SMART SPACE TECHNOLOGY

L • GARDE INC. CORPORATE PRESENTATION

Large Inflatable Deployable Antenna Flight Experiment Results

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LARGE INFLATABLE DEPLOYABLE ANTENNA FLIGHT EXPERIMENT RESULTS

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ABSTRACT

Large space-based deployable antenna structures are needed for a variety of applications. However, recent reductions of antenna user resources have resulted in a real need for low-cost, large-size, light-weight, and reliable deployable space antenna structures. Fortunately, a new class of deployable space structures, called "inflatable space structures" is under development at L'Garde, Inc. The potential of this new concept was recognized by NASA who selected it for a flight experiment. The objective of the experiment was to develop a large, low-cost inflatable antenna structure and demonstrate its mechanical performance in the space environment. The carrier for this free-flying experiment was the STS-launched and recovered Spartan spacecraft. The experiment hardware consisted of a 14-meter diameter off-set parabolic reflector structure. The Spartan 207/IAE was successfully flown on STS 77, deployed on May 20, 1996 with Spartan recovery on May 21, 1996. The basic antenna structure deployed successfully, but in an uncontrolled manner, that clearly demonstrated the robustness of this new type of space structure. The low cost of the flight antenna structure hardware and the outstanding mechanical packaging demonstrated on orbit clearly validated the potential of this new class of space structure for enabling new, low-cost missions.

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INTRODUCTION

Large, space-based antennas are needed for a variety of different applications that include mobile communications, earth-observation radiometry, active microwave sensing, space-orbiting very-long-baseline interferometry, and Department of Defense (DOD) space-based radar.[2, 3, 4, 5, 6, 7, 8] Since there is no meaningful orbital assembly capability planned at this time, any large space structure will have to be based on self-deployable structural concepts. Current concepts for large, conventionally mechanical, selfdeployable space structures tend to be very expensive and mechanically complicated. Current antenna-user requirements are so stringent (with respect to the need for very low-cost, high-deployment reliability, low weight, and packaged-volume and usable aperture precision) that new and innovative approaches to accommodate large space antenna structures are needed. Fortunately, a newly developed class of space structures, called inflatable-deployable structures, has great potential for satisfying these stringent user requirements. A structural concept under development at L'Garde, Inc., for a large, inflatabledeployable antenna represents an excellent example of this new type of space structure.[12]

The NASA Office of Space Access and Technology initiated the In-Space Technology Experiments Program (IN-STEP) specifically to accommodate the verification and/or validation of unique, innovative, and high-payoff technologies in the space environment.' The potential of the L'Garde, Inc. concept was recognized and resulted in its selection for an IN-STEP experiment. [9,10,11,13] The IN-STEP Inflatable Antenna Experiment (IAE) was intended to address and demonstrate the technologies necessary to obtain serious user interest in this new class of space structure. This paper addresses the results of the design, assembly, launch and orbital performance of a large inflatable-deployable antenna structure.

EXPERIMENT DESCRIPTION

The IN-STEP IAE was managed by JPL for NASA. The antenna concept used for the flight hardware was based on the L'Garde, Inc. inflatable deployable structural concept that had been under development for about 10 years. L'Garde, Inc. of Tustin, California participated in the experiment as JPL's industrial partner. The experiment conceptual design started in **1989,** preliminary design in 1991, detail design and hardware development in 1993 and launch in 1996. Details of the experiment conceptual design, preliminary design, detail design and hardware development are given by References 9, 10, 11, 13, **16.**

Objectives

The objectives of the IAE were intended to specifically address the antenna user-application criteria. Consequently, the resulting specific objectives were to (a) validate the deployment of a 14-meter diameter, inflatable-deployable, offset parabolic reflector antenna structure in a zero-gravity environment, (b) measure the reflector surface precision, which was expected to be on the order of l-mm rms, for several different sun angles and inflation pressures in a realistic thermal environment, and (c) demonstrate that a large flight-quality structure could be built at low cost and that it could be stowed in a very small-size container.

Technical Approach

The experiment-system technical approach was based on the experiment objectives, the L'Garde, Inc. inflatable-structures concept capability, the NASA experiment resources available and the capability of the experiment carrier, the Spartan recoverable spacecraft.[16] The antenna structural configuration was based on the L'Garde, Inc., basic inflatable-antenna structural concept. The 14-meter-diameter reflector size was based on an extrapolation of the 9-meter baseline structures database and the current size limit for manufacturing capability at L'Garde, Inc. Moreover, this structure could be accommodated by Spartan, and it was large enough to be used for real applications, such as VLBI, commercial mobile communications and others. The surface-precision goal of 1 mm rms on orbit was based on the current analytical performance projections, previous hardware developments, manufacturing, assembly, and alignment capability at L'Garde, Inc. Validation and characterization of the deployment sequence would be done on orbit, which would provide a realistic operational environment. High mechanical-packaging efficiency would be demonstrated by stowing the large inflatable structure in a small canister. The in-flight single-orbit measurement of **surface** precision and its thermal stability would provide a measurement of the concept value for different potential applications.

Experiment **Functional Configuration**

The antenna experiment orbital system configuration is shown in Figure **1.** The basic elements of the system included the (a) inflatable

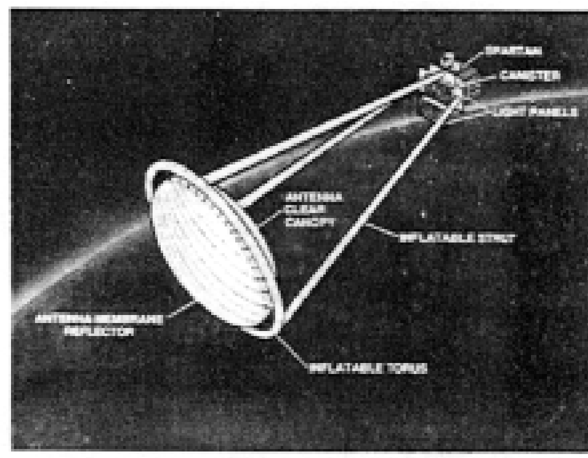

Figure 1. Experiment Configuration on Orbit

torus, which is the support structure for the reflector, (b) the inflatable parabolic membrane reflector structure and canopy, (c) the inflatable struts, which have capability for supporting a feed or subreflector structure, but, for this experiment, terminated at the canister, (d) the canister, which interfaced the antenna experiment to the Spartan, supported the stowed antenna and other experiment equipment, incorporated deployable doors to access the antenna structure to the space environment, and provides mounting for the surface measurement system light panels, (e) the instrumentation system that consisted of high-resolution television cameras and a digital imaging

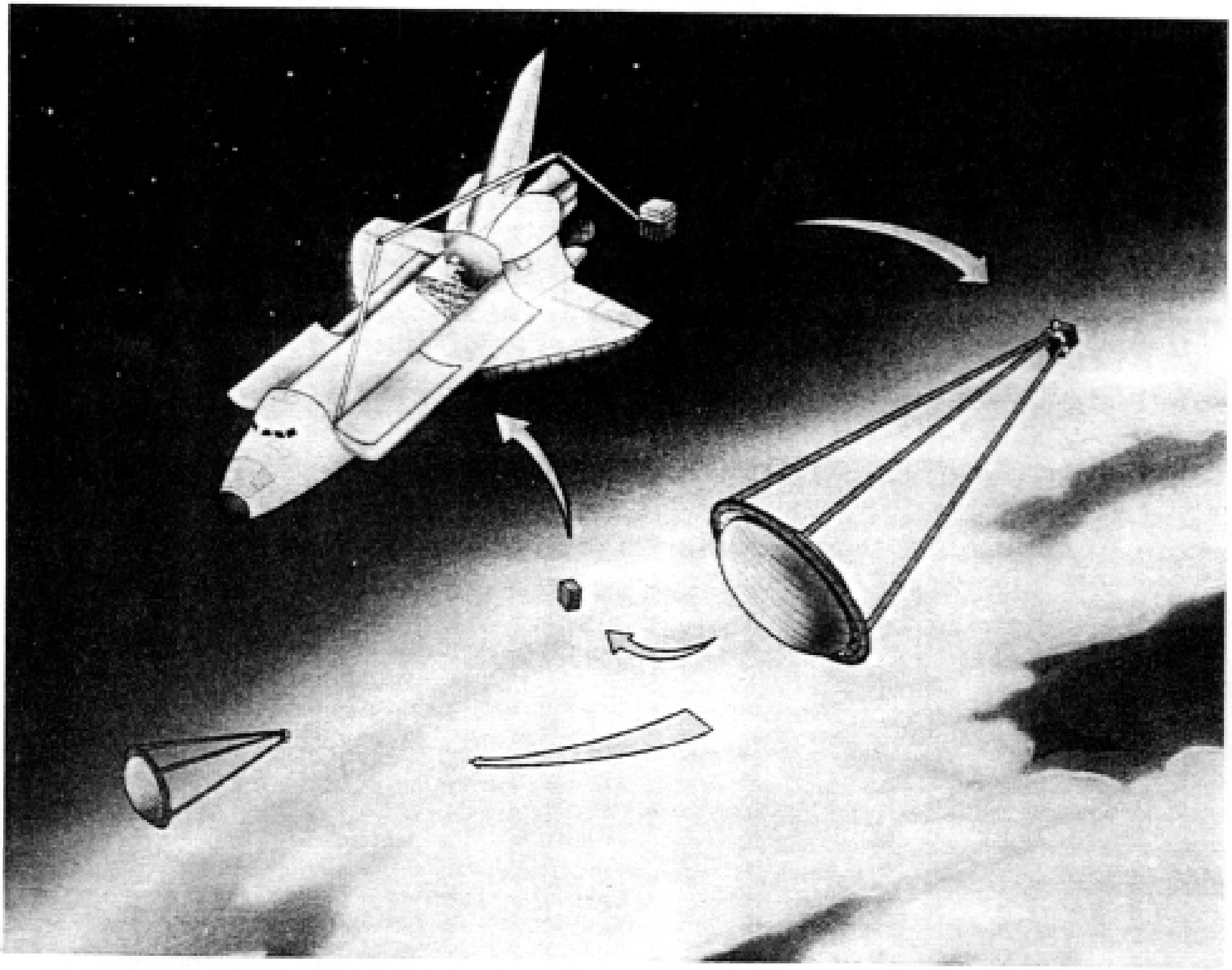

Figure 2. Orbital Functional Scenario

radiometer for measuring the reflector surface pressure, which were also mounted in the canister, and (f) the Spartan, which was the carrier for the experiment and provided initiation commands to the experiment controller, power, attitude roll control, data recording and ejection of the antenna structure after one orbit.

Planned Orbital Functional Scenario

The planned orbital functional scenario for the IAE was to start with the Spartan being placed overboard by the STS Remote Manipulator System (RMS) as shown in Figure 2. Once the orbiter moved a safe distance away and the Spartan had been stabilized by its attitude control system, a start command from the Spartan to the experiment controller was to initiate implementation of the experiment. Antenna deployment would commence with the opening of the canister doors; the spring-loaded floor plate called the ejector panel would then push the stowed structure away from the canister. The inflation system would then provide nitrogen gas to the stowed inflatable structure. The entire deployment sequence was expected to take on the order of 5 minutes. High-resolution photography, motion pictures, and video recording from the STS would document the entire deployment of the antenna structure and its orbital configuration. Measurements of surface precision for several sun angles and reflector/canopy inflation pressures would be made during the one orbit. Since the high drag of the reflector structure would cause separation of the Spartan from the orbiter, and only one orbit was required to implement the experiment, the antenna would be separated from the Spartan at the completion of the measurements. The Spartan with the experiment data would then be recovered by the orbiter at the end of its standard mission.

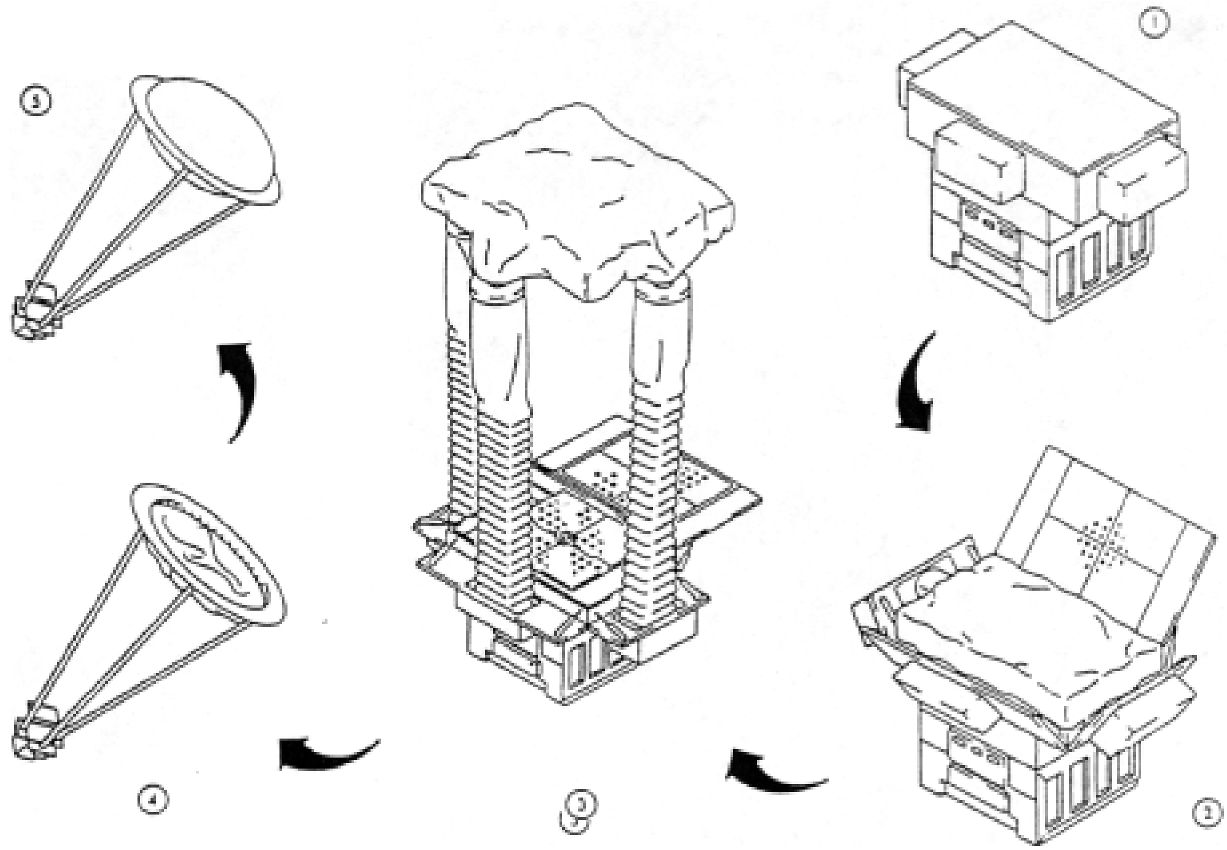

Figure 3. Antenna Deployment Sequence

Planned Antenna Deployment Sequence

The validation of antenna structure deployment, to be meaningful from a technical point of view, needs to address all of the elements involved, which include (a) the initial position and configuration of the stowed reflector structure after release from the canister, (b) the change of structural configuration associated with each of the four deployment phases, (c) the velocity of the structural elements, and (d) the time required for inflation of each phase. Deployment starts when the canister doors open and the stowed inflatable structure **is** ejected from the canister by a spring-loaded floor plate, Figure 3. Next the deployment of the struts is initiated by residual air and the strain energy release resulting from stowing the inflatable members. Once the stowed reflector structure has moved about 60 to 80 feet from the canister and the struts are partially extended, deployment is then completed by inflation of the struts. By this time, deployment of the torus has been initiated by release of its strain energy and residual air and completed by inflation. After this support structure has been completely deployed, the lenticular structure is then inflated.

ON-ORBIT PERFORMANCE

The STS-77 mission began on May 19, 1996 with the launch of Space Shuttle Endeavour. Onboard was Goddard Space Flight Center's (GSFC) eighth Spartan mission, the Spartan 207/Inflatable Antenna Experiment (Sp207/IAE).[17] The spacecraft was nominally deployed by the STS crew using the Remote Manipulator System (or RMS, the robotic arm) on Flight Day 2, Figure 4. With all spacecraft functions operating correctly, the antenna was inflated at the proper time **1** ½ orbits later, just after orbital sunrise. The IAE experienced unexpected dynamics during the initial ejection of the inflatable structure from its launch restraint system and inflation of the structure, but the correct final orbital configuration of the antenna support structure was attained. After full inflation of the antenna support structure, the spacecraft began rotating unexpectedly. During the deployment of the inflatable structure and throughout the science orbit, Endeavour's crew took extensive video, photographs, and motion pictures of the orbital activities. After operating for the desired orbit of the IAE operations, the inflated antenna was

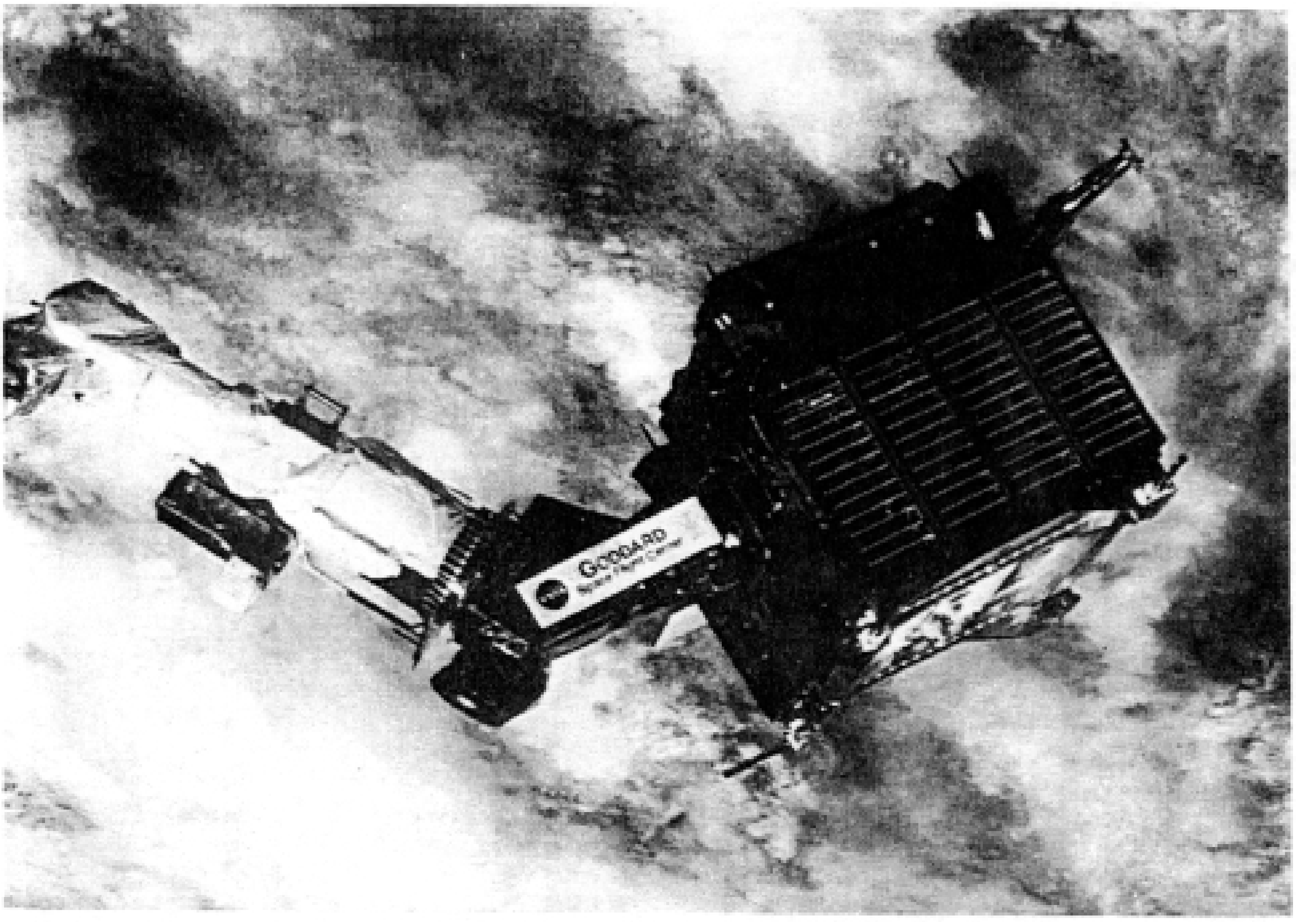

Figure 4. Spartan 207/IAE Connected to RMS

jettisoned from the Spartan 207 spacecraft. On the following day, the Spartan 207/IAE was successfully retrieved and stowed for return to Earth.[17]

Antenna Deployment

The deployment of the inflatable antenna structure was intended to be somewhat sequential in order to minimize interaction of all the inflatable structural elements which would tend to produce random transitional motions and thereby reduce deployment reliability. As it turned out the inflatable structure deployment was not sequential at all due entirely to an unpredicted amount of residual air in the stowed structure and a significant amount of strain energy released from the torus structure. This resulted in the near instant expansion of the torus and lenticular structure subsequent to its release by the launch restraint system. Consequently, when the ejector plate was actuated, only 4 seconds after release of the torus and lenticular structure, their premature expansion prevented them from being propelled away from the canister at the design velocity, Figure 5. Because of this situation, the struts were not pulled out of their "launch restraint" pods by the torus structure as expected. So when the inflation gas was introduced simultaneously to the three struts, at their interface with their pods, the gas flow path was different in each strut. As a result, each strut deployment was initiated in series rather than in

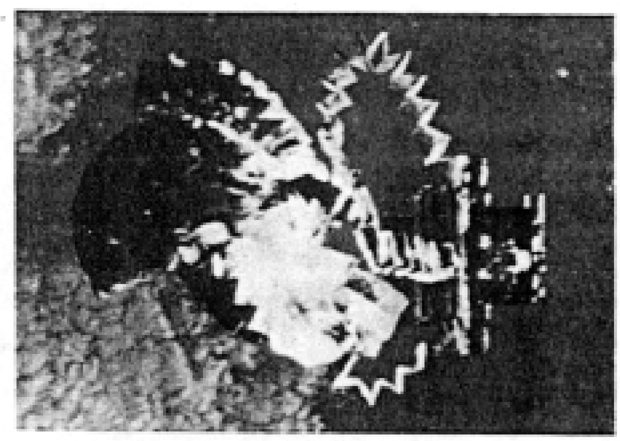

Figure 5. Early Orbital Deployment

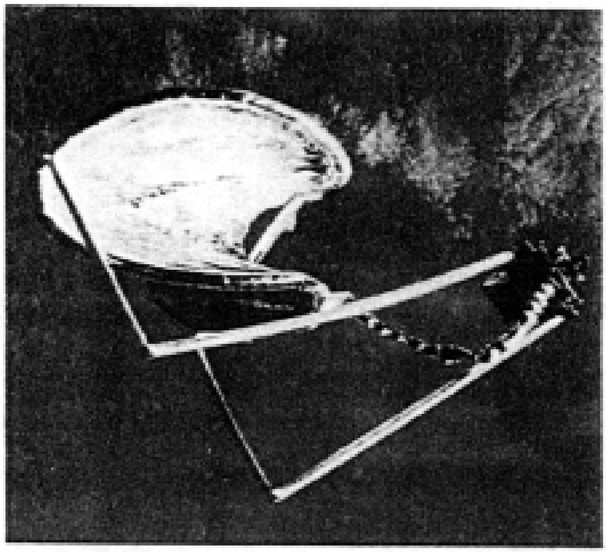

Figure 6. Partial Orbital Deployment

parallel as planned. As each strut extended during its deployment, the close proximity of the torus caused each one to react against its inertia and move away past the Spartan Spacecraft. Meanwhile, the torus structure was continuing to expand in a "planned deployment type manner" due to the residual air. By the time inflation gas first reached the torus through one of the struts, it was over 25% deployed, Figure 6. Within several minutes the other two struts and the torus were completely deployed. As the torus changed from the stowed to the deployed configuration, the lenticular structure was extended from its stowed to its pre-inflation configuration by the motion of the torus. However, inflation gas was never introduced to the torus as a consequence of a malfunction of the gas inflation system. Only partial inflation was achieved from the residual air in the lenticular structure. This partial inflation did not stretch the membrane reflector structure enough to achieve the specularity needed to accommodate operation of the surface measurement system.

The NASA sponsored IN-STEP experiments were focused on the demonstration of high payoff technologies and were not intended to actually develop basic technologies. Consequently, the development of basic control techniques for inflatable deployable space structures is currently being addressed in a NASA-sponsored technology development program.[15]

ANTENNA STRUCTURAL CHARACTERISTICS

The basic antenna support structure achieved full and complete deployment and maintained its design configuration for the duration of the one orbit experiment, Figures 7. and 8. The alignment of the lenticular structure with respect to the torus, the torus with respect to the struts, and the struts with respect to the canister were within design tolerances, as verified by high resolution photography. Examination of the photographs of both the thin reflector and canopy membranes that comprise the lenticular structure showed no signs of

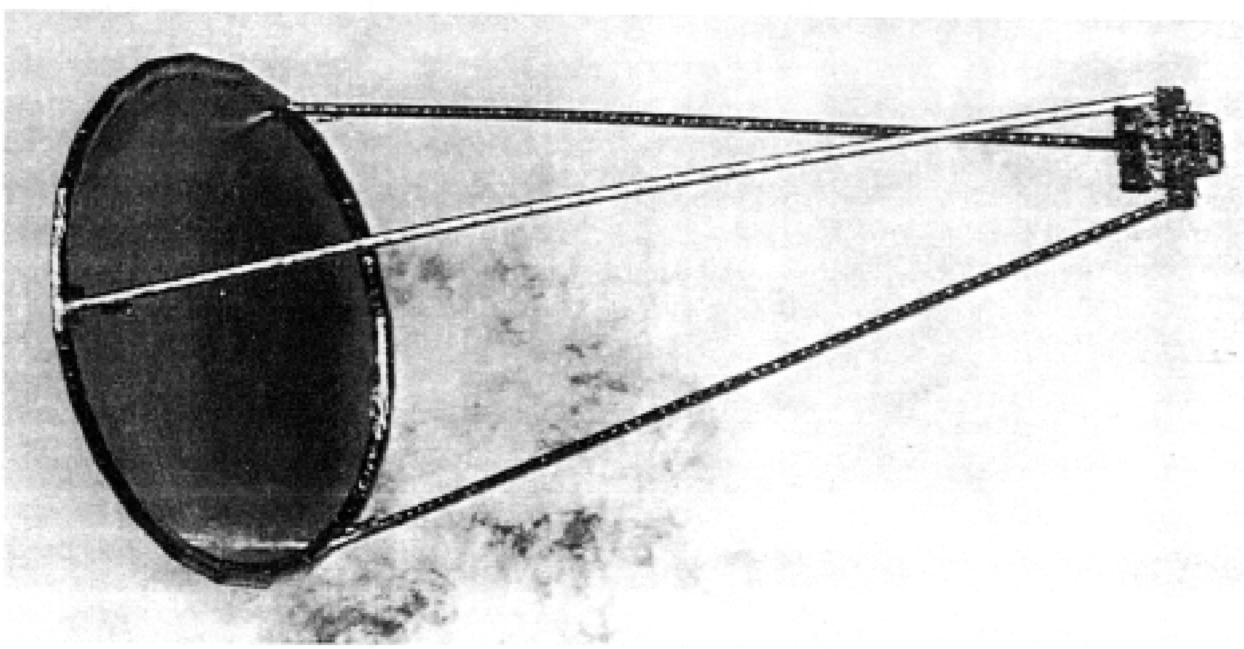

Figure 7. Deployed Orbital Configuration

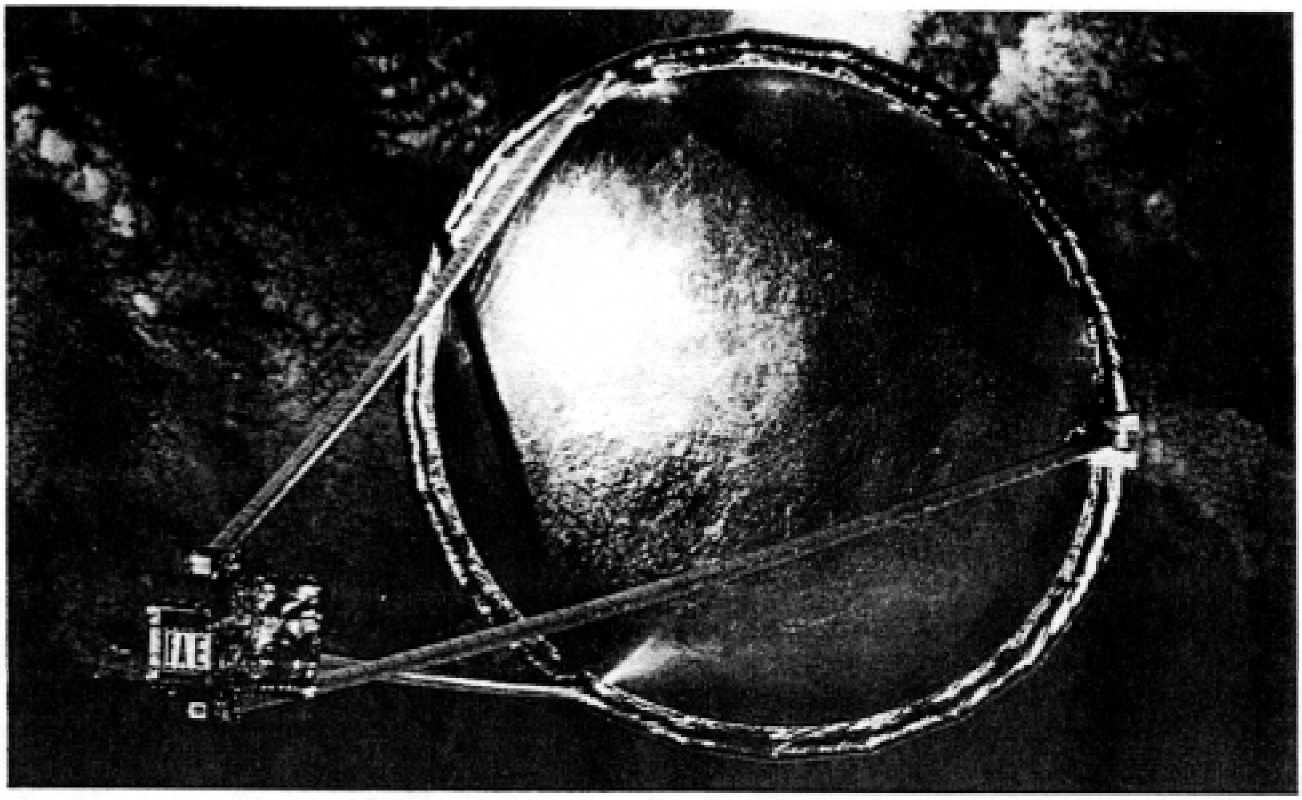

Figure 8. Deployed Orbital Configuration

holes or tears as a consequence of the vibratory launch environment, deployment of the torus structure or its change from the stowed configuration to the "trampoline"-type support provided by the torus prior to inflation. Figure 9. depicts a fully inflated lenticular structure on the ground prior to launch. Pre-flight analysis showed that the deployed structure would be stable on orbit due to atmospheric drag on the reflector structure. During inflation of the structure, the Spartan was correctly oriented with the antenna axis parallel to the ram direction and the reflector structure facing it. Shortly after inflation, the spacecraft and antenna started to rotate, possibly as a consequence of a leak in the nitrogen gas inflation system or the inflated structure itself. This rotational rate continued to increase until the end of the experiment. The deployed stiffness of the antenna support structure was sufficient to maintain the alignments observed during the initial part of the experiment even with the unexpected rotations.

FLIGHT DATA AND ANALYSIS

The flight data recorded during the experiment included (a) pressure time histories, (b) temperature time histories, (c) IAE micropresser command time histories, (d) antenna surface measurement system, (e) high-resolution photography, video and motion picture coverage from the orbiter and (f) command and control time histories from the Spartan. The pressure measurements from the IAE covered the high-pressure nitrogen inflation system and the low pressures in the torus, strut and lenticular structures. Temperatures were measured on the reflector film, torus and strut structure neoprene surfaces and their MLI and on canister-mounted instruments. The IAE preprogrammed microprocessor, which was initiated by command from the Spartan controlled all antenna functions. The IAE surface measurement system functioned nominally, but did not provide useable data for the characterization of the reflector structure due to improper inflation of the lenticular structure. The photographic and video coverage of the experiment from the orbiter were outstanding in every way. Post-flight analysis of the engineering data from the Spartan free-flyer indicated that all functions performed nominally.

ENVIRONMENTAL INTERACTIONS

The interactions of the inflatable antenna structure with the space environment were exploited by the experiment, accounted for in the functional design

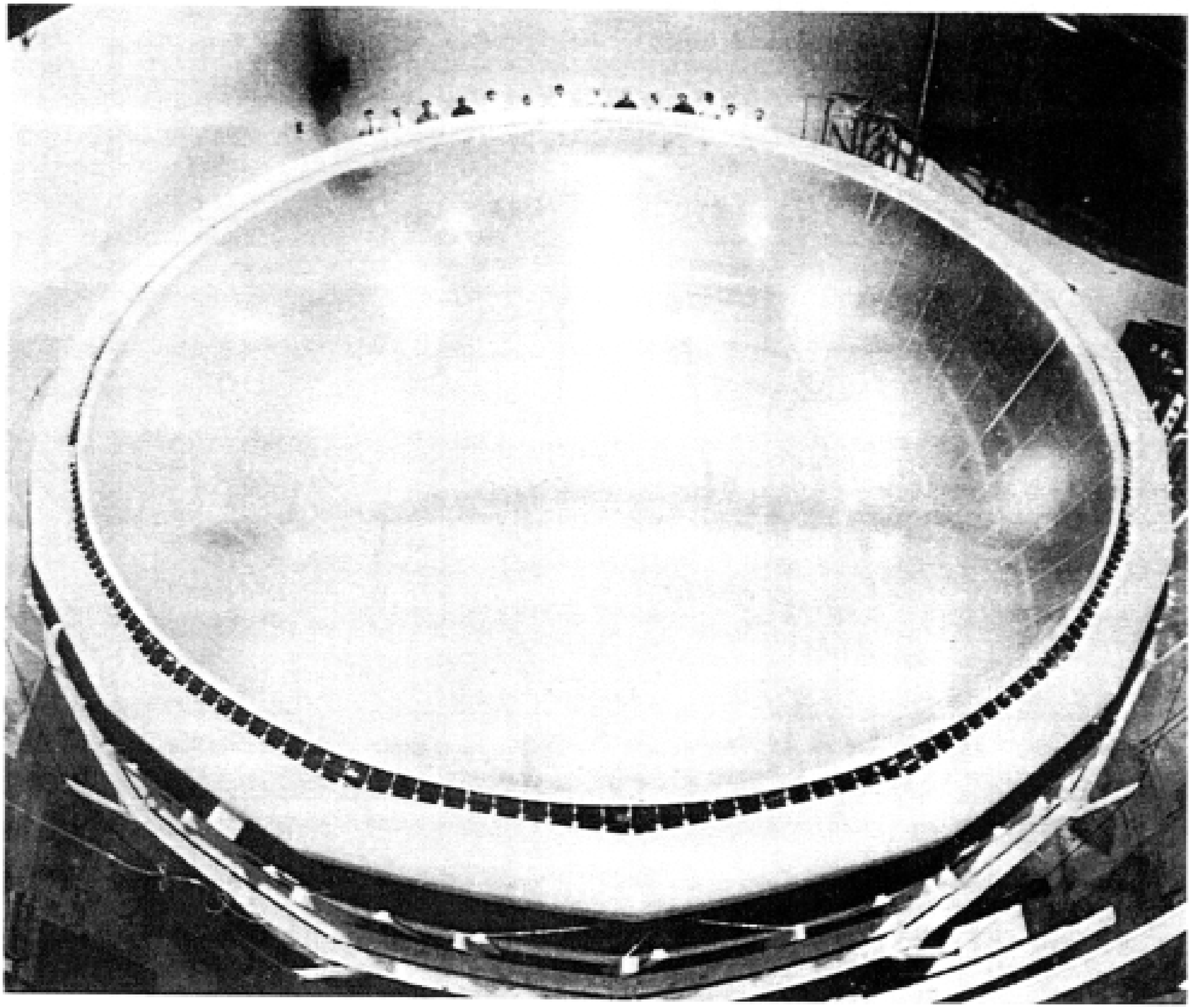

Figure 9. Reflector Structure

of the experiment, and characterized as part of the experiment.

A realistic demonstration of deployment for this new class of space structure can only be done in the space environment. Gravity loading and/or zero g simulation fixturing will totally mask the kinematic performance of this type of space structure. The actual space-based deployment revealed the importance of several factors affecting deployment that could not have been accurately characterized on the ground. These factors were the energy released from residual air and strain energy in the folded membrane materials and its effect on the deployment dynamics. Additionally, the atmospheric drag in the low orbit was used to stabilize a large structure which could not be controlled by a small spacecraft.

The design of the orbital system scenario was based on structure/environment interactions. The timing of the Spartan 207/IAE mission during the flight of STS 77 was tailored to maximize avoidance of the IAE electronics with respect to the South Atlantic Anomaly. The experiment duration was limited to only one orbit due to the relative separation of the antenna from the STS due to its drag. A longer-duration experiment would have required the STS to expend significant propellant to maintain a close proximity to the Spartan.

The measurement of the temperature on the thin-film reflector structure validated the predictions of the near instantaneous changes associated with radiation heat loading during earth occultation. The temperature of the reflector film dropped from approximately 40°c to < -70°c on the order of one second. The sensitivity of these thin films, which have near-zero heat capacity, to almost any changes in thermal radiation loading must be accounted for in the design and orbital operations of such structural systems. Factors affecting these films would include coatings having tailored optical properties. The torus and struts were blanketed with three layers of multilayer insulation. Consequently, their change in temperature was only from 20°c maximum to -10°c minimum. Additionally, it is important to note that there was essentially no temperature gradients across the structural members. The experiment equipment mounted below the ejector plate was protected with eighteen layers of multilayer insulation and, therefore, experienced essentially no temperature changes during the one orbit experiment.

IAE EXPERIMENT ACCOMPLISHMENTS

The accomplishments of the experiment are a function of the satisfaction of the technical objectives, the level to which the technologies were characterized, and the degree to which the technology maturity level was established. Such an assessment is based on knowledge of the state-of-the art inflatable space structures technology prior to IAE, the experiment hardware development results and the orbital performance.

The experiment accomplishments include the following:

- Built a very large flight quality inflatable antenna structure for on the order of $1M.
- Stowed a 16- by 28-meter inflatable space structure in a container the size of an office desk.
- Manufactured a 14-meter diameter membrane reflector structure with a surface precision on the order of a few millimeters rms.
- Built and demonstrated performance of a space qualified surface accuracy measurement system with a resolution of 0.1 to 0.2 mm for on the order of $1M.
- Demonstrated successful and robust deployment of a large, multiple element, inflatable antenna structure on orbit.
- Successfully used the Spartan free-flyer carrier to accommodate an experiment that was many times larger, once deployed, and had a rotary inertia six orders of magnitude more than payloads for which the Spartan was originally designed.
- Results of the experiment contributed significantly to the technology database for this new class of space structure.
- Demonstrated the ability to predict and use the structural interaction with the space environment in the IAE design, and its operation and verification on orbit.
- All the experiment objectives were met with the exception of the inflation of the lenticular reflector structure.

SIGNIFICANCE OF EXPERIMENT

Large inflatable-deployable space structures have been around for over 40 years, i.e. Echo I, Series 1959-63, but only recently have a very few organizations learned how to design and manufacture thin membrane structures with geometric precision." At the same time, the potential of this new type of space structure for different classes of application became evident. However, due to the immaturity of this new technology, there was no serious user interest at that time. Consequently, the advent of the IAE was pivotal in determining the future of inflatable space structures, technology development, and their subsequent applications.[1]

The advent of IAE has had a significant impact in the area of large space structures.

- The IAE was enabled by the availability of the Spartan free-flyer carrier as a consequence of its low cost, flexibility, and its near proximity to the orbiter which was essential for photographic coverage of the experiment.
- The potential mechanical performance of inflatable space structures has been recognized for some time, but serious user interest materialized only after the successful advent of IAE.
- The results of the experiment have verified the low hardware cost, characterized the orbital performance, and established the potential of this new class of space structure for a variety of applications.
- The results of the experiment have clearly identified the technology areas requiring additional investment by both NASA and the DOD.

- The next orbital demonstration of inflatable structure performance is expected to address the limitations of IAE which will be the measurement of aperture precision and the characterization of RF performance.
- The interaction of this new class of space structure with the environment is extremely significant and must be accounted for in the design, launch, and orbital operation of this type of space system.
- While IAE was a major step in the validation of inflatable space structures, a great deal more work still needs to be done to fully realize the tremendous potential of this new technology.

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