

Quick Feasibility Demonstration for an Inflatable Antenna System in Space

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Abstract

This paper describes a DARPA funded program to test the feasibility of combining very large, lightweight, inflatable, and rigidizable structures with photonic RF data links, flexible broadband antennas, and flexible solar cells for possible use in large space-based antenna arrays.

1.0 Introduction

Recent Government-funded and commercial programs have significantly improved some key technologies:

- Very large, lightweight, inflatable, and rigidizable structures for space applications
- Photonic data links and RF/optical transducers
- Novel and reconfigurable antenna designs
- Flexible solar arrays
- Digital beamforming, interference rejection, and element self location in large antenna arrays
- High-speed, high-dynamic-range, analog-to-digital (A-D) converters

Ultimately these technologies might be combined into very large array antennas (perhaps many tens or hundreds of meters in length) in space, with the capability to steer multiple simultaneous beams and adaptively null interference while receiving and relaying to earth digitized signals over very wide frequency bands. These very large array antennas could have beamwidths of less than one degree in the high VHF band, and down to a milliradian or less in the microwave bands. One notional system is sketched in **Figure 1**, but in fact extremely large structures of many possible geometries are possible with the inflatable structures technology.

Report Documentation Page

Form Approved
OMB No. 0704-0188

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1. REPORT DATE FEB 1999		2. REPORT TYPE		3. DATES COVERED 00-00-1999 to 00-00-1999	
4. TITLE AND SUBTITLE Quick Feasibility Demonstration for an Inflatable Antenna System in Space				5a. CONTRACT NUMBER	
				5b. GRANT NUMBER	
				5c. PROGRAM ELEMENT NUMBER	
6. AUTHOR(S)				5d. PROJECT NUMBER	
				5e. TASK NUMBER	
				5f. WORK UNIT NUMBER	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Toyon Research Corporation, 75 Aero Camino Suite A, Goleta, CA, 93117				8. PERFORMING ORGANIZATION REPORT NUMBER	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)				10. SPONSOR/MONITOR'S ACRONYM(S)	
				11. SPONSOR/MONITOR'S REPORT NUMBER(S)	
12. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release; distribution unlimited					
13. SUPPLEMENTARY NOTES The original document contains color images.					
14. ABSTRACT see report					
15. SUBJECT TERMS					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES 12	19a. NAME OF RESPONSIBLE PERSON
a. REPORT unclassified	b. ABSTRACT unclassified	c. THIS PAGE unclassified			

The DARPA / STO funded feasibility demonstration program described here makes a first step toward such a system, combining several of the key technologies identified above in a ground-based experiment to demonstrate the availability, compatibility, and feasibility of combining these technologies. One of the key issues is the mechanical survivability of these technologies during the deployment of an inflatable structure.

2 Concept Description

2.1 Space Structure

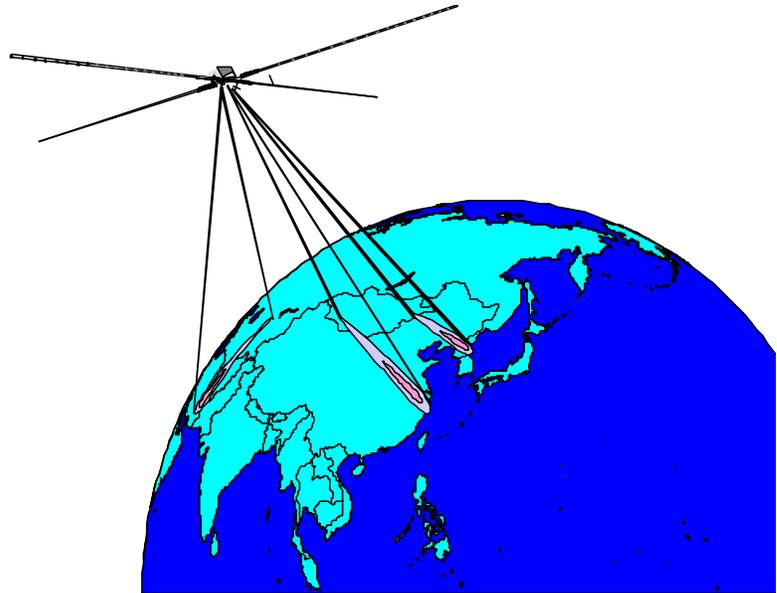


Figure 1 - Steerable space array concept

A system such as illustrated in **Figure 1** might be deployed from a comparatively small package launched by an expendable booster. **Figure 2** illustrates a possible deployment scheme for the array. The satellite body would contain all of the receivers, computers, communication equipment, and power. The only attachments to the elements would be fiber-optics lines.

The antenna arms deployed in this fashion could be extremely long, perhaps greater than 100 meters. Each array arm would be a long, thin, inflatable tube, with antenna elements and solar cells patched onto the skin. The deflated tubes, along with the fiber-optics links to the elements, could be rolled up and stored in bays in the satellite body.

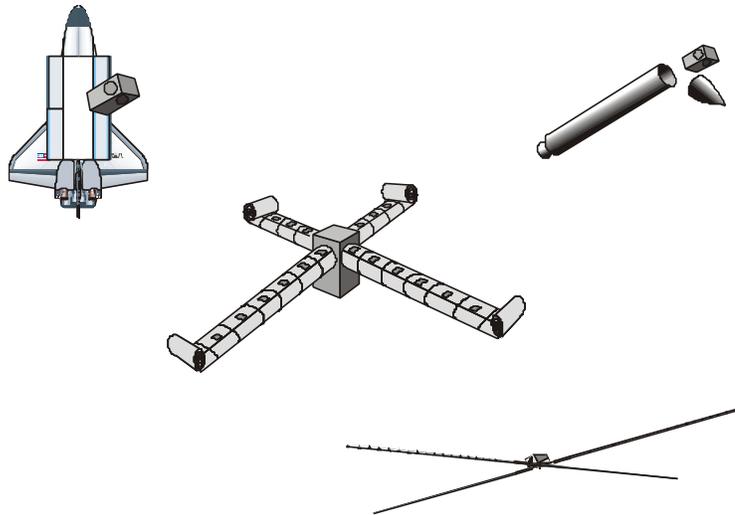


Figure 2 - Deployment of array in space

The flexibility of the fiber-optic lines would enable them to be rolled up and deployed without damage. By comparison, coaxial cables would be heavier, bulkier, and exhibit much greater loss. When the bays are opened, the tubes slowly unroll as they are inflated to low pressure. Once inflated to full size, the flexible tubes would gradually become rigidized by one of several existing techniques. Eventually the inflation gas would be released, but the tubes retain shape due to rigidization of the tube wall. Any off-nominal deployment of the inflatable structure or any movement of the array structure due to station keeping can be compensated by techniques (e.g., onboard beacons) for self-location of elements.

The ultimate deployment of such an array system in space depends upon a lightweight but rigid structure. In May 1996 L'Garde, Inc. of Tustin, California deployed Space Shuttle STS-77 Inflatable Antenna Experiment, a 14-meter-diameter inflatable reflector with three 28-meter struts (**Figure 3**). The pre-deployed volume of the inflatable structure was about that of an office desk and it weighed about 60 kg.

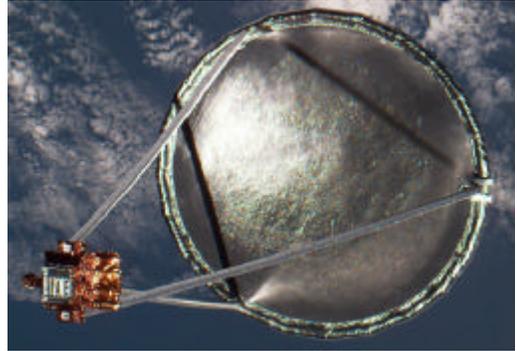


Figure 3 - L'Garde Inflatable Antenna Experiment

2.2 Antenna Array

One of our concepts for a very wideband array antenna uses long array arms oriented orthogonally. Each arm holds a large number of elements that are not all uniformly spaced. One specific concept arranges the antenna elements into multiple segments of 2^n elements (a convenient number for digital beamforming); each element is very broadband (for example, a log-spiral or a flared notch); and the element spacing is uniform within a segment, but different from segment to segment (see **Figure 4**). Each element is connected to a widely tunable receiver and A-D converter, and all beamforming is digital. The array can be scanned to wide angles off boresight without grating lobes.

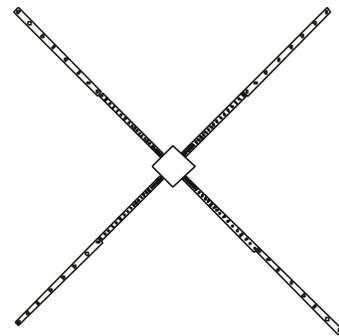


Figure 4 - Multi-Segment Antenna Array

An alternative concept would combine multiple elements into subarrays, with the outputs of the subarrays sampled and combined digitally for beamforming. This approach reduces the number of receivers required (one per subarray, not one per element), but loses some flexibility in beamforming.

The main advantage of a highly segmented antenna system is that it can cover as many frequency bands as segments (or more if the elements are divided within a segment), but segments can also be combined to yield a larger array with narrower beamwidth at any desired frequency. Each segment is designed for approximately one-half-wavelength element spacing for a frequency in the tunable bandwidth of the entire array. With this spacing, the segment can be operated as a single array with broad grating-lobe-free scan limits. Adjacent segments are designed for lower and higher center frequencies. A possible element-spacing rule would be to space the elements in the m^{th} segment at $(I+a)^m I/2$, where I is the wavelength for the highest-frequency segment and a is a positive constant.

Figure 5 compares the antenna pattern for the shortest 16-element segment with that of an 8-segment, 128-element array. When multiple segments are combined at the same frequency, the array takes on the characteristics of a thinned array, with many fewer elements than a filled array with nominal $\lambda/2$ spacing. As a result, its gain is less than a filled array at the same frequency and the sidelobes are typically somewhat higher, but the angle resolution is the same as the filled array of the same width.

The frequency coverage of an antenna array and beamforming system depends upon the desired application. Some types of antenna elements, such as logarithmic spirals, are capable of covering a decade of frequency. Hence, the array could cover at least the same bandwidth. An example might be 200 MHz to 2 GHz. Choosing elements designed for different center frequencies could extend the array bandwidth even more. Although the entire aperture might not then be usable at the high and low frequency extremes, a substantial part of the aperture would be available at every frequency.

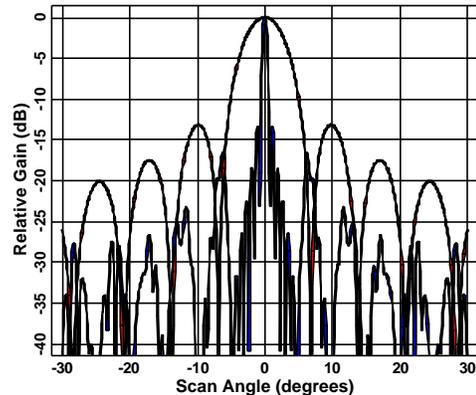


Figure 5 - Patterns of single segment (smooth) and eight segments (jagged)

2.3 Photonics and Digital Processing

Each antenna element can be connected to a centralized receiver/digitizer/beamformer via a photonic link as indicated in **Figure 6**. This photonic link has many advantages:

- No metallic connections to the antenna
- Very broad bandwidth
- Low loss
- Very light weight (key for space or airborne applications)
- Mechanical flexibility
- Low susceptibility to electromagnetic interference

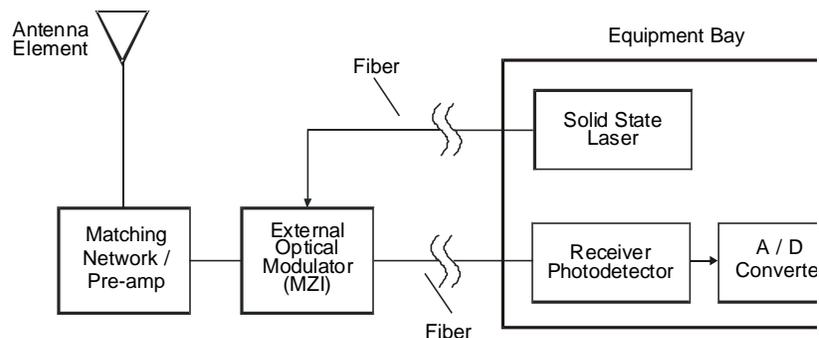


Figure 6 - Photonics link to element and receiver

The particular link shown uses passive external modulation, with the voltage induced in the antenna modulating the light in the laser link through a Mach-Zehnder interferometer (MZI). Lasers and receivers can be remoted at any convenient distance from the elements. An alternative configuration could use direct modulation. Laser light could deliver power to the element over a first fiber to a photodiode array, which would then produce DC power. This power would then drive an RF amplifier and directly modulated laser to downlink the signal over a second fiber.

3 DEMONSTRATION PROGRAM

3.1 Objectives and Approach

In many respects the space structure represents the greatest challenge and opportunity. The ability to build and deploy a boom of tens to hundreds of meters in length and make it rigid so that it can support antenna elements and their accompanying photonics / electronics is exciting. However, it was clear that this technology needs to be demonstrated on the ground. Hence, the main objective of this demonstration was to quickly (in six months or less) build and deploy a long inflatable boom that contains four working photonic antenna links.

Specifically the objectives of this quick demonstration were:

- To demonstrate controlled deployment of a long, inflatable cylindrical boom.
- To demonstrate the survivability of fiber optic cables, mechanical photonic connections, electrical photonic connections, antennas, and solar cells after multiple rollout / deployment cycles.
- To demonstrate integration of a photonic RF link and antenna into the boom so that they can be used as a phased array antenna system.

To meet these objectives the deployable test system had the following features:

- Two booms, each 100 feet long, were built. (It was decided that two independent inflatable boom systems would be built and instrumented. L'Garde, Inc. and ILC Dover, Inc. each, independently developed inflatable booms for this test. Their systems will be described below.)
- The booms were deployed (unfurled) in a party favor (noisemaker) manner. (Hence, all of the photonics, fiber, antennas, and solar cells were rolled into a compact package.)
- The booms were pressure stabilized after deployment.
- There were four broadband photonicly linked antenna systems placed in the booms before they were initially rolled up. Externally modulated, commercially available links were used.
- After deployment the four antenna systems were to be tested across the working band.

3.2 The Photonic Link System

Figure 7 presents a block diagram showing the interconnectivity of the antenna, the photonic link, and the instrumentation used in the test. Each boom had four complete antenna links. The descriptions of the various components are given below. The numbers relate to the numbers in **Figure 7**.

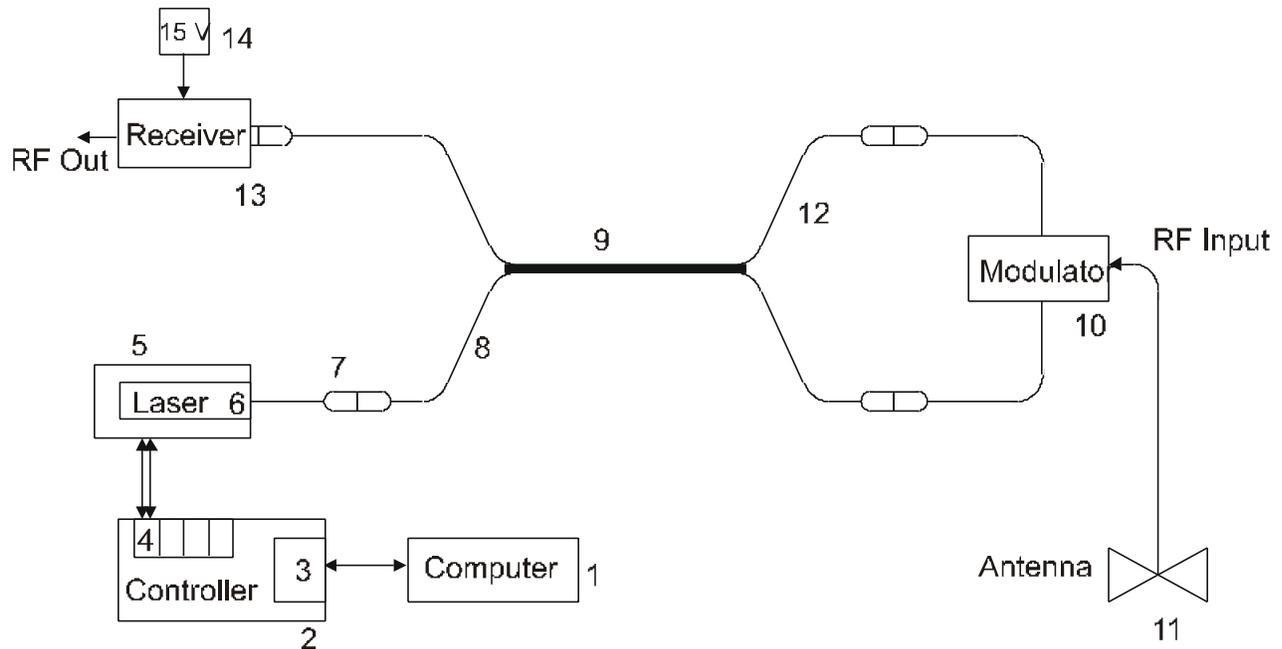


Figure 7 - Schematic block diagram of photonic / electronic links and instrumentation in test.

1. **Computer:** A laptop computer with National Instruments PCMCIA-GPIB card and NI-488.2M software for Windows 95.
2. **Laser Diode Controller:** ILX Lightwave LDC-3900 modular laser diode controller with 4 LCM-39420 combination modules (4) and option-1231 GPIB/IEEE 488.2 interface.
3. **GPIB:** ILX option-1231 GPIB/IEEE 488.2M interface for the laser diode controller.
4. **Combination Module:** ILX Lightwave LCM-39420 combination module with 200 mA max laser drive current and -99.9°C to $+199.9^{\circ}\text{C}$ temperature set range.
5. **Laser Diode Mount:** ILX Lightwave LDM-4980 laser diode mount.
6. **Laser:** Philips 20 mW CW 1550 nm GaInAsP DFB laser with integral photo-diode monitor, TE cooler, and PM fiber pigtail. Typical threshold current: 25mA. Typical differential efficiency: 0.14 mW/mA. Typical max bias current: 160mA.
7. **Optical Connector:** RIFOCS FC/APC optical connectors. Quantity: 19.
8. **Fiber:** Fujikura polarization maintaining singlemode optical fiber.
9. **Ruggedized Skinny Duplex Cable:** Northern Lights Cable, Inc. A two fiber small ruggedized skinny duplex cable manufactured with one each Corning SMF-28 single mode fiber (13) tight buffered to 900 μm and one Fujikura polarization maintaining singlemode optical fiber (8) with no additional tight buffer. The fibers are parallel served with Kevlar aramid yarn and have a black polyurethane jacket semi pressure extruded overall to a nominal diameter of 2.2 mm.
10. **Intensity Modulator:** Uniphase Telecommunications Products (UTP) 1550 nm, 2.5 Gbit/s single output electro-optic intensity MZM modulator, with 1m polarization maintaining input and output fiber pigtails buffered with 900 μm loose tube and terminated with FC/APC connectors. Nominal insertion loss: 4.2 dB. Nominal RF electrode half-wave voltage: 3.0 V. Nominal bias electrode half-wave voltage: 4.3 V.
11. **Antenna:** Toyon Research Corporation. Notch antenna (3 each); virtual antenna (1), and bow-tie antenna (4 each).
12. **Fiber:** Corning SMF-28 singlemode optical fiber.
13. **Photoreceiver:** UTP 2 GHz photoreceiver module. Nominal current draw: 35 mA.
14. **Power Supply:** Hewlett Packard adjustable DC power supply.

Optical Fiber Cables

Five optical fiber cables were built. The booms used four of the cables; a fifth backup cable was made in case of a fiber break. The cables had lengths of 75, 100, 125, 150, and 105 ft. The optical fibers that connected the laser, modulator, and photoreceiver were comprised of several components. Polarization maintaining (PM) single-mode fibers (8) connected the lasers (6) and modulators (10), and non-PM single-mode fibers (12) connected the modulators to the photoreceivers (13). Wrapping the two fibers in Kevlar Aramid yarn and a polyurethane jacket ruggedized them. A meter of fiber was exposed at both ends of the jacket and was protected by only thin plastic sheathing. This sheathing did not adequately protect the fibers and one fiber broke while the fiber cable was being installed into the L'Garde boom. The backup cable was used while the broken cable was repaired.

Both ends of the PM fiber were terminated with FC/APC optical connectors (7). The non-PM fiber was terminated with a FC/APC optical connector on one end, and a Diamond AVIM connector on the other end. The lasers had FC/APC optical connectors attached to their pigtails. The optical connectors on the modulators were also the FC/APC type. The photoreceiver accepted AVIM terminated optical fibers.

Laser Control

The heart of the laser control circuitry was the ILX Lightwave LDC-3900 laser diode controller (2). The LDC-3900 had four bays into which laser current control modules and laser temperature modules could fit. Four LCM-39420 combination modules (4) were used. These modules could accurately control the current and temperature of the lasers. The LDC-3900 also had a GPIB interface (3), which enabled the laser current and temperature to be monitored and controlled by a computer (1).

The lasers (6) contained a photodiode which monitored the optical power output. The signal produced by the photodiode was used by the LDC-3900 to control the laser's current to provide a constant output power. The lasers also contained a thermoelectric cooler and thermistor. The signal generated by the thermistor was used by the LDC-3900 to control the temperature of the laser to provide a constant temperature.

The lasers were mounted on LDM-4980 laser diode mounts (5). These mounts were large aluminum blocks were served as a heat sink and shock absorber for the lasers, and as an interface to the LDC-3900. The internal wiring of the mounts was configured for the Philips CQF939/D20 lasers.

RF path

The RF signal was captured with the antenna (11), which fed into the modulator (10). The modulated laser signal traveled through the non-PM fiber (12) to the photoreceiver (13). The photoreceiver demodulated the optical signal. The photoreceiver output the RF signal through a SMA connector.

3.3 L'Garde, Inc. Boom System

Structurally, a tapered boom (conical mast) offers the potential of reducing boom mass by as much as 40% with no loss in bending buckling strength. The tapered demonstration boom built by L'Garde (**Figure 7**) showed that the geometrical complexities involved have no adverse impact on antenna performance or fiber optic packaging.

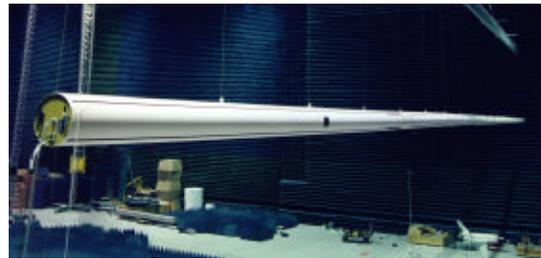


Figure 7 - L'Garde Boom - 100' Long; Root 12" Diameter; Tip 8".

The boom was made of two long neoprene-coated Kevlar gores, aligned and cut on a laser gore cutting table, then tape seamed together using a special straightness fixture. The 11 mil thick material is mechanically similar to the rigidizable materials being proposed for the space mission.

The antennas placed on the L'Garde boom were of two types: three broadband tapered notches (**Figure 8**) and one narrowband aperture antenna (**Figure 9**). The narrowband antenna represents a possible reconfigurable design. The antennas consist of copper foil bonded directly to the boom skin. On orbit, RF-transparent multi-layer insulation (MLI) would jacket the boom.

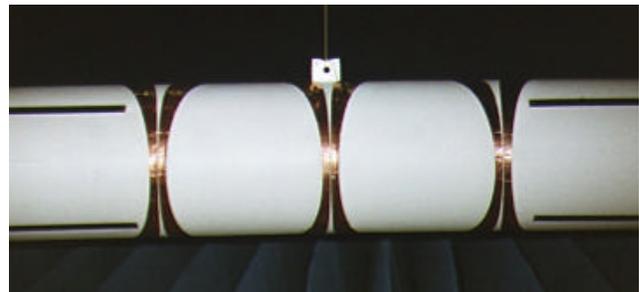


Figure 8 - Broadband notch array

The antenna leads penetrate the boom skin at rigid internal rings (**Figure 10**), which provide a protective hard mount for the leads, Mach-Zehnder interferometers (MZI), and fiber optic connectors. A cable routing methodology was developed to prevent damage to the delicate fiber optics during packaging and rollout.

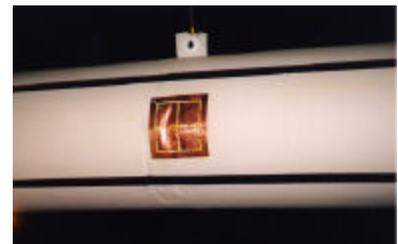


Figure 9 - Narrowband aperture antenna

The rings are laid flat, and the tube is rolled up for packaging. In the mission design, the rings must be spaced at least one to two diameters apart to accomplish this, but each ring can hold several MZIs and service several antennas via leads. The rolled-up package is quite compact (**Figure 11**).

After some initial difficulties with the test setup, the tube was successfully deployed horizontally and suspended by wires from a long truss (**Figure 12**). Velcro strips resist the deployment, keeping the inboard section pressure stabilized to handle any deployment dynamics. These strips would be replaced by cleaner Ziploc-like strips for flight.

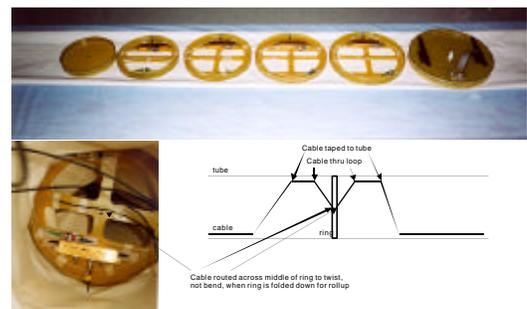


Figure 10 - Populated Rings & Fiber Optic Routing



Figure 11 - Rollup Packaging ~21" diameter; 19" width, ~31 lbs

RF tests went smoothly, but we noticed some boom oscillations, despite the aerodynamic damping. This illustrates the need for a stiff beam and a quiet spacecraft. Thin-walled large radius tubes are quite stiff, but an even stiffer alternative might be a lightweight truss with inflatable rigidizable longerons.

A basic feature of the boom is the use of lightweight, low loss fiber optics to carry the signal inboard along such a long distance. The same low mass philosophy should apply to the power necessary at each ring. To that end, Lockheed-Martin thin film flexible copper indium diselenide (CIS) solar arrays are bonded along the tube (**Figure 13**), generating power where it is used so that no heavy, lossy distribution wires are necessary. They were tested before and after deployment to demonstrate that packaging does not damage them.



Figure 13 -Solar array being tested

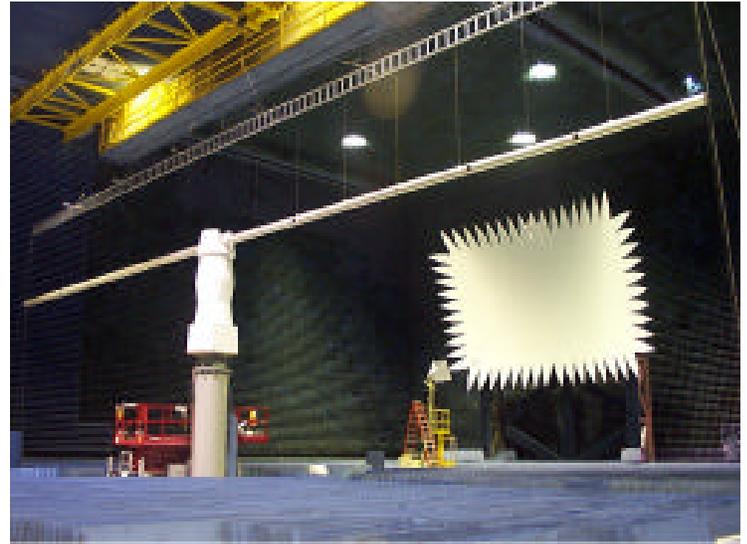


Figure 12 - Boom Antennas Being Tested in RF Chamber

3.4 ILC Dover, Inc. Boom System

The 30-meter antenna boom manufactured by ILC Dover consisted of a 25-cm diameter inflatable boom with a partition bisecting the tube longitudinally that acts as the mounting surface for the antenna elements and photonics (**Figures 14, 15**). The partition allows the antenna elements and photonics to be mounted to a flat surface exposing them to the least amount of stress and flexing possible during packing and deployment (**Figure 16**). This increases the reliability of the system, simplifies the design, and improves the manufacturability of the design. The partition of the boom consists of a carrier that acts as the mounting surface for the antenna components and its interface sleeve that is permanently mounted to the boom's inner wall. All components are mounted to the carrier and inspected prior to insertion into the boom. This allows the boom to be fabricated, tested and inspected independently from the electronics portion of the system. By locating all of the antenna elements inside the boom with the photonics, the reliability of the system is increased because no penetrations of the pressure

barrier have to be made. The boom was closed and made leak-tight by inserting endcaps into the ends of the boom.

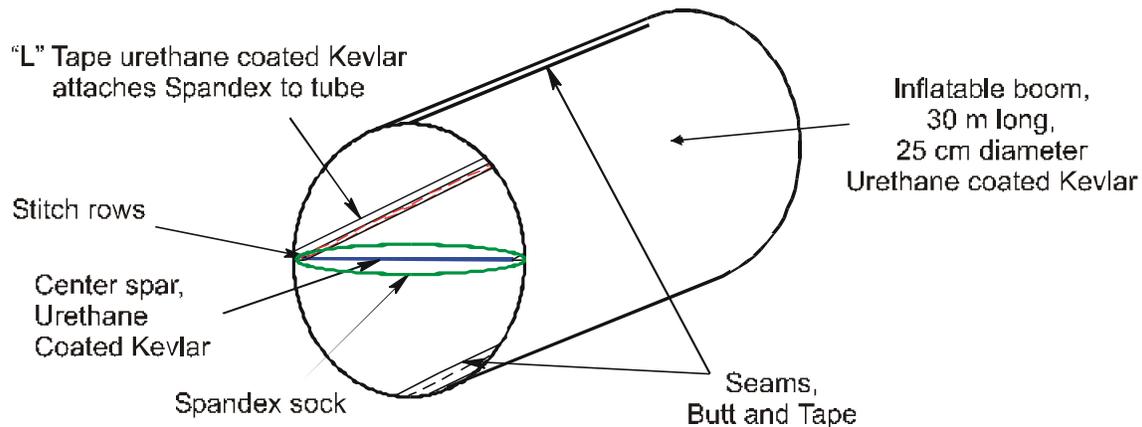


Figure 14 - Cross section of ILC Dover boom showing center partition for mounting antenna and photonic elements.

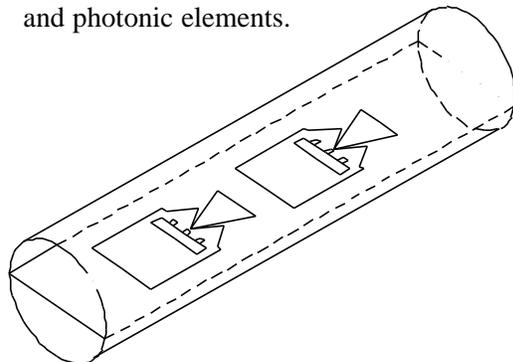


Figure 15 - ILC Dover boom showing center partition containing antennas.

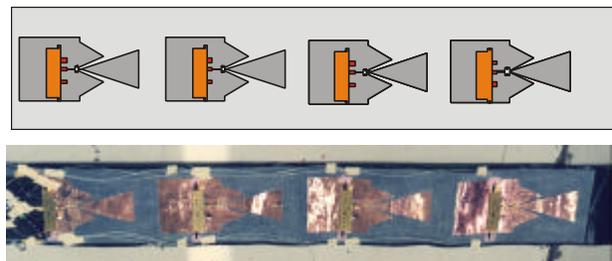


Figure 16 - Drawing and photograph of ILC Dover center partition. The 4-broadband (0.5 - 1.5 GHz) bowtie antennas are shown in an array with their accompanying photonic link components.

The endcap at the tip is the mounting surface for the controlled deployment mechanism and the packaging mandrel (**Figure 17**). The controlled deployment mechanism dictates the rate, linearity, impulse shock, and structural rigidity of the system during deployment. The device utilized is a rotational brake mechanism that applied a torque to the rolled boom to keep it in its rolled state from deployment initiation to completion. The system is deployed by introducing inflation gas into the base of the boom and allowing it to build until the force overcomes the constraining torque of the controlled deployment mechanism. The tip-mounted deployment mechanism eliminates the need for mechanisms installed along the entire length of the boom, thus reducing system mass. Deployment trials conducted at ILC Dover demonstrated a smooth, linear deployment of the

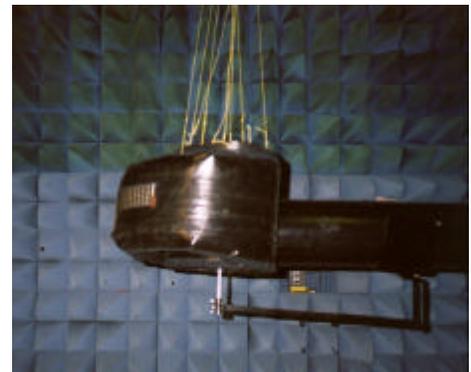
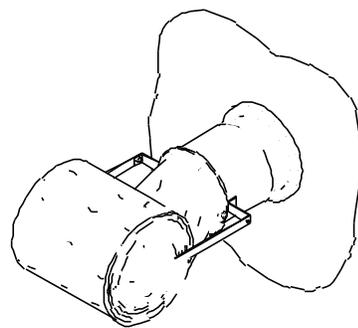


Figure 17 - Deployment mechanism and rolled ILC Dover boom.

antenna with very low impulse force imparted to the mounting surface. After some initial difficulties with the test setup, the tube was successfully deployed horizontally and suspended by wires from a long truss (Figure 18).

The boom was manufactured from urethane coated Kevlar for the demonstration antenna. This material was thermally sealed together using radio-frequency sealing techniques. The finished boom displayed minimal deviation from being perfectly straight (<5 cm over 30 meters). These materials were used for the demonstration model because of their ability to be used in multiple deployments. Flight systems will utilize materials that are "rigidizable" in-situ. The rigidizable materials are composite laminates that are packed and deployed in a flexible state and become rigid when an outside influence acts on them such as heat or UV radiation. Once the boom is rigidized, inflation gas is vented leaving a solid composite structure.

The boom that was tested was populated with flexible solar cells to demonstrate the ability of generating power locally for individual antenna components. The cells used were single junction amorphous silicon cells on a 50 micron polyimide substrate available from Iowa Thin Film Technologies. The cells were mounted to the exterior of the boom (Figure 19) and cell function was demonstrated without decrement before and after the deployment process.

4.0 Conclusions

This quick (five months from beginning to end) test and demonstration program was designed to demonstrate controlled deployment of two long, inflatable cylindrical booms while at the same time testing the survivability of integrally mounted fiber optic cables, mechanical photonic connections, electrical photonic connections, antennas, and solar cells after multiple rollup / deployment cycles. In addition, the tests were designed to demonstrate integration of a photonic RF link and antenna into the boom so that they could be used as a phased array antenna system. All of the components survived the multiple deployments of both of the booms. This is despite the fact that the initial deployment attempts of both booms were very stressful to the booms. Both phased array antenna systems performed as predicted. The only instability in the results

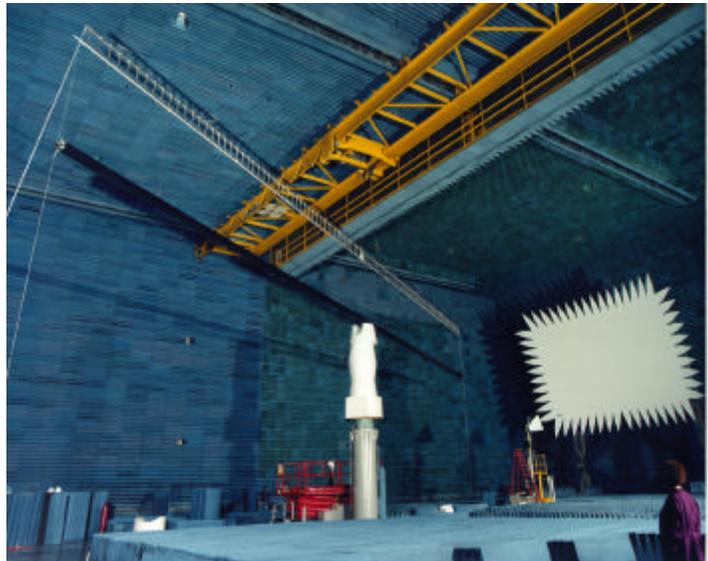


Figure 18 - ILC Dover's boom about to be set in the test cradle at the Pt. Mugu Radar Reflectivity Laboratory.

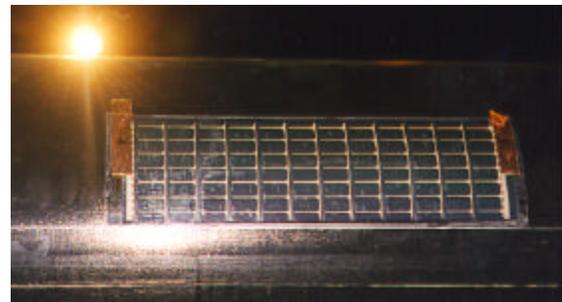


Figure 19 - Solar cell array on surface of ILC Dover's boom.

was found to be due to a sinusoidal oscillation in the boom. This is not considered a problem because the technology to track the location of antenna elements on a vibrating boom is well in hand.

As a result of this demonstration program it has been shown that the technologies are mature enough to make very large phased-array antennas in space practical. In particular, the following conclusions can be drawn.

- Antenna and photonic systems can be packaged, rolled, and deployed in inflatable structures without damage.
- Antennas can be placed either inside or outside the inflatable boom effectively. Specific issues relating to placement will depend on ultimate antenna design and connection to electronics / photonics module.
- Thin film, broadband antennas can be designed and fabricated.
- The cylindrical boom can support varied antenna designs - wideband, reconfigurable, narrow band antennas and array systems.
- Solar cells can be mounted on the surface of the inflatable booms and can be rolled and deployed without damage to the cells.
- Making a 100 foot long boom straight is quite feasible and bodes well for longer structures.
- Trying to simulate a large boom deployment in a 1-gravity environment is very tricky at best.
- Vibration modes generated in the inflated booms seem to be very simple. Hence, they are easy to remove from array calculation.