Development of a Strain Energy Deployable Boom for the Space Technology 5 Mission

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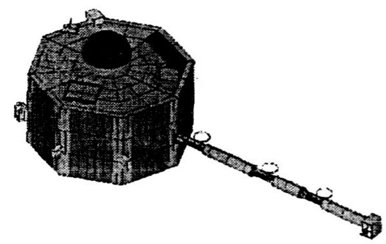
The ST-5 Mission

The Space Technology 5 (ST5) mission is one of a series of technology demonstration missions for the New Millennium Program. This mission will fly three fully functional 25 kilogram micro class spacecraft in formation through the Earth's magnetosphere; the primary science instrument is a very sensitive magnetometer. The constraints of a 25 kg "Micosat" resulted in a spin stabilized, octagonal spacecraft that is 30 cm tall by 50 cm diameter and has state of the art solar cells on all eight sides. A non-magnetic boom was needed to place the magnetometer as far from the spacecraft and its residual magnetic fields as possible. The ST-5 spacecraft is designed to be spun up and released from its deployer with the boom and magnetometer stowed for later release. The deployer is the topic of another paper. This paper describes the development efforts and resulting self-deploying magnetometer boom.



ST-5 Spacecraft Boom Deployed

Deployed requirements:

- The spacecraft shall include structure and mechanisms that deploy the magnetometer sensor away from the vehicle central body.
- The magnetometer sensor shall be at least 1.5 spacecraft diameters away from the central body.
- The magnetometer alignment to the spacecraft coordinate system after deployment shall be repeatable to within 0.25 degrees of nominal orientation and within 1.0 cm of nominal distance.
- The natural frequency of the deployed structure for the magnetometer shall be between 5 and 11Hz.
- Any initial disturbance on the deployed structure shall be reduced by 95%, as measured as the peak-to-peak displacement at the magnetometer sensor head, within 20 seconds of the impulse.
- The spacecraft shall be designed so that generated electric and/or magnetic fields do not interfere with magnetometer measurements.
- Spacecraft-induced magnetic fields as measured at the magnetometer sensor location shall be less than 10.0 nano Tesla (D.C.), and less than 0.5 nano Tesla (A.C., $\leq$200Hz).

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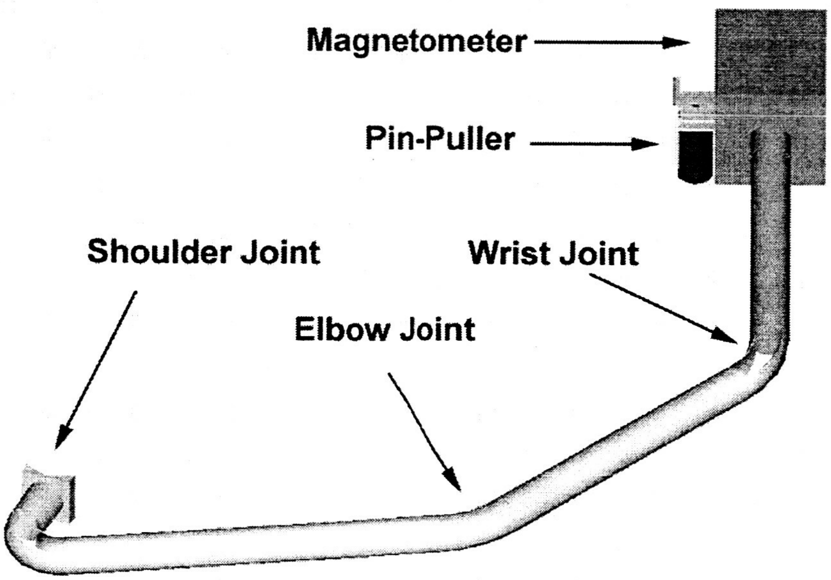
Stowed requirements:

- Coupled Rigid Natural Frequency shall be greater than 50 Hz.
- Fixed-base Natural Frequency shall be greater than 100 Hz.
- Deploying Torque Margin shall be at least 2:1 (GEVS)
- Design Loads shall be 16G in each axis independently
- Mass budget for the magnetometer boom, without magnetometer sensor head elements shall be less than 750 g
- Survival temperature limits shall be from -80°C to +70°C
- Operating temperature limits shall be from -55°C to +50°C
  (These temperature limits are under review because of the shift from a secondary payload on a Delta/Atlas class launch vehicle to a primary payload on a Pegasus launch vehicle.)

Obviously, meeting these requirements was a challenge. Further complicating the task was the fact that no launch vehicle had been selected, thus requiring the worst case load conditions enveloping Ariane, Delta, and Atlas be used.

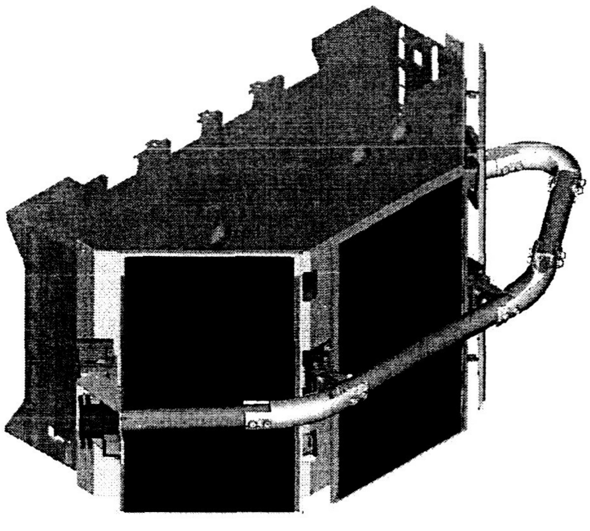
The Initial Concept

From the start, it made sense to use a composite boom for the magnetometer to minimize the magnetic contamination. The boom needs to be folded around the periphery to get the length required and minimize volume and deployer interference. This boom wrap-around design requires three hinges, anthropomorphically referred to as the shoulder, elbow and wrist joints. Integral folding "carpenter tape" hinges with no sliding or rotating parts were chosen as the simplest way to ensure positive deployment torque-ratios at the least mass while avoiding the issues of designing for friction and damping. This boom design relies on the strain energy in the buckled hinge to straighten the hinge and deploy the boom.



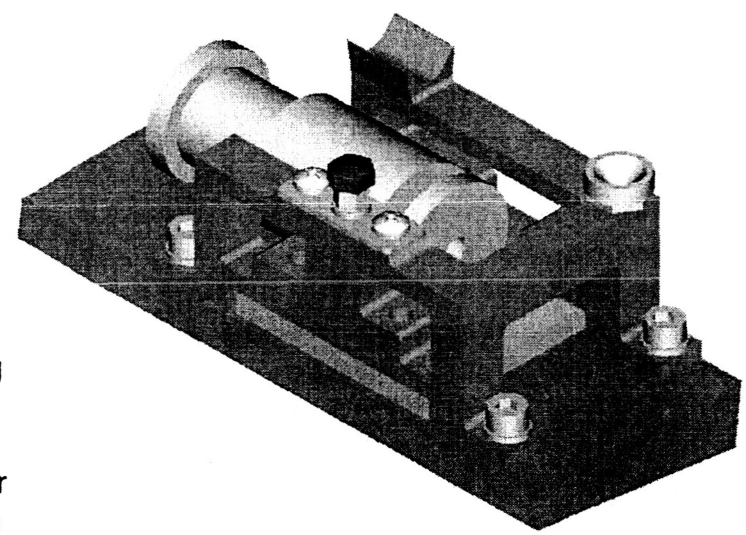
Mounting

The sides of the spacecraft are covered with solar panels and hard points are available only at two vertices of the octagon. These coincide with the cast aluminum card cage that provides the primary load path of the satellite. The shoulder joint of the boom is attached at one of these reinforced vertices and the pin puller that holds the magnetometer uses the other. Thus the ends holding the boom are connected to the card cage rather than the sheet metal sides that support the solar arrays. The intermediate elbow and wrist joints are supported at the intermediate vertices by snubbers mounted to the sheet metal.



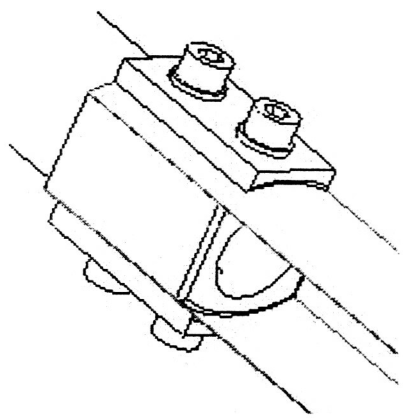
Boom Release

The method of boom release was driven by the low-power low-mass characteristics of the ST-5 micro-satellite. Low-power actuators from both StarSys and TiNi Aerospace were considered. Pyro actuators had been ruled out early on because of concern for shock in a very compact structure and the current requirements on a 5 volt spacecraft bus. In the end TiNi produced a modified version of their P5-404-6SC pin-puller that was selected. The magnetometer is held to the spacecraft through a tang and clevis design that utilizes the pin-puller pin in double shear. This holds the boom to the spacecraft in the stowed configuration. The magnetometer mount is a semi-kinematic design consisting of a cup-cone and spring arrangement. The relatively low minimum lateral load capability of the pin puller, only 15 pounds shear in the worst case condition over the entire operating range, further drives the stowage scheme. To establish this number rather extensive testing was done with a test rig using parts that were as flight like as possible. To maintain a release force margin of two to one 7.5 pounds was used as the maximum allowable shear load on the pin puller. This value limits the maximum tension that can be applied to the boom stowed.

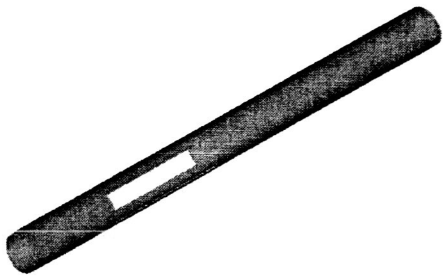


Design Trades
Initially it was hoped that an all composite "monolithic" design could be made with sections of the boom cut away to create the hinges. While graphite fiber is not normally considered a flexible material, when used in this design, it allows the boom to bend over 90° and has many features that make it optimal for its intended use. The graphite provides an electrically conductive path to bleed off static charge –a great benefit on the highly charged mission orbit. It resists creep and remains stable under large temperature fluctuations, allowing for precise science measurements even under direct solar radiation. The thermal conductance is optimum for controlling heat loss from the spacecraft. Furthermore, the composite material exhibits nearly none of the thermal magnetic effects that currently plague the metal hinge units.

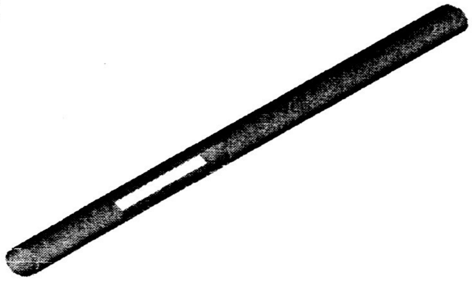
Considerable effort was expended developing this concept. Various shapes were tried for the cut outs and different materials were tried, including Kevlar®, E-Glass, S-Glass, and various weaves and types of carbon fiber. Different lay-ups of the materials were also tried. One notable result from this study was the fact that the desired radius of a tubular boom section was not usually the optimal radius of curvature of the leaf or blade element of the hinge. An oval section boom with cutouts for the hinge section was considered, but rejected in favor of a saddle piece to adapt the different radii. Once it was realized that the hinge design requirement was necessarily different than that of the basic tube, the concept of cutting windows in a tube to create a monolithic boom was abandoned. It was also found that adding a fourth facet in attempt to move the magnetometer further from the spacecraft resulted in the boom hitting the solar array on deployment.



Saddle Adapter to Provide
Larger Radius for Hinge



Monolithic Boom With Integral
Hinge Cut Out

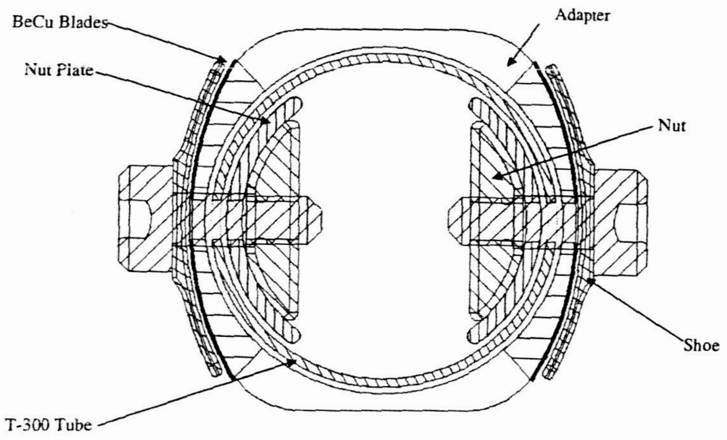


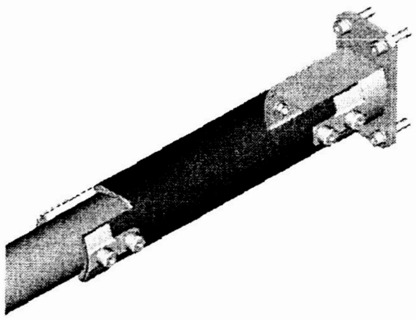
Oval Attempt to Have Larger
Radius for Hinge Area

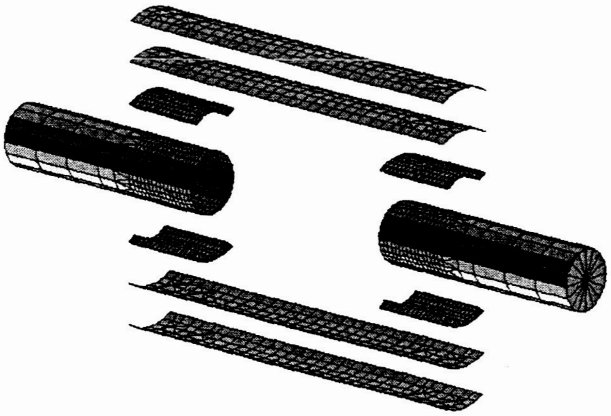
Design Development

Titanium adapter shoes were bonded to the boom with the hinge blades bolted to them. A variety of composite and metallic blades were tried. The problem was to make a hinge that was stiff enough when deployed, but that would buckle at a low enough strain energy not to destroy itself. The boom joints are made up of two different length carpenter tape hinges (longer at the shoulder joint and shorter at the wrist and elbow). The length of the hinges is driven by the angle through which the hinge has to bend (120 degrees, shoulder and 45 degrees, wrist and elbow). Each hinge is made up of four "carpenter-tape" blades stacked two thick on each side. Analysis and development testing showed that the bending strain in a single blade that was as thick as the two stacked blades was too high. Every time the thick hinges were bent they permanently deformed. Splitting the hinge into two separate tapes cut the bending strain in half for each individual blade. This allows the boom to buckle and deploy as designed and still have almost all the stiffness of the earlier single hinge design.

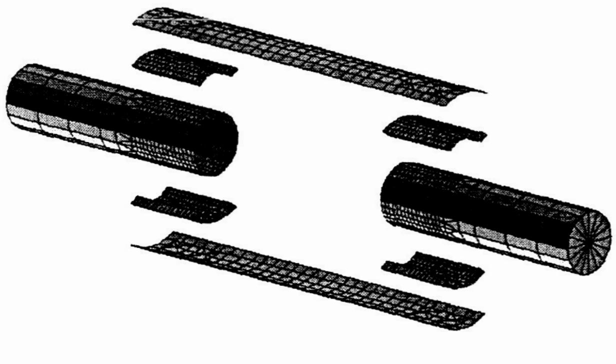
While these experiments and trades continued, another approach using either Elgiloy or Beryllium-Copper hinges was pursued as a back up.







Stacked tapes (actual)

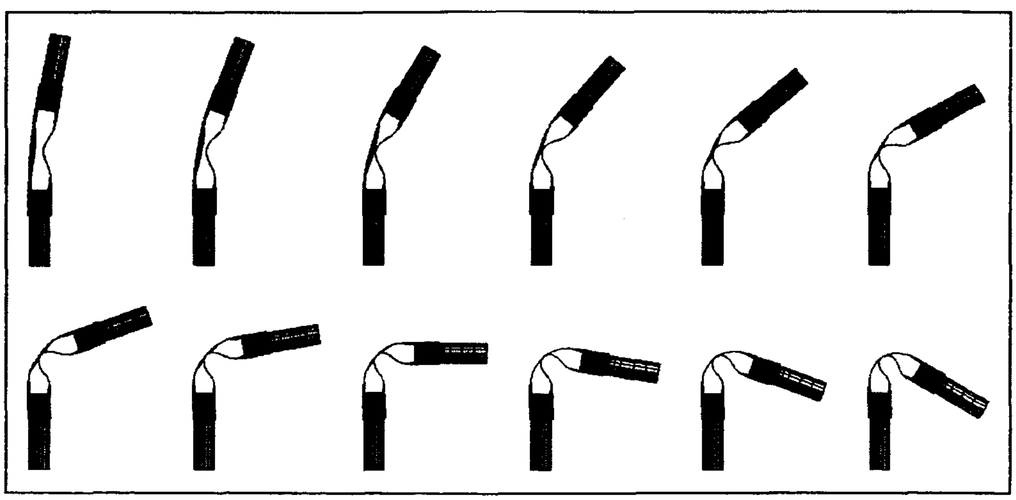


Unstacked tapes (as-run)

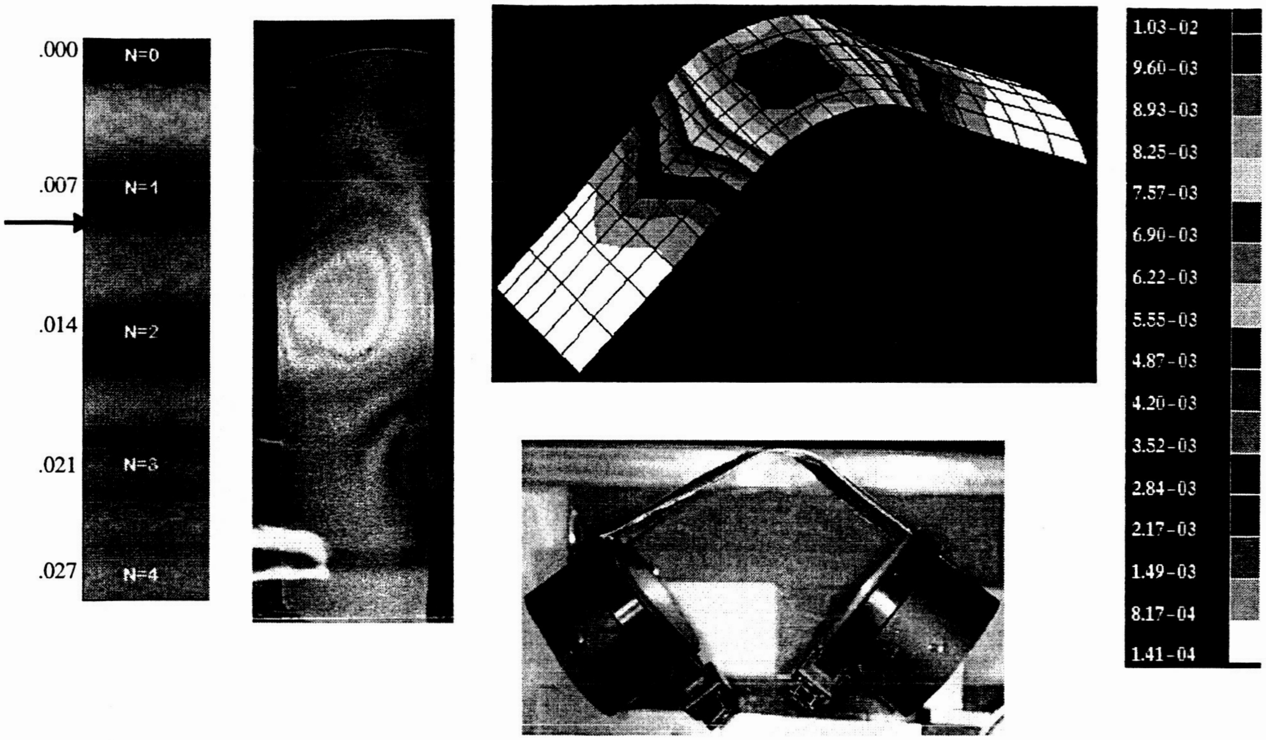
The Analysis Program

Hinge development involved both analysis and testing. This boom design relies on the strain energy in the buckled hinge to straighten the hinge and deploy the boom. The deployed boom results in the hinges being in a state that requires considerably more force to buckle again. Deployment tests of the complete boom system have shown that the stored strain energy is sufficient to cause the shoulder hinge to snap over. This snap over is the buckling of a hinge in the direction of deployment (opposite its originally stowed state). However, after several cycles the system damps out with the boom deployed. The buckled state required a non-linear approach for analysis. There was significant effort in developing and correlating stowed hinge behavior models. Through strain-gauged mechanical bending tests and photo-stress methods a high degree of correlation between the analysis models and the physical models was achieved. This correlation between analysis and test has given confidence to the modeling technique employed. Through this analytical tool material, lay-ups, hinge length and subtended angle were traded off against strain and peak snap-over moment. Thus a few highly likely candidates were selected for further testing. The stress/strain results indicated that a successful composite blade would have to be very thin. Subsequent testing showed that the very thinnest composite hinges did work, but the resulting booms had very low deployed natural frequency and long snap-over damping times.

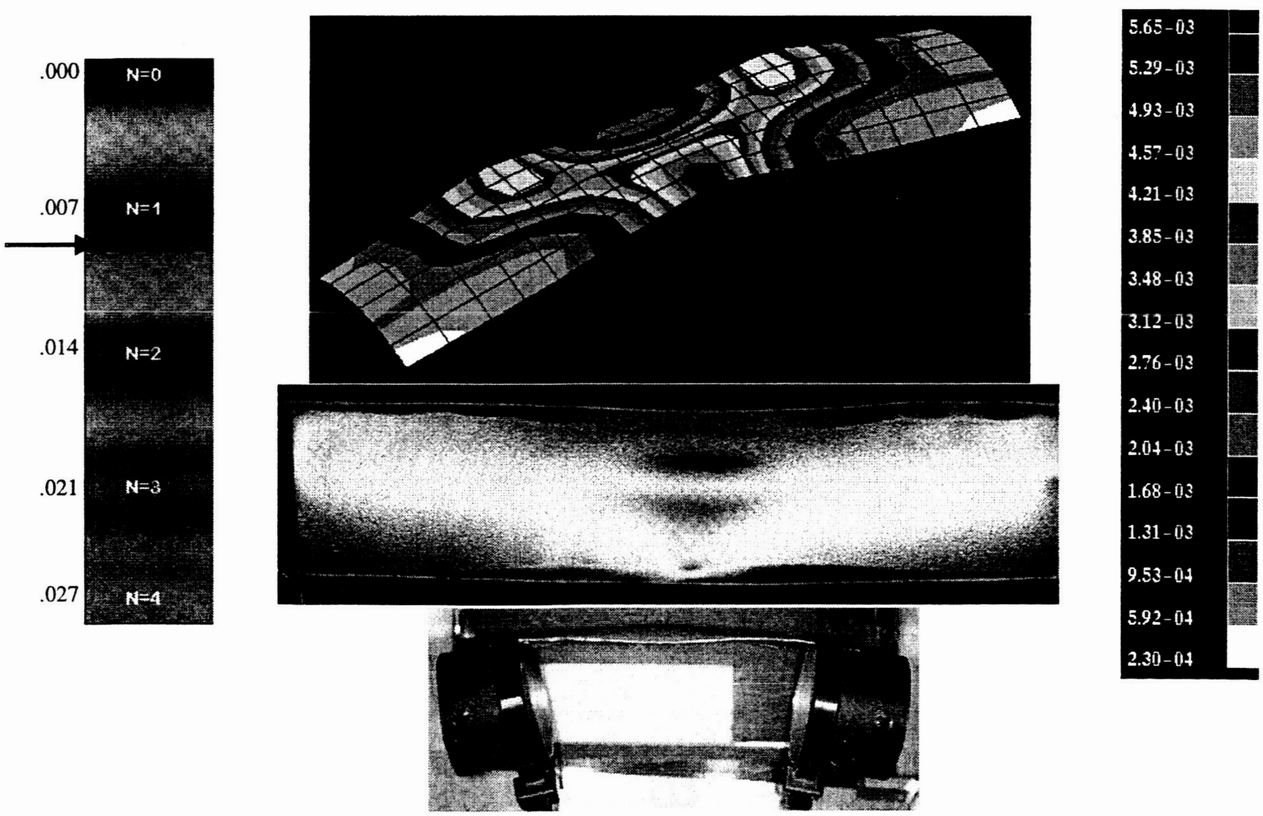
The stiffest 3/4" diameter boom with composite hinges tested had a frequency of about 2.7 Hertz. The diameter of the boom was increased above the nominal 3/4" in an effort to get the deployed frequency above the required 5 Hertz. It was determined that even significant increases in tube diameter resulted in only small increases in the deployed boom's natural frequency. In addition, the project objected to the increased shadowing of the solar arrays. In the summer of 2002 the design effort was concentrated on the metallic BeCu hinge.



Analytical snap-thru and stow sequence for joint with 0.006 in thick tape and 3.25 in window.

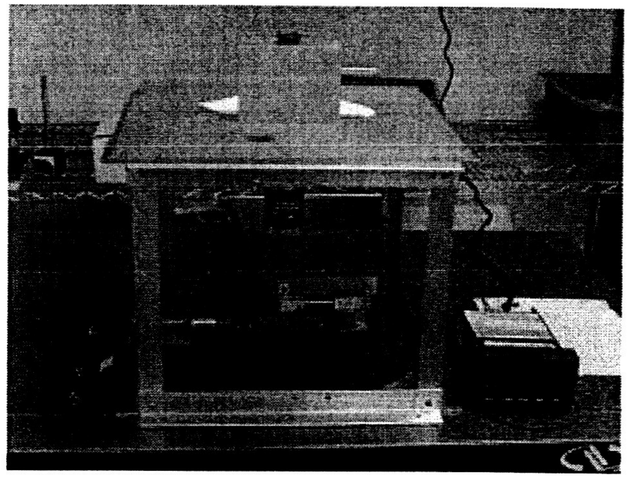


Correlation of Analytical to Experiment for the 72 Degree case above and 22 Degree below



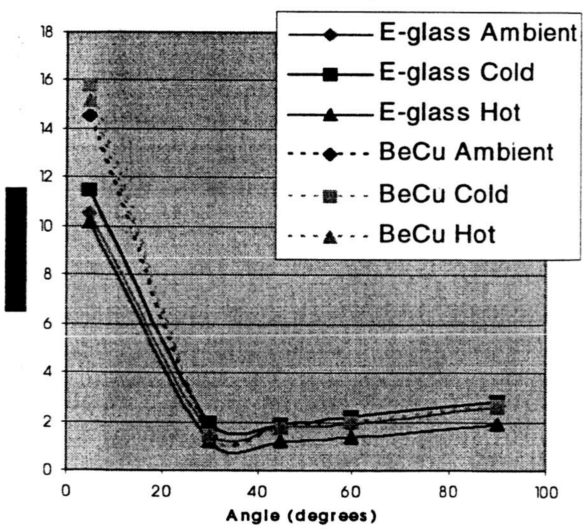
Moment /Life test fixture

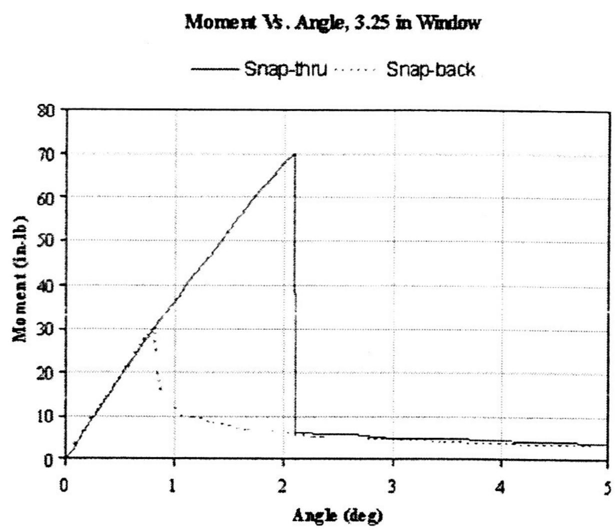
Hinge testing falls into two categories: characterization and qualification. Sometimes, of course, these distinctions are artificial. In order to determine the deployed frequency, the deployed stiffness in the folding plane and normal to it need to be measured. Since the deployment force is the buckled restoring force, this force needs to be measured as a function of angle of buckle. The cycle life, how many buckling operations can the hinge survive, also needed to be known. A Moment /Life test fixture was built to make these measurements. The torque resistance of the harness was also measured with this rig. The fixture was designed to operate in thermal chambers so that measurements could be taken over a range of environments.



Moment /Life test fixture

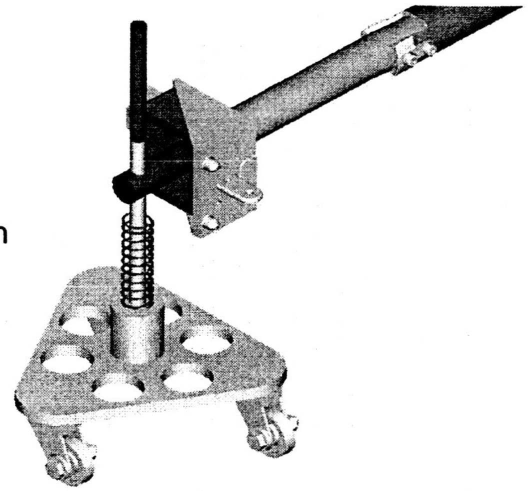
Torque vs Angle



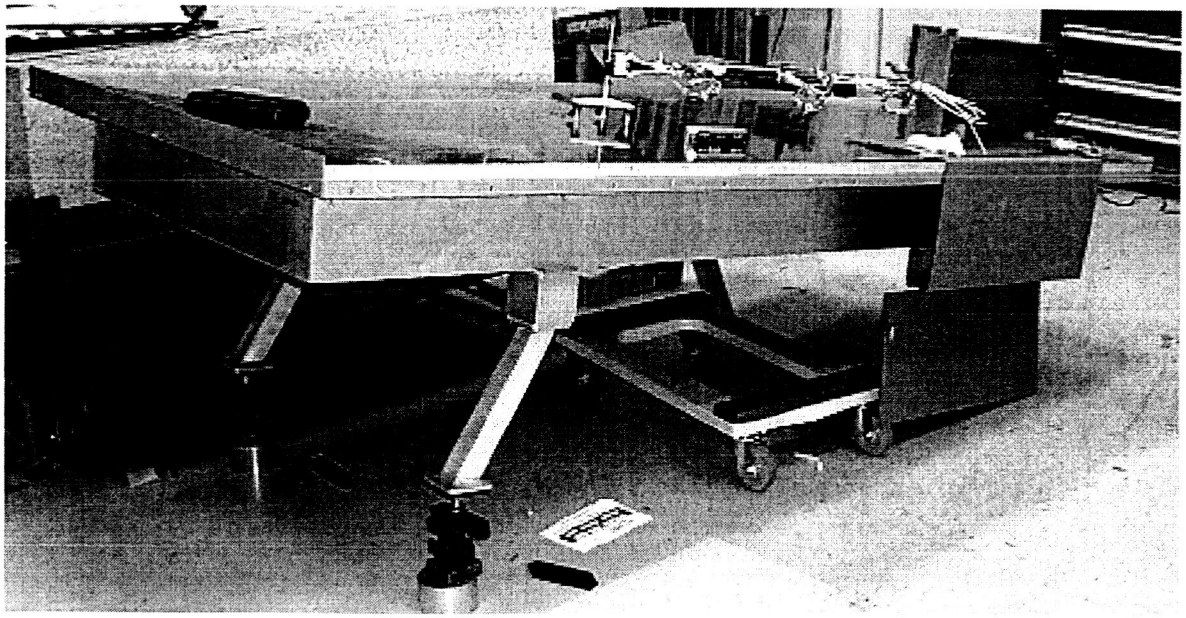


The ratio of peak snap-back moment is less than half of peak snap-thru moment. This is the damping action that makes the deployment stable.

Deployment testing of a complete boom.



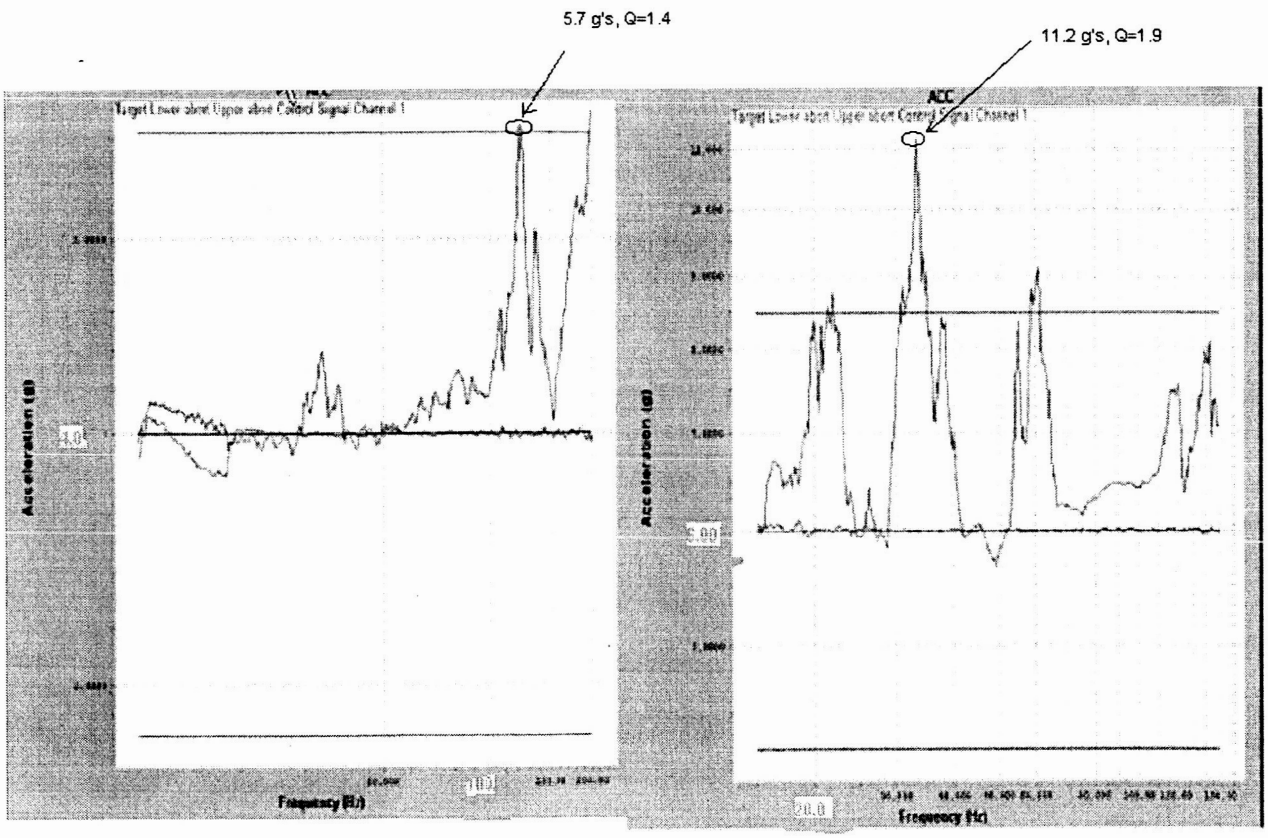
Once it is deployed, the boom is able to support itself under gravity; however it needs a "g" negation system while it deploys. During deployment, the collapsed hinges do not have enough lateral rigidity to support the boom. A low friction trolley was developed to support the boom payload mass during deployment. The trolley consists simply of a spring loaded support for the magnetometer on a trolley base. This trolley moves along a flat plate of aluminum. A simulated spacecraft structure holding the boom is also mounted to this plate. Because of the boom's deployment characteristics, the plate is 5 ft. x 6 ft. This trolley has been designed to be compatible with the requirements of the thermal-vacuum test chambers. The boom deploys from the outboard segments inward (e.g. the wrist joint locks in first, followed by the elbow and then the shoulder joint). Extensive testing of the full boom has shown that the shoulder joint snaps over (the hinge collapses in the opposite direction) on all deployments. The number of times that the hinge snaps over is a function of the deploying energy. During ambient, horizontal testing the boom snaps over an average of just one time. The angle that the plate is mounted with respect to the horizontal allows gravity to simulate the rotational "g" field. During life testing, when the centripetal acceleration of the spinning spacecraft is taken into account the boom snaps over an average of seven times at the lowest energy level and nine times at the highest energy level.



Trolley on the Tilt Table

Vibration Tests

Another dummy spacecraft was built as a vibration fixture adapter to allow the stowed configuration to be tested. The vibration survival of the stowed boom turns out to be a real concern. The magnetometer mount is held securely by the pin puller, but not much tension force is available to retain the boom sections in the snubbers. Consequently during vibration the flexible collapsed hinges allow considerable motion of the boom segments. It is a rattling fit in the snubbers. This in turn results in the boom system behaving non-linearly under vibration. A finite element model exists for the boom in its stowed configuration, but because of the non-linear nature of the stowed boom extensive testing was needed. The stowed boom "natural frequency" is very dependent on the vibration environment. Extensive sine sweep testing has determined that at low levels, less than 1G, the boom resonates around 50 Hz. As input levels increase towards 8Gs the boom "natural frequency" drops to around 20 Hz. Naturally this means qualifying the stowed configuration by test. Such extensive testing, obviously, is going to result in a few failures.



X Axis Response vs. Input. Left is 4-g input and right is 6-g Input

Note the Y response of the center segment of the boom moving transversely has the most non-linear characteristics, followed by the X response moving out of the snubbers, as the collapsed hinges are softest in these directions.

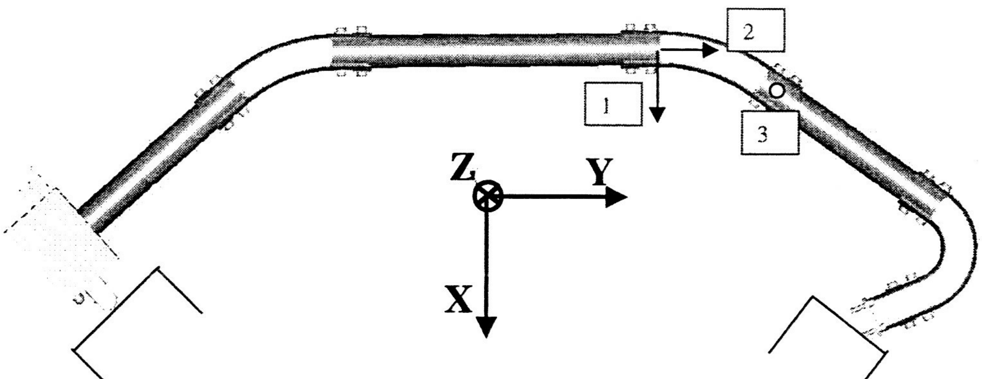
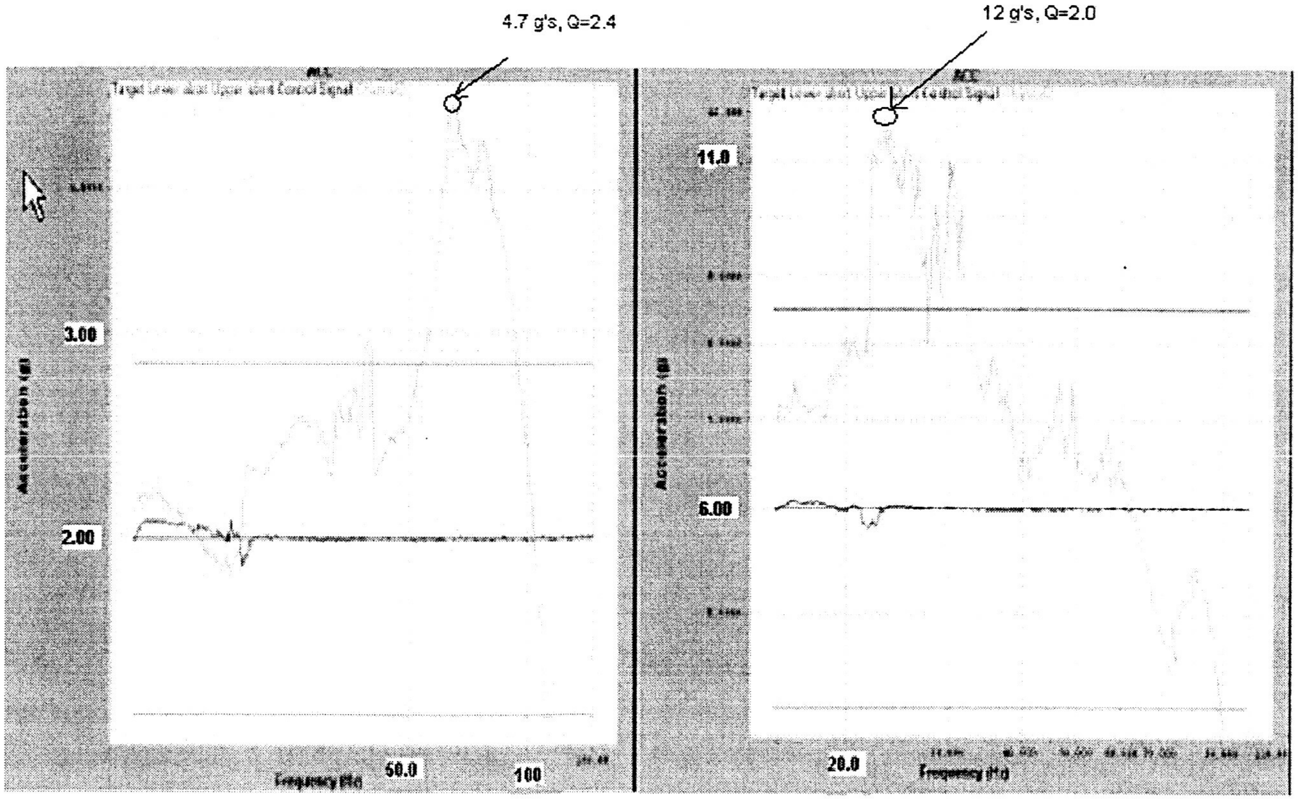


Figure 4: Bottom View Model of Accelerometer Locations



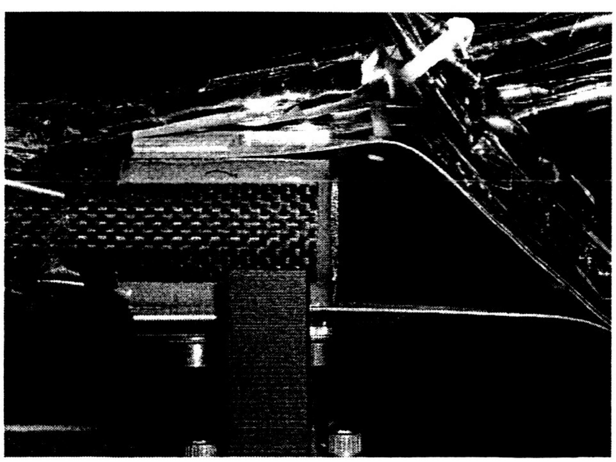
Y-Axis Response vs. Input. Left is 2-g Input and Right is 6-g Input

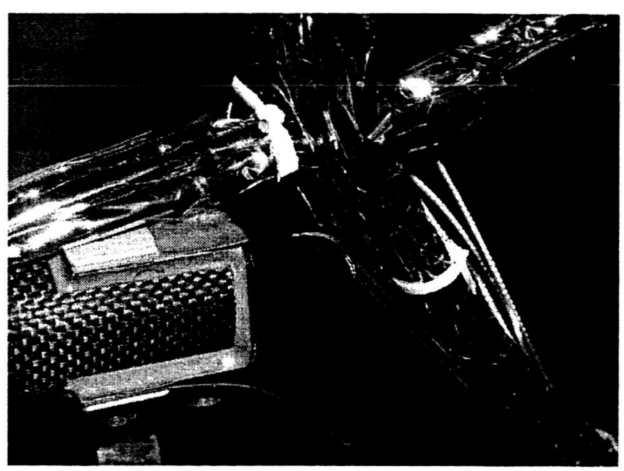
Failures

During a ETU spacecraft qualification test, the stowed boom was included to gather information about its capabilities. In general, the boom behaved as expected. However, the Ultem tang that holds the magnetometer mount to the spacecraft broke during a 17 GRMS random vibration run. The tang, it turned out, had been manufactured thinner than the drawing called for. Materials investigation of the part showed there were two failures. There was an initial fatigue failure at the junction between the top hat and the tang and this led to a subsequent fatigue failure of the tang itself. The tang was remade to the correct dimensions and the testing proceeded. It was later decided to replace the Ultem tang with a titanium piece which was non-magnetic and stronger.

During a subsequent 8.5G, 15 Hz sine burst test in the last axis (during the same time frame) the outer elbow tape failed. A materials investigation of this hinge showed that it had failed due to low cycle fatigue. Further study of this problem revealed that the hinge shoes that hold the hinges to the boom were causing a sharp bend in the hinge just before it attached to the boom. The fatigue failure of the hinge had occurred right where the sharp bend was identified. The shoes have been modified to cure this.

The outer elbow tape again failed during a 17G, 14 Hz sine burst test. This failure was due to an oversight by the mechanical team. Following the ETU sine burst failure it was realized that the natural frequency of the stowed boom was so close to the sine burst frequency that a burst test on the stowed boom was out of the question. During planning for this testing, this detail was overlooked. Materials investigation of the failed hinge showed that it had failed as a result of a single event overload. No changes to the design were needed to fix the problem.


Before

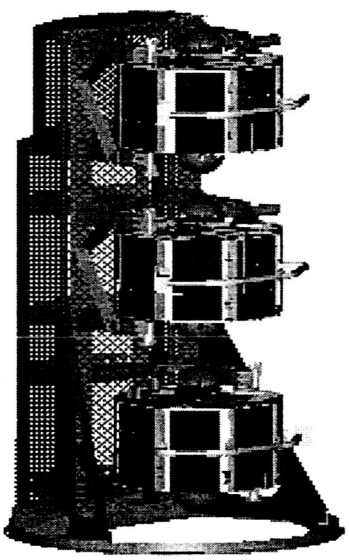

After Sine Burst.

Production Problems

The ETU 3/4" T300 boom sections were fabricated by a local contractor, and the initial test pieces worked fine. The flight units, however, were made by an "improved" technique with the mandrel continuously wrapped with the lay-up rather than by using cut layers. The resulting booms had resin starved sections. Another delay to order new materials and do it right. Since hinge blades were not going to be made from the material, it was changed to M55J, higher modulus but less tough.

Thermal Magnetic Considerations

Now some thermal results began coming in and the scientist became concerned with thermal gradients producing Peltier voltages which in turn would produce eddy currents and a resulting magnetic field higher than the extremely low fields he was setting out to measure. All metallic pieces became suspect. In particular the titanium tang with its low heat conductivity gave rise to big gradient. The tang was changed to polished aluminum and the surface was coated with SiO. The hinge leaves were also gold plated to cut down on the thermal gradients across them. The composite boom had already been blanketed, as had the cabling. The desire on the part of science to apply thermal blankets to the working hinges was resisted in the favor of their working. The stainless screws were replaced by custom built titanium shoulder screws.



A new Launch Vehicle

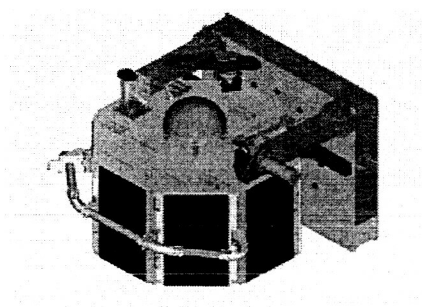
At this point the idea of getting a ride as a secondary payload on an large Expendable Launch Vehicle faded as the primaries raised objections. The option of a ride to orbit as the primary on a Pegasus became a real possibility. A new support structure was required because the honeycomb base of the baseline deployer system was designed as an adapter to an ELV Payload Attach Fitting. Most of the loads are well under those enveloping Ariane, Delta, and Atlas. Because the ST5 mission consists of three spacecraft, the dimensional limitations of the Pegasus fairing drove the support structure to a new cantilevered design. This has led to concerns about the coupling between the Pegasus environments and the primary modes of the support structure, the ST5 spacecraft bus and the stowed boom. The driving technical question is the response of the boom to the Pegasus drop transient and captive carry random vibration. Again the non-linear aspect of the boom precludes a direct analytical approach. Orbital Science Corporation has been given a finite element model of the payload with the boom represented by a sprung mass. The results of a coupled loads analysis will be applied to an ETU boom on the test fixture to make sure it can survive the drop transient and captive carry response. After a technical interchange meeting with OSC the support structure was redesigned to raise the frequency from 22 to 37 Hertz.

Test Results

A capability test of the spacecraft and boom was performed with preliminary support structure response data to determine problem areas. The boom survived the drop transient excitation which was modeled as a 10 G peak 10 Hz input and a random vibration environment that had a peak of 0.2 g2/ Hz below 60 Hz. A similar environment with a peak input of 0.4 g2/ Hz below 60 Hz, however, caused the elbow hinge to fail with what looks like a single event overload. The application of this load based on the softer support structure was a gamble that did not pay off. The random response that is expected with the new stiffer support structure is expected to have a peak value closer to 0.2 g^2/Hz below 60 Hz. No action is being taken until the new levels are in and the boom is tested to them.

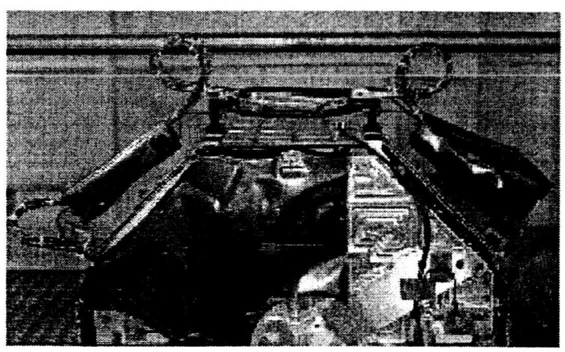
Current Flight Boom Status

The boom comprises three 3/4" diameter M 55J graphite composite tube segments with Titanium adapters at each end to mount "carpenter tape" spring hinge blades. Each hinge is made up of four "carpenter-tape" blades stacked two thick on each side. These blades are formed from a Beryllium-Copper alloy strip (6 mil thick) that has been tempered to meet design needs. When stowed, the boom folds around three sides of the spacecraft. It is supported with stand-offs at either end of the middle segment to keep it off the solar panels. A low-shock, SMA pin puller from TiNi Aerospace, Inc. is used in conjunction with a kinematic retention cage to restrain the sensor head during the launch phase of the mission. The thermal treatment consists of gold plating the hinges and blanketing everything else except the magnetometer mount tang which is coated with SiO. Titanium screws are used throughout the boom system. This boom system is about to undergo flight qualification testing.



ST-5 on ELV Deployer Mount

The Future?



In order to fully satisfy the science requirements for a magnetically clean boom system at least the wrist joint nearest the magnetometer should be completely non metallic to reduce thermal magnetic contamination. This is probably achievable with more development work. The center boom section between the wrist and elbow should be positively restrained. This will take another actuator but is readily doable and will greatly improve the boom's ability to resist random vibration. A custom cable made from printed circuits on Kapton would further enhance the system being lighter and able to be run inside the tube. The large external cable loops currently over hanging the joints contibute to the non-linear respnse of the system.