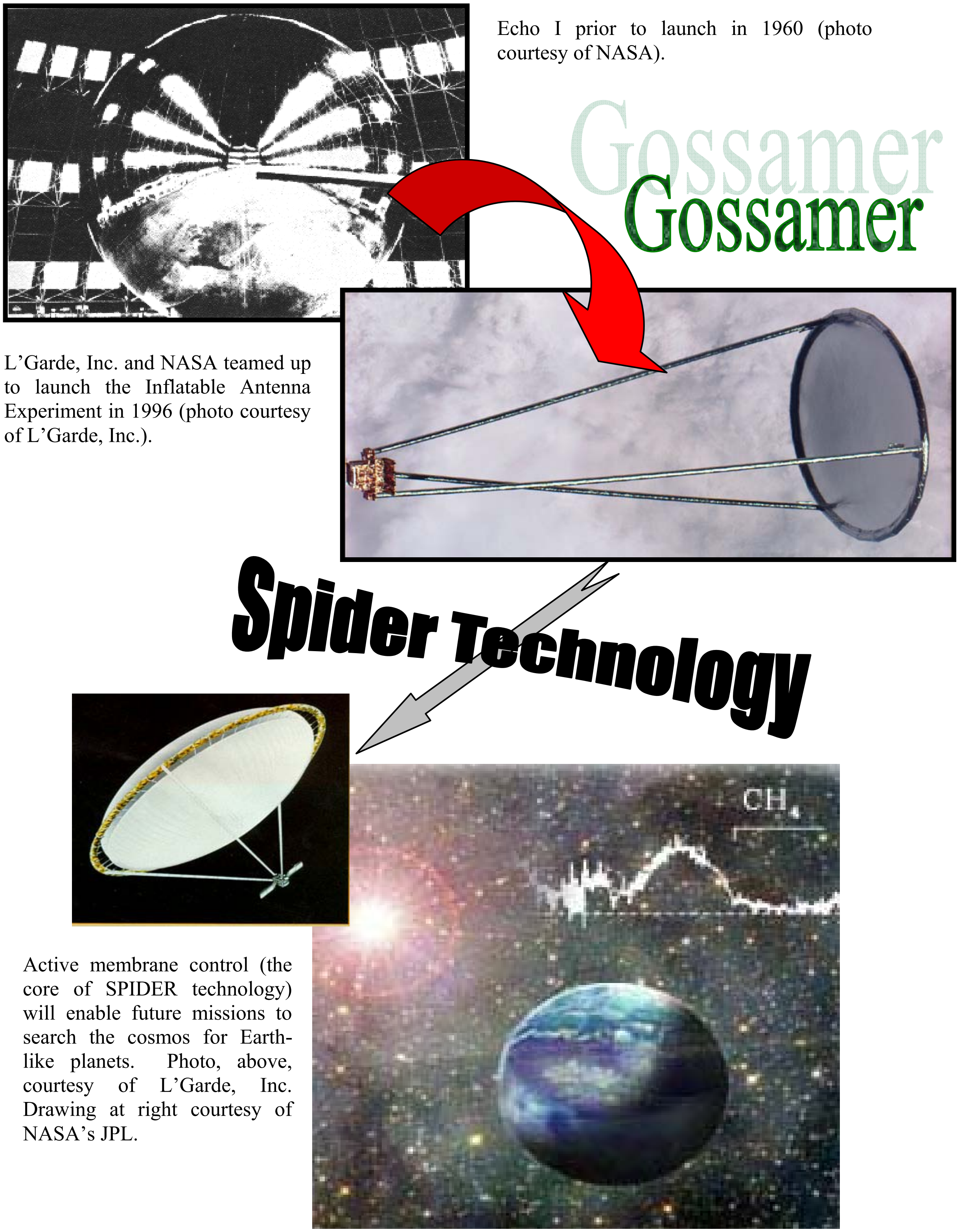
# Chapter 1: Introduction

## 1.1 The Concept of SPIDER Technology

In the past, large inflatable satellites were referred to as gossamer structures. Gossamer literally means “tenuous wisps of cobweb blowing in the wind” (Chmielewski, 2000). However, multifunctional satellites used for both imaging and communications purposes cannot just float through the air like pieces of cobweb. They require active controllers for the gross reflector shape as well as nanoscopic surface tolerance of the dish for optical imaging purposes. Since the next level of research will require active dynamic analysis, vibration control, and shape morphing control of these satellites, a better-suited name for this technology is Super Precise Intelligent Deployables for Engineered Reconnaissance, or SPIDER (Ruggiero, Jacobs, and Babb, 2004). Unlike wisps of cobweb caught in the wind, SPIDER technology will dictate the functionality and versatility of the satellite—much like an arachnid weaving its own web.

SPIDER technology possesses ideal space launching characteristics, including minimal storage volume and minimal mass. By overcoming the limitations of the current state-of-the-art, SPIDER structures will help spawn the next generation of space satellites and applications. However, certain key issues must be investigated before such satellite structures are implemented. In particular, the surface conditioning of thin, flexible, and inflatable membranes must be well understood. Optical imaging satellites must be tightly controlled from a surface accuracy standpoint to achieve optical-level tolerances. Developing a reliable, durable, and accurate membrane for optical surveillance is critical to mission success and satellite longevity. Figure 1.1 shows the transition from traditional gossamer craft to next generation SPIDER craft.



Echo I prior to launch in 1960 (photo courtesy of NASA).

L’Garde, Inc. and NASA teamed up to launch the Inflatable Antenna Experiment in 1996 (photo courtesy of L’Garde, Inc.).

Active membrane control (the core of SPIDER technology) will enable future missions to search the cosmos for Earth-like planets. Photo, above, courtesy of L’Garde, Inc. Drawing at right courtesy of NASA’s JPL.

**Figure 1.1.** To meet stringent surface requirements for membrane-based optics and satellite buses, passive gossamer designs will have to transition to active SPIDER designs.

## 1.2 Motivation for Research

The Air Force Research Laboratory Directed Energy Directorate (AFRL/DE) in Albuquerque, New Mexico has been working hand-in-hand with SRS Technologies (Huntsville, Alabama) to develop an optical-quality membrane material. Currently, SRS Technologies can cast a thin film polymer disc 1 m in diameter with a 30 nm peak-to-peak surface undulation over the entire disc and with a surface roughness on the order of 1 – 2 nm. These incredible tolerances mean that from a materials science standpoint, membrane materials can now be fabricated as optical surfaces for satellite lenses or mirrors. In 2001, the AFRL/DE used a 3.5 inch membrane lens in a diffraction-limited telescope to view Saturn. The fact that the telescope was operating at the diffraction limit means that an equivalent lens made of traditional glass would have the same resolution, as the diffraction limit of a telescope refers to the minimum angular separation of two point sources that a telescope can distinguish. The raw image photograph of Saturn taken at the AFRL is shown in Figure 1.2.

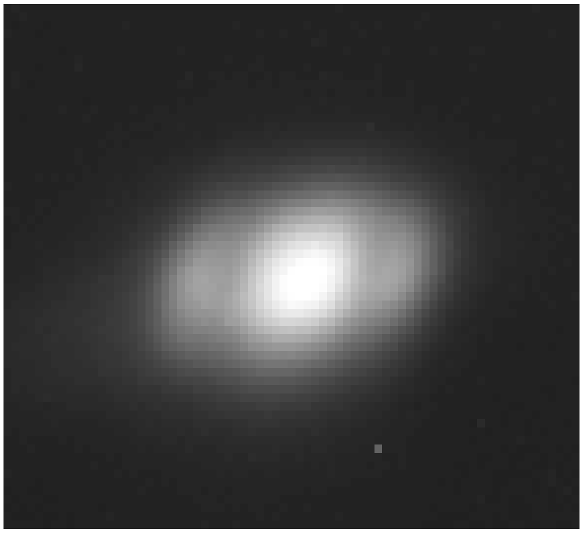


**Figure 1.2.** Raw image photograph of Saturn from a 3.5 inch, diffraction-limited membrane mirror telescope. Photo courtesy of Dan Marker, AFRL/DE (2001).

To get large membrane mirrors on-orbit, satellite designs similar in form to the Inflated Antenna Experiment (as shown in Figure 1.1.) have been proposed. Such a design relies on inflation pressure to create the rigid supports for the satellite bus. Because these structures are inflated, issues such as inflation pressure, pressure distribution, and skin wrinkling are of primary concern. In terms of space applications, inflated structures are subject to severe environmental changes as the satellite passes from orbital day to orbital eclipse. It is envisioned that these structures can be rigidized through material property changes but may have primary vibration modes less than 1 Hz. Any thermal environmental changes with such a flexible structure translate into wave front error in the payload. Further, these satellites are susceptible to vibration while on orbit because of on-board disturbances or maneuvering dynamics. Therefore, the membrane or aperture of a huge, inflatable satellite must possess active and passive means to control the surface used for optical imaging. By accurately controlling the membrane surface, the satellite will be able to see more of the earth at a single moment with minute slew and scan requirements. In transitioning the satellite from passive to active, or from gossamer to SPIDER, research into augmenting the membrane with an active material must be performed. Such is the focus of this work.

### 1.3 Research Objectives and Contributions

There are four main objectives in the current work: 1) to understand the structural mechanics of a membrane held under tension with active material augmented near the boundaries; 2) to use the augmented active material for active vibration control of the membrane; 3) to demonstrate modeling techniques to enable system-level design of active membrane mirrors; and 4) to understand the dynamic interaction between large surface area membrane lenses backed by small-depth cavities.

Understanding the structural mechanics of the active membrane is the first critical technological pathway that must be traveled. Recent research endeavors have looked into the mechanics of membranes under tension, but implementing a theory to capture the localized mass and stiffness changes of an augmented, active membrane has not been pursued until now. This work looks at modeling the active membrane as a beam under axial loading (in the 1-D case) and as a thin plate under axial loading (in the 2-D case). By using these theories, we can capture the localized mass and stiffness changes of the active membrane—a feat that cannot be accomplished using membrane theory alone due to the fundamental assumptions used in developing membrane dynamics.

One of the main benefits of integrating an active material, like piezoelectric material, with the membrane mirror is that vibration control and disturbance rejection can be accomplished through state feedback control. By keeping the active material near the rim of the optic, the central portion of the lens can still maintain its optical-level tolerances. This is a critical requirement in the overall mission goal of designing an optical membrane lens.

Another goal of this work is to develop a system model so that the dominant physics are well understood and can be used as a design tool. The incorporation of active material with the membrane will change the dynamic response of the structure due to the additional mass and stiffness. The bandwidth of the membrane optic determines the effective operating range of the lens, especially if it is being used as a deformable mirror in an adaptive optics scheme. Having an accurate model of the physical system will enable simulation of different active membrane designs and consequently save on prototype development cost and time.

Finally, another goal of this work is to understand the dynamic interaction between a membrane lens backed by a shallow cavity. Although much research has been performed in understanding the behavior of drum-like membranes and cavities, where the depth of the cavity is on the same order as the diameter of the taut membrane, little research has been performed on membranes backed by shallow cavities. The benefits of designing a system that includes a shallow cavity include superior, passive damping characteristics of the membrane and the possibility of additional structural control through distributed pressures applied via the back plate.

The present research presents a complete look at different design and modeling issues facing researchers in the development of an active membrane lens. An outline of this development is provided in the next section.

## 1.4 Outline of Dissertation

An outline of the research performed in the area of active, SPIDER membranes is as follows. First, in Chapter 2, a comprehensive literature review encompassing the various research efforts in the area of membrane mirrors, inflated satellite buses, and control of such structures is presented. Then, in Chapter 3, a review of the Rayleigh-Ritz, Galerkin, and Finite Element methods of approximation is presented. Although the models discussed in latter chapters will use the Finite Element method, the Rayleigh-Ritz and Galerkin methods are also discussed as a method of comparison and an argument as to why the Finite Element method should be used. Chapter 4 reviews the theory behind thin plates and membranes and forms the premise for using thin plate theory (in the 2-D case, and beam theory in the 1-D case) for modeling the active membrane. Chapter 5 presents a thorough development of the beam under axial load equation for modeling the transverse vibration of a thin membrane strip with attached piezoelectric bimorph. Both the theoretical analysis and experimental validation is presented. Chapter 6 extends the results of Chapter 5 into the 2-D case, and uses thin plate theory to capture the dynamics of the augmented membrane system. Simulated control results are presented that use the piezoelectric actuators to suppress the vibration of the membrane. In Chapter 7, research into the dynamic interaction between a membrane and a thin cavity is presented. The response of the membrane under constant tension but with various cavity depths will be analyzed. In Chapter 8, the concept of transforming incoming wavefront aberrations, typically expressed as Zernike polynomials by optical engineers, into the mode shapes of a clamped membrane will be explained. In doing so, the mode shapes of the membrane can be used as a mapping for distributed, pressurized control of the membrane. Such a concept would be advantageous if the membrane optic was to be used in an adaptive optic scheme as the deformable mirror. Finally, the dissertation will conclude with a summary of contributions and a discussion of future work.