

The Design of the SAPPHIRE Separation System and Launch Vehicle Interface

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Abstract

Small satellites create unique challenges in the design of deployment mechanisms and attachments to launch vehicles. The SAPPHIRE satellite, designed and built by students at Stanford University, is 35 pounds and is designed to be launched as a secondary payload on any of a variety of launch vehicles. The design of the interface and separation system is intended to optimize simplicity, size, weight, and cost.

The SAPPHIRE design uses a single hold down bolt with a single separation spring. Deployment is achieved through the use of a Frangibolt (TiNi Alloy Co.). This device utilizes properties of the shape memory alloy Nitinol which forcefully expands when heated in order to fracture a quarter inch Titanium bolt. The Frangibolt was used previously on the Clementine mission to the moon to deploy solar arrays but has not been proven yet to actually deploy a satellite. The power requirement of the Frangibolt (60 Watts minimum) is met through the use of a thermal battery designed for use with ejection seats. The interface between the satellite and the launch vehicle provides four attachment points to the rocket, supports the satellite and separation system components and isolates the satellite from high frequency vibrations during launch and ascent. This paper describes the design and testing of the SAPPHIRE separation system and launch vehicle interface.

Introduction

The Stanford Audio Phonic
PHotographic Infrared Experiment (SAPPHIRE)

is the first small satellite designed and built by students in Stanford's Satellite Systems Development Laboratory (SSDL). [1] SAPPHIRE was designed using the philosophy of "cheaper, better, faster" with the added requirement of simplicity so that all manufacturing can be done by students in university shops. SAPPHIRE's weight is 35 pounds and it has a hexagonal form with a height of 10.4 inches and diameter of 17 inches. The structure is a stacked tray design with four trays housing power, communications, processor and payload subsystems. All side panels and trays are made with half inch aluminum honeycomb. Four threaded #10-32 rods placed in a square pattern hold the trays together and provide the support points for the launch vehicle interface.

Power for the satellite is obtained through solar cells which are mounted on the top and bottom hexagons and the six side panels. The four through rods protrude through the bottom hexagon and provide the support points for the interface. The bottom panel is covered with solar cells except for a three square inch patch in the center and the four support points.

The unique requirements of the SAPPHIRE satellite necessitated an original design for the launch vehicle interface and deployment system. With the requirements for simplicity and minimal cost in mind, it was decided that it would be best look for a suitable existing separation system. The interface was then designed around the separation system and the satellite support points.

Interface and Separation System Requirements

The requirements for the separation system and launch vehicle interface are imposed by their intended function and by the restrictions imposed by the size of SAPPHIRE and goals of the SSDL program. The primary function of the interface is to safely attach the satellite to the launch vehicle without damaging any of the solar cells. The interface must also be stiff in order to isolate the satellite from high frequency vibration during launch and ascent which could damage the sensitive electronics. The separation system which is mounted to the interface is required to safely deploy the satellite once given the separation command from the launch vehicle. The separation velocity is required to be between two and three feet per second.

The very small mass and size of this satellite created interesting challenges in the design of the deployment system. The small size does not allow for sensitive equipment to be separated from the deployment mechanism so that it can be isolated from shocks at separation. SAPPHIRE is intended to be launched as a secondary payload, necessitating a small interface and separation system so that the entire system can fit inside the envelope given by the launch vehicles. This gave the requirement for the maximum height from the vehicle to the bottom panel to be four inches.

The SSDL program's goal is for students to design and build small satellites quickly and cheaply. SAPPHIRE is the first project for the program and the hope is that successful designs developed for SAPPHIRE can be used again for future satellites. This goal meant that the interface and separation system should be versatile. The short design period encouraged the use of a preexisting separation device in order to minimize development time. The limited budget was also a strong driver in the decision making process. All of the program's goals encouraged the use of a simple, small, reliable, and inexpensive separation device.

DESIGN

Basic Interface Design

The form of the SAPPHIRE structure set the first design decision to have four support points on the interface. It was quickly decided that one hold down bolt would be adequate. Due to symmetry, the logical placement for the single hold down bolt is in the center of the bottom panel. The decision to have a single bolt was made after an equilibrium calculation was

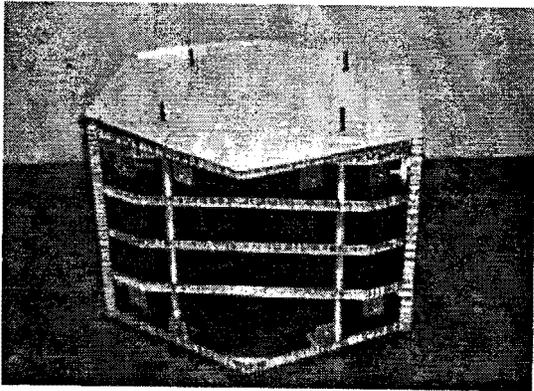


Figure 1 SAPPHIRE's Stacked Tray Structure

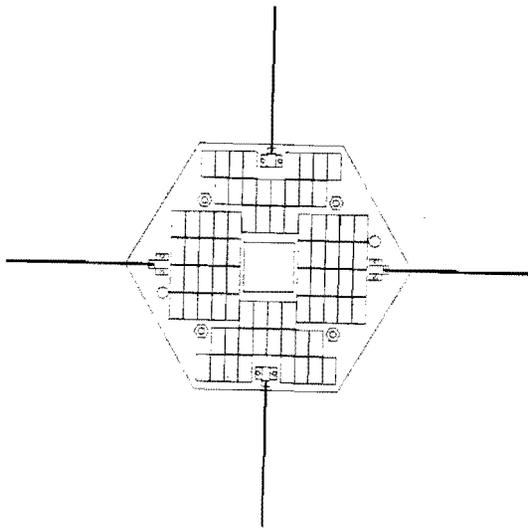
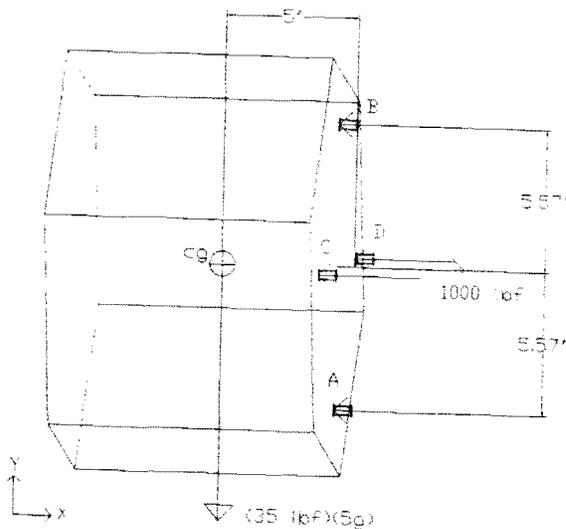


Figure 2 Bottom Panel Showing Solar Cells and Rod Placement

performed which showed that under the worst possible static loading conditions, a tensioned quarter inch bolt would keep all support points in compression. The worst case was assumed to be a lateral load of 5g. The calculation below shows that a pre-load in the center bolt of 1000 pounds force will cause a minimum compression load at point B of 171.5 pounds force.



$$A+B+C+D=1000$$

$$C=D \quad \text{by symmetry}$$

$$C=(A+B)/2$$

Sum of moments about the z axis
taken about the center

$$B(5.57') + (35 \text{ lbf})(5g)(5') - A(5.57') = 0$$

$$A - B + 2((A+B)/2) = 1000$$

$$A = 157.1 + B$$

$$2(157.1 + B) + 2B = 1000$$

$$B = 171.5 \text{ lbf}$$

With the four support points in a square pattern and the hold down bolt in the middle, a web pattern was chosen to support all points.

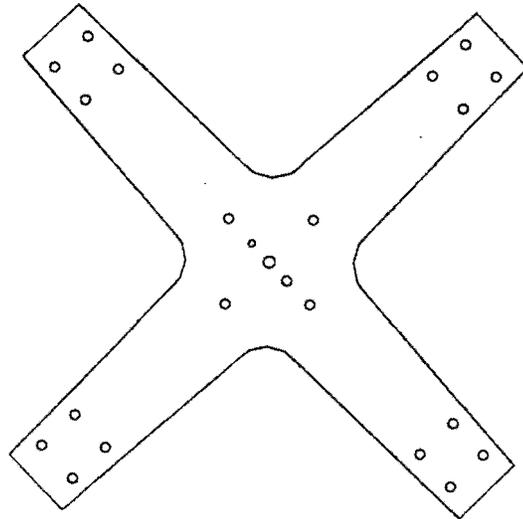


Figure 3 The Basic Interface Web

Separation Device Selection

After the basic interface design was chosen, the search for a separation mechanism began. Mentors from the Lockheed Martin Co. helped by giving advice on what types of mechanisms had been used in the past. The most widely used deployment mechanism, a pyrotechnic separation nut was examined first. This device is very expensive, rarely available in limited quantities, creates high shocks at actuation, is not reusable, is relatively large and heavy and does not allow for easy tensioning of the hold down bolt from below. These are many of the disadvantages to this type of mechanism which caused it to be abandoned early and other possibilities sought. Table 1 displays the devices studied and the relevant advantages and disadvantages of each.

| DEVICE | ADVANTAGES | DISADVANTAGES |
|----------------------------|---------------------------------------------------------------------------------------|---------------------------------------------------------------------------------|
| Pyro Sep Nut | proven technology | cost, size, shock, not reusable, not easily able to pretension bolt |
| Pin Pullers | can be made small | not simple, not readily available, too much development time required |
| Paraffin Actuator | can be reused, currently being used by mentors at Lockheed (technical help available) | too long to activate, strict temperature requirements, large |
| Bolt Cutters | used by the WeberSat, hardware available | containment of shrapnel required, large, development and modifications required |
| G&H Non-Explosive Actuator | non-pyrotechnic, can be reused | large in size and not easily able to tension from below |
| FRANGIBOLT | Simple, Reusable, Inexpensive | large power requirement (60W min.) |

Table 1 Comparison of Deployment Devices

Frangibolt

After comparing all the devices listed above, it was clear that if the large power requirements for the Frangibolt could be met, this would be the best choice. The Frangibolt is made by the TiNi Alloy Co. of San Leandro Ca. The device consists of a one inch long tube of Nitinol with an inner diameter made for a quarter inch bolt clearance and wall thickness of 0.2 inches. Nitinol is a shape memory alloy which can be deformed and will hold its deformed shape until heated to its phase transformation temperature. Once the material reaches this temperature (approximately 220 degrees Fahrenheit) the tube will forcefully return to its original shape. In the case of the Frangibolt, it is axially compressed three percent. A heating element with insulation is wrapped around the Nitinol which, when powered, raises the temperature of the material to 220 degrees. When it reaches this temperature, which on average takes approximately 25 seconds, it goes through the phase transformation. As it does this the Nitinol forcefully expands to its original length, fracturing the bolt going through it. The bolt going through the Frangibolt is Titanium and has a groove machined into it to initiate fracture in the desired location. This is shown in figure 4.

The Frangibolt is ideal for the deployment of SAPHIRE. It has a total mass of only 2.5 ounces and its volume is a very compact 0.5 cubic inches (excluding power supply). The cost is the lowest of all the devices studied and it is completely reusable, only having to be recompressed after each actuation. It produces no shrapnel, eliminating any need for

bulky containment boxes. The force imparted on the satellite is due only to the strain energy in the bolt which is minimal compared to a pyrotechnic device.

The Frangibolt was used previously in space on the Clementine mission to the moon. On this mission it was used solely to deploy solar arrays. It has also been used for marine, land and air applications. The SAPHIRE mission, however will be the first time for the Frangibolt to be used to actually deploy an entire satellite.

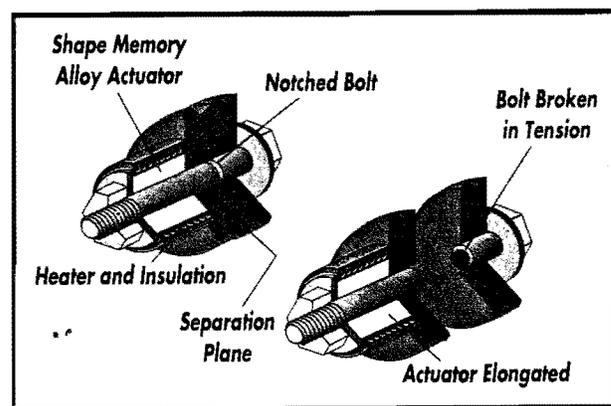


Figure 4 Frangibolt Operation [2]

Frangibolt Power Supply

As explained previously the use of the Frangibolt was dependent upon finding a suitable power supply. For all previous Frangibolt applications, the power (60 Watts for 30 seconds) was supplied by the main power bus of the parent craft. In the case of SAPPHIRE the main power bus is not sufficient nor available for power on ascent. Therefore, a separate battery had to be found. Several battery manufacturers were contacted in the attempt to procure a thermal battery capable of supplying 60 Watts for one minute at a temperature of -15 degrees Fahrenheit (F). Fortunately a suitable battery was currently being manufactured by Eagle-Picher Industries' Electronics Division in Joplin, Missouri. They were manufacturing a thermal battery for use in actuating ejection seats for military aircraft. This battery, although designed for a life of two seconds, was tested at -15 degrees F and was found to produce 30 Volts at two Amps for over a minute. The rise time for this battery is 0.09 seconds. It has a peak voltage of 31.9 and runs down to 17 Volts in 165 seconds. This battery has a squib incorporated in it and is ignited by a standard launch vehicle separation command of 3.5 Amps for 20 ms. In addition to having the proper power requirements, the Eagle-Picher battery is small and light weight, it weighs 5.3 ounces, is 2.25 inches long and 1.25 inches in diameter. This battery was decided to be ideal for the actuation of the Frangibolt.

The Frangibolt's actuation time is dependent upon temperature and power supplied. At 80 degrees F with 28 Volts and 2 Amps, it will actuate in approximately 20 seconds. The lower the temperature and power the longer the time until actuation. The worst case temperature anticipated for ascent is -15 degrees F. Although the Frangibolt and Eagle-Picher battery combination has not yet been tested under these conditions, each component has been tested separately at -15 degrees F. The combination, operating under these conditions, is anticipated to cause deployment within 40 seconds of the separation command. As SAPPHIRE will be flown as a secondary payload and the primary payload will have been deployed by the time SAPPHIRE gets its separation command, the 40 second delay will not be a problem.

Separation Spring

SAPPHIRE's separation velocity was required to be between 2 and 3 feet per second. The Frangibolt's strain energy will impart a very small change in velocity, necessitating the

assistance of a compression spring. The interface has already been shown to have five contact points with the satellite, four at the base of the through rods and one in the center at the Frangibolt attachment. It was decided that one compression spring should be used in the center rather than four at the rod contact points. If four springs were used it would have created difficulties in matching the springs exactly and compressing them properly. The danger of tip off was very high with four springs. The problem with one center spring was that it had to fit around the outside of the Frangibolt, requiring a minimum inside diameter of 1.6 inches. The Century Spring catalog was consulted to find a suitable compression spring. An energy balance calculation was performed to find the range of height and stiffness for which to search the catalog. The assumption was made that all potential energy $(1/2 k (\Delta x)^2)$ stored in the spring would be converted into kinetic energy of the satellite $(1/2 M (\Delta v)^2)$. This assumption gave the acceptable range of $k(\Delta x)^2$ to be between 52 and 117 lb.in. With this information a suitable spring was found with the following properties.

| | |
|-------------------|--------------|
| free length = | 2.75 inches |
| solid height = | 1.053 inches |
| wire diameter = | 0.162 inches |
| stiffness = | 36.07 lb/in |
| OD = | 1.906 inches |
| number of coils = | 6.5 |

The interface is designed so that the compressed length of the spring is 1.3 inches. This gives the value of $k(\Delta x)^2$ equal to 75.8 lb.in which imparts a change in velocity equal to 2.4 feet per second.

Support Points

Originally it was decided that the four support points would all be cup/cone assemblies in order to take out shear loads and prevent the satellite from twisting about the interface. The possibility of a snag was then considered and this decision was reevaluated. In order to ensure compressive contact at all four support points the web was intended to bend slightly under the load at the center bolt. This bending presented the possibility of a snag at one or more of the cup/cones if four were used. Therefore the decision was made to have three button rest supports and one cup/cone assembly. The three button rest supports were made of steel cylinders with one spherical end and one flat end which was tapped with a #10-32 thread and screwed onto

the bottom of three of the rods. Matching supports had a shank on one end of the cylinder and were press fit into supports on the interface web. The fourth rod supported the cone fixture. This was similarly made of steel, tapped for a #10-32 and threaded onto the rod. The cup assembly under this piece also had a shank which allowed it to be press fit into a support on the web. These pieces are shown in figure 5.

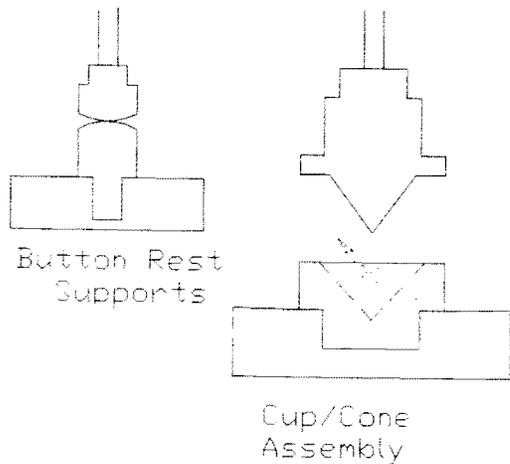
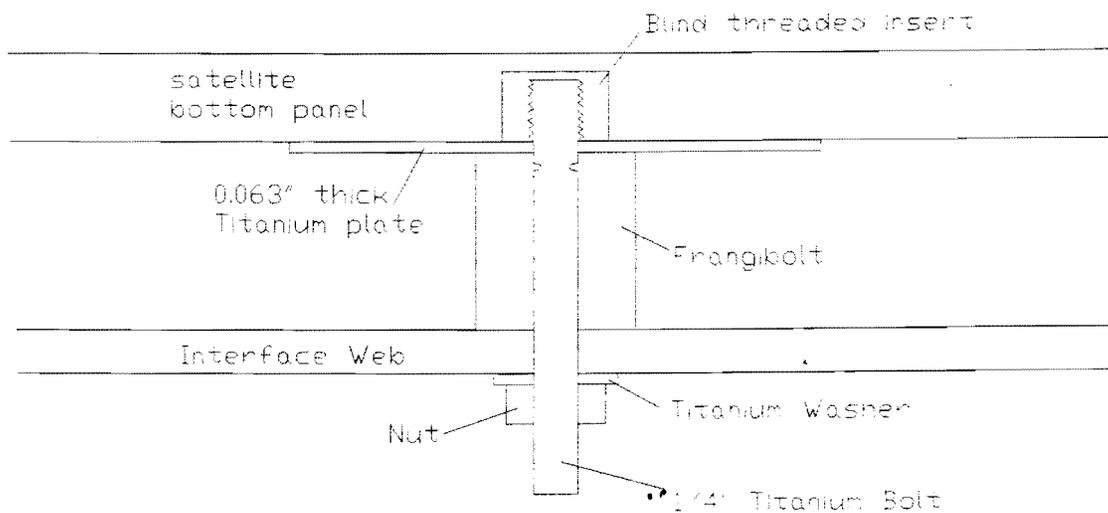


Figure 5

The most critical part of the interface design is the connection of the Frangibolt. In order for the Frangibolt to function properly, the length of the bolt between the attachment point (the satellite) and the nut on the other side of the Frangibolt must be minimized. The stress caused by the elongation of the Frangibolt must be concentrated around the notch. If this stress is carried by a long length of bolt it may not cause enough strain at the notch to cause the bolt to fracture. In addition the surfaces contacting each end of the Frangibolt must remain flat and be very hard so as not to compress under the required tension. The design also had to ensure that all parts would be contained after the deployment.

The Frangibolt requires a tensile load in the bolt of 1600 - 2000 lbf. The interface, as previously shown, requires a minimum tensile load of 1000 lbf at the center bolt. It was originally thought that one nut would be sufficient to serve both purposes. The arrangement essentially sandwiched the Frangibolt between the web and the satellite. This original design is shown in figure 6 below.



Frangibolt Joint Design Figure 6

After analyzing the design for the Frangibolt joint shown in figure 6, it was realized that there were a few significant problems. The main problem with this design stemmed from trying to combine the Frangibolt and the interface bolt tension requirements. Both requirements are derived from the assumption that the tension in the bolt will be counteracted by compression in specific pieces. It was discovered that the Frangibolt requirement of 1600-2000lb of tension in the bolt must be carried by the nitinol cylinder in compression. In addition the surfaces next to the cylinder must be flat. Both of these requirements help to ensure that when the Frangibolt expands to its original shape it will transmit the expansion force to the bolt causing it to fracture. The interface requirement for 1000lb of tension in the center bolt relies on the assumption that the tension will cause a compression-load at each of the support points. The original design violated the compression requirements at the support points and the nitinol cylinder. Another problem with the design involved the bending of the interface web which was to provide the bottom support surface for the Frangibolt cylinder. Since this piece was designed to bend to maintain compressive contact at all four support points it would no longer be

flat at the center joint, possibly causing problems with the function of the Frangibolt. With these considerations in mind a second design was made.

The primary modification to the original design was to add a second nut. The modified design is shown below in figure 7. This sketch shows that one nut is placed directly below the Frangibolt and another is placed below the interface web. By doing this, all of the Frangibolt requirements are successfully met. Both nuts can be separately tensioned in order to satisfy the load requirements of the interface and Frangibolt individually. This design also allows the interface web to bend freely without interfering with the function of the Frangibolt.

The concern with this design was how to properly tension both nuts. The question arose that if the Frangibolt nut were properly tensioned first, what would happen to the joint when the interface nut was tensioned? It was discovered that the required experiments had already been performed by engineers at TiNi Alloy Co. They determined that if the Frangibolt nut was tightened first to a torque of 65 in lb (1600 lb tension) and then the additional load at the bottom nut was added, the Frangibolt would function properly.

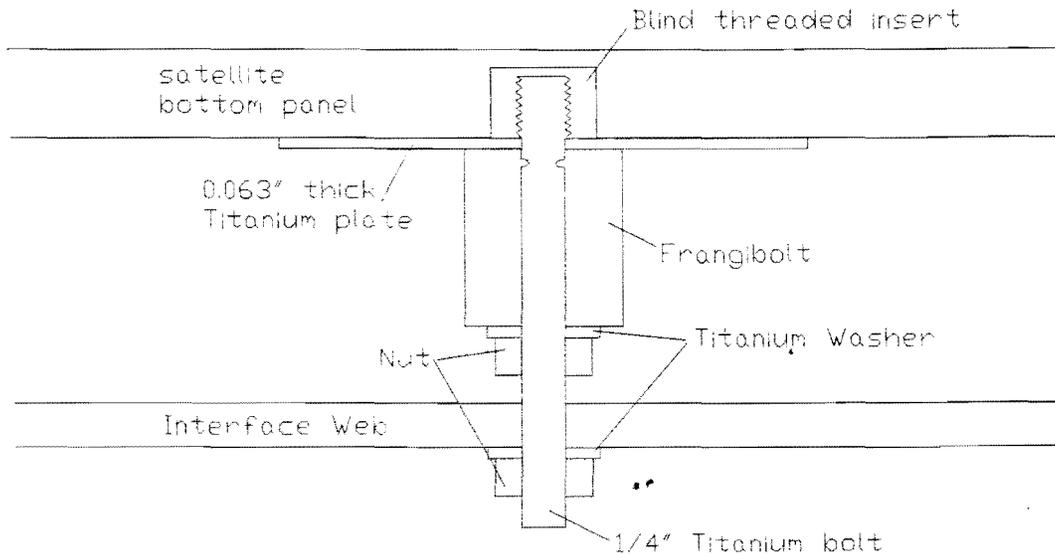


Figure 7

Titanium Base Plate

A titanium plate is designed to be attached to the bottom of the satellite in the center. The plate measures 3"x3"x0.063" and is attached by four #10/32 bolts in a square pattern and has a hole for the center hold down bolt. This plate serves several purposes. First it serves as a rub plate for the separation spring. The bottom panel has 0.02" thick face sheets which would not support the force and friction of the spring. The plate also provides a flat, hard surface support for the Frangibolt cylinder. Finally the plate prevents the center blind insert from pulling out. Any tensile load experienced in the center insert is distributed by the plate to four additional inserts.

Details of the Interface Web

After all the interface components had been decided and the Frangibolt joint had been designed, the final details of the interface web could be finalized. The following items were added to the interface.

- Spring Base/Support

The spring base surrounds the Frangibolt, supporting and aligning the spring. The spring is epoxied to the spring base so it will not separate at deployment, possibly causing damage to the satellite.

- Frangibolt Tie Down

Following satellite deployment, all interface components will be contained so as not to have debris flying around. Most components are either bolted or epoxied to the web, however this is not possible with the Frangibolt cylinder.

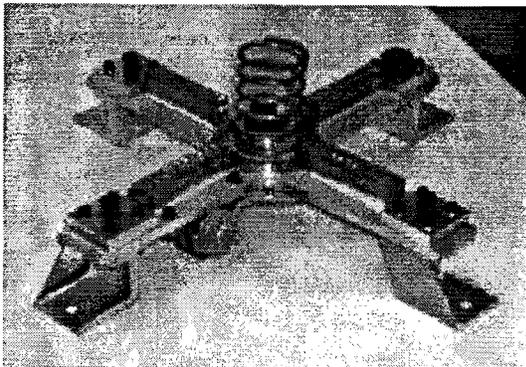


Figure 8

Safety wires are used to keep this piece from floating away. Two safety wires are wrapped around the outside of the insulation of the Frangibolt and then tied to bolts on the interface web.

- Battery Mount

The Frangibolt battery is mounted to the bottom side of the interface web. A 9 pin D type connector is also mounted here. The male half of the connector is attached to the battery. The female connector will provide means for the separation command from the launch vehicle to the battery and for power to get from the battery to the Frangibolt.

- Stiffening Ribs

One of the requirements for the interface is to provide a stiff mount for the satellite so that high frequency vibrations will not be transmitted to the satellite. The web design itself is not very stiff and therefore stiffening ribs are epoxied to each arm of the web to improve vibration test performance.

- Mounting Feet

The interface web needs to be rigidly attached to both the vibration test stand and the actual launch vehicle. One mounting foot is attached to the end of each web arm. These feet are designed so that they can be easily modified to fit different bolt patterns.

All details of the interface can be seen in figures 8, 9, 10 and 11. Figures 8 and 9 are photographs of the actual interface. Figures 10 and 11 are AutoCad drawings of the interface.

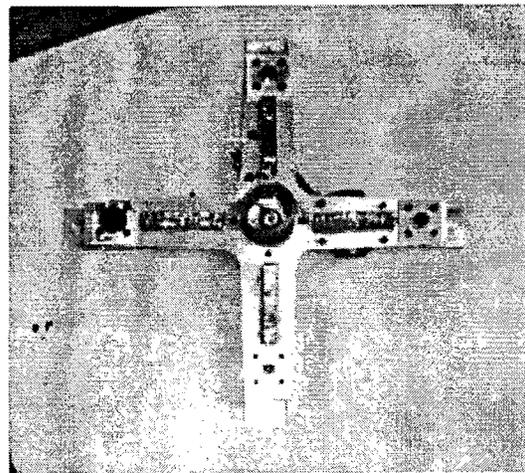


Figure 9

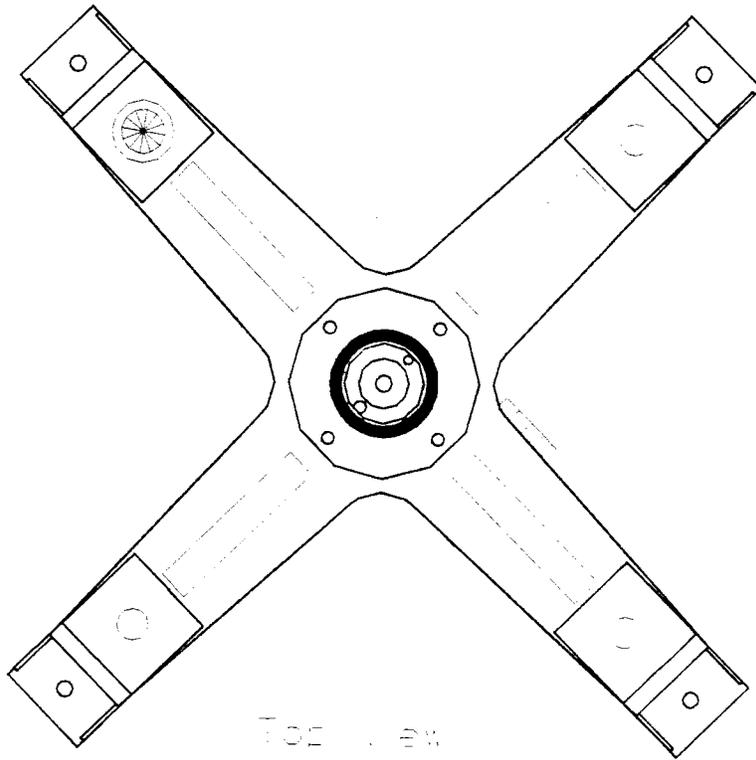


Figure 10

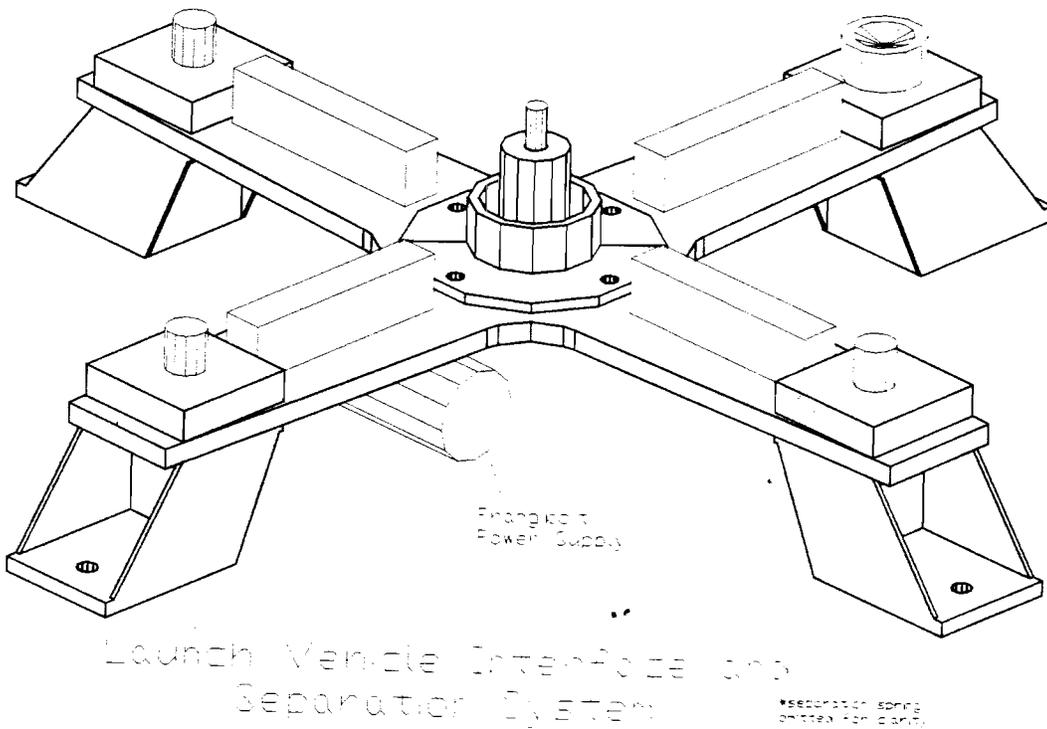


Figure 11

Vibration Testing

The SAPPHIRE satellite mounted to the interface described and shown in this paper has successfully undergone a three axes vibration test at Space Systems Loral in Palo Alto, Ca. The test was performed to the qualification specifications for a Delta rocket. As SAPPHIRE only weighs 35 lb. the level of vibration required was 30g rms. The satellite and interface mounted to the vertical axis vibration stand is shown in figure 12. In each of the three axes the structure underwent a preliminary signature test to find the natural frequencies, a sine sweep, a random vibration test and another signature test to see if the natural frequencies had shifted. The lowest natural frequency was found to be approximately 80 Hertz. No frequency shift between pre and post test was observed for the axial and one of the lateral tests. The other lateral test showed a frequency shift of twenty Hertz. This was attributed to the fact that the epoxy holding the spring in place broke loose. The structure was loaded with dummy loads so the electronic equipment has not yet been tested under vibration. It was found, however, that the interface did an excellent job of decoupling the high frequency vibrations between the shake table and the payload tray. Therefore it is believed that the actual electronics and sensors will survive launch and ascent without any problems due to vibration.

Conclusion

The Stanford Audio Phonic Photographic InfraRed Experiment (SAPPHIRE) is a unique, student designed and built, small satellite. Its small size and unique goals required a unique design for its launch vehicle interface and separation system. Early in the design process it was decided that a single separation point would be used. Existing deployment mechanisms were then researched and a trade study was performed to choose the most appropriate one. Six different deployment mechanisms were examined and the Frangibolt was clearly the best for our uses. The Frangibolt could only be used, however, if a high power, short life, separate power supply could be found. Several battery options were researched and a suitable thermal battery was found. The interface was then designed around the Frangibolt, its power supply and the existing support points on the SAPPHIRE structure. The interface with the structure attached has successfully survived a three axes vibration test to a Delta spectrum at the level of 30g rms.

SAPPHIRE is anticipated to be launched before the end of 1995. Further tests need to be done on the structure and separation system as well as on all electrical subsystems. The primary separation test which stills needs to be performed is a combined test of the Frangibolt and its power supply under the anticipated deployment environment of -15 degrees Fahrenheit.

References

[1] Kitts, C. A. and Kim, W. H. "The Design and Construction of the Stanford Audio Phonic Photographic Infrared Experiment (SAPPHIRE) Satellite", 8th Annual AIAA/USU Conference on Small Satellites, Logan, Utah, September 1994.

[2] picture taken from the Frangibolt Non-Explosive Release Systems brochure distributed by the TiNi Alloy Company, San Leandro, Ca.

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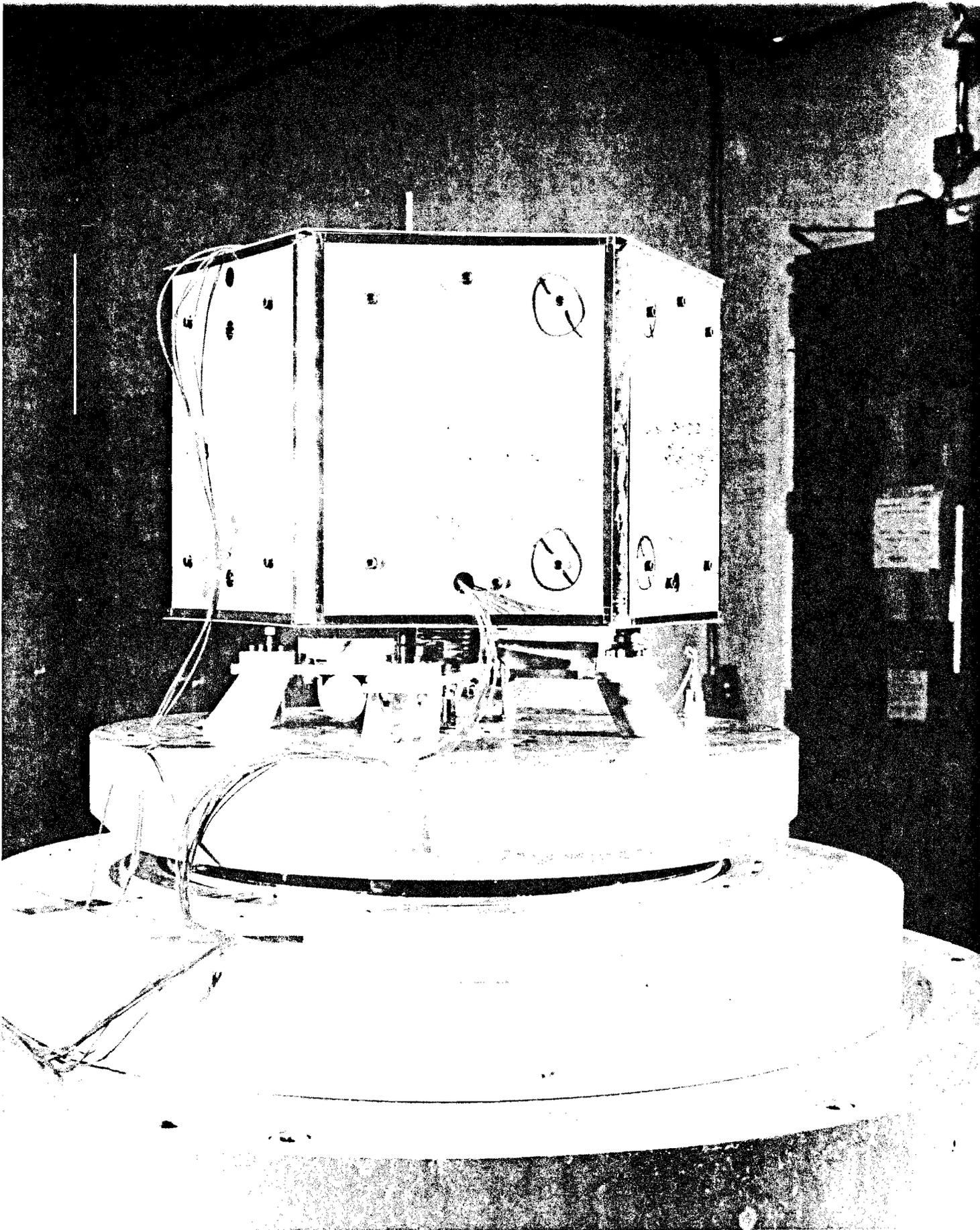


Figure 12