The Lightweight Deployable Antenna for the MARSIS Experiment on the Mars Express Spacecraft

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Abstract

TRW Astro Aerospace developed and built an antenna subsystem for the MARSIS (Mars Advanced Radar for Subsurface and Ionospheric Sounding) experiment on behalf of the University of Iowa, who provides antenna and transmitter to the NASA Jet Propulsion Laboratory (JPL). The antenna flies on the extremely weight limited Mars Express spacecraft due to reach Mars in 2004. The MARSIS antenna is an example of a lightweight deployable structure that is designed purely for the space environment. Because of this, any significant friction or drag that would occur on Earth will prevent its deployment, and its large dimensions make it impractical to deploy in any test facility on Earth. The verification process has been developed through the program and dynamic simulation has become the most important verification tool.

This paper will describe the unique design of the MARSIS antenna and provide details of the test and verification program.

Introduction

The basic design for the foldable tube used in the MARSIS antenna experiment was originally conceived for use on the weight limited Sounder Antenna for the planned NASA EUROPA Orbiter spacecraft. These launch weight limits forced the creation of a completely new antenna element design that has been named the Foldable Flattenable Tube[1] (FFT).

The Mars Express spacecraft is also mass limited. It was determined that using the FFT would fit within the MARSIS weight budget and allow the experiment to fly. The antenna deploys from its stowage box on the sidewall of this small spacecraft to provide capability for a very low frequency sounding radar. It deploys in Mars's orbit as a 40-meter tip-to-tip transmit/receive dipole aligned in the flight vector and a 7-meter receive-only monopole in the nadir direction. The whole mechanical antenna, excluding the feed electronics, weighs 7.1 kg.

The goal of the MARSIS experiment, a joint endeavor between the University of Rome in Italy and JPL, is to find water strata beneath the surface of Mars and to study the Martian ionosphere.

Background

The MARSIS instrument is a low-frequency ground penetrating radar sounder and altimeter, which uses synthetic aperture techniques and a secondary receiving antenna to isolate unwanted reflections. The operating altitudes of MARSIS are up to 800 km for subsurface sounding and up to 1200 km for ionospheric sounding.

As implemented, MARSIS consists of two electronics assemblies and two antennas mounted on the spacecraft. In operation, the MARSIS control electronics generates a linear frequency modulated chirp, which is amplified and then radiated by the nadir-facing dipole antenna. Then the MARSIS switches to receive mode and the return signal from the Martian surface is processed through both the dipole antenna and the secondary monopole antenna. The monopole antenna, oriented along the nadir axis, receives the off-nadir surface clutter, which will then be subtracted from the primary data in the ground re-processing. The MARSIS radar operates at frequencies up to about 6 MHz.

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[1] Patent Pending

The required mechanical configuration for the deployed antenna shown in Figure 1 is a dipole transmit/receive antenna deployed in the orbit vector with a total tip-to-tip length of 40-meters, plus a 7-meter monopole receive-only antenna in the nadir direction. Traditional designs such as a STEM antenna were considered for the application but would not meet the combination of requirements for stiffness, weight (~8 kg mass budget), thermal stability and cleanliness (no debris generation). The FFT, despite its early stage of development, met these requirements and its simplicity gave the experiment team sufficient confidence in a successful outcome to proceed. The program start date was in February 2000. After overcoming some minor design problems the qualification was completed in October of 2001. At the time of writing this paper, the flight hardware is assembled and ready for acceptance test.

The antenna structure consists of lightweight S-Glass/Kevlar composite tubes. The dipoles are 38 mm in diameter and the monopole is 20 mm in diameter. With these dimensions the tubes are sufficiently stiff to achieve the deployed frequency requirement of 0.05 Hz.

The tubes are folded and then compressed for stowage. They are folded at points along the length where cutouts in the side of the tube prevent a singularity in the material. This allows the extremely flexible composite to fold in a manner similar to a “carpenter’s tape hinge”. The 20-meter dipoles fold to a length of 1.53 meters and the smaller monopole is folded to 1.3 meters. When folded, the tubes are compressed into a stowage box for launch. The stowage box is a Nomex Honeycomb graphite-skinned construction with three doors that enclose the compressed elements.

The stowage method is shown in Figure 2 and is shown in process in Figure 3. The three tubes are stowed in boxes in layers and released sequentially so that there is no danger of entanglement during the process. The tubes are stowed by folding them at defined points along their length where cutouts, as shown in Figure 4, relieve the stress singularities at each side and allow the rest of the tube to flex into the folded shape. The dipoles and the monopole are compressed from 38-mm to 19-mm and from 20-mm to 10-mm, respectively, and consequently have considerable stowed strain energy. Deployment of the tubes is initiated sequentially by small pyrotechnic devices that release the door latches. Once triggered, the tubes push the doors open very rapidly on release and deploy out to their required configuration by releasing the energy of stowage and the strain energy in the hinges. (This door energy is absorbed by innovative, progressive friction dampers).

The stowed tubes emerge rapidly from their stowage all heading in the same direction. The root mounting turns the two dipoles through 90 degrees into the flight vector while the monopole fires straight out in the nadir direction and stays there. The tubes reach their full extension in less than two seconds because of the initial release of stowed energy but the dipole tubes take another 30 seconds to rotate into position. The dipole hinges have a very low torque of 0.2 N-m and therefore accelerate the fairly large inertia slowly. On reaching full deployment, the tubes oscillate before completely straightening, though the tubes’ construction significantly dampens this oscillation, as explained below. The dipole element deployment sequence is shown in Figure 5.

The composite tubes are not conductive per se although they are Indium Tin Oxide (ITO) coated to prevent static build up. The actual antenna structure is a pair of stranded 22-gauge, silver-plated copper wires that run along the length of the tube. These wires are interconnected ladder-style along their length to provide redundancy. In addition, they are slightly rippled along the length to prevent differential thermal motion between the wires and the near zero coefficient thermal expansion (CTE) tubes. The wires are connected to the feed and sensing electronics, which are mounted close to the antenna roots and beneath the stowage box as shown in Figure 6.

As discussed below, one of the most controversial aspects of the antenna project has been the test program. The structural tubes of the antenna (thin-wall S-Glass/Kevlar composite, 38-mm diameter for the dipoles and 20-mm for the monopole) are unable to sustain their own weight in Earth’s gravity. Additionally, the deployment kinematics shown in Figure 5 prevent the use of conventional deployment support rigs while the deployment motion requires a very large area. Various methods for supporting this motion were conceived but all proved impractical. The normal environmental tests such as stowed vibration and thermal cycling are straightforward. The challenge is to test the function of the antenna elements after exposure. The pyro-releases can be fired and the doors will be forced open and the compressed tubes will eject themselves from the box. But after that point - unless there is a zero-g environment - the tube hinges do not have enough torque to deploy and any significant friction will prevent deployment. The agreed method is to verify that the hinge joint will always unfold –there is no friction effect to stop it – and verify that it will release from the box. The remainder of verification is provided by analysis. An ADAMS (Automated Dynamic Analysis of Mechanical Systems) model was constructed and the individual elements of the model were correlated to test hardware. The model verifies the deployment dynamics and the interaction with the spacecraft. A sample of the output is shown in Figure 5.

The Design

The Tube Elements

Requirements:

- The tubes are required to meet the minimum deployed frequency of 0.05 Hz.
- The long dipoles must maintain a total tip deflection of 20 cm under all thermal extremes.
- The external finish must dissipate static charge and must not generate debris when deployed.

Construction:

- The tubes are a Kevlar and S-Glass composite that is specifically laminated to provide near zero CTE in the longitudinal direction and to prevent creep of the matrix in the stowed condition (the tubes remain compressed for up to two years on the trip to Mars). The tubes are laid up in 3.0-meter lengths and then ITO coated. They are then sorted for straightness so that the combination of the sorted tubes, when correctly oriented, will achieve the straightest possible finished element. The tubes are then machined to create the fold points. The individual tubes are then spliced together to form the complete element (Figure 7). The splice is designed to flex with the rest of the tube when compressed into the stowage box. Although the splice effectively doubled the wall thickness, the use of a flexible adhesive allowed the high degree of strain to be tolerated.
- The tubes were punched with a number of additional holes to provide access to install and support the conducting elements. The conductive wires were soldered into a ladder frame such that extensions to the rungs penetrated the tube walls and were staked in place. That way the legs of the ladder were supported along opposing walls of the tube.

The Stowage Box

Requirements:

- To take advantage of the extreme low weight of the conducting elements a lightweight stowage box was required. The design of the box was quite challenging. The three tube elements must be stacked one on top of the other and mounted across the spacecraft wall as shown Figure 1. The monopole is able to exit the box and fire straight out, so it could be contained in a four-sided box with a back and lid. The elements of the dipole had to exit in the same direction as the monopole but then needed to rotate through 90 degrees, each in different directions. The end walls of the box therefore could not exist, compromising the structure of the box. The box is also required to support the local electronics and mount in a kinematical manner to the spacecraft sidewall.

Construction:

- The box is constructed of graphite-skinned Nomex honeycomb panels joined by graphite clips. The box structure is then completed, as much as possible, by the doors keyed at the latch points as described below. The panel skins are 0.19-mm M46J graphite laminates and the door skins are 0.38 mm laminates, designed for high strength and stiffness but with a low mass. The external faces of the box are painted with a conductive white paint for thermal and static conductivity considerations. The box is mounted to the spacecraft sidewall on raised aluminum brackets designed to flex to allow relative thermal expansion of the box and spacecraft.

The Mechanisms

Requirements:

- The compressed tubes needed to be stowed by a hinged door and latching mechanism. The doors needed to resist the deploying force of the tubes through vibration and thermal cycling and still release upon pyro-activation. Upon release, the doors would accelerate rapidly from the stowed strain energy of the tubes and would need to be damped rapidly after a 90-degree rotation to clear the tube deployments. This presented the challenge to allow the doors to rotate fairly free from 0 to 90 degrees to remove them from the deploying path of the tubes and then stop them between 90 and 180 degrees of rotation before hitting the box structure with any significant force. This required a special type of fast-acting damping device to be integrated in a limited volume. The door latching mechanism needed to constrain and latch the door at multiple points without interfering with the tubes. It also needed to keep the door closed despite both thermal and vibration forces and then release the door from a pyrotechnic bellows actuator at all temperature extremes along with a limited volume.

Construction:

- The composite door has internally bonded hinge/latch inserts made of Titanium that interface with Titanium hinge/latch inserts bonded in the box panels. The door has a graphite rib bonded on the outside for added stiffness. The unique hinges were designed to be multi-functional providing both a hinge and latch point as well as having a special tapered hinge tang for the damping feature. The tapered hinges will compress Belleville and composite washer stacks that are mounted on the hinge pins and latch rods as the door rotates. Clearance is adjusted to allow the washers to be engaged at the correct rotational point. Energy is absorbed by both frictional forces and spring compression.

- The latching is performed by a high-strength Titanium rod that functions both as a hinge pin and latching mechanism. The Vitralube-coated rod runs the full length of the door and has machined flats at the latch points. As the rod is rotated and constrained by the pyro-mechanism, the flats rotate and compress down on the latch from the door and hold it onto the latch receptacle on the box panel hinge/latch insert. A pyro-release mechanism holds the rod in place after it is rotated into position. In the latched position, the rod is twisted torsionally to hold force on the latches. A link arm is pressed onto one end of the rod to provide the torque. A latch arm runs off of the link arm and is held back by two disks in the pyro-mechanism. As either bellows' pyro is activated, a disk will drop and release the latch arm allowing the latch rod to rotate freely and release the door and tubes. (Shown in Figure 8)

Analysis

Deployment Analysis

The ADAMS dynamic modeling software was the most important verification tool for on-orbit performance predictions. The model that was used to predict the deployment profile and the on-orbit dynamics incorporated component test data for the compression preload, for the hinges and for the boom stiffness.

Stiffness correlation measurements were made on the completed flight- and qualification-tube assemblies as they floated on a water table. The calculations were also checked using a COSMOS finite element model. The data is used to prepare the spacecraft control system algorithms.

Launch Phase

The stowed antenna assembly was evaluated for the predicted launch sine, random vibration, acoustic and shock environments using a finite element model generated in COSMOS/M. While no detailed representation of the flattened antenna tubes was put in this model, their mass was distributed proportionally through the structural box model. Preload stresses were superimposed on results of the dynamic analysis for the defined environments. Two percent structural damping was assumed for this analysis. In fact, test results indicated significantly higher damping, which varied by frequency and load level.

Transfer Phase

The transfer phase of flight, with the antenna elements still stowed, involved very low mechanical loads, but significant temperature variations from ambient build temperature. The structure, which incorporates design features to accommodate the stresses resulting from the dissimilar coefficients of thermal expansion of the build materials, was again evaluated using a COSMOS/M finite element model.

Deployed Phase

The deployed system was evaluated using another COSMOS/M model. Frequency response and strength were evaluated for the predicted environment.

Testing

As stated above, the test program was non-conventional because of the difficulty of testing the extremely lightweight tubes in a representative manner. The philosophy followed was to demonstrate that the components of the tube were 100 percent reliable such that if the doors opened it could be assumed that the elements would fully deploy. It was an accepted fact the tubes were only able to fire themselves onto a flat table as shown in Figure 9. The test program has qualified the hardware as follows.

Element Tests

The tube elements were tested to demonstrate the following properties:

- Hinge actuation reliability. Multiple operations of sample hinges were made under all temperature extremes including in liquid nitrogen. The tests did demonstrate some problems with the initial cut out configuration. Design modifications were made, arriving at the shape shown in the figures.

- Hinge torque/rotation angle characteristics in all axes – this data was used as an input to the ADAMS analysis.

- Tube lateral compression stiffness - also used in the ADAMS analysis.

- Tube and tube splice long-term creep properties under compression. Tube samples have been kept under compression for upwards of a year and have shown no significant load decrease.

- Tube strength and stiffness have been measured for all root configurations. The tube strength is reduced at the fold cut-outs. The nominal tube has a bending strength of 150 lb-in with 120 lb-in with the slots in the neutral axis, and 60 lb-in when rotated 90 degrees.

Structural Model

A model of a containment box for the larger tube element was constructed to prove the various functions. It was subjected to repeated deployments to demonstrate the robustness of the tube elements and the wire installation. It proved the function of the release system and the door energy dampers. It was also subjected to vibration test and thermal testing. All functions were successfully demonstrated.

Radio Frequency (RF) Performance Model

One of the unknowns of the whole instrument design was exactly how the antenna would work. To prove its performance two of the 20-meter dipoles were delivered to the University of Iowa. They were bold enough to construct a field experiment in which the two dipoles and a representation of the spacecraft body were lifted from the ground and suspended vertically beneath a helicopter. The test was carried out in Colorado where the whole assembly was lifted 10,000 feet above the ground, looking sideways at the neighboring mountains. The experiment worked well, proving the function, and the whole experiment was carried out with no significant damage to the fully flight representative hardware. The event is shown in Figure 10.

Qualification Hardware

A fully flight-like assembly was built as shown in Figure 2. It was subjected to the following tests:

- Functional Test - The release functions and element performance were demonstrated. The elements were released onto the deployment table in turn. During this test contamination samples were taken to verify that the tubes did not generate debris contaminants.

- Vibration Test - The assembly was mounted to a vibration fixture and subjected to sine and random vibration environments.

- Thermal Vacuum - The assembly was thermal cycled in vacuum. The safety straps (the red clamps shown in Figure 2) were kept on for this test. The doors were released at temperature extremes during the test and the safety straps prevented deployment of the tubes.

- Final Functional Test - The full performance of the release mechanisms and tube energy release was again tested. The tubes were again deployed in sequence onto the flat table and again particulates were monitored. The particulate count was small and acceptable.

Flight Hardware Test

At the time of writing this paper, the flight assembly is almost complete and will be subjected to the same test sequence as the qualification hardware.

Conclusions

This program required new methods to be developed to validate the design and to assure performance of flight hardware. A combination of analysis and component test was utilized to accomplish this goal.

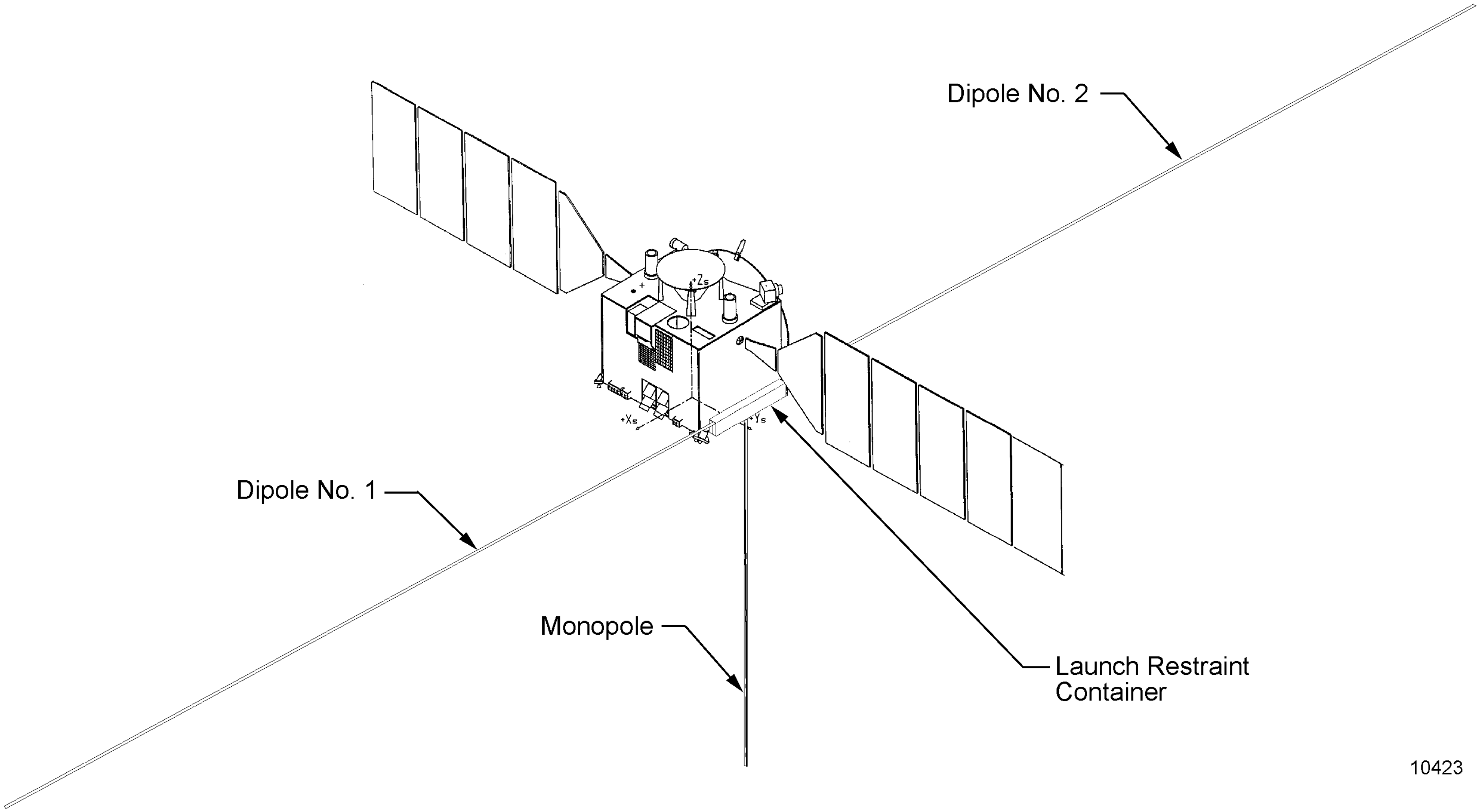


Figure 1. Mars Express Spacecraft with Deployed MARSIS Experiment

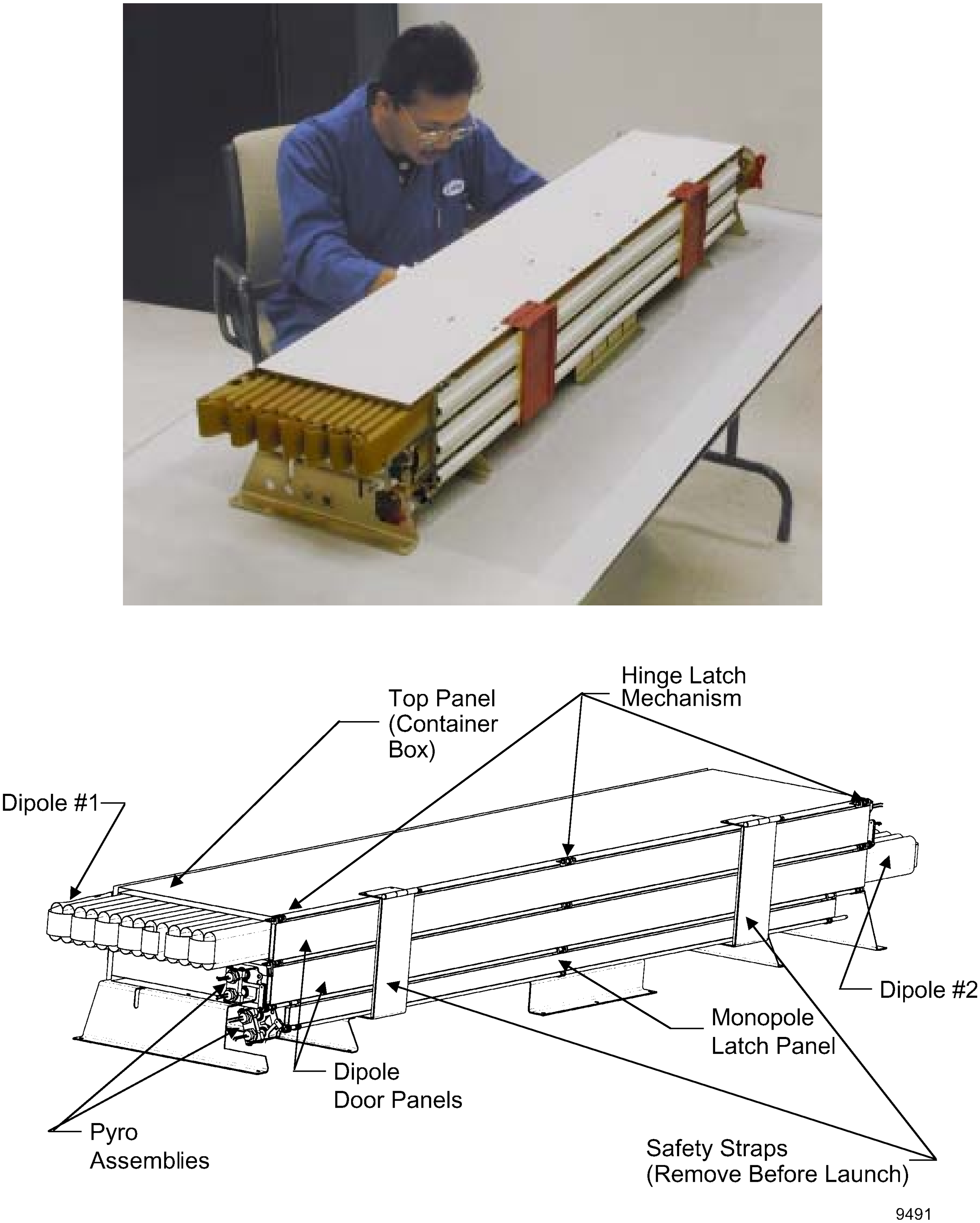


Figure 2. MARSIS Antenna Stowed for Launch with Safety Clamps in Place

Figure 3. Stowage in Process

Figure 4. Tubes with Cutouts

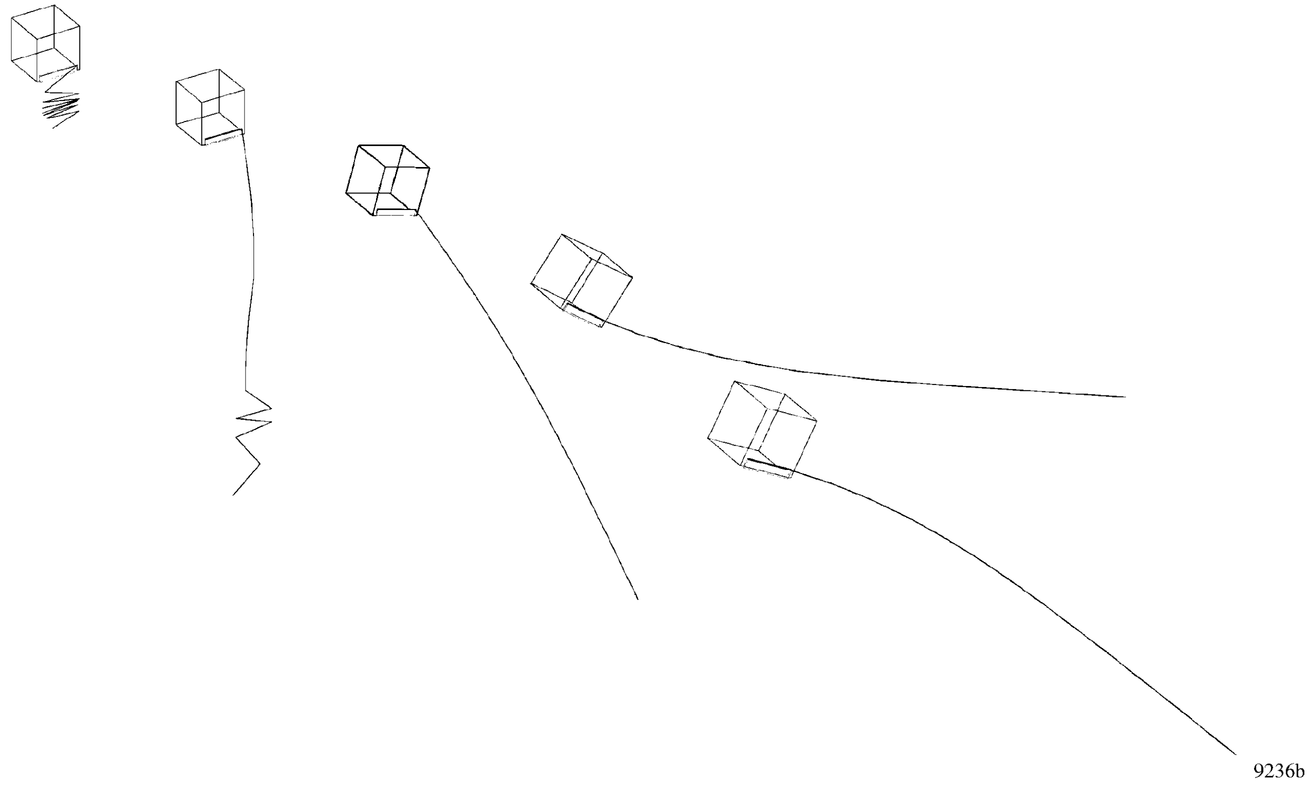


Figure 5. Dipole Sequence

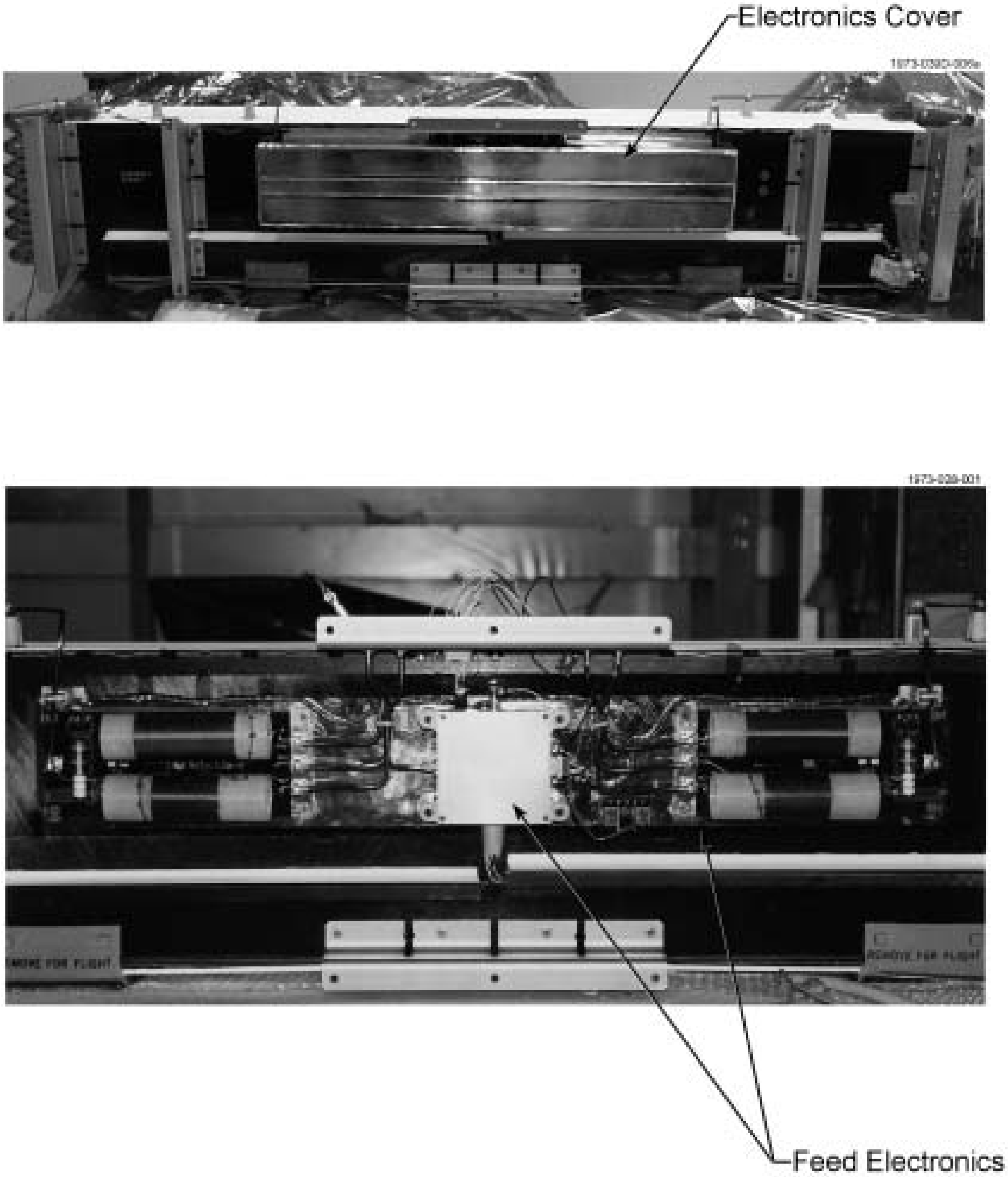


Figure 6. Electronics

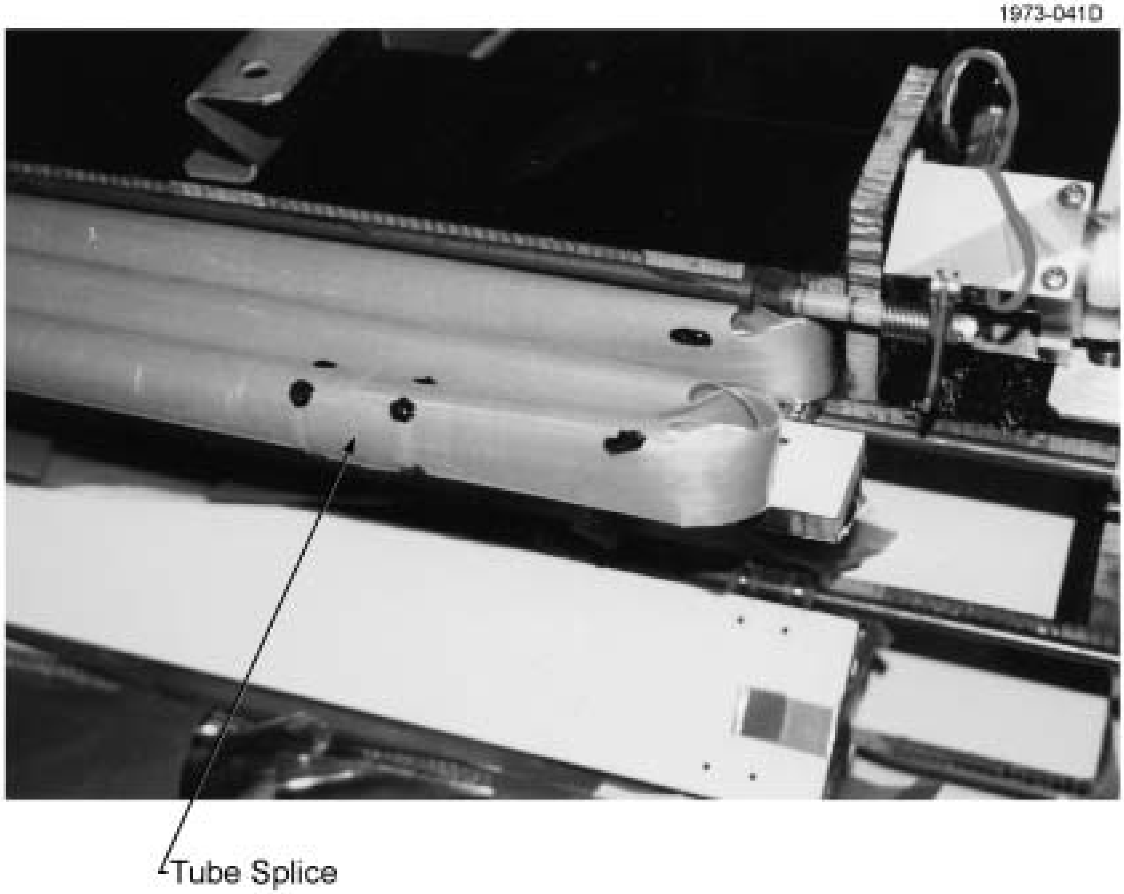
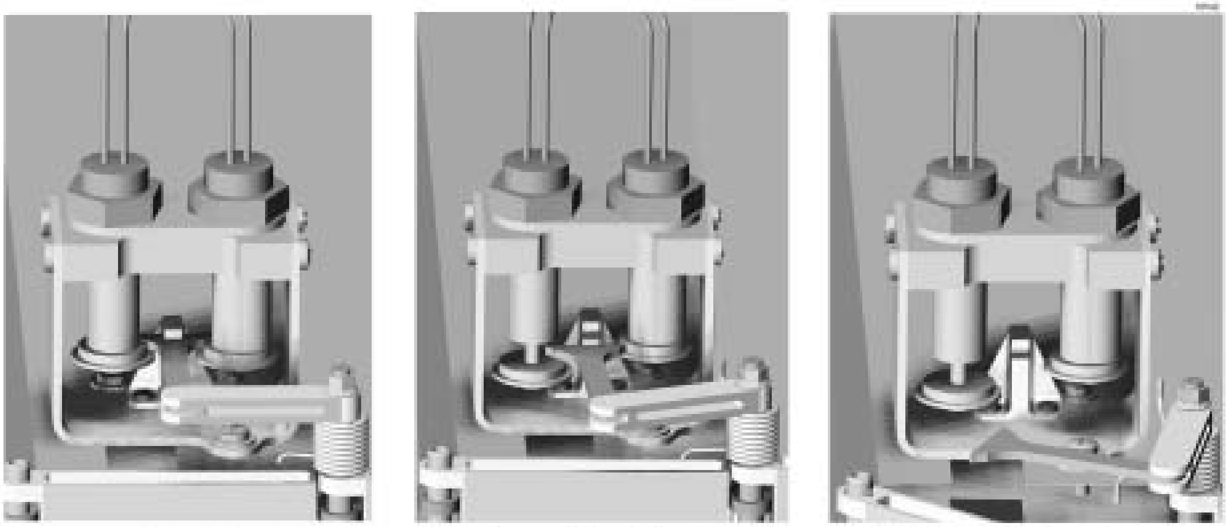


Figure 7. Spliced Tubes



1. Latched Position

2. Primary Pyro Fired and Latch First Motion

3. Latch Released and Door Opening

Figure 8. Pyro Release

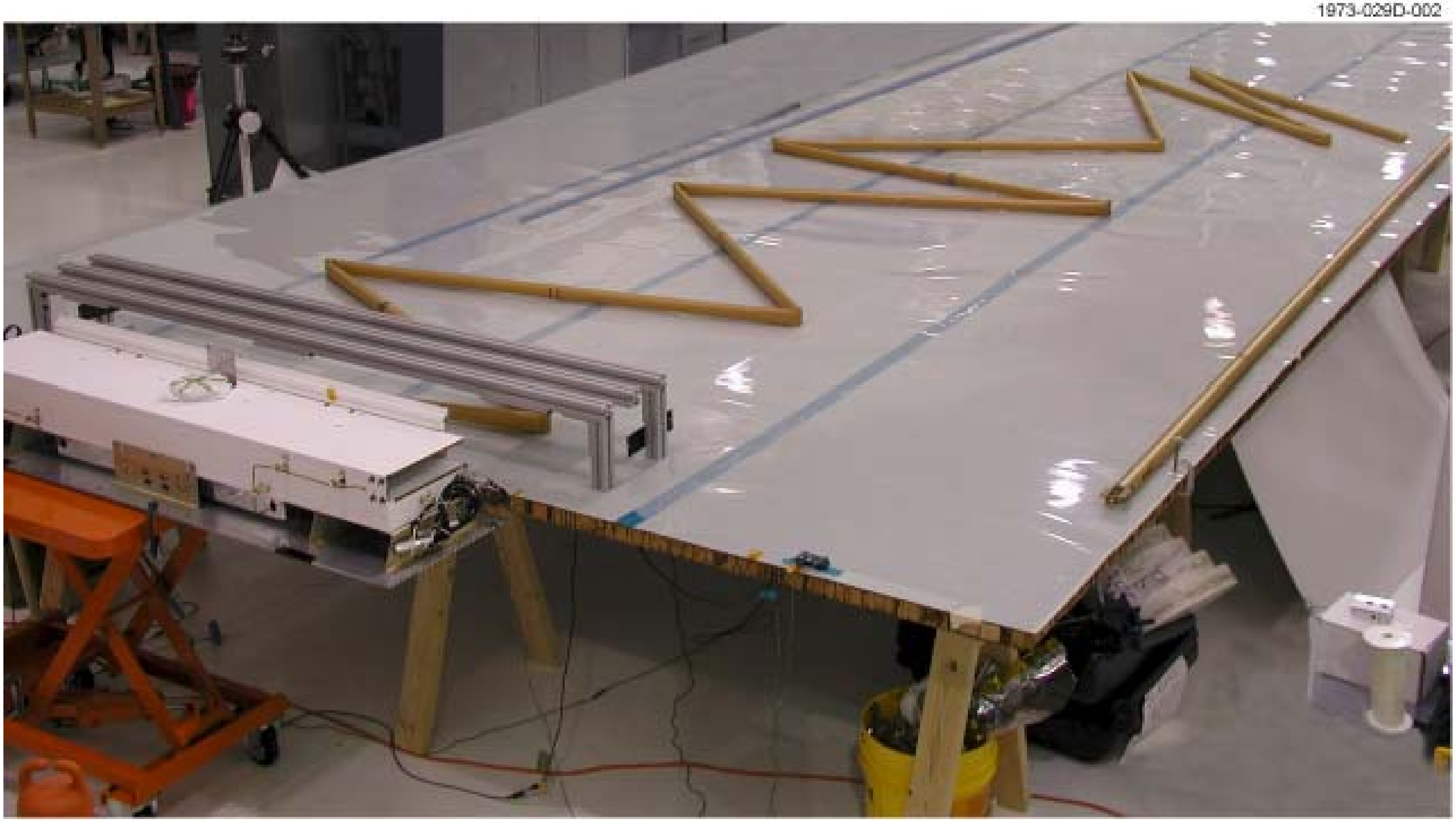


Figure 9. Deployment Test

1973-045D-007

Figure 10. RF Test Equipment Suspended from Helicopter