Stanford University
Department of Mechanical Engineering
Design Division
Stanford, CA 94305

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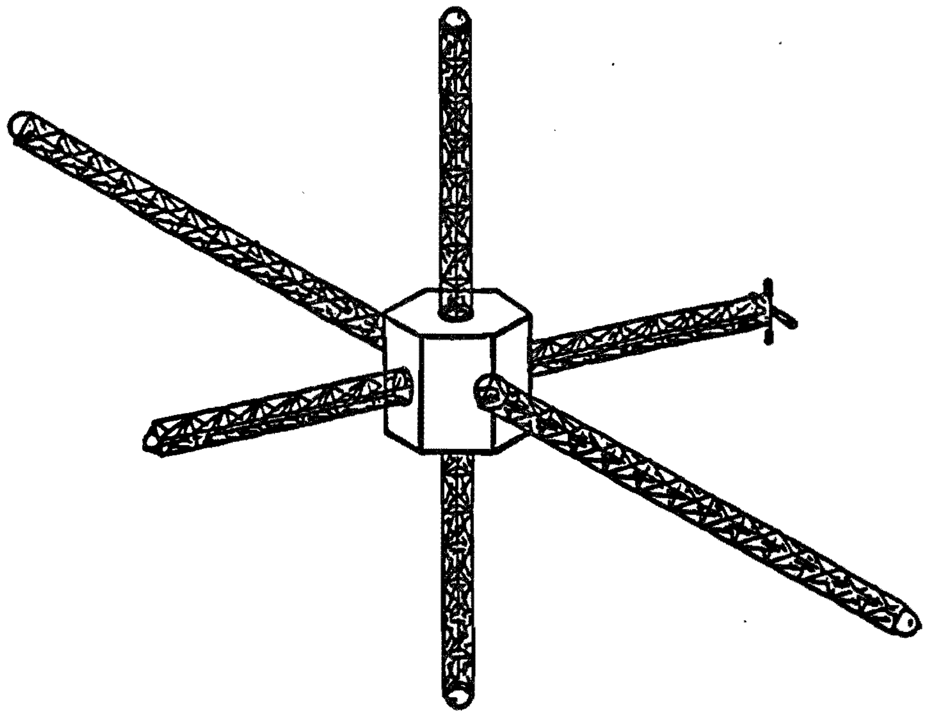
SENSOR DEPLOYMENT MECHANISM FOR SURFER SATELLITE



by
Robert Dill
James Flom
Donald Gibbons

Final report of a project carried out as part of the course
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Professor Ernest Newman

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Master's Course in Engineering Design ME210 | 1987-1988 Academic Year

Sensor Deployment Mechanism for SURFER Satellite

Design Team: Bob Dill
Jim Flom
Don Gibbons

Faculty Advisor: Emery Reeves
Company Sponsor: Stanford STARLab

PROBLEM STATEMENT

SURFER, the Stanford University Radio Frequency Emissions Receiver, is a small, free flying, spin stabilized satellite. It will take measurements of the earth's ionosphere during the joint US/Italian Shuttle tether experiment. To obtain these measurements several sensors must be extended from the satellite to specified positions. This will increase the resolution of the instruments and decrease the electromagnetic interference from the satellite electronics. The primary requirements for the deployment mechanism are:

1. The sensors must be positioned at least 60 inches from the satellite with a ±5% tolerance on the known deployed length and a ±1° tolerance on the known angular position.
2. Opposing sensors must be deployed simultaneously to within 10% of the total deployment time.
3. Full piece part redundancy is desired to eliminate single point failure.

DESIGN

The design solution is based on the concept of a folding arm. Three aluminum **links** are pinned at their ends with steel clevis pins (see Figure 1).

- To ensure that the arm deploys linearly, two sets of **kinematic constraint cables** are wound around pulleys at the joints (these operate as four bar linkages).
- Torsion springs at each of the joints provide a positive deployment force, in addition to the centrifugal force acting on each boom.
- **Restraint cables** from each boom are attached to the outboard link and wound around a common central **spool**, performing two functions: it slows down the deployment velocity of the boom via a **centrifugal damper** which is attached to the spool; and it synchronizes the deployment of all four radial booms.
- All restraint cables are preloaded, which safely secures the booms against the **snubber assemblies** which are fixed to the satellite. A non-pyrotechnic **pin puller** releases the spool which initiates the deployment of all four radial booms.

A folding arm will be placed in each of the four radial positions. Because the folding arm does not meet the volume requirements of the axial positions, we are recommending that STEM or STACER booms be used there. Both are commercially available and meet the looser design requirements for these sensors.

RESULTS

To prove the feasibility of the concept, a development model consisting of two folding arm booms was constructed and tested. The data gathered from these tests confirmed that the design has met all of its requirements. The primary requirements are:

	required	capability
1. deployed length	> 60.0"	60.4"
length tolerance	± 3.0"	+0.3" -0.4"
angular tolerance	±1.0°	±1.0°
2. simultaneity	±10%	±0.14%
3. redundancy	The deployment mechanism has redundant piece parts in all of its components with the exception of the centrifugal damper.	

The folding arm boom represents a unique solution to nonmotorized instrument extension while maintaining high positioning accuracy. The folding arm prototype has been developed on a small budget and thus may lead to a cost effective means of extending instruments several times the major diameter of small satellites.

RECOMMENDATIONS

We recommend the following actions:

- Once the instrument geometries are specified, design and construct the mounting fixture which will attach them to the end of the outboard link.
- Identify a rotary damper and non-pyrotechnic pin puller for this project which are commercially available and flight qualified.

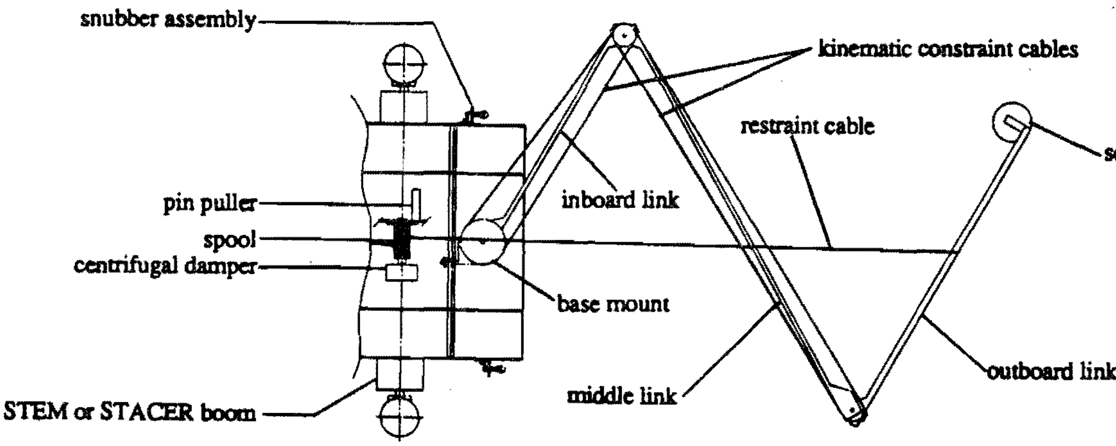

Figure 1: Partially Deployed Folding Arm

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1.0 OVERVIEW

This report describes the present design for a sensor deployment mechanism for the SURFER satellite. This mechanism will extend scientific instruments from SURFER to examine the earth's ionosphere during the shuttle tether experiment. This extension not only improves the resolution of the instruments but also improves SURFER's spin stability. The chosen design uses four folding arms to extend the radial sensors and two STEM or STACER booms to extend the axial sensors. The design decision was based upon the information below. Background information is presented and followed with a problem statement. The functional specifications, which describe our exact design requirements are discussed. State of the art spacecraft boom designs are presented. Our design solution, the folding arm, is discussed in depth, including the operation of the mechanism and the function of each major component. The testing goals and test plan are then discussed. The results of our test program are presented and recommendations for further improvements are given.

2.0 BACKGROUND

SURFER is a field measurement satellite. Its 54 hour mission is to take measurements in the earth's ionosphere during the shuttle tether experiment, a joint U.S./Italian effort. This experiment consists of dragging a 20 km conducting tether through the earth's magnetic field. SURFER will be carried into orbit in a Hitchhiker-G (HH-G) canister and will be ejected from the shuttle before tether deployment . SURFER will maintain a co-orbital path approximately 100 km from the shuttle. The instrumentation on SURFER will take measurements of the ionosphere during the tether experiment and relay the data to earth via the shuttle.

3.0 PROBLEM STATEMENT

The purpose of our project is to design and test a system that will extend various instruments from the SURFER satellite to specified positions without destabilizing the spin of the satellite. Deploying the instruments from the satellite will:

1) Improve the sensitivity of the instrumentation.
2) Help shield the instruments from electromagnetic interference generated by the satellite electronics.

4.0 FUNCTIONAL SPECIFICATIONS

4.1 Introduction

The functional specifications for the sensor deployment mechanism include essential and desirable features as well as an outline of the important constraints imposed on the project.

4.2 SURFER Satellite Description

The satellite is still in the design stages; however, Figure 4.1 and Table 4.1 outline the characteristics that are assumed fixed in order for the deployment mechanism design to proceed.

Table 4.1: SURFER Satellite Physical Characteristics

Geometry:	a regular octagonal prism (a cylinder with an octagonal cross section)
Height	15 inches (Max. Height: 20 inches)
Diameter	17 inches
Mass	150 lbm
Center of Mass	anywhere in a cylinder of radius .25" about its geometrical longitudinal axis.
Moment of Inertia (longitudinal axis)	Initial: 4000 $lbm\text{-}in^2$ Final: 40,000 $lbm\text{-}in^2$

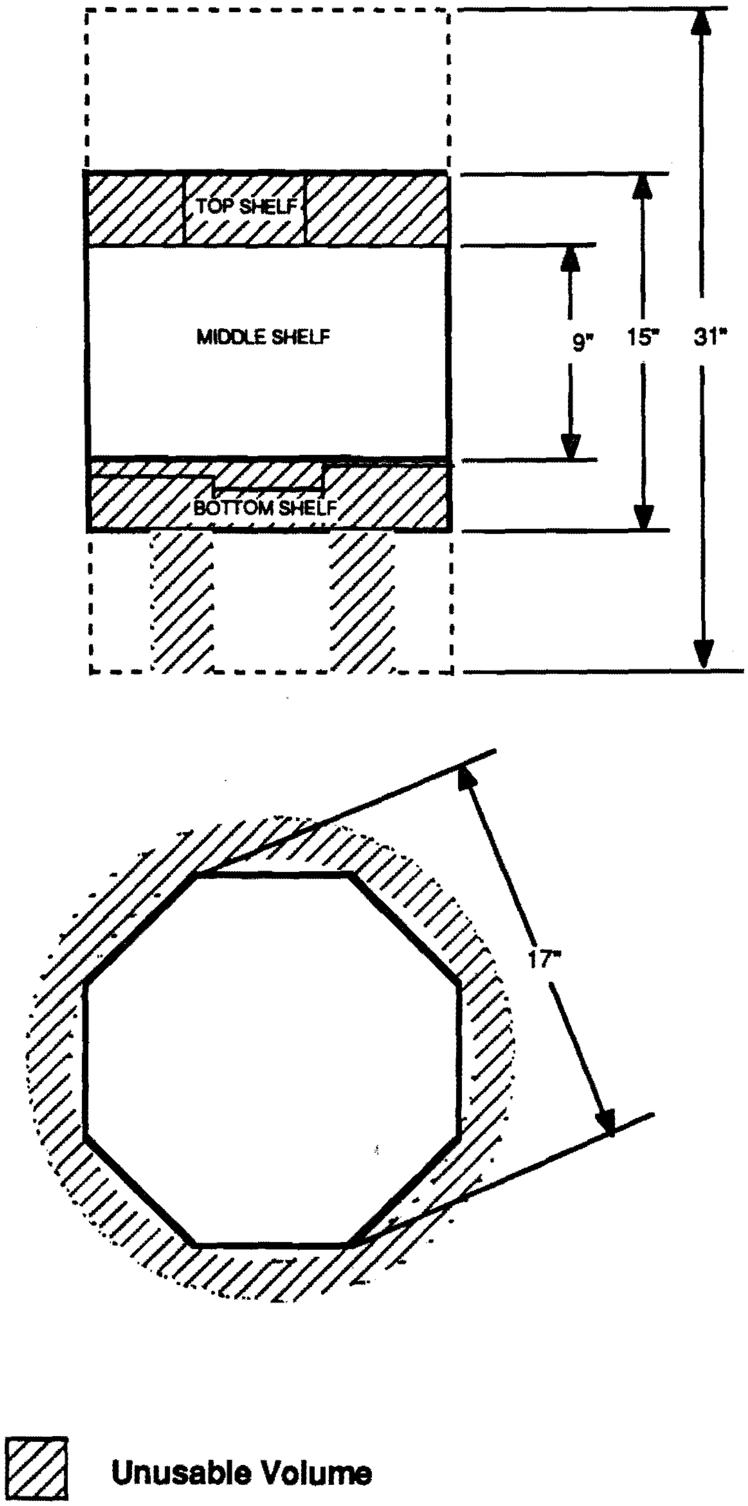


Figure 4.1: SURFER Satellite Dimensions and Usable Volume

4.3 Instrumentation Positioning Requirement

Because the purpose of SURFER is to make scientific measurements, the accuracy of the data must be assured. To achieve this accuracy, certain positioning requirements are needed for the six SURFER boom mounted instruments. These instruments are shown in Figure 4.2 and the exact requirements are as described below:

a) Deploy radial E-field sensors a minimum of 60" from the SURFER body. The separation distance between the probes can vary by no more than ±5%.
b) Deploy axial E-field sensors a minimum of 40" from SURFER body. The separation distance between the probes can vary by no more than ±5%.
c) Deploy search coil a minimum of 40" from SURFER body. The angle at which the search coil is mounted can vary by no more than ±1° about nominal position on any axis.
d) Deploy Langmuir probe a minimum distance of 12" from SURFER body with a ±5% positioning tolerance.

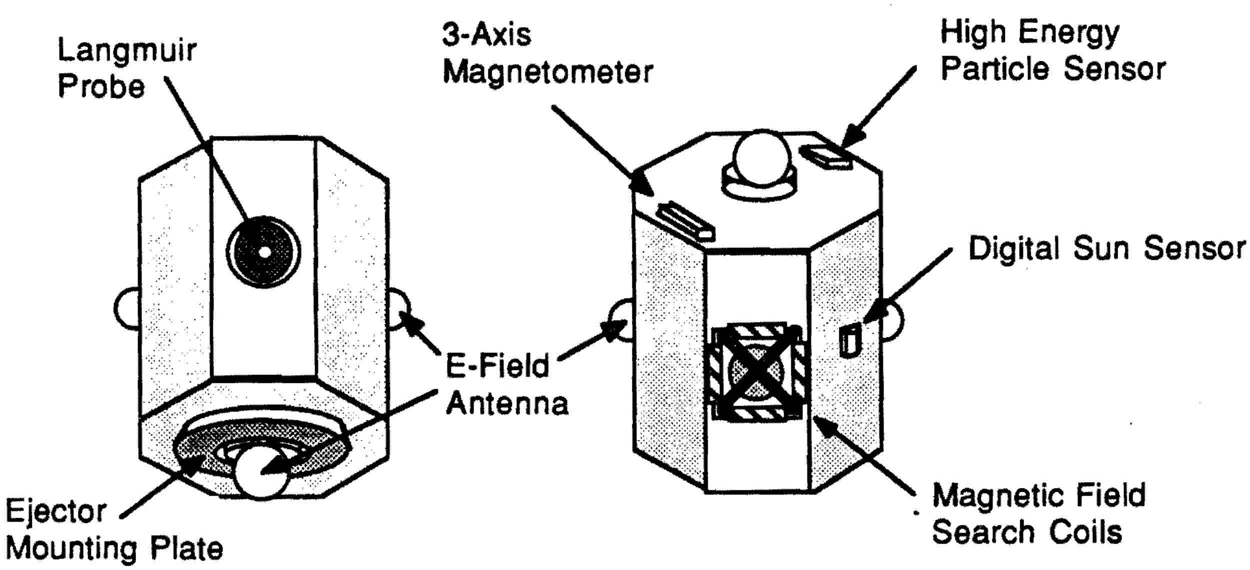


Figure 4.2: Instrument locations on SURFER

4.4 Deployment Mechanism Integration

4.4.1 Volume Constraints

No more than 50% of the volume in the middle shelf, or 1021 in^3, is available for all deployment mechanism hardware and corresponding instruments (refer to Figure 4.1). The external volume constraints are fixed, however, as they reflect the satellite's position in the HH-G Canister as shown in Figure 4.3.

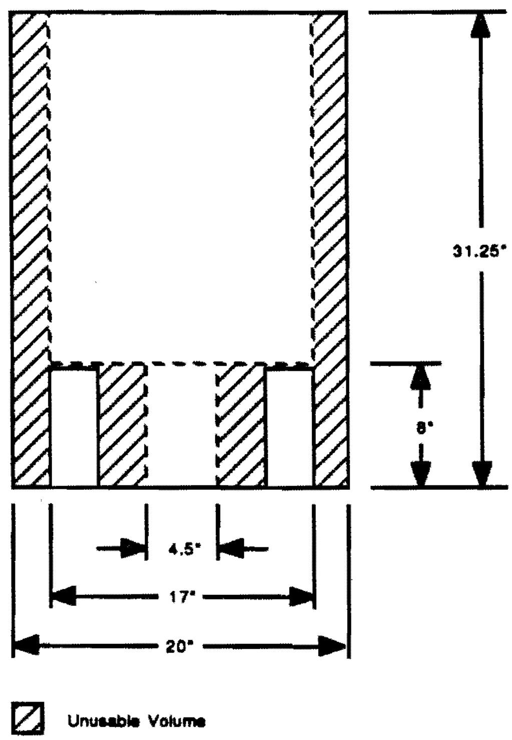


Figure 4.3: SURFER Design Envelope in HH-G Canister

4.4.2 Mass Properties

The maximum mass of the deployment mechanism, excluding the sensor and coaxial cable, is 25 lbm. The satellite CG must lie within a cylinder of radius 0.25" about its geometrical longitudinal axis.

4.4.3 Insulated Instrument

The deployment mechanism must be insulated from the instrument. However, the mechanism can be constructed of conducting materials.

4.4.4 Electrical Cable

The mechanism must accommodate a single coaxial cable running from the satellite to each instrument.

4.4.5 Payload Mass

The mechanism must be designed to deploy a payload of 2.5 lbm.

4.4.6 Materials

All materials used in the deployment mechanism design must be approved by NASA. Appendix B-1 of the Hitchhiker G Customer Accommodations Manual and MilSpec 522A contain information on selecting acceptable materials for space use.

4.5 Environmental Requirements

4.5.1 Temperature

The deployment mechanism must operate normally in the expected thermal environment of the Orbiter bay and, once ejected, in orbit. The range of temperatures to which the deployment mechanism and satellite are exposed depends on the Shuttle orientation, mission time line, and thermal characteristics after ejection. For the SURFER mission, the deployment mechanism must function normally within the temperature range of 40° to 140° F.

4.5.2 Launch Loads

Table 4.2 lists the acceleration loads the HH-G Canister will expect to see on a Shuttle mission. The Acceleration Load Factors in the table are actually a combination of acceleration and vibration loading lumped into one number. The deployment mechanism must survive and not experience any loss of function due to the lift-off loading scenario along all three axes simultaneously. If for any reason the SURFER satellite is not ejected from the HH-G Canister during the mission, the deployment mechanism should not be damaged by loads experienced during STS landing.

Table 4.2: Maximum Acceleration Load Factors (g's and radians/sec^2)

	Linear Acceleration			Angular Acceleration		
	Nx	Ny	Nz	Rx*	Ry*	Rz*
Lift-off	8.8	10.6	8.1	75	20	55
Landing	6.0	7.0	8.0	85	30	50

* Taken about the center of mass of the satellite.

4.6 Dynamic Stability Requirements

4.6.1 Sequenced Deployment

A critical function of the booms and instrumentation is to improve the stability of the satellite. If the radial booms are deployed first, the moment of inertia about SURFER's longitudinal axis, I_{zz}, becomes significantly larger than I_{xx} and I_{yy}, and thus the satellite's spin stability about its desired spin axis is improved. The axial booms may then be deployed without affecting the spin axis.

4.6.2 Spin Stability

The deployment mechanism must also deploy the instruments so as not to destabilize the spin of the satellite. To achieve this, there cannot be more than a 10% variation in the deployment time of the radial booms.

4.7 Reliability

4.7.1 Mission Success

For the mission to be successful, the following requirements must be satisfied:

1) The deployment mechanism must survive the boost phase of flight.
2) There must be positive verification that the instruments have not deployed before SURFER ejection.
3) The deployment of the instruments must not destabilize SURFER.
4) There must be successful operation of the instruments after deployment.

In addition, there must be visual verification by the STS crew of successful instrumentation deployment (Note: SURFER will be out of STS visual range approximately two minutes after ejection from the HH-G Canister.)

4.7.2 Redundancy

Piece part redundancy is a design goal of the deployment mechanism; no single point failures should exist. Parts shall receive special treatment if redundancy is not possible.

4.8 Safety

The following items of safety are required in the design of the deployment mechanism:

1) The deployment sequence shall commence no earlier than 30 seconds after SURFER ejection from the HH-G Canister.
2) The instruments must not deploy within the HH-G Canister.

4.9 Testing

Tests shall be performed to verify the function of the deployment mechanism. Test objectives, conditions and success requirements are discussed in Section 7.0.

4.10 Cost

The SURFER satellite organization has allocated $4000.00 for the development and testing of the deployment mechanism prototype.

5.0 STATE OF THE ART

5.1 Overview

Section 5.2 outlines the basic technology involved in deployment mechanism designs. Section 5.3 will be devoted to several deployment mechanism designs that are currently being used to deploy instruments. The mechanisms discussed are the Astromast, the STEM boom, the STACER boom, the folding arm, the tongs boom , the telescoping boom and inflatable tubes.

5.2 Basic Deployment Mechanism Technology

The deployment of an instrument from a host satellite represents a major event that must be successfully executed to fulfill mission requirements. Deployment mechanisms vary as widely in physical and functional properties as the performance requirements that they must satisfy. They can, however, be divided into two categories: those deploying by using potential energy and those using motors.

5.2.1 Potential Energy

Many boom designs exist that use springs or the strain energy of materials as the driving force for deployment. Typically, these systems have fewer parts and are lighter than motor deployed booms. However, deployment mechanisms which use potential energy require some sort of damping method to slow down the deployment and thus reduce impact loads. The greatest disadvantage of using potential energy is that the rate of deployment cannot be controlled as well as with motors. Thus, if timing is critical, a potential energy system with damping may not be appropriate.

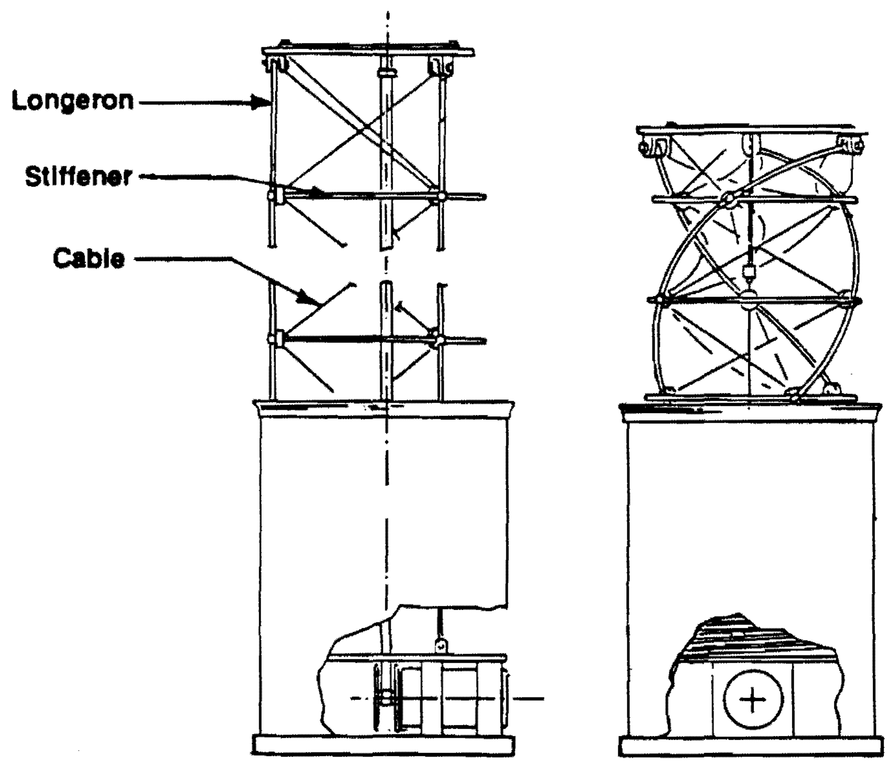
5.2.2 Motors

Motors are used both to provide positive deployment force and to provide restraining force. Even though the use of motors adds parts and potentially reduces reliability of a deployment mechanism, it has one considerable advantage: motors accurately control deployment speed and therefore greatly reduce impact loads.

5.3 Deployment Mechanisms

5.3.1 Astromast

The Astromast is a linear lattice structure, or boom, which is automatically deployed from and retracted into a very compact stowage volume. Figure 5.1 depicts the Astromast in partially deployed and fully deployed configurations.



Deployed Stowed

Figure 5.1: Astromast

The Astromast's lattice structure of fiberglass longerons, fiberglass stiffeners, and diagonal cables, is retracted by forcibly twisting it about its axis. This twisting causes the horizontal longerons to buckle, which provides the elastic energy for deployment. The deployment is typically restrained by a lanyard controlled by a motor. So, although the Astromast is self-deploying, it typically requires a motor to control the speed of the deployment.

The size, strength, stiffness, and length to which the Astromast can be fabricated is virtually unlimited--as is the case with any conventional truss or lattice boom. Astromasts have been designed, manufactured and flown in sizes ranging from 7 to 18.5 inches in diameter for numerous types of applications. The Astromast has been used to deploy instruments on the following spacecraft: S-3, Voyager, Dynamic Explorer (A & B), and CR RES.

Although the Astromast is an ideal structure for deploying satellite instruments, there are some disadvantages that prevent it from being used on the SURFER mission: 1) the Astromast is not manufactured in diameters smaller than 7", which is too large for the SURFER booms; 2) the Astromast is probably the most expensive deployment device available on the market, and far beyond the ME 210 budget; and 3) since the Astromast is a commercial product, the SURFER team's task would simply be one of integrating the Astromast with the SURFER satellite; the lack of design content in this is not appropriate for this Engineering Design course.

5.3.2 STEM Boom

The STEM (Storable Tubular Extendible Member) is a thin metallic element, which assumes a tubular shape of high strength when extended. It can be stored in a minimum of space when flattened and coiled on a drum. Figure 5.2 depicts the STEM boom deploying from its rolled shape to its tubular shape.

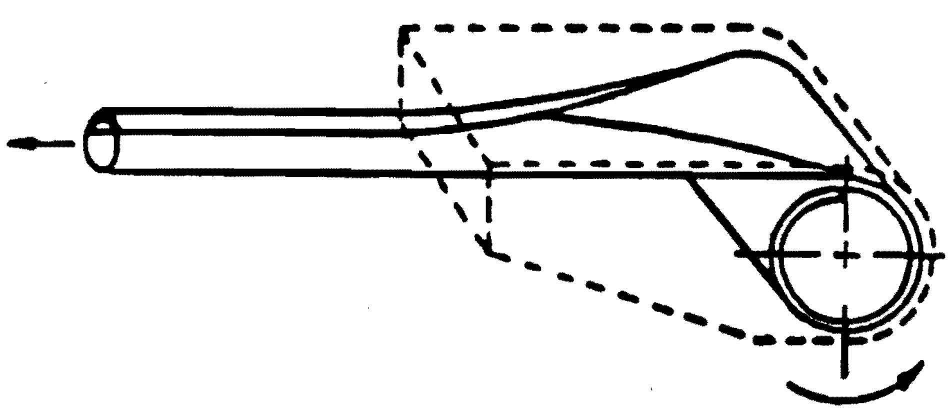


Figure 5.2: STEM Boom

The STEM is free of stress in its natural shape as a straight tube. If the element is attached to a storage drum and wound up, strain energy is stored in the element with the result that it tends to self-extend. The STEM can also be deployed by a motor driving the drum; this provides for a more controlled deployment. A number of STEMs can be wound on the same drum and thus can provide for synchronous deployment of multiple booms.

The STEM booms are primarily used as conduction antennas, but were used as instrument booms on the Viking mission.

The STEM boom is a near ideal system for the SURFER satellite for the following reasons: 1) it stores in a very small volume; 2) synchronized deployment of the four radial booms could be achieved by winding four STEM elements onto the same drum; and 3) Astro Corp. manufactures sizes appropriate for SURFER's booms.

Although the STEM is an ideal system for SURFER, there are reasons that prevent its use: 1) in view of the fact that ME 210 is an Engineering Design course, a commercial product would be inappropriate; and 2) the cost of a single STEM boom is beyond the ME 210 group's budget.

5.3.3 STACER Boom

The primary structural element of the STACER boom is a spirally wound, self-extending tube. This tube, as shown in Figure 5.3, is formed by a helically prestressed strip of metal whose overlapping coils form a rigid member when extended.

A key disadvantage of the STACER boom is that it would not be able to hold the angular position tolerance required by the search coil. Additional disadvantages as well as the advantages of the STACER boom are similar to those of the STEM boom. Advantages include: 1) compact storage volume; and 2) existing sizes that could be implemented on the SURFER satellite. Disadvantages include: 1) cost; and 2) the lack of design content for this course.

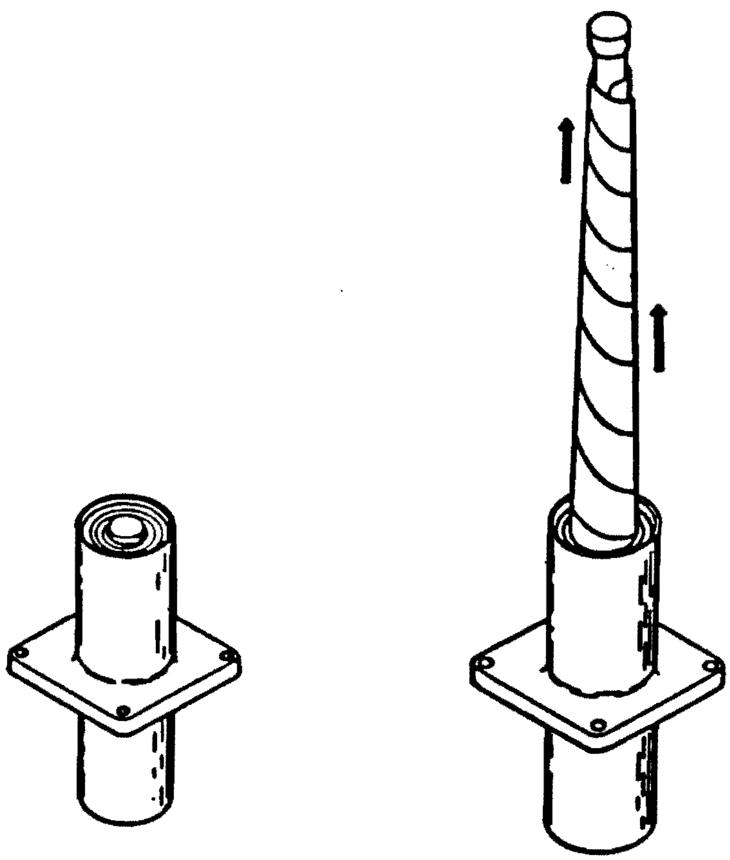


Figure 5.3: STACER boom

5.3.4 Folding Arm

The folding arm consists of a number of members pinned together at their ends and extend like an arm. The individual members can be of any type of cross section: tubular, rectangular, etc. The length of each member, however, is limited to a major dimension of the satellite. In a typical application, only two to three members comprise a folding arm; as the number of members increases, so does the difficulty of synchronizing the members during deployment. Figure 5.4 depicts the folding arm in a typical stowed and deployed configuration.

Folding arms are typically used to deploy large structures, such as solar arrays and antennas, but have been used to deploy instruments as well. The folding arm represents a simple way to deploy an instrument and has been chosen as the basis for our mechanism design that will deploy the radial sensors.

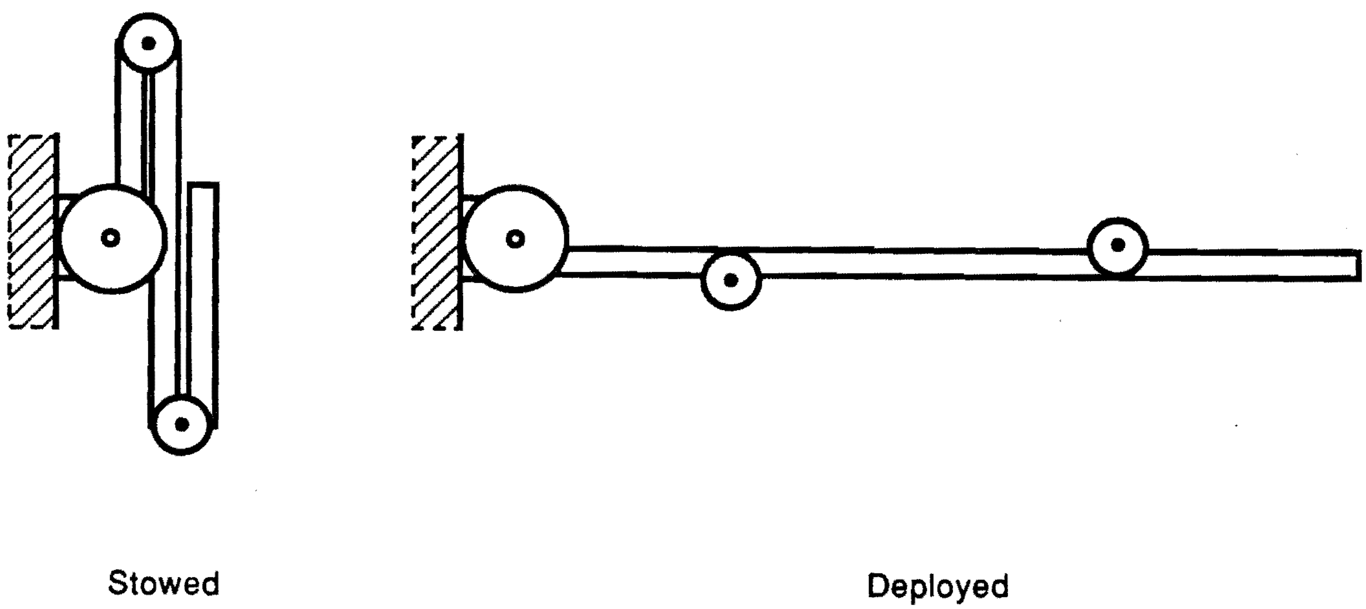


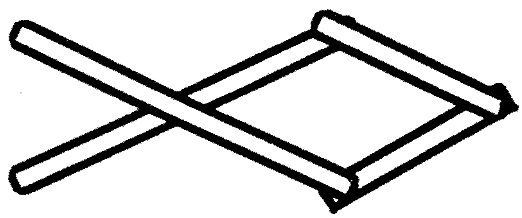
Figure 5.4: Folding Arm

5.3.5 Tongs Boom

The tongs boom consists of a series of links pinned at their centers and ends. Figure 5.5 shows a tongs boom in a typical stowed and deployed configuration. This boom can be deployed by fixing the center pin of the inboard link and driving the innermost ends of the inboard link in toward each other by a motor driven lead screw. Pairs of tongs booms have been used to deploy sections of solar panel arrays, however there is no flight experience using this design to deploy instrumentation.

An advantage of the tongs boom is the synchronized deployment of the booms by using the same motor and lead screw combination to drive a pair of opposed booms. The disadvantages of the tongs design are that a relatively large stowage volume is required, and that force multiplication occurs in the links. The force multiplication is a result of all of the links being loaded in bending; this consequently increases the loading on the links. This design was dismissed as the folding arm requires less stowage volume, does not experience force multiplication, and does not have the added complexity associated with electric motors.

Stowed



Deployed

Figure 5.5: Tongs Boom

5.3.6 Other Designs

Telescoping boom: Similar to an automatic car antenna, a telescoping boom consists of concentric tubes in graduated diameters. There is no known flight experience with the telescoping boom, but models have been developed for space applications by Sanders Assoc. Inc. in New Hampshire and by the Royal Aircraft Establishment in England.

Various methods exist for deploying the sections. One possible method is to "push" the smallest member out with a wire loaded in compression (this is similar to what is done in a automatic car antenna). Another method is to use a complicated pulley and cable system where a set of cables wind their way lengthwise over pulleys down every section, ending with the innermost section which is deployed last.

The SURFER satellite would require approximately 6 sections to meet the maximum deployment distance. With the first method, approximately 150 lbs. of compression are required to overcome the worst case sliding friction between sections. A design to meet this requirement could not be achieved; therefore, the design was dismissed. The cable and pulley method would require an inordinate number of pulleys, rollers, pins and other small fixtures, which make the system unnecessarily complex, and therefore was dismissed.

Inflatable tubes: Gas tight tubes (typically of sandwich construction using mylar and foil) are flattened and folded for storage. An external gas supply then inflates and erects the tubes. They may be used in a multiple tube system, which is then stiffened by spacers and guy wires. Several loop antennas of 6 to 9 ft. diameter were flown on the OGO series (Stanford University experiments). Also, Lockheed M.S.C. has done development work on inflatables.

Pressurized systems are generally avoided for space applications based upon the severe consequences of leakage in the system, and thus are not being considered on the SURFER mission.

5.4 Patents

A search of the patent information in Meyer Library at Stanford University was conducted under the following categories:

- Subject Aeronautics, 244
  - deployment mechanisms, 1
  - spacecraft, 158R
    - w/solar panel, 173
- Subject Bolts and Restraining Devices, 411

Most of the information discovered dealt with the deployment of large solar panels or antennas, and was not applicable. Some information was found concerning STEM booms (patents 3,144,104; 3,144,215; 3,243,132; 3,371,453; and 3,380,204); however, these patents are held by Astro Research Corporation and the information received from Astro is considerably more detailed and more useful than that in the patent abstract.

Ametek, Inc. holds the patent on the STACER boom under the following numbers: 3,467,329; 3,587,658; 3,680,802; 3,743,267; 3,822,874 and 3,863,405. Wietzmann Consulting, Inc. in San Francisco manufactures the STACER boom under direct license from Ametek, Inc. As was the case with the STEM boom, the manufacturer's literature about the STACER boom is considerably more detailed and more useful than the information contained in the patent abstract.

6.0 DEPLOYMENT MECHANISM SOLUTION

6.1 Satellite Configuration

Appendix I depicts the entire satellite from a top view and a break-away side view. The folding arm is shown in each of the four radial positions; however, STEM booms are shown in each of the two axial positions. The folding arm will not meet the volume requirements of the axial positions, so STEM or STACER booms--each of which store in very small volumes--are being used in the axial positions. For specifications on the STEM and STACER booms see Appendix F.

Although STEM booms are capable of deploying all the sensors on the SURFER satellite, there are reasons which prevent its use for the radial sensors: 1) in view of the fact that ME 210 is a Design Engineering course, a commercial product would be inappropriate; and 2) the cost of a single STEM boom is beyond the ME 210 group's budget.

6.2 Folding Arm Overview

The folding arm was chosen to be the design solution. It meets all the functional specifications while minimizing parts and not using heavy electric motors. The key features of the folding arm include: three links pinned at their ends; kinematic constraint cables which synchronize the deployment of the links in a linear manner; torsion springs at the joints which provide a positive deployment force; a restraint cable which reduces the deployment speed and synchronizes the deployment of all four radial booms; and two snubber assemblies which provide the boom with hard supports for protection from the severe launch loads. On the next page is a photograph of our prototype model which incorporates all of these features. Appendix J displays the final design of the folding arm in a partially deployed position. Appendix K contains the detail drawings for the machined parts.

The following sections examine each of the components in detail, providing the underlying assumptions and design guidelines which drove the design to its final state.

6.2.1 Links/Joints

Three aluminum links of lengths 16", 28" and 19.5" comprise the main elements of the arm. In addition, there is an aluminum "Base Mount" which connects the inboard link to the satellite structure. The links are pinned at their joints with .25" dia. stainless steel pins in a clevis-within-clevis configuration shown in Figure 6.1 and the following photograph. The clevis arrangement eliminates asymmetric loading at the joints, and spreads any torques out over a large moment arm. If a clevis pin should seize against one of the links, it would still be able to rotate relative to the other link; thus, the joint is redundant in rotation.

A 2 in-lbf torsion spring around the middle of the clevis spring provides a positive deployment force for the boom (in addition to the centrifugal force induced by the spinning satellite). The springs are sized to provide a safety factor of three comparing the deployment force to the worst case static friction in the joints. The circular sections at the end of each link serve as pulleys for the kinematic constraint cables, which are the next component to be examined.

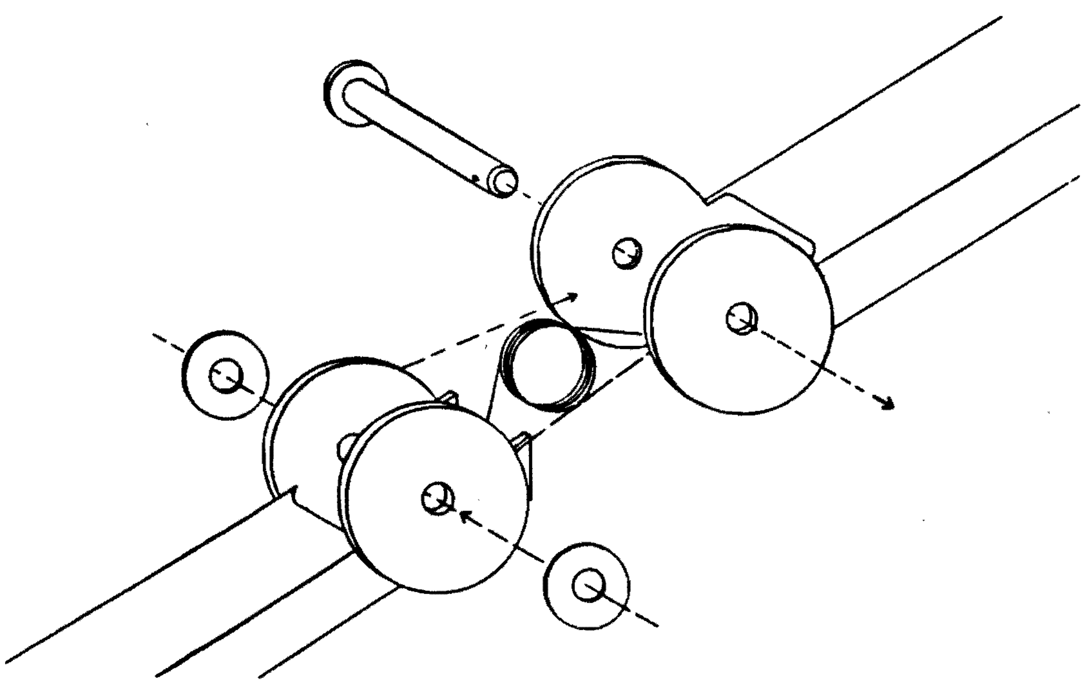


Figure 6.1: Joint Configuration

6.2.2 Kinematic Constraint Cables

A very simple method to ensure synchronization of the links is to create a four bar mechanism. This extra "link" will provide driving torque to a link that is extending too slowly. Conversely, this extra "link" will provide a restraining torque to a link moving too quickly.

A cable system has been devised to create this extra "link". If the extra member were a rod it would see both tension and compression loads. Because of this, two cables must be used to provide both positive and negative control over the linkages. Because the cables are on opposite sides of the pulley, as seen in Figure 6.2 and the following photograph, one cable will see tension loading at all times. The cables have turnbuckles which will be used to provide a preload tension. In addition, two sets of kinematic constraint cables on both sides of the link prevent any asymmetric loading at the joints.

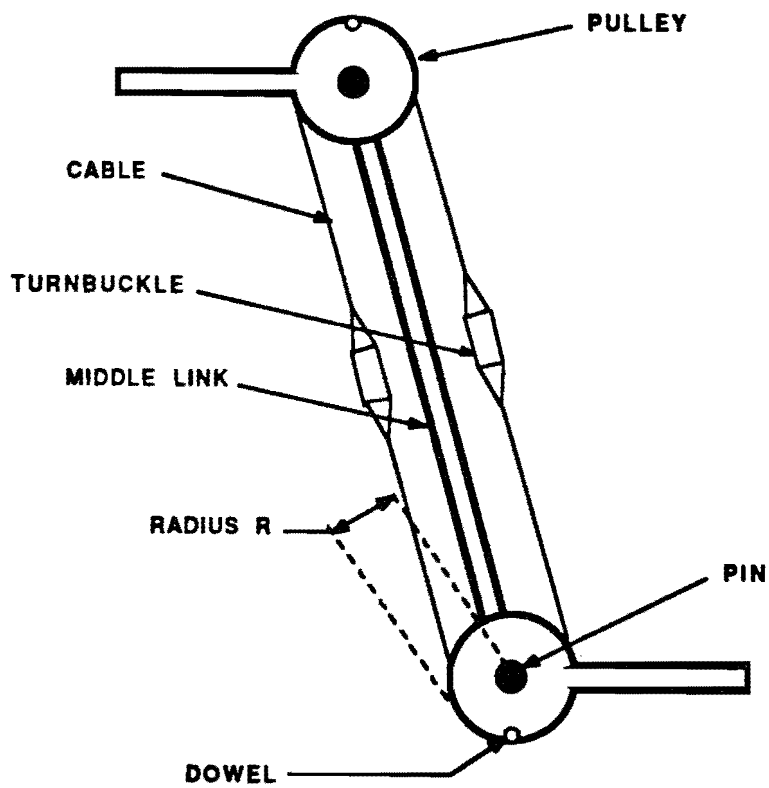


Figure 6.2: Kinematic Constraint Cables

By running the cables over pulleys at the ends of the links, one achieves a permanent separation of the cable from the pulley. It is this separation, the radius of the pulley, which provides the moment arm for the torque that is developed through the cables on the arm. However, the determining factor was the minimum bend radius of the cable selected. We selected a $^{3}/_{64}$" dia. stainless steel cable with a 7x19 construction and a proof rating of 225 lb. The minimum pulley diameter for this of cable is 1.4 in.

There are two constraint cables assemblies, each forming a loop. The first set wraps around the base mount and the middle link's pulley, synchronizing the inboard link and middle link. The second set wraps around the inboard link's pulley (which is inside the middle links pulley) and the outboard link's pulley; this connection synchronizes the inboard and outboard links. The cables are fixed to the pulleys by running them through, then swaging them to, a $^{3}/_{16}$" dowel which sits in a slot in the pulley. Any tension in the cable will be reacted at the pulley through this dowel. This arrangement is shown in the photograph of the link joint shown above. This completes the four bar mechanism which will synchronize the motion of the base mount with the middle link, and the inboard link with the outboard link.

6.2.3 Restraint Cable

The partially deployed boom in Appendix J also depicts a restraint cable, which is attached to the outboard link and then wrapped around a central spool in the middle of the satellite. The spool is then fastened to a centrifugal damper. Note that two cables will ultimately be used for each arm, one on either side of the arm. This will be further discussed in the following section. The centrifugal damper slows down the deployment velocity of boom via the restraint cable. Smaller deployment velocities reduce the loads on the boom produced both by the Coriolis effect and impact loads (the shock produced when the boom reaches its fully deployed position and stops). Since the restraint cables from all four radial booms are wound around the same spool, they will all deploy at the same speed, fulfilling the synchronization requirement.

6.2.4 Preload and [illegible]

In order for the [illegible] being preloaded. To [illegible] each arm will be preloaded to approx[illegible] against snubber assemblies [illegible] one at the bottom of the satellite [illegible] assemblies are actually a pair of [illegible] near the preload, they are [illegible]ation is such that any combination [illegible] assemblies and the base mount.

The four radial booms [illegible] at the top of the spool. After the [illegible] the restraint cables from all four [illegible] synchronous deployment prevents [illegible] requirement.

7.0 TEST PLAN FOR THE FOLDING ARM BOOM

7.1 Planned Test Goals

Our test plan for the folding arm has three levels of goals.

<u>Primary Goals</u>

- measure the simultaneity in the deployment of opposed booms
- determine the deployed position and the repeatability of deployment

The primary goals will determine the ability of the folding arm to meet the functional specifications. Fulfilling only the primary goals will be adequate for a successful test program.

<u>Secondary Goals</u>

- determine the dynamic loads on the arms during deployment
- determine the impact loads at the end of deployment

Fulfilling the secondary goals is not necessary for a successful test, however it would be of great use in refining the next generation folding arm.

<u>Tertiary Goals</u>

- examine the effects of piece part failure

The tertiary goals would yield interesting information but will only be performed after the first two goals are met.

7.2 Test Plan

7.2.1 Static Tests

To obtain the information to achieve our test goals, we used a sequence of tests examining static and dynamic deployment. First we ran two sets of static tests. In the first test, we deployed each arm individually to ensure that each folding arm's hardware was functional. In [illegible] folding arms simultaneously to check the [illegible] compensation mechanism, and to examine [illegible]. The arm deployment was filmed using [illegible] the video recording during playback, [illegible] of the arms. On the next two pages is a sequence [illegible] deployment of the folding arms.

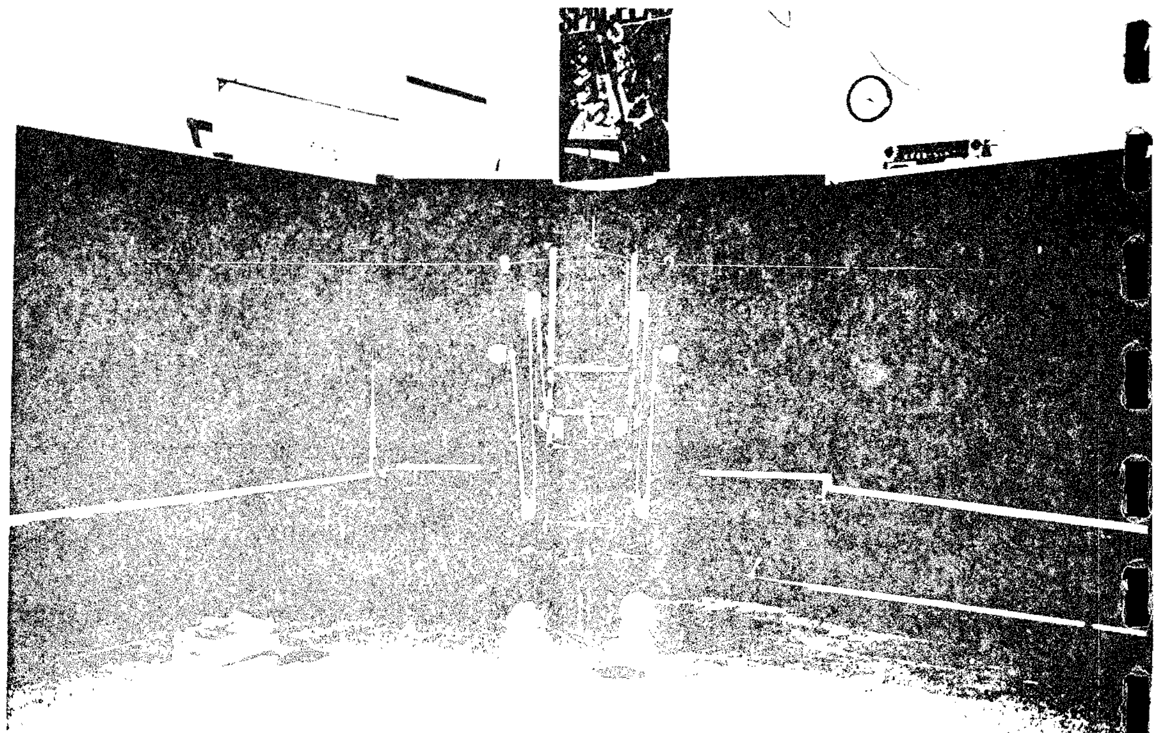
7.2.2 Dynamic Tests

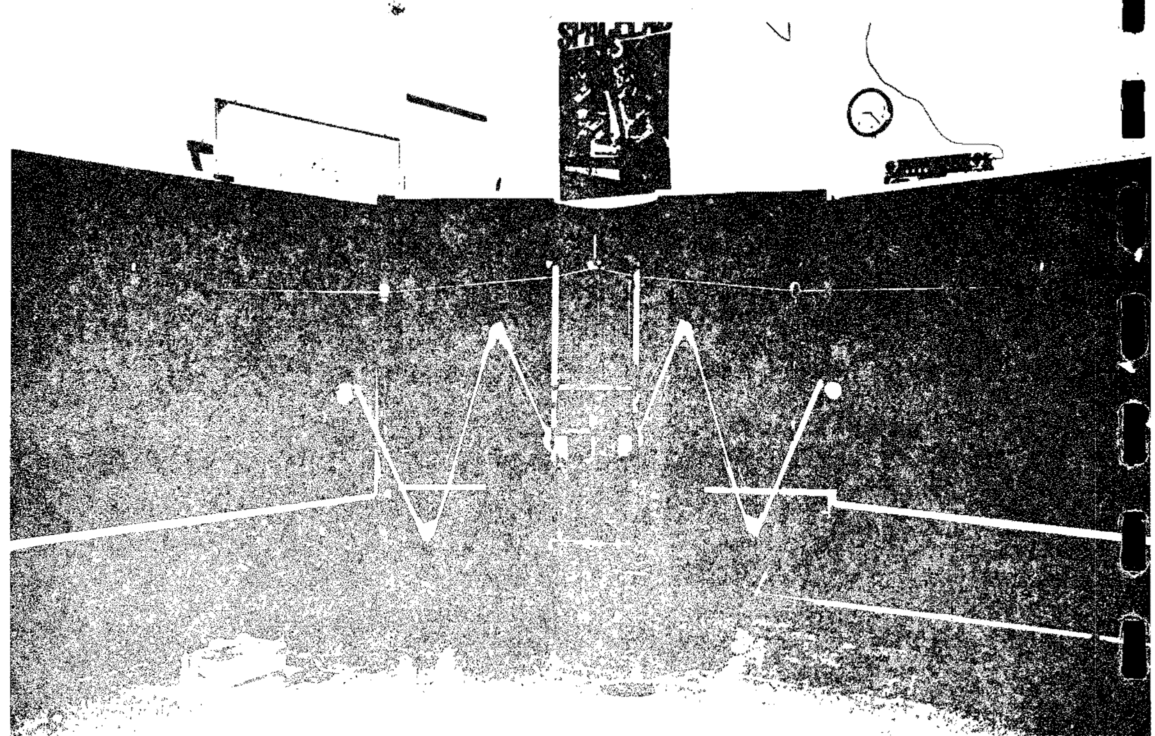
We ran the dynamic testing [illegible] velocity up to the maximum seen by the satellite [illegible] we ran the model at low angular velocities (0-[illegible] [illegible] test stand. In the second set of tests we ran [illegible] RPM) to examine deployment under less than [illegible] integrity of the arms under small increases [illegible] ran the model at full speed (40-60 RPM) so each [illegible] under full mission loads. All tests were filmed [illegible] primary source of data.

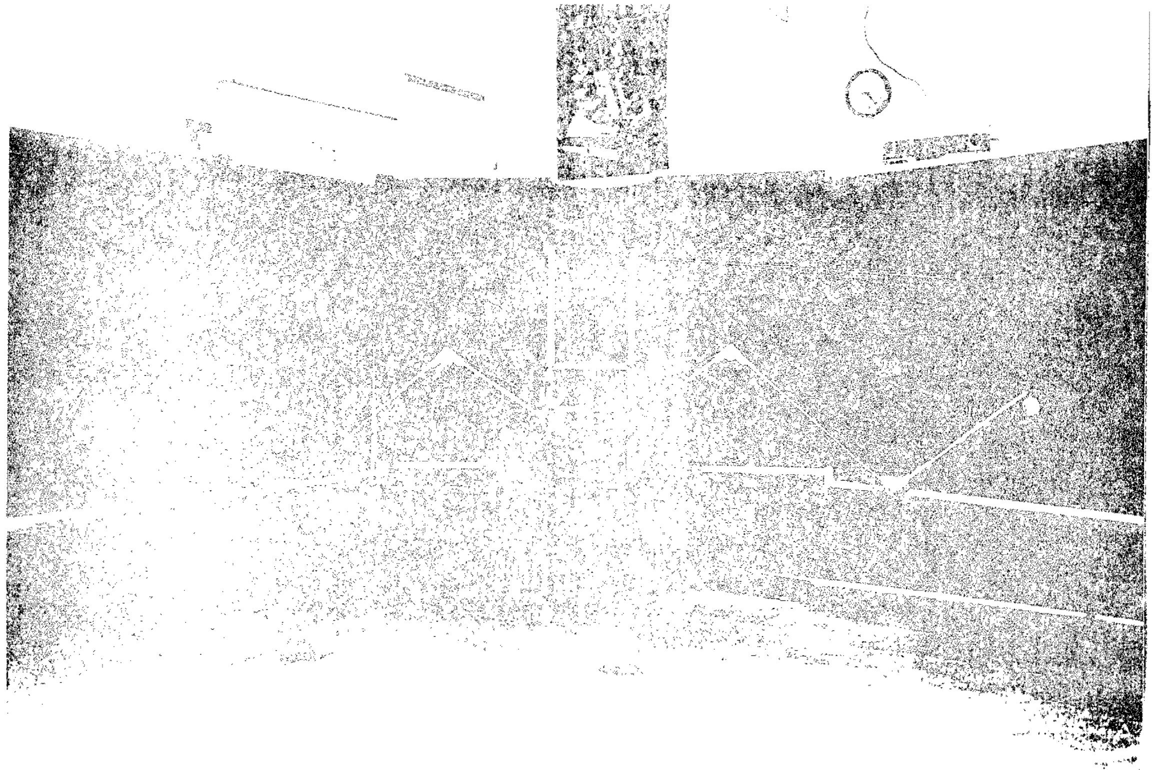
7.3 Test Setup

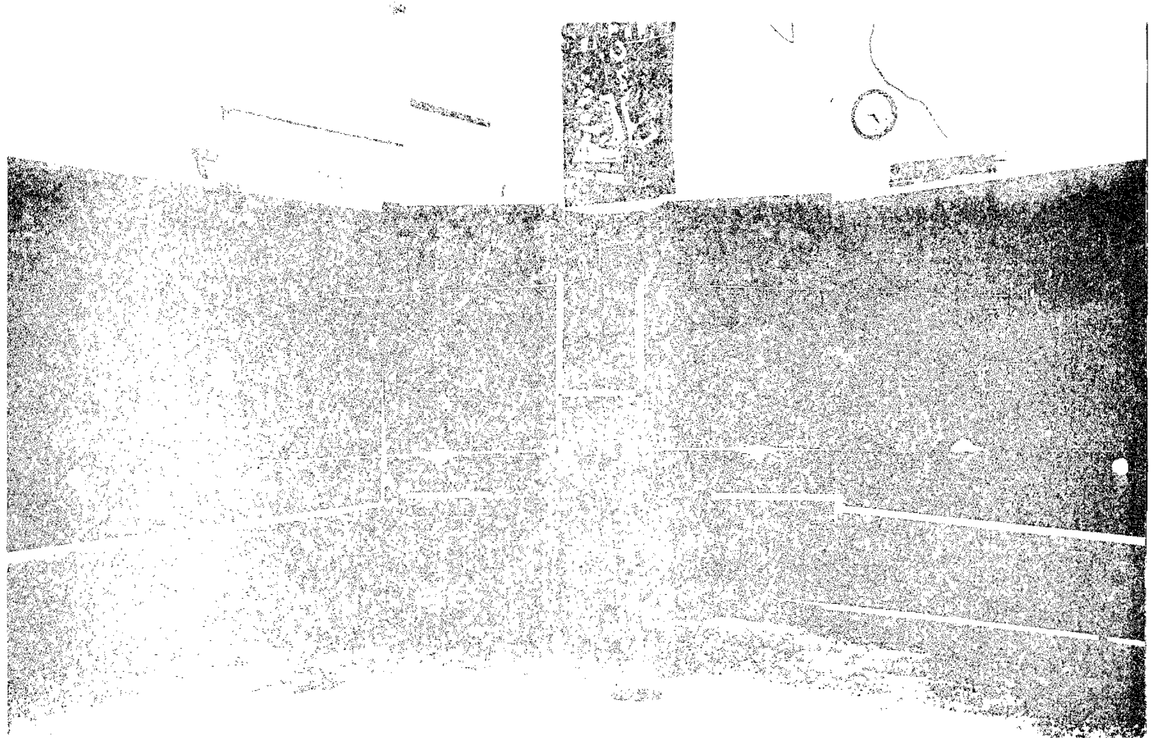
Our test model used only two [illegible] was adequate to achieve all of our test goals. [illegible] check for simultaneity in deployment. Four folding arms [illegible] exists in the arrangement of the four radial [illegible] Testing with four radial arms would not yield [illegible] add unnecessary complexity and cost to the [illegible] arm and four arm test is that the two arm setup will [illegible] of inertia by a factor of ten but rather by ~5.7. This [illegible] will see slightly higher loading than in a four arm [illegible]

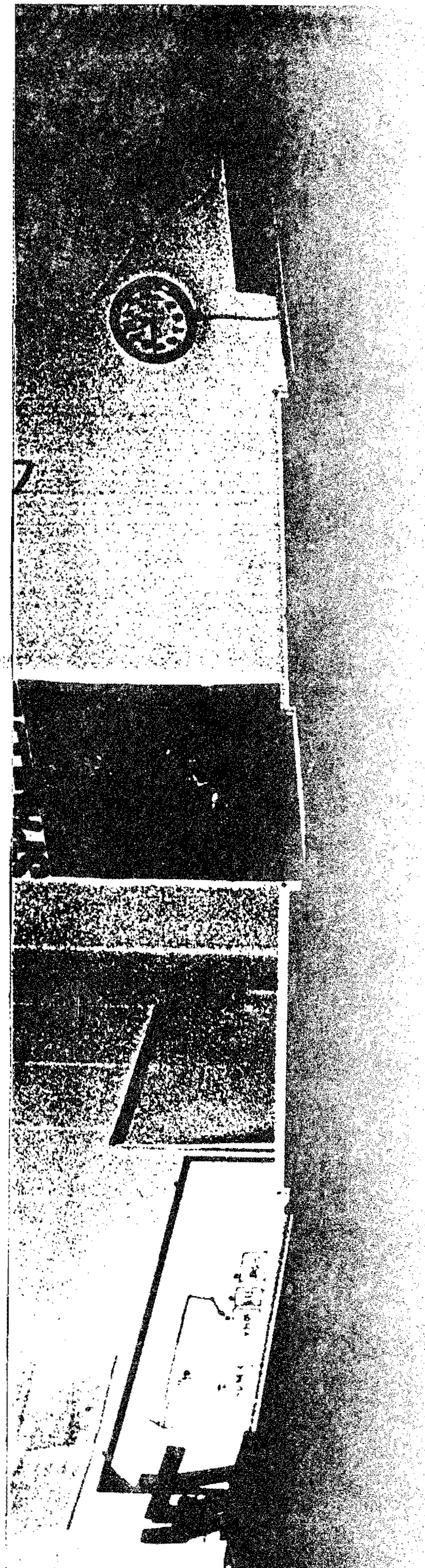
A test fixture which models [illegible] provides arm attachment points similar to the [illegible], and provides a way











to remove some of the gravity loading on the arm was required. We designed and built a test fixture that provides these capabilities. A photograph of the constructed test setup is shown on the previous page. The fixture is described below.

The base of the test setup was constructed from 2x4 lumber to provide a stable support for testing and handling loads.

To support the 1g loading on the arm, which is not seen in space, we supported the end of the arm by a cable attached to a constant force spring on a roller. The roller was supported on a cable suspended along a beam fixed to the top of the frame. This allows for small amounts of vertical travel without losing tension in the support cable. For a detailed photograph see the top of the next page. The beam was constructed from a 1"x1" x $^{1}/_{16}$" square aluminum extrusion with a total length of 122". Lightening holes were drilled in the beam to match the spin moment of inertia of the test setup to the actual satellite and a fairing was added to reduce the significant air resistance seen at high RPM.

The fixture is made of 1"x1"x$^{1}/_{8}$" thick aluminum "L" sections and plates and is mounted on a lazy susan bearing which enables the fixture to be spun. A tachometer was used to determine the angular velocity of the fixture during the test runs. Note that the tachometer data was used for feedback during the tests and was not used in the analysis. We spun the fixture by pulling on a rope wound around the base of the fixture. The fixture was spun up to an angular velocity slightly higher than the required velocity and when the fixture had slowed down to the test velocity the arms were released. The spool was secured with a pin, which locks the arms in the stowed position. This pin can be seen in the photograph of the spool/damper assembly on the bottom of the next page. A piece of string was run from the pin down to the base of the fixture and out through the center of rotation; pulling the string released the arms and began the deployment.

The deployment velocity during the test was controlled using a centrifugal damper acquired from a rotary-dial telephone. This can be seen attached to the spool in the photograph on the bottom of the next page. To better understand the relationship between the torque applied to the damper and the angular velocity tests were

performed on the test hardware. The results, shown in Figure 7.1, suggest that the damper operates at a constant angular velocity of approximately 4 rad/sec. Under the higher loading of the actual test, the damper operated at an angular velocity of 6.4 rad/sec.

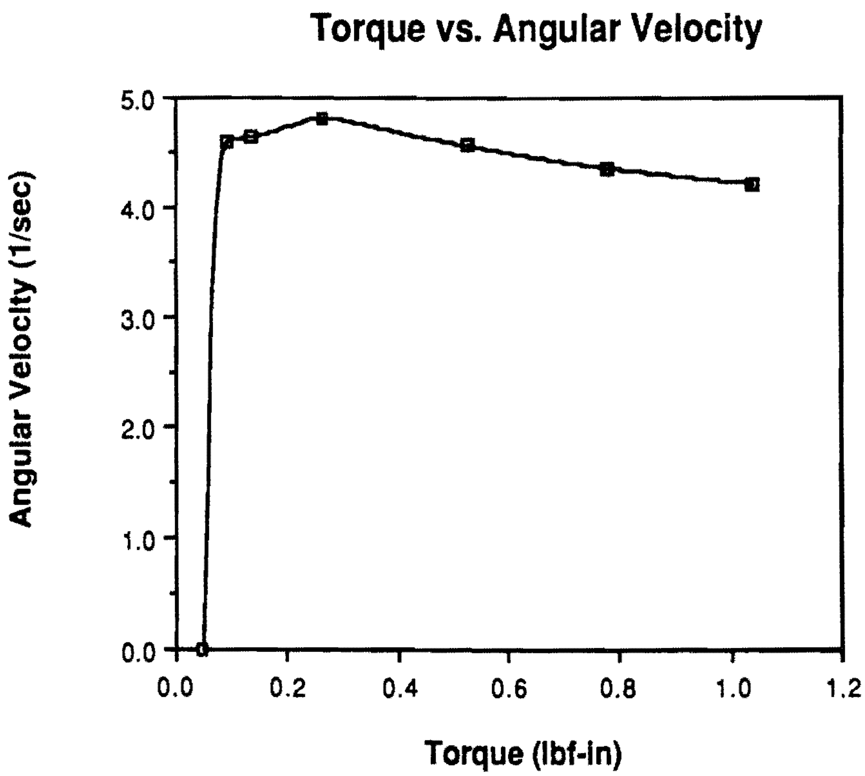


Figure 7.1: Centrifugal Damper Test Data

7.4 Achievement of Test Goals

The test program was a success as both the primary and secondary goals for testing were achieved. Simultaneity, repeatability and deployed position were measured from the video tape. In addition, we measured position versus time to derive the impact and dynamic loads.

The tertiary goal, piece part failure,was not examined. This test was decided to be unnecessary at this stage in the design. Examination of this sort would yield interesting information, however, due to time constraints this type of testing was not done. In addition, piece part failure would risk damage to the prototype model of the arms. Damage to the arms is not acceptable to the SURFER project at this time because of the value of keeping a working model for engineering reference and for use as a showcase model for visitors.

7.5 Summary

We achieved both the primary and secondary test goals of our test plan. Primary goals were to measure simultaneity in the deployment of opposing booms and to determine the deployed position and repeatability of the deployment. Secondary goals were to evaluate the dynamic and impact loads seen by the boom during deployment. The tertiary goal of examining the effects of piece part failure were decided to be unnecessary at this time. The testing program provided all the information necessary to properly evaluate our design at this stage in development and therefore was a success.

8.0 EVALUATION OF THE FOLDING ARM

Below is a comparison between the critical design requirements and the degree to which the Folding Arm design meets these requirements. In addition, our assessment of the dynamic and impact loads is given.

8.1 Instrument Positioning

	required	capability
a) length	60.0"	60.4"
b) tolerance	± 3.0"	+0.3" - 0.4"
c) angular tol.	±1.0°	± 1.0°

The length tolerance is the sum of the worst case tolerances, thermal changes and random variations due to deployment. During testing, we measured the distance the arm had deployed by inserting shim stock between the link stops; this enabled us to calculate a deployed length variance. In all tests we measured this variance to be +0.0 inches, -0.1inches. The angular tolerance is the sum of the worst case tolerances.

8.2 Dynamic Stability

In order to keep the satellite dynamically stable during deployment of the payload, the radial booms must fully deploy within the simultaneity tolerance, which is given as a percentage of the deployment time. We measured the simultaneity directly from the video footage by counting the number of frames between the full deployment of the first and second arms. In all 8 dynamic tests that we examined, the arms fully deployed within 1 frame which corresponds to a simultaneity of $^1/_{60}$ second.

	required	capability
simultaneity (% deployment time)	10%	0.14%
payload	2.5 lbm	2.5 lbm

The measured deployment times averaged 11.6 seconds. During testing, 2.5 lbm weights were mounted at the end of the outboard links as per the design specifications.

8.3 Internal Satellite Volume Used

required: 1021 in^3 capability: 572 in^3

By making use of the otherwise unused external volume both above and below the satellite, we were able to reduce the internal volume used.

8.4 Deployment Mechanism Mass

required: 25 lbm   capability: 18 lbm

The weight capability listed includes four radial booms, the snubbers, spool, damper, and axial booms. The payload, payload mounting hardware, and coaxial instrument cables are not included in either the requirement or capability.

8.5 Environmental

The snubber assemblies and preloaded restraint cables will support the loads imposed on the folding arm boom during launch. The arms are capable of deploying in the required 40° F to 140° F range. After deployment the arms are capable of withstanding temperatures up to approximately 500° F. Extremely low temperatures will not cause the arm to fail after it has deployed. Calculations concerning the thermal effects on the folding arm can be found in Appendix E.3.

8.6 Reliability

The deployment mechanism has redundant piece parts in all of its components. The centrifugal damper is not redundant, however it was outside the scope of our project. We do recommend that a pin puller disengage the centrifugal damper from the central spool some time after the first pin puller has released the spool. If the centrifugal damper has frozen then the arms will still deploy, although it will be an undamped deployment.

8.7 Dynamic and Impact Loads

We determined the dynamic and impact loads by an analysis of the position versus time data from the video footage of the deployment tests. For information about the test procedure see Section 7.0. For information about the data analysis see Appendix A. The maximum Coriolis force applied to the arms was 1.25 in-lbf. Using a conservative impact model, which assumes that only the link stops deform, the stresses in the link stops are:

$$\sigma_1 = 37.8 \text{ ksi}$$
$$\sigma_2 = 42.0 \text{ ksi}$$
$$\sigma_3 = 18.5 \text{ ksi}$$

This model is conservative as the yield stress for aluminum 6061-T6, the material the prototype arms are made of, is 40 ksi and we observed no deformation of the link stops. Using a less conservative model, which assumes that the block that the link stops run into deforms as much as the link stops, the stresses in the link stops are:

$$\sigma_1 = 26.7 \text{ ksi}$$
$$\sigma_2 = 32.5 \text{ ksi}$$
$$\sigma_3 = 13.0 \text{ ksi}$$

The actual impact loads are somewhere between the two estimates. At worst the actual loading is 40 ksi, the yield strength of 6061-T6 aluminum which is the material used for the prototype arms. The flight hardware will be built from 7075-T651 aluminum which has a yield strength of 73 ksi, which gives a minimum safety factor of 1.8. Although the link stops have proved adequate for damped dynamic deployments and undamped dynamic tests were not performed, we feel that a full speed (50 rpm) undamped deployment would deform the current link stops.

8.8 Summary

Stowage volume is limited on small, spin stabilized satellites. In addition, they generally have a small capacity for electrical power. The folding arm boom represents a unique solution to nonmotorized instrument extension while maintaining high positioning accuracy. The folding arm prototype has been developed on a small budget and thus may lead to a cost effective means of extending instruments several times the major dimension of small satellites.

9.0 RECOMMENDATIONS

We recommend the following actions for further work on the deployment mechanism:

1) Once the instruments' geometry are known in detail, design and construct the mounting fixture which will attach them to the end of each outboard link.

2) Identify commercially available and flight qualified rotary dampers which would be applicable to this project. The ideal damper would deploy the booms at a constant radial velocity, similar to the centrifugal damper used in our test set-up. Weitzmann Consulting has a friction damper with flight experience which is used with the STACER boom. Another attractive alternative is an eddy current damper, which has been used in numerous space applications. Purchasing a commercial damper would avoid the costs associated with development of space hardware.

3) Identify commercially available and flight qualified non-pyrotechnic pin-pullers. It is a requirement that there be no pyrotechnic devices inside the Hitchhiker G Canister. We know that an expanding wax pin puller has been developed, but we do not know if there are any that are flight qualified and commercially available. Another option is a spring loaded pin released by a burn wire.

4) Make the cross section of the links in the shape of a U-channel in order to reduce the mass of the links. The existing cross section is a solid rectangular bar of aluminum because we decided the additional costs associated with machining a more complex part were unnecessary for this prototype. It is important that in the redesign of the link that neither strength nor stiffness be significantly altered.

5) Increase the width of the stops at the joints from 0.075" to 0.15". At this width, they will be able to withstand the impact loads of a deployment <u>without</u> damping, which all other boom components are currently capable of surviving. This could be taken from the internal area of the clevis because that gap was sized for a larger torsional spring than was finally used.

6) Examine the effects of piece part failure. This would yield interesting information about the failure characteristics of the folding arm, and might provide ideas for

minimizing the effects of a failure. An example of such a test would be to detach the kinematic constraint cables on one side of the links. In this situation, the effects of cable failure leading to asymmetric loading at the joint could be examined.

7) Test the preload and snubber system. In order to preform the preload tests the following steps must be done:

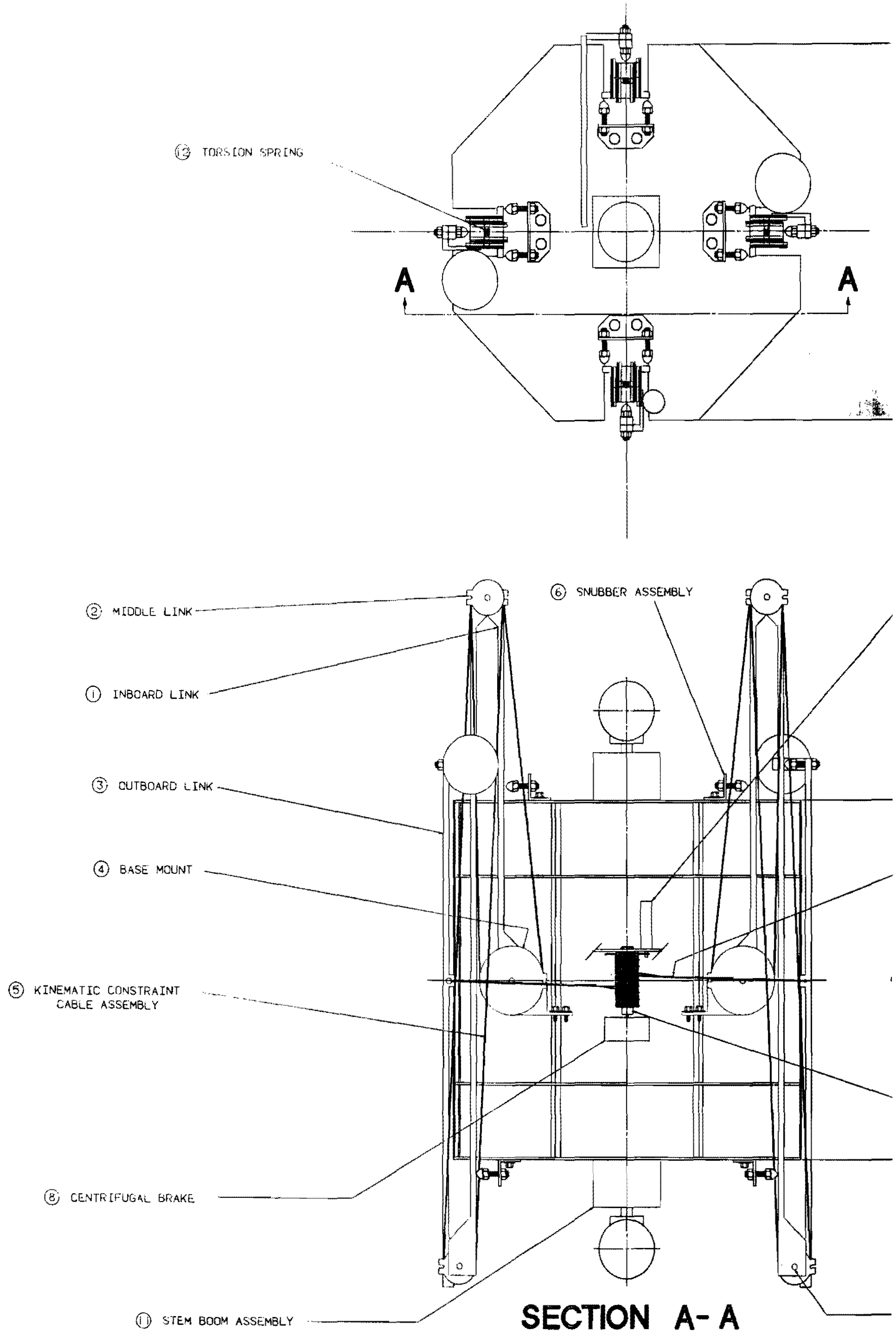
a. The instruments and instrument mounting fixtures must be designed and built. Note that the instruments should be cradled if they extend on to the surface of the satellite.
b. Two restraint cables must be attached to each arm. Only one restraint cable per arm was needed for the dynamic tests.
c. Construct and mount the preloading tabs onto the links. These are the tabs with spherical sockets which snub up against the snubber assemblies. To prevent cold welding under high loads and vibration, it is necessary to make the snubber bolts and the preloading tabs from different materials. Since the snubber bolts are stainless steel, it is recommended that a hard plastic, possibly Delrin, be used within the socket on the preloading tabs. Application of a dry lubricant, such as molybdenum disulfide, could also help prevent cold welding.
d. Construct the actual snubber assemblies to be mounted onto the satellite structure. The carriage bolts used on the test fixture were only to provide a stop and do not represent flight hardware. A more conical headed bolt with fine threads would be ideal. In addition, the two bolts need to be mounted 2" apart in an L-section which is mounted to the satellite structure. This provides the proper base necessary for adequate rotational constraints.

8) Integrate the folding arm fully with the satellite structure. The base mount is currently designed to mount onto the test fixture. The base mount should be designed to integrate with the satellite structure once the structural design is finalized. In addition, the integration of the spool/damper/pin puller assembly and the snubber assemblies must be considered.

9) Examine the possibility of disengaging the centrifugal damper from the spool or the damper from the satellite. This would allow the arms to deploy even if the damper has frozen. One suggestion is to use a pin puller similar to the one used for initiating deployment.

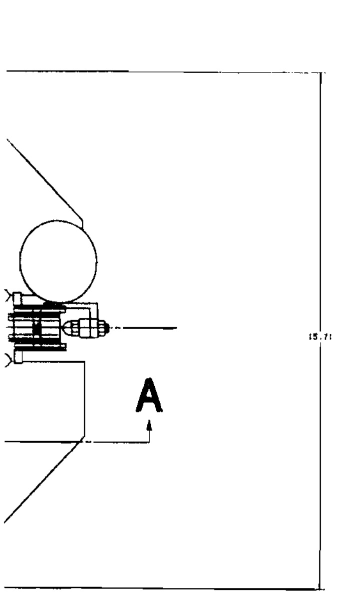
APPENDIX I

DEPLOYMENT MECHANISM LAYOUT

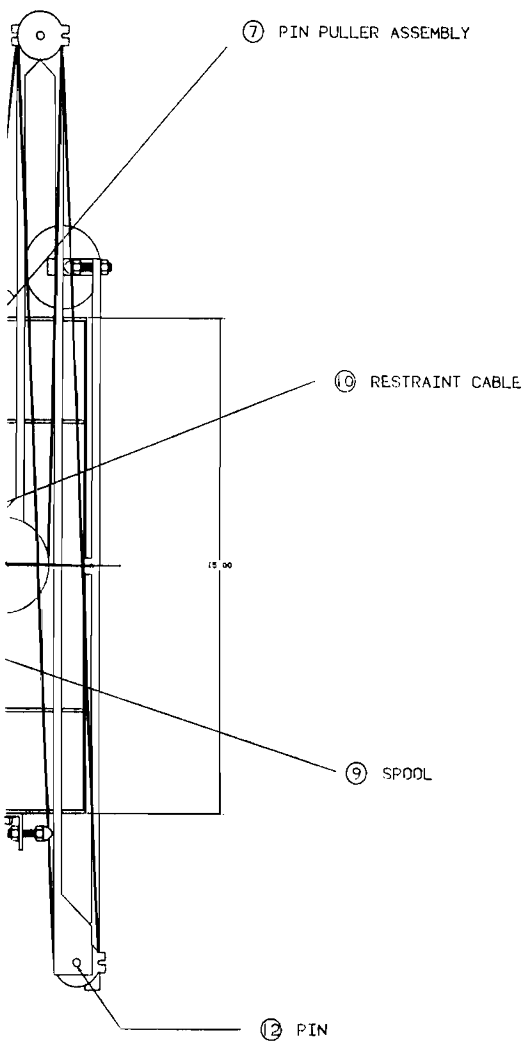


⑬ TORSION SPRING
A
A
② MIDDLE LINK
⑥ SNUBBER ASSEMBLY
① INBOARD LINK
③ OUTBOARD LINK
④ BASE MOUNT
⑤ KINEMATIC CONSTRAINT CABLE ASSEMBLY
⑧ CENTRIFUGAL BRAKE
⑪ STEM BOOM ASSEMBLY

SECTION A- A



STOWED POSITION



CALL NO.	PART NO.	QTY.	PART NAME
1	8-2001-02, 8-2002-01	4	INBOARD LINK
2	8-2001-03, 8-2002-02	4	MIDDLE LINK
3	8-2001-04, 8-2002-01	4	OUTBOARD LINK
4	8-2001-01	4	BASE MOUNT
5	SAVA INDUSTRIES	8	KINEMATIC CONSTRAINT CABLE ASSY
6	ORCHARD SUPPLY	8	SNUBBER ASSEMBLY
7	PIVOT POINT IND.	1	PIN PULLER ASSEMBLY
8	AT&T	1	CENTRIFUGAL BRAKE
9	8-2003	1	SPOOL
10	SAVA INDUSTRIES	8	RESTRAINT CABLE
11	ASTRO CORP.	2	STEM BOOM ASSEMBLY
12	PIVOT POINT IND.	12	CLEVIS PINS
13	ASSOCIATED SPRING	12	TORSION SPRING

SENSOR DEPLOYMENT MECHANISM FOR SURFER SATELLITE

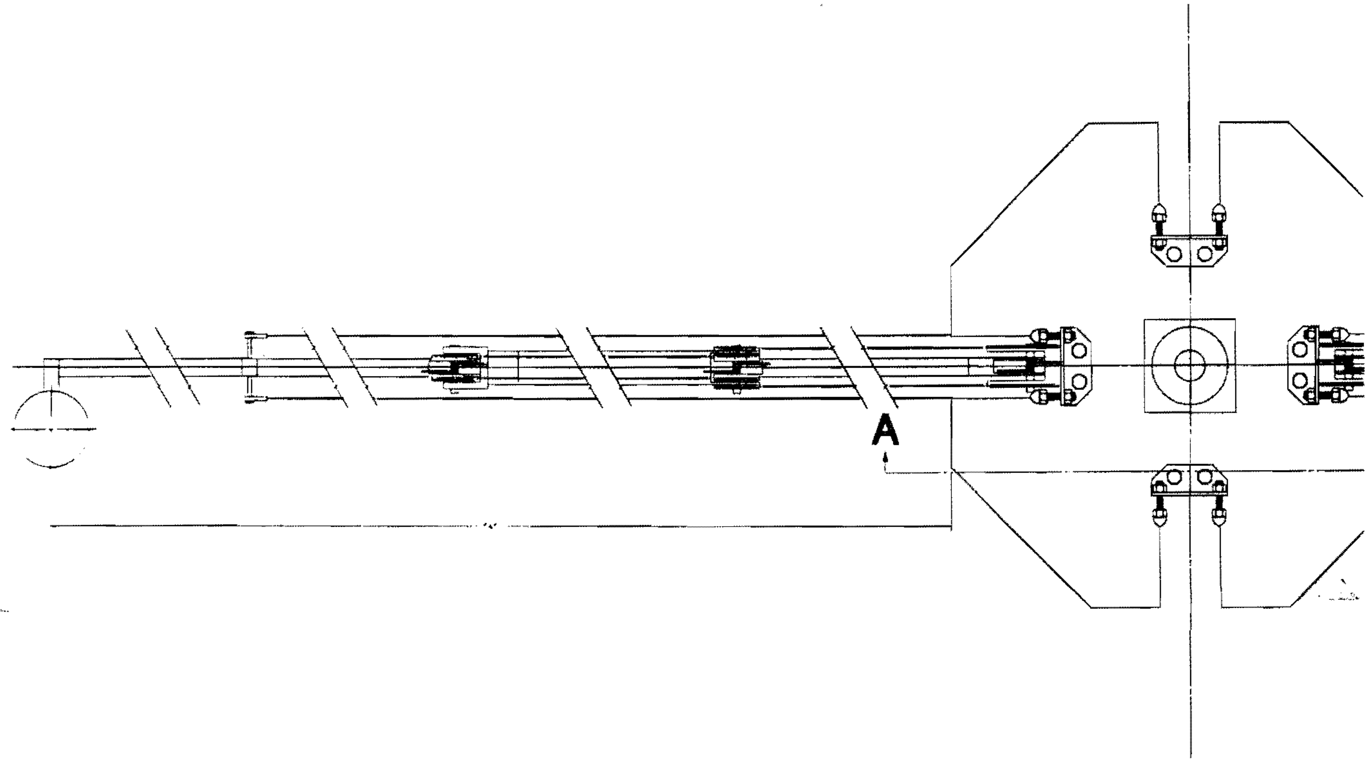
DRAWN BY: JIM FLOM

UNLESS OTHERWISE SPECIFIED DIM. ARE IN INCHES, TOLERANCES ON:

FRACTIONS=±1/16
DECIMALS: X=±.1
.XX=±.010
.XXX=±.005
ANGLES=±15 MIN

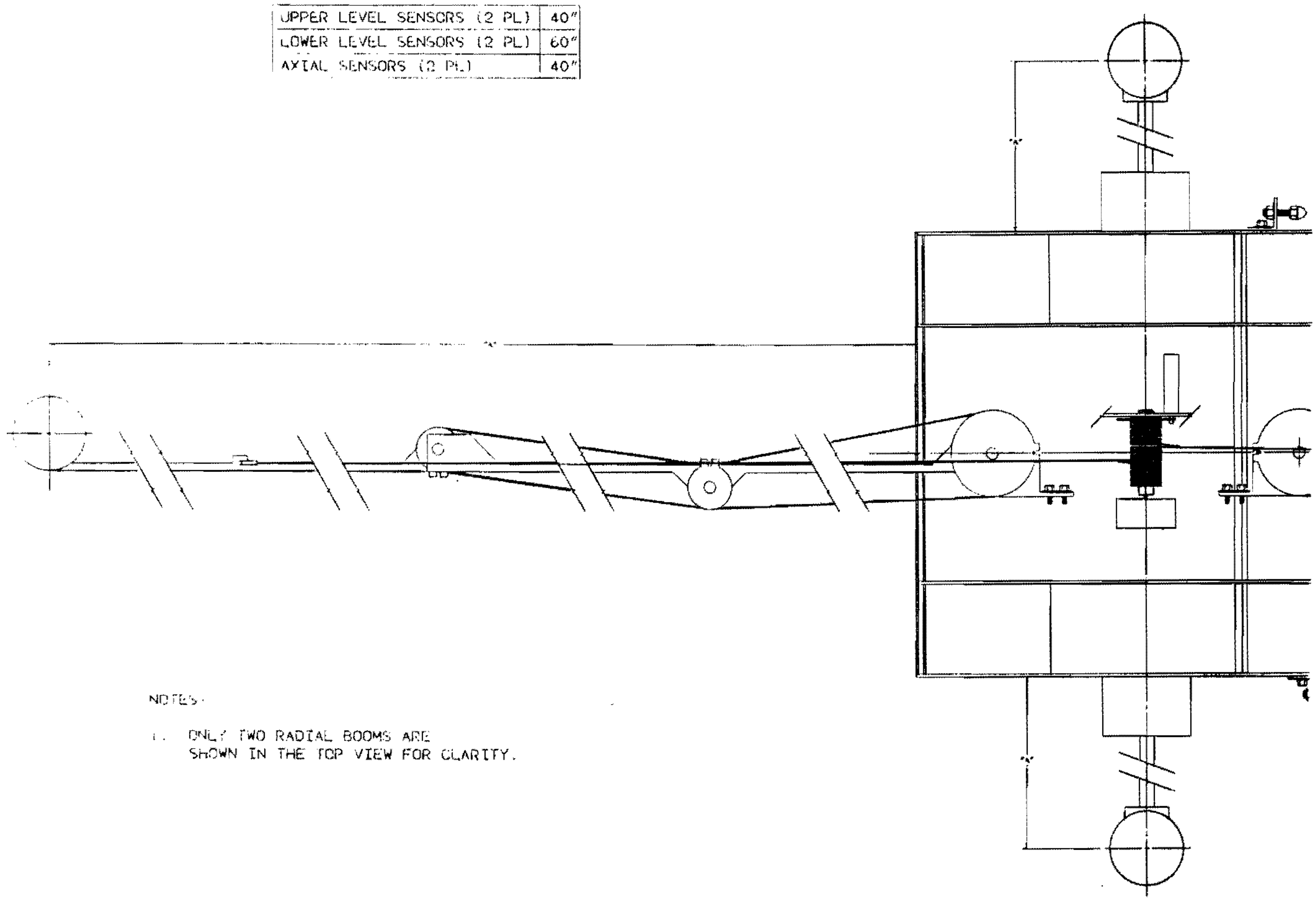
STANFORD UNIVERSITY
MECHANICAL ENGINEERING DEPARTMENT
ME 210: ENGINEERING DESIGN
TEAM MEMBERS:
BOB DILL
JIM FLOM
DON GIBBONS

E | 3/7/88 | DRAWING NO 8-2000
SCALE: 1/2 | SHEET 1 OF 2



BOOM DEPLOYMENT LENGTHS

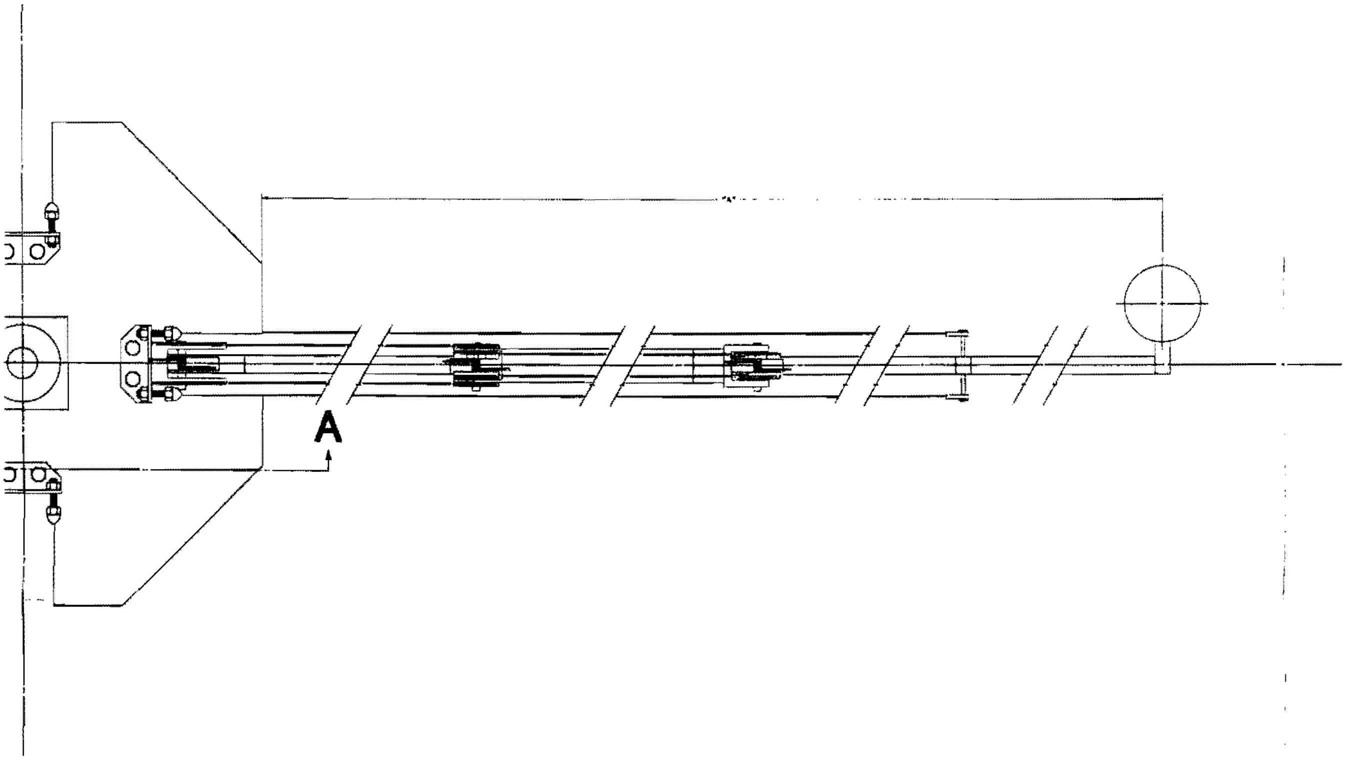
SENSOR	A
UPPER LEVEL SENSORS (2 PL)	40"
LOWER LEVEL SENSORS (2 PL)	60"
AXIAL SENSORS (2 PL)	40"



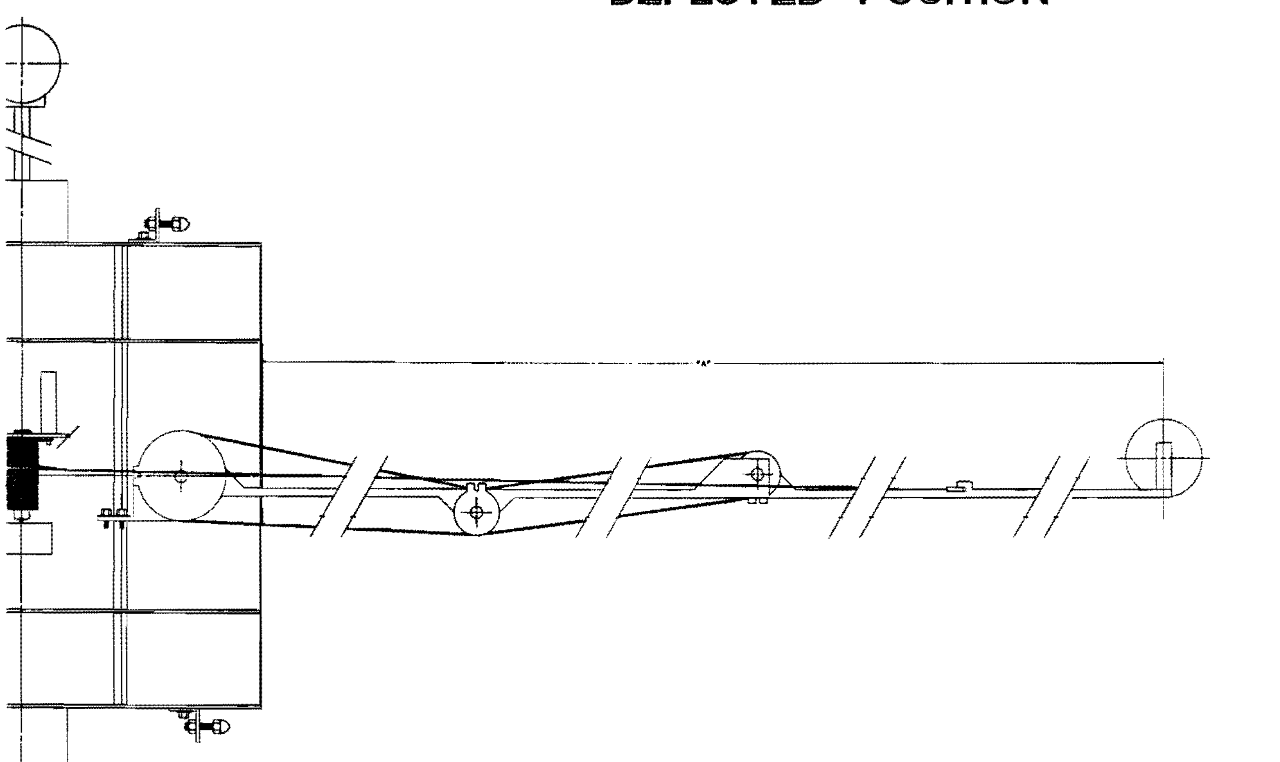
SECTION A-A

NOTES:

1. ONLY TWO RADIAL BOOMS ARE SHOWN IN THE TOP VIEW FOR CLARITY.



DEPLOYED POSITION



ON A- A

SENSOR DEPLOYMENT MECHANISM
FOR SURFER SATELLITE

UNLESS OTHERWISE SPECIFIED DIM. ARE IN INCHES, TOLERANCES ON:

FRACTIONS=±1/16
DECIMALS: X=±.1
.XX=±.010
.XXX=±.005
ANGLES=±15 MIN

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MECHANICAL ENGINEERING DEPARTMENT
ME 210: ENG. DESIGN
TEAM MEMBERS:
BOB DILL
JIM FLOM
DON GIBBONS

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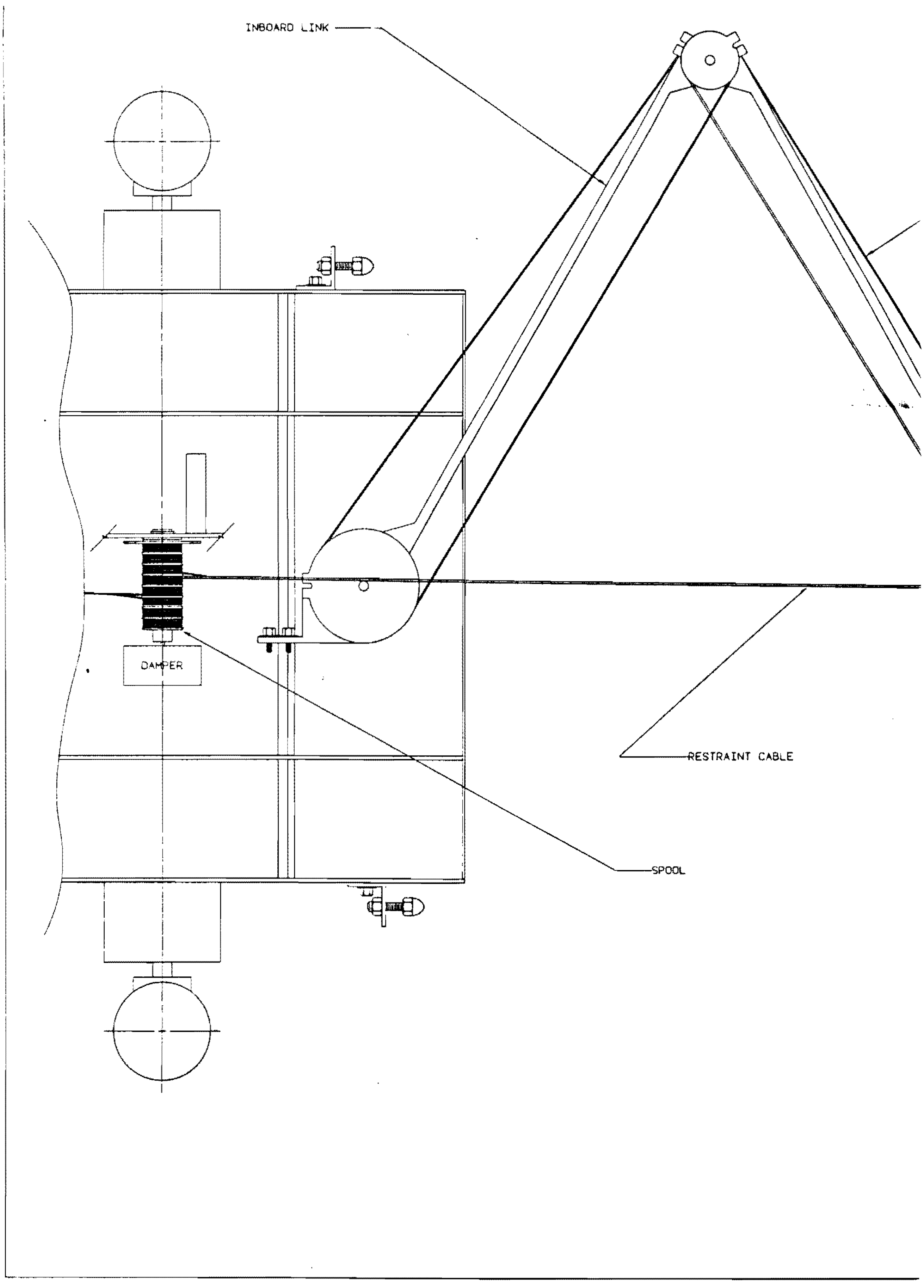
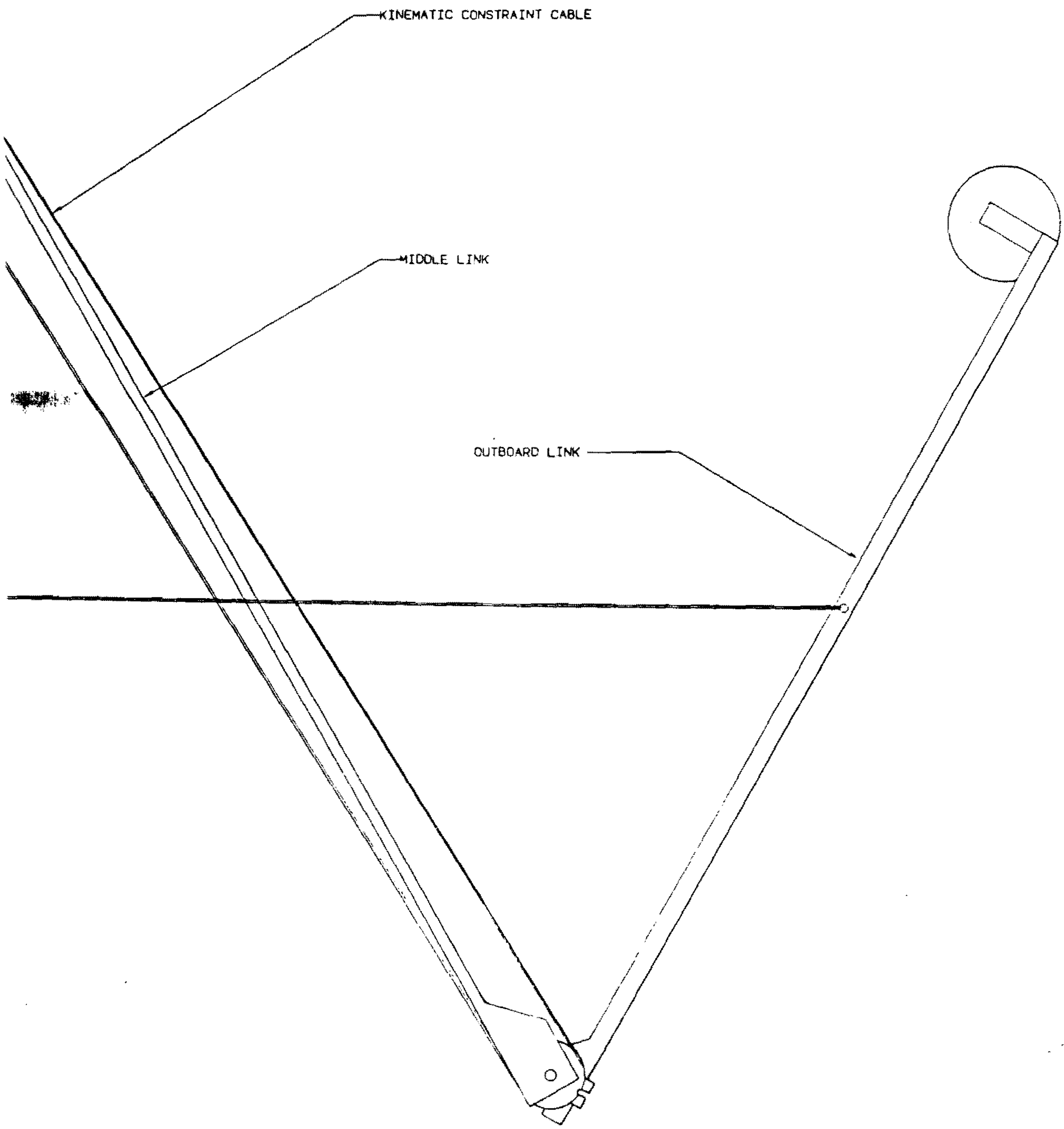
SCALE: 1/4 | SHEET 2 OF 2

APPENDIX J

FOLDING ARM PARTIALLY DEPLOYED



INBOARD LINK
DAMPER
RESTRAINT CABLE
SPOOL



CONTRACT NO	UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN INCHES TOLERANCES ARE	MECHANICAL ENGINEERING DEPT. STANFORD UNIVERSITY
APPROVALS / DATE	FRACTIONS ±1/16 DECIMALS .XX ±.01 .XXX ±.005 ANGLES ±.5°	
DRAWN BY J FLOR 2/88	MATERIAL	FOLDING ARM--PARTIALLY DEPLOYED
CHECKED	FINISH	D REV A DRAWING NO
		SCALE 1/2 SHEET 1 OF 1