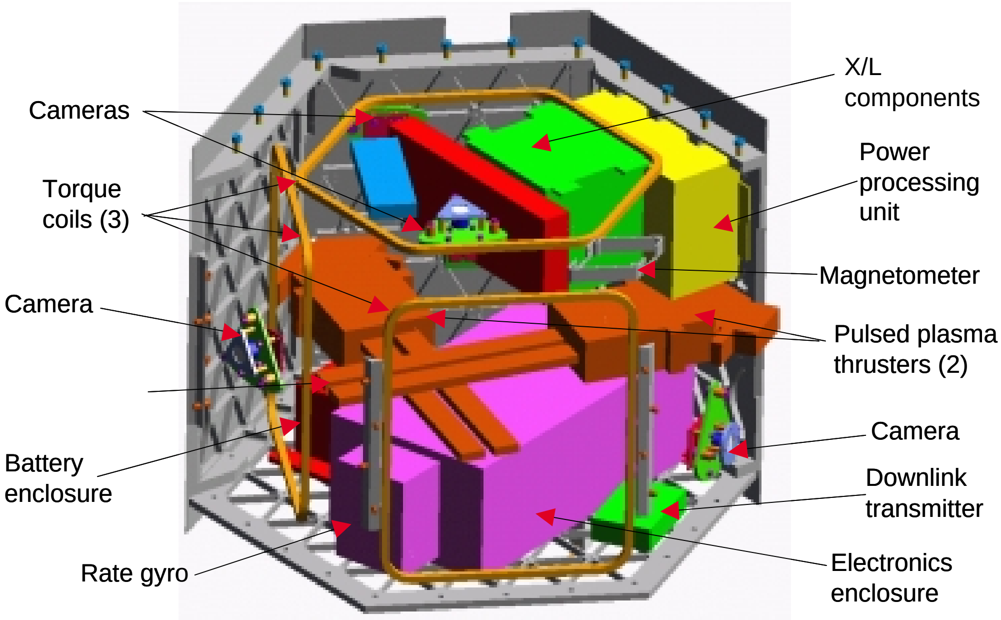

Figure 3 Internal configuration of HokieSat

The structural assembly consists of eight isogrid plates (see Figure 5). The two end panels are open isogrid plates that measure 18 inches in major diameter and are 0.25 inches thick. The six side panels are constructed out of open 0.23 inch thick isogrid plates adhered to a 0.02 inch outside skin (see Figure 6). The composite side panels are less expensive to manufacture than a monocoque structure. The skins reinforce the side panels and provide a surface to affix body-mounted solar cell arrays. The side panels are modified to extend one inch above and below the end panel surfaces to provide more area to support the cell arrays. Modifications to the isogrid occur in four of the side panels to allow the nozzles of the pulsed plasma thrusters to protrude through the structure to the outside of the spacecraft. Based on previous analysis of isogrid structures, these modifications have a negligible effect on the structural integrity of the panels [4, 5].

ANALYSIS

The analysis of the structure is divided into three areas: static, dynamic, and mass properties. The static analysis ensures that the structure can support the masses of the other spacecraft, and the dynamic analysis investigates the stiffness properties of the structure. The mass properties analysis defines the mass moments of inertia and center of mass location of the spacecraft which are important to the spacecraft attitude and orbital dynamics.

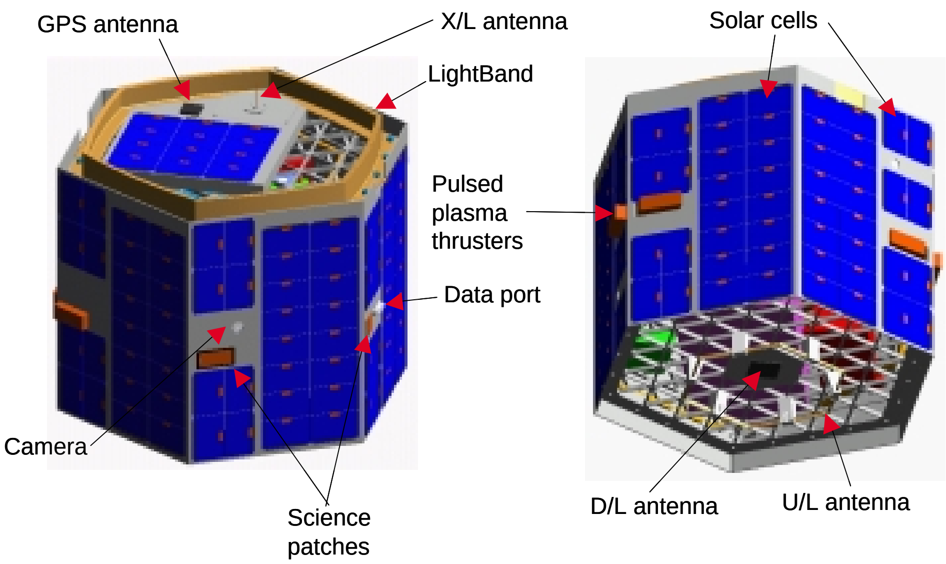

Figure 4 External configuration of HokieSat

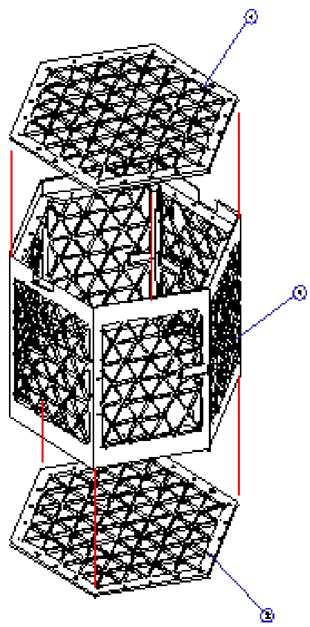

Figure 5 Assembly drawing of HokieSat

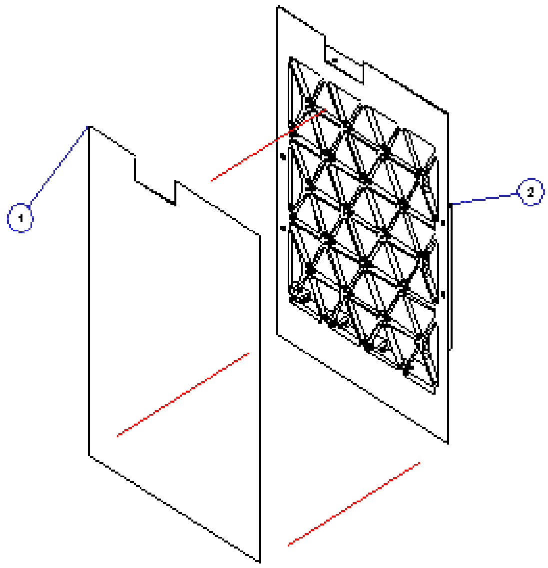

Figure 6   Assembly drawing of composite side panels

A spacecraft typically experiences its greatest loads during launch. The launch configuration of ION-F is comprised of a stack of three interconnected satellites as shown in Figure 1. The NASA Space Shuttle payload requirements dictate that the structure survive all of the system loads in all three directions simultaneously. NASA also adds a factor of safety to this requirement that equates to multiplying all of the system loads by 11. Figure 7 illustrates the method used to perform a static finite element analysis (FEA) using I-DEAS version 8 [6]. The isogrid is modelled using arrays of beam elements simulating the webs and arrays of shell elements emulating the side panel skins and all other solid aluminum entities (see Figure 7). The effects of other two spacecraft of the stack are simulated using a resultant load applied approximately 13 inches above the zenith surface of HokieSat so as to provide the appropriate moment. The resultant load is distributed at nodes over the top of a rigid fixture that models the correct load path. All significant internal spacecraft components are simulated by applying the appropriate forces at each connection point using the method stated above. Examining the results from Figure 8 demonstrate that the spacecraft survives the launch loads with a margin of safety of 1.

The complex launch configuration explained above also affects the structural dynamics analysis and design of the satellite. A modal finite element analysis of a side panel and the assembled structure was conducted using I-DEAS version 8 [6]. The structure is modelled using the same element assembly that is detailed above. The results from the side panel analysis, shown in Figure 9, show that the first mode natural frequency occurs at 131 Hz and the second mode natural frequency occurs at 171 Hz. The first mode exhibits a twisting shape about the longitudinal axis whereas the second mode exhibits a bending shape about the lateral axis. Subsequent mode shapes observed at frequencies above 400 Hz have little significance on the structural dynamics of the panel. The assembled structure modal analysis results are shown in

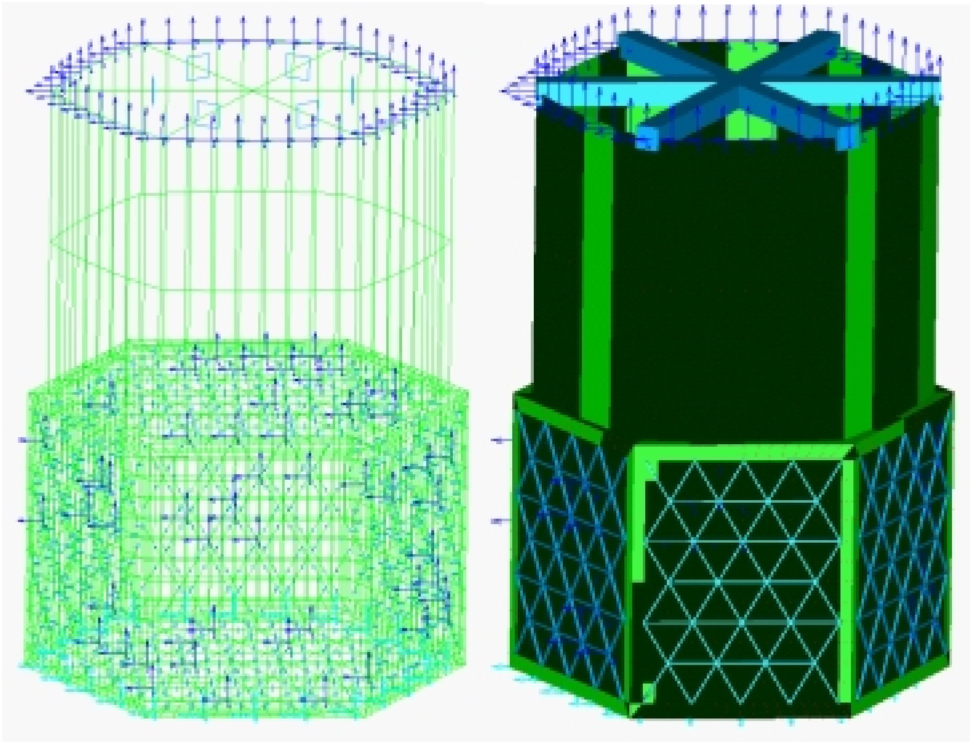

Figure 7 **Static finite element model of HokieSat (wireframe and shaded views)**

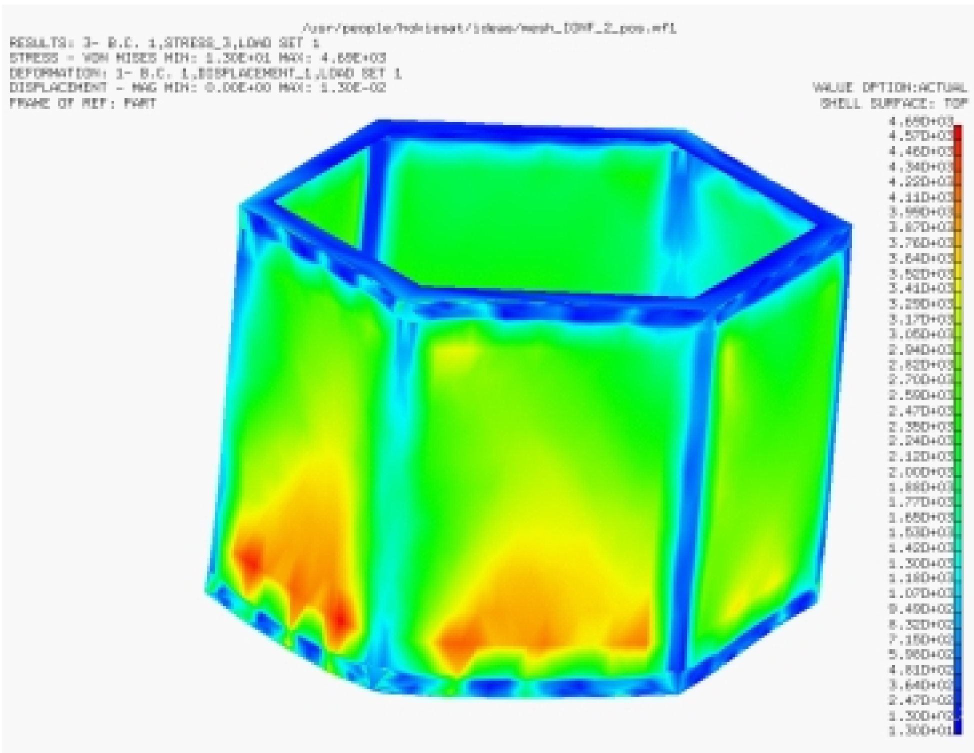

Figure 8 **Static finite element model results**

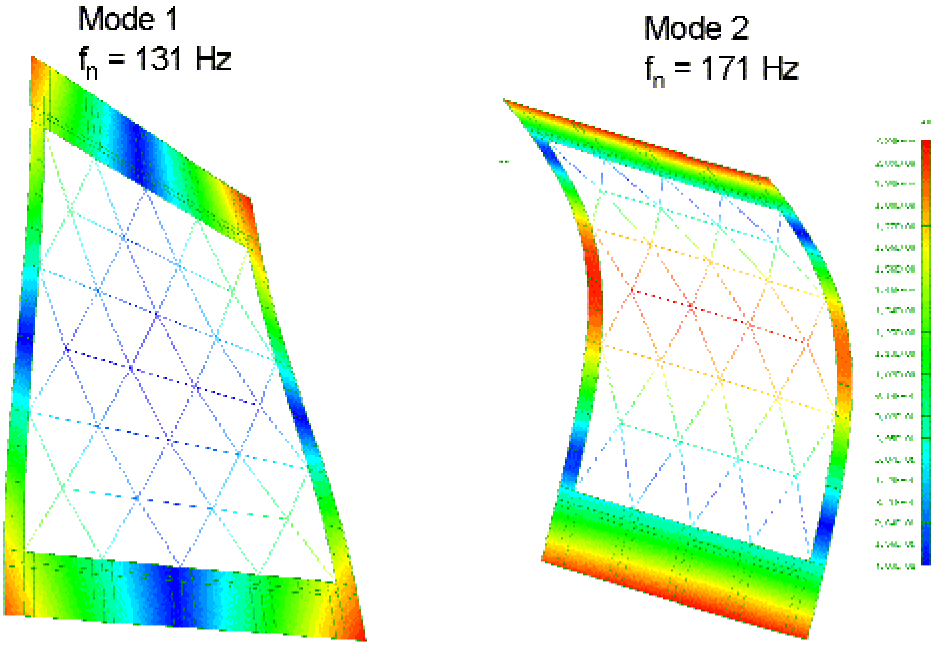

Figure 9   Side panel modal FEA results

Figure 10 and Figure 11. The first mode of the assembly has a natural frequency of 249 Hz. At this frequency, the mode shape exhibits large deflections of the end panels (typically called a "drum mode") that resonate 180° out of phase. The second mode of the structure occurs at 263 Hz. The second mode shape is also a "drum mode;" however, the bottom panel vibrates in phase with the top panel. The analysis demonstrates that components mounted on the center of these panels will experience the greatest accelerations during launch.

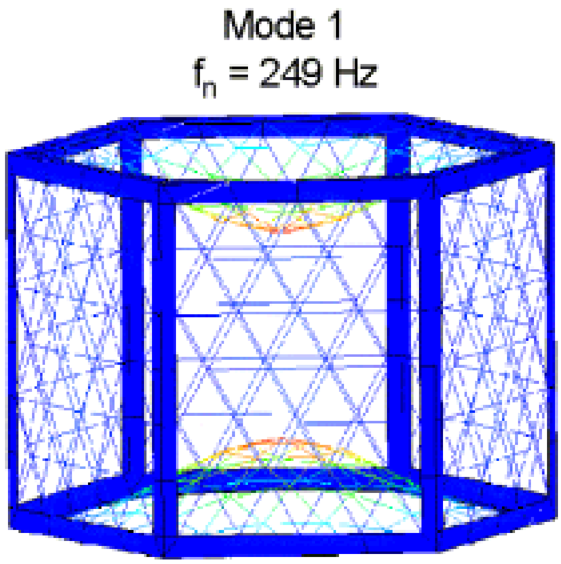

Figure 10   Structural assembly modal FEA results

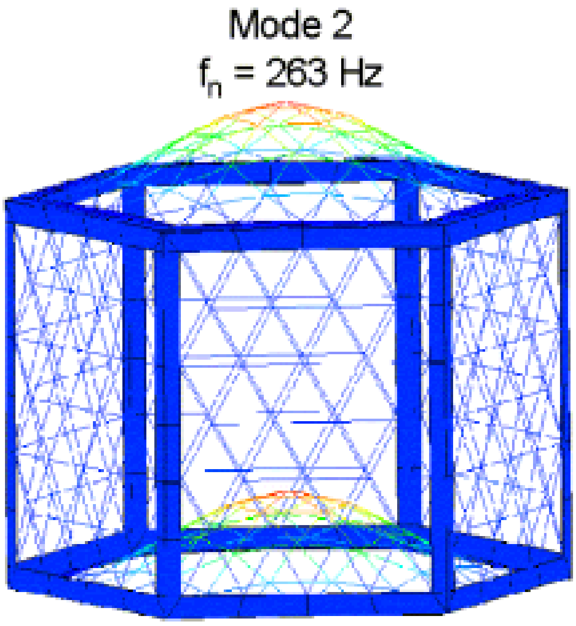

Figure 11 Structural assembly modal FEA results

FABRICATION

Spacecraft fabrication is a high risk operation for typical low budget programs. Several methods were implemented to alleviate fabrication and design errors and assure quality of the components. The fabrication of isogrid has simplified in recent years due to the innovation of computer node controller (CNC) milling machines. The CNC machines were used to mill the isogrid, while the rest of the fabrication required conventional methods of manufacturing. All of the aluminum in the flight structure was subsequently iridited for corrosion protection while also allowing adequate thermal and electrical conductivity [7].

The side panels are designed to be stiffened using a composite structure as shown in Figure 6. Each side panel was adhered using a standard 2216 gray epoxy purchased through 3-M. The epoxy was chosen for its effectiveness at bonding aluminum and its durability in the arduous space environment [8]. A meticulous procedure ensured a sufficient cure of the bond and satisfied all of the NASA safety criterion (see Figure 12). All of the hardware is stored in a Class 100,000 clean facility. The environment is maintained at a temperatures between 70 and 76° Fahrenheit and a humidity range of 40 to 60%. These ideal conditions prevent oxidation of the aluminum and minimize the risk of damage to the electronic components (*e.g.* electrostatic discharge).

SYSTEM IDENTIFICATION

HokieSat is a complicated system of aluminum, computer boards, cameras, solar cells, and other subsystem components. Computational analysis of the structural properties

Figure 12 Assembly of HokieSat composite side panels

and mass properties is based on several assumptions and neglects certain components. We overcame these deficiencies in the analysis by experimentally determining the properties of the system.

The chosen static experiment performed on the structure was a cantilever strength and stiffness test. The cantilever test was chosen to model the launch configuration described above. The test was administered by attaching HokieSat to a rigid back wall constructed out of steel I-beams. A fixture was then fabricated to allow the proper moment to be applied to the zenith panel of HokieSat (see Figure 13). A load was applied at the end of the fixture and defections at that point were recorded using a linear dial gage. The test was performed for 3 configurations: test fixture assembly, isogrid panel assembly, and composite panel assembly. The test fixture assembly was tested to determine the tare values of the fixture itself. This calibration enables absolute values of the satellite deflections to be calculated. The experiment also allows a comparison of the isogrid panel assembly and the composite panel assembly stiffnesses to be made. The composite side panels demonstrate a 32% increase in stiffness in the cantilever mode while increasing less than 8% in total mass. The results therefore show a 300% increase in stiffness per mass of the spacecraft in the cantilever mode.

A modal survey was conducted on the isogrid structure to evaluate the correlation between the analytical and experimental results. The structure was tethered from a crane with elastic cords to provide unrestrained boundary conditions (see Figure 14).

A 75 pound shaker with a four-inch vertical stinger was used to apply a burst chirp impulse to the structure ranging from 20 Hz to 1000 Hz. A three-axis accelerometer was attached at different locations on the spacecraft for each test. A statistical analysis was performed on the results and the mean values for the first and second modal natural frequencies are shown in Table 1. The analysis correlates well with the experimental results. The first and second mode shapes are similar and the first mode analytical natural frequency deviates approximately 1% from the mean experimental result.

Table 1 Modal survey test data

Mode	Analysis (Hz)	Experiment (Hz)
1	249	246
2	263	272

Tap testing was performed on the side panel to quantify the structural performance of the composite side panels with respect to the unskinned isogrid. The panel was supported by hanging it from a fixture using packaging tape (see Figure 15). An accelerometer placed on the center of the panel measured accelerations normal to the component. The tap hammer was used to provide an impulse at locations around the panel to collect adequate resolution of the data. The data points were interpolated and plotted using Matlab. The results are shown in Figure 16 and Figure 17, where the x-axis is defined as the lateral or bottom edge of the panel. The unlaminated isogrid results exhibit the same mode shapes as computed in the analysis (see Figure 9). The first two modal frequencies also correlate nicely between the analysis and experiment as shown in Table 2. The experimental data also demonstrate that the first twisting mode of the isogrid panel increases to a frequency out of the spectrum of the experiment. The second mode of the isogrid panel increases by approximately 26% in frequency, which becomes the first modal frequency of the composite panel. The error in the analytical solution is approximately 1%, which is standard acceptable modeling error for most applications.

Table 2 Tap test data (unlaminated isogrid panel)

Mode	Analysis (Hz)	Experiment (Hz)
1	131	131
2	171	169

Dynamic structural testing was performed at NASA Wallops Flight Facility. Mass models of the major components were constructed and attached to the satellite to simulate the integrated system (see Figure 18). Fifteen accelerometers were used to record the accelerations that the major components and panels experience. The spacecraft was inspected for any yielding or failure after each test. The test sequence and results are tabulated in Table 3. The dynamic testing demonstrated that the satellite will survive the launch environment. Using the results of these tests, we were able to relocate internal components to increase the natural frequencies of the spacecraft.

Table 3 Dynamic test sequence and results

Test	Description	Result
Sine Sweep X	20 – 2000 Hz, 0.5 g RMS	Pass
Random Vibe X	9 g RMS, 1 min	Pass
Sine Burst X	24 g, 23 Hz,	Pass
Sine Sweep Y	20 – 2000 Hz, 0.5 g RMS	Pass
Random Vibe Y	9 g RMS, 1 min	Pass
Sine Burst Y	24 g, 23 Hz	Pass
Sine Sweep Z	20 – 2000 Hz, 0.5 g RMS	Pass
Random Vibe Z	9 g RMS, 1 min	Pass
Sine Burst Z	24 g, 23 Hz	Pass

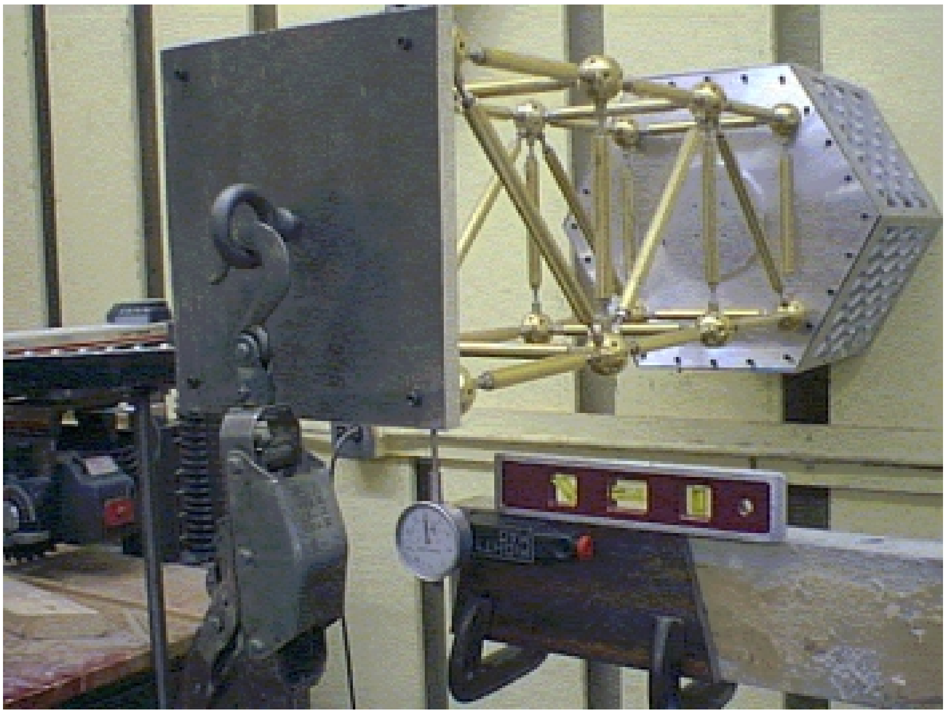

Figure 13 Strength and stiffness test assembly configuration

Figure 14 Modal survey test configuration

Figure 15 Tap test configuration (Unlaminated isogrid panel)

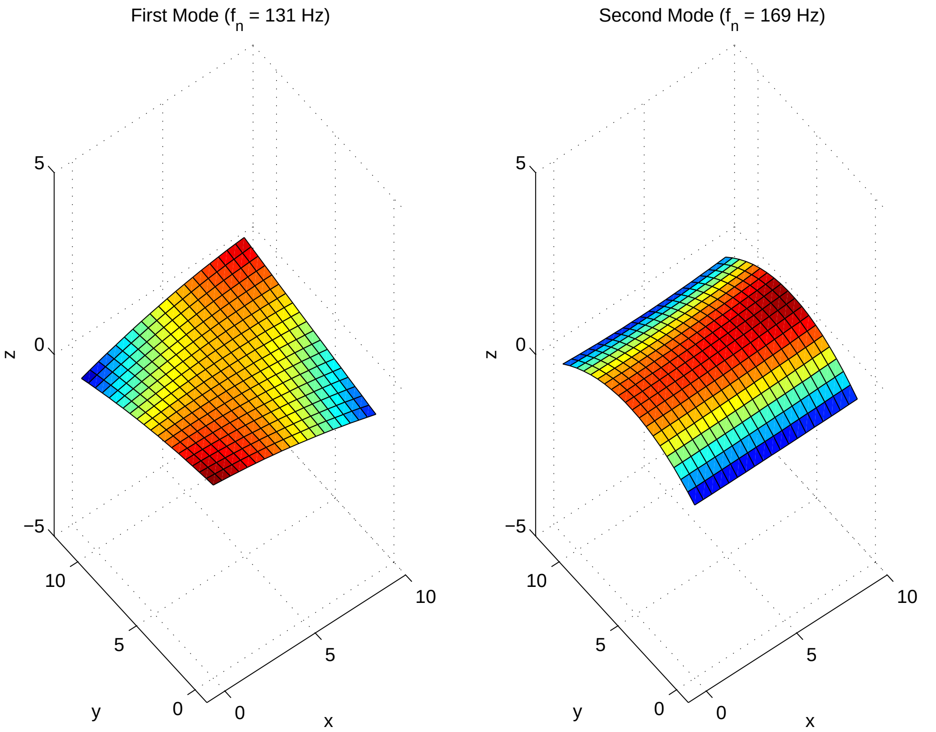

Figure 16 Tap test results (unlaminated isogrid panel)

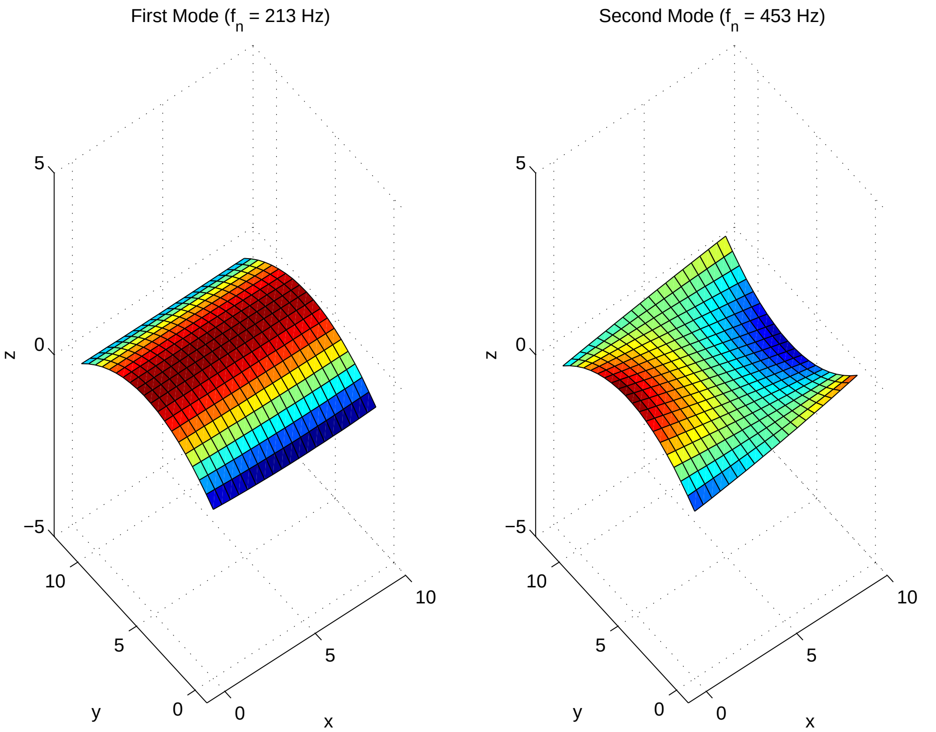

Figure 17 Tap test results (composite panel)

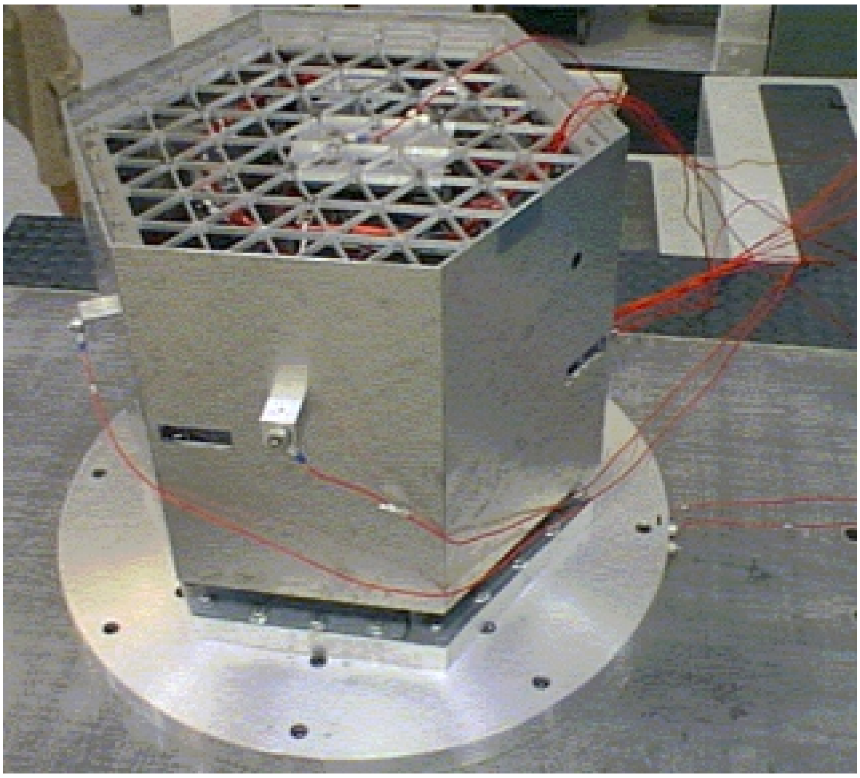

Figure 18 Dynamic testing configuration

IDENTIFICATION OF MASS PROPERTIES

The mass properties of the spacecraft will be estimated using the Spacecraft Attitude Control System Simulator (SACSS). SACSS, shown in Figure 19, is an experimental testbed for the investigation of the attitude dynamics and controllability of rotational systems. The structure is a 3-foot diameter platform mounted on a hemispherical air bearing; this configuration allows unrestricted, low-friction rotation about the platform's normal (z) axis, and $\pm 5°$ of tilt about the x and y axes. SACSS operates as an autonomous satellite simulator influenced by negligible disturbance torques, using a complement of sensors, along with a power supply, wireless communications, and a control computer. SACSS is instrumented with two three-axis ± 1g accelerometers and one two-axis $\pm 45°$ tilt sensor.

One of the first tasks which must be completed in order to use SACSS as a true satellite simulator is the calculation of the system's mass properties and moments of inertia. Rather than making approximate measurements or calculations of these values, SACSS is programmed to experimentally determine its own system parameters. A simple extension of this process is the ability to mount a secondary system onto the SACSS platform and measure the full system's parameters; subtracting out the tare values from SACSS alone returns the parameters of the secondary system. It should be noted that the "subtraction" step is a matrix operation, not a scalar one.

Rotation about the y axis is physically constrained by the configuration of the

Figure 19 The Spacecraft Attitude Control System Simulator

air bearing, so an Euler angle sequence using θ_y as the second rotation can be used without the risk of encountering a singularity. Thus, the equations of state become

$$\dot{\boldsymbol{\theta}} = \mathbf{S}^{-1}(\boldsymbol{\theta})\boldsymbol{\omega} \tag{1}$$

$$\dot{\boldsymbol{\omega}} = -\mathbf{I}^{-1}\boldsymbol{\omega}^{\times}\mathbf{I}\boldsymbol{\omega} + \mathbf{I}^{-1}\mathbf{g}_{ext} \tag{2}$$

where the only external torque is that from gravity.

The Extended Kalman Filter (EKF) is a standard algorithm for nonlinear satellite sensor fusion and control. System identification is included within the EKF structure by using a parameter-estimating EKF. In this algorithm, the parameters of the system are included as time-invariant members of the state vector, $\mathbf{x}$, so that $\mathbf{x} = \left[\boldsymbol{\theta}^{\mathrm{T}}\ \boldsymbol{\omega}^{\mathrm{T}}\ mg\ \mathbf{r}^{\mathrm{T}}\ \widetilde{\mathbf{I}}^{\mathrm{T}}\right]$ where $\widetilde{\mathbf{I}}$ is the "flattened" moment of inertia matrix.

CONCLUSIONS

The design and system identification of Virginia Tech's nanosatellite has been completed using several analytical and experimental techniques. The aluminum isogrid design provides an improvement over the structural performance of flat plates and allows students and university technicians to fabricate most of the spacecraft, while the use of thin aluminum skins improves the stiffness of the overall structure. Finite element analysis is used to characterize the performance of the primary structure. Modal testing results verify the accuracy of the isogrid side panel finite element model within an error of approximately 1%. The test also demonstrates a 300% increase in structural performance by using a composite structure incorporating the thin aluminum skins. The results from the finite element analyses and experiments verify that the structure satisfies all of the NASA Space Shuttle payload requirements. Further testing will be performed to verify the structural integrity of the composite side panels and to determine the mass properties of the spacecraft.

ACKNOWLEDGEMENTS

This project has been supported by the Air Force Research Laboratory, the Air Force Office of Scientific Research, the Defense Advanced Research Projects Agency, NASA Goddard Space Flight Center, NASA Wallops Flight Test Center, and the 3 universities. We especially acknowledge the efforts of many of the students on the HokieSat, USUSat, and Dawgstar teams who have contributed to the analysis and development of the structural subsystem. Professor A. Wicks of Virginia Tech's Mechanical Engineering Department provided invaluable assistance with the modal testing.

REFERENCES

[1] Campbell, M., Fullmer, R. R., and Hall, C. D., "The ION-F Formation Flying Experiments," *Space Flight Mechanics 2000*, AAS/AIAA, 2000, AAS 00-108.

[2] Brackett, C. E., "AFRL's Multi-Satellite Deployment System (MSDS)," *15th Annual AIAA/USU Conference on Small Satellites, Logan, Utah, August 13-16, 2001*, AIAA, 2001.

[3] Mangonon, P. L., *The Principles of Materials Selection for Engineering Design*, Prentice Hall, Upper Saddle River, NJ, 1999.

[4] "Isogrid Microspacecraft Structures Final Report," Tech. rep., Space Dynamics Laboratory, Utah State University, 1994, SDL/94-037.

[5] *Isogrid Design Handbook*, McDonnell Douglas Astronautics Co., Huntington Beach, CA, 1973, Major Reference.

[6] "I-DEAS General Capabilities User's Guide," Tech. rep., Structural Dynamics Research Corporation, Milford, OH, 2001.

[7] "Military Plating Specifications," Tech. rep., Alexandria Metal Finishers, Inc., Lorton, VA, 2000.

[8] "UW Dawgstar/ION-F CDR Document: Structures Subsystem," Tech. rep., University of Washington, 2001, AA-22801-DOC100.