October 2004

Constellation-X SXT Assembly Design

Devin Collins Brande
Worcester Polytechnic Institute

Michael Andrew Planka
Worcester Polytechnic Institute

Monika A. Goodrich
Worcester Polytechnic Institute

Project Code: FJL-CONX

Constellation-X SXT Assembly Design

A Major Qualifying Project

Submitted to:

The Faculty of Worcester Polytechnic Institute

In partial fulfillment of the requirements for the degree of Bachelor of Science

Project Team:

Devin Brande
branded@wpi.edu

Monika Goodrich
cbwb07@wpi.edu

Michael Planka
mplanka@wpi.edu

Advisors:

Fred Looft, PhD
fjlooft@wpi.edu

Stephen Bitar
sjbitar@wpi.edu

14 October 2004

conx04@wpi.edu

Abstract

Constellation-X is a long term NASA project intended to develop a satellite X-ray telescope to study the structure and evolution of the universe. As of October 2004, the Constellation-X satellites were in the design phase. The goal of this project was to develop alternative methods of reflector installation for the Spectroscopy X-ray Telescope portion of Constellation-X. Our team developed designs for telescope structure and for reflector handling.

Table of Contents

List of Figures

LIST OF TABLES

Acknowledgements

Jeff Stewart – For his unwavering patience and commitment to the success of our project

Bobby Nanan – For his constant assistance in our modeling efforts

Burt and Janet Squires – For their valuable insight and assistance on our design efforts

Ben Rodini – For explaining composites to us in less than thirty minutes

Chris Kolos – For machining our 55 lb. mandrel on short notice

Andrew Carlson, Thomas Meagher, Josh Schneider – for their constant assistance and good humor

Fred Looft – For his guidance on the project and remarkably prompt turnaround on drafts

Stephen Bitar – For his concern about making the overall project experience positive

1 Introduction

This chapter begins by discussing the background and goals of the Constellation-X mission for the National Aeronautics and Space Administration (NASA) Goddard Space Flight Center. This chapter also gives a brief overview of the work our Worcester Polytechnic Institute (WPI) project team sought to accomplish while part of the Constellation-X Spectroscopy X-Ray Telescope (SXT) Mechanical Systems team. In addition, descriptions of several problems the NASA engineers have encountered while working on the SXT aspect of the Constellation-X telescope are mentioned. Finally, the following report describes: our background, goals, tasks, objectives, methods, results, and conclusions for the project.

1.1 Constellation-X Introduction

The Constellation-X mission is a long term NASA project designed to create what will be the world's most powerful X-ray telescope with a tentative launch date of 2013. In its current configuration the Constellation-X telescope is designed as an interferometer with four identical satellites that will act jointly as one large telescope, very similar to the way that the Very Large Array radio telescope works. Briefly, "An interferometer consists of two or more separate telescopes that combine their signals as if they were coming from separate portions of a telescope as big as the two telescopes are apart. The resolution of an interferometer approaches that of a telescope of diameter equal to the largest separation between its individual elements (telescopes)."[1] The four telescope configuration offers the advantage of creating a larger aperture by combining the signals of the four satellites. The Constellation-X telescope is intended to be at least 100 times more powerful than Chandra X-ray telescope[2], currently the most powerful X-ray telescope.

1.2 Constellation-X Applications and Issues

The goal of the Constellation-X project is to develop and design an X-ray telescope that will help scientists view more distant X-ray sources with greater accuracy and higher resolution than has been produced by previous X-ray telescopes. According to NASA's Constellation-X website, "…scientists will investigate black holes, Einstein's Theory of General Relativity, galaxy formation, the evolution of the Universe on the largest scales, the recycling of matter and energy, and the nature of 'dark matter.'"[3]

NASA has specified certain scientific objectives to be pursued by the Constellation-X. The objectives are as follows:

- The study of super massive black holes and how they were formed,

---

1 http://astrosun2.astro.cornell.edu/academics/courses//astro201/interferometer.htm
2 http://constellation.gsfc.nasa.gov/
3 http://constellation.gsfc.nasa.gov/

- The study of dark matter and dark energy,
- And the use of the telescope to gain a better understanding of the evolution of different types of matter throughout the universe

These objectives will be discussed in greater detail in Section 2.5.2 of this document.

GSFC has encountered numerous obstacles in the design and construction of such an ambitious telescope. As a result of the nature of X-rays and their high energy, a large number of precisely aligned reflectors are required in each satellite to properly focus incoming X-rays for imaging. Each satellite will have on the order of 4000 reflectors, all of which will require precision alignment and bonding. Some of the more significant problems the SXT group has encountered on this project are:

- Maintaining the shape of and the relationship between the parabolic and hyperbolic reflectors as they are removed from the replication mandrel and installed in the module sections of the SXT,
- Precisely aligning the reflectors within the modules,
- And locating the optical reference axis from which to align the reflectors

One of the major difficulties engineers at NASA are facing is the precision alignment and bonding of such a large volume of reflectors. While a method for manually aligning each reflector using precision dial actuators and a Centroid Detector Assembly (CDA) has been researched, it is considered too time consuming to be a practical solution for aligning approximately 16,000 reflectors. Once each reflector is successfully aligned it must then be bonded in position in such a way that it will maintain its shape. The bonding process requires a similar level of precision as the alignment process. Additional issues arise in the bonding process because of the multiple locations that must be bonded and also because of the confined space in which any bonding method has to operate.

1.3 Project Statement

The precision installation and alignment of approximately 4000 reflectors in the SXT portion of each Constellation-X satellite is one of the goals of the SXT Mechanical Systems team at GSFC. As a result, the goal of our project was to develop new methods of precision installation of the reflectors.

The designs that our team developed are the "bed of nails" design, the composite draping design, and the "glass-pack" design. The purpose of the bed of nails design is to take and hold the form of the reflector, without causing any type of deformation, while the reflector is still attached to the replication mandrel. The composite draping design was proposed and researched as an alternative to the bed of nails design. The glass-pack design consists of composite strut and support structures attached to each reflector pair that allow them to be grouped together in packs containing on the order of ten reflector pairs. The purpose of the glass-pack design is to replace the current reflector module design and make the processes of SXT assembly and damaged reflector replacement less complicated. These ideas will be discussed in more detail in later sections of this report.

1.4 Summary

This chapter has provided an overview of the Constellation-X mission along with the ultimate goal of the Constellation-X telescope. The work accomplished by the NASA engineers as well as some of the problems they have faced has also been presented. Finally, a project statement for the 2004 project group was proposed and several objectives discussed. The following report details the background, process, and results of our report, along with the teams' conclusions.

2 Background

This chapter presents information on the history and background of the Constellation-X mission and the organizations responsible for the mission, NASA and the Goddard Space Flight Center within NASA. Further, information on X-rays and the history of X-ray telescopes is presented as a study of research and technology leading up to Constellation-X. Information about the Constellation-X mission is broken up into two main areas. First, an overview of the mission and the technology is presented. Second, a review of the previous work performed by WPI project is presented.

2.1 National Aeronautics and Space Administration

The National Aeronautics and Space Administration (NASA) was formed on October 1, 1958, absorbing the National Advisory Committee for Aeronautics, the Langley Aeronautical Laboratory, the Ames Aeronautical Laboratory, and the Lewis Flight Propulsion Laboratory. The space science group of the Naval Research Laboratory, the Jet Propulsion Laboratory, and the Army Ballistic Missile Agency were also incorporated shortly after NASA was formed[4].

Although NASA's own fact sheets mention that NASA was formed in response to the Cold War and the Soviet Union's space efforts, notably the launch of the artificial satellite Sputnik 1 on October 4, 1957, the preamble to the act which created NASA states that it was, "An Act to provide for research into the problems of flight within and outside the Earth's atmosphere, and for other purposes"[5].

Shortly after it was formed, NASA focused its efforts on manned space flight. NASA was successful in their manned space flight efforts with the Mercury, Gemini, and Apollo projects. NASA was able to put a man in space and in 1969, with Apollo 11, NASA put the first human on the moon. Manned space flight was continued with the Space Shuttle program that is currently still putting astronauts in space who are assisting with the construction of the International Space Station, continuing to conduct research missions in space, and performing tasks such as routine maintenance on the Hubble Space Telescope[6].

NASA also conducts aeronautics research in a variety of areas including aerodynamics and wind shear. Projects include the X-Plane program that was used as a flight test program for a variety of experimental concepts and designs[7], and the F-8 digital fly-by-wire program, which was important in developing electronic flight control for aircraft such as the space shuttle[8].

Further, NASA is responsible for a diverse array of work in non-manned space flight. NASA has launched a variety of scientific instruments into space, including the Hubble Space Telescope and the

---

[4] http://www.hq.nasa.gov/office/pao/History/factsheet.htm
[5] http://www.hq.nasa.gov/office/pao/History/factsheet.htm
[6] http://history.nasa.gov/brief.html
[7] http://www.hq.nasa.gov/office/pao/History/x1/appendixa1.html
[8] http://history.nasa.gov/brief.html

Voyager spacecraft, along with a variety of communications satellites, such as the Echo and Syncom satellites. These scientific missions have had a profound impact on the way scientists understand the solar system and the Earth[9].

Under the administration of President George W. Bush one of NASA's current primary goals is to increase human exploration of space by returning a person to the Moon by the year 2020 in preparation for extending human exploration throughout the solar system. NASA is tasked with providing a sustained and cost effective human and robotic presence in previously unvisited areas of the solar system[10].

2.2 Goddard Space Flight Center

The Goddard Space Flight Center (GSFC) is a large research center under the umbrella of NASA administration. Established on May 1, 1959 in Greenbelt, Maryland, the mission of GSFC is ". . . to expand knowledge of the Earth and its environment, the solar system and the universe through observations from space"[11]. GSFC is considered ". . . a major U.S. laboratory for developing and operating unmanned scientific spacecraft"[12].

In pursuit of its mission GSFC is constantly involved in a variety of unmanned missions aimed at studying a wide variety of subjects. Some of the missions that GSFC has been involved with that are scheduled for launch in 2004[13] include the AURA mission, which will allow researchers to carefully study the Earth's atmosphere[14], and the Swift observatory, which is designed to collect data about gamma-ray bursts[15]. Further, one of GSFC's long term projects is the Constellation-X mission in which scientists seek to continue to gather data about X-ray emissions from a variety of sources in space[16].

2.3 Electromagnetic Spectrum and X-Rays

One area of research that has been the focus of numerous manned and unmanned space missions is the study of electromagnetic radiation or electromagnetic waves. Electromagnetic waves are a result of electron movement in atoms emitting photons with varying amounts of energy. The varying energy levels that the photons can have determine the wavelength of the corresponding electromagnetic waves[17]. A higher photon energy level corresponds to a shorter wavelength[18].

---

9 http://history.nasa.gov/brief.html
10 http://www.nasa.gov/pdf/55583main_vision_space_exploration2.pdf
11 http://www.gsfc.nasa.gov/about_mission.html#content
12 http://www.gsfc.nasa.gov/indepth/about_facilities.html
13 http://www.gsfc.nasa.gov/mission.html
14 http://eos-chem.gsfc.nasa.gov/
15 http://swift.gsfc.nasa.gov/
16 http://www.gsfc.nasa.gov/GSFCStrategicPlanCharts.pdf
17 http://health.howstuffworks.com/x-ray1.htm
18 http://www.lbl.gov/MicroWorlds/ALSTool/EMSpec/

Figure 1 displays the range of electromagnetic wavelengths, the names given to certain wavelength ranges, and the types of objects that might emit a given wavelength of radiation. As Figure 1 depicts, the visible light portion of the spectrum, the portion that the human eye can perceive, is quite small. Further, objects that are smaller than a given spectrum wavelength cannot be "seen" using that wavelength of radiation. Therefore scientists use and study shorter wavelength radiation, such as ultraviolet, X-rays, and gamma rays to investigate properties of objects that are not evident under the visible light spectrum[19].

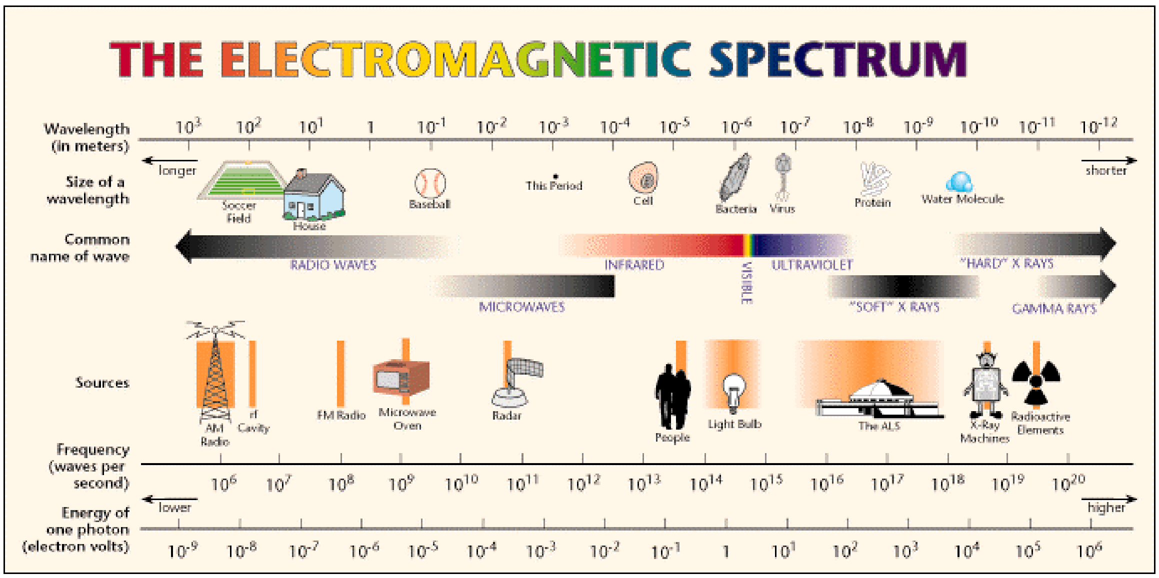

Figure 1The Electromagnetic Spectrum[20]

X-rays, discovered by accident by Wilhelm Roentgen in 1895[21], are an important spectrum for studying objects in space. Many objects that scientists are eager to study emit X-rays, such as black holes, stars, comets, and matter remnants from major events such as supernovas[22].

2.4 X-Ray Telescopes

Electromagnetic energy in a variety of spectrums, including the X-ray spectrum, is filtered by the Earth's atmosphere. Thus high altitude, orbiting, or space traveling instruments are required to study energy in these spectrums when it is emitted by objects in space[23]. Further difficulties arise from the high energy state of the photons in the X-ray spectrum. Because of the high energy of X-ray photons they tend

[19] http://www.lbl.gov/MicroWorlds/ALSTool/index.html#electromagspec
[20] http://www.lbl.gov/MicroWorlds/ALSTool/EMSpec/EMSpec2.html
[21] http://health.howstuffworks.com/x-ray.htm
[22] http://imagers.gsfc.nasa.gov/ems/xrays.html
[23] http://imagine.gsfc.nasa.gov/docs/science/know_l1/emspectrum.html

to penetrate many materials that lower energy wavelengths, such as visible light, tend to reflect off of[24]. Therefore, to study X-rays emitted from objects in space, not only must the telescope be above the Earth's atmosphere, the telescope must also be designed differently than visible light telescopes.

Although X-rays tend to penetrate most materials used for visible light telescopes, X-rays will ricochet off of a surface, such as a reflector, if they impact the surface at a shallow enough grazing angle[25]. Figure 2 depicts the technique that is commonly used to focus incoming X-rays to a single focal point. A parabaloid reflector surface and a hyperbaloid reflector surface are used in conjunction to reflect the incoming X-rays. As a result, X-ray telescopes have barrel shaped reflector elements versus the dish shape common in visible light telescopes[26].

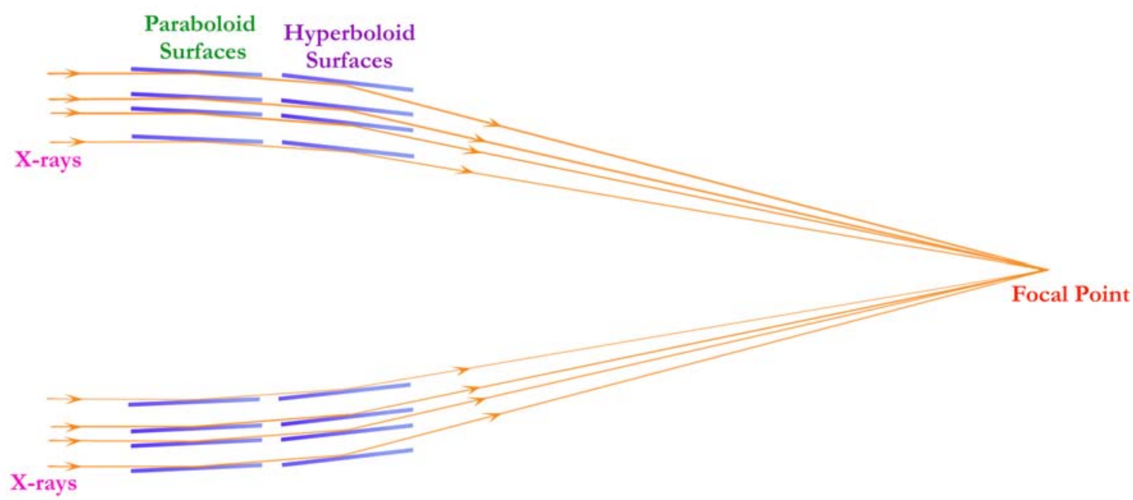

Figure 2 X-rays Reflected at a Grazing Angle[27]

Although several designs for X-ray telescopes exist, very few have actually been employed in current or past X-ray telescope designs. German physicist Hans Wolter, in 1952, determined that using a combination of a parabaloid reflector surface and a hyperbaloid reflector surface an X-ray telescope can focus X-rays to satisfy the "Abbe sine condition"[28].

> "The Abbe sine condition states that an optical system will form an image of an infinitely distant object only if for each ray in the parallel beam emanating from the source **h/sin(theta) = f** where **h** is the (radial) distance of the ray from the optical axis, **theta** is the angle of the final path of the ray relative to its initial path. . .and **f** is a constant for all rays"[29].

---

24 http://chandra.harvard.edu/xray_astro/history.html
25 http://chandra.harvard.edu/xray_astro/history.html
26 http://chandra.harvard.edu/xray_astro/history.html
27 http://chandra.harvard.edu/xray_astro/history.html
28 http://imagine.gsfc.nasa.gov/docs/science/how_l2/xtelescopes_systems.html
29 http://imagine.gsfc.nasa.gov/docs/science/how_l2/xtelescopes_systems.html

While Wolter detailed three configurations of the parabaloid and hyperbaloid reflector surfaces, known as Type I, Type II, and Type III, the Type I Wolter design is most commonly used due to its simple configuration and ability to accommodate a "nesting" design to increase useful reflecting area. The use of Wolter Type telescope design gives an X-ray telescope the characteristic barrel shape of the reflectors[30].

The first X-ray telescope to record images, Sco X-1, was launched in 1962 and was installed in the compartment of a small rocket. Sco X-1 was used to record images for approximately 350 seconds and included images of the Scorpio constellation[31]. Although the first X-ray telescope to record images was launched in 1962, scientists and researchers have launched numerous X-ray telescopes since then to take advantage of advances in technology that allow for higher resolution images and images formed from sources farther away than previously detectable[32].

There have been several key innovative X-ray telescopes launched since 1965. The Uhuru satellite, launched in December of 1970, was the first orbiting satellite devoted solely to X-ray astronomy[33]. An X-ray telescope mounted to the Apollo Telescope Mount (ATM) on Skylab[34] used two reflectors to image a variety of objects and set the stage for later, more advanced reflector telescopes[35]. The Einstein observatory, launched in November of 1978, ". . . was the first fully imaging X-ray telescope put into space . . . [with] a sensitivity several 100 times greater than any mission before it provided. . .[36] " Both the Skylab ATM X-ray telescope and the Einstein observatory used Wolter Type I telescope designs[37]. Currently the most powerful X-ray telescope to have been launched is the Chandra observatory, launched in July of 1999[38] .

2.5 Background on the Constellation-X Mission

The following sections provide information specifically regarding the Constellation X mission and the components of the Constellation X telescope. An explanation of previous work done and work that will be accomplished at NASA Goddard is additionally discussed.

The following sections begin with an overview of the Constellation X mission including information regarding launch and researchers. A description of the Constellation X satellites, the spectroscopy X-ray telescope (SXT), the hard X-ray telescope (HXT), and information dealing with data

---

30 http://imagine.gsfc.nasa.gov/docs/science/how_l2/xtelescopes_systems.html
31 *Revealing the Universe*; Wallace and Karen Tucker: Harvard University Press; Cambridge, Massachusetts; London, England 2001 (p.24-26).
32 http://chandra.harvard.edu/xray_astro/history.html
33 http://heasarc.gsfc.nasa.gov/docs/uhuru/uhuru.html
34 http://www.hao.ucar.edu/public/research/mlso/Skylab/sky_about.html
35 http://chandra.harvard.edu/xray_astro/history2.html
36 http://heasarc.gsfc.nasa.gov/docs/einstein/heao2.html
37 http://harris.roe.ac.uk/~jcm/thesis/node41.html
38 http://chandra.harvard.edu/xray_astro/history4.html

collection and imaging is also included. The main focus of this section is the SXT because this project focuses on the SXT and its reflector assembly. An overview of previous work done by WPI project groups at NASA Goddard dealing with the Constellation X mission is provided along with an overview of the work that is being researched in preparation for the 2004 WPI project.

2.5.1 Overview of the Constellation-X Project

Constellation X is part of a continuing NASA research project to understand the structure and evolution of the universe (SEU). The set of four satellites are intended to create a telescope roughly one hundred times more powerful then any previous X-ray telescope[39].

2.5.2 Description of the Constellation-X Mission

Constellation X's four scientific objectives are closely connected to the theme of understanding the SEU; these objectives are as follows:

- To measure the effects of strong gravity near the event horizon of super massive black holes,
- To study the formation of super massive black holes,
- To trace visible matter throughout the universe and constrain the nature of dark matter and dark energy,
- To trace the evolution of dark matter, dark energy, and super massive black holes with cosmic time, and to study the life cycles of matter and energy and understand the behavior of matter in extreme environments[40].

To measure the effects of strong gravity near the event horizon of super massive black holes the Constellation-X telescope will obtain detailed spectra of faint quasars at high redshift. Black holes are objects whose gravity is so strong not even light can escape from it. The event horizon is the boundary or region around the black hole from which nothing can escape once crossed. Quasars are enormously bright objects on the edge of the universe that emit large amounts of energy and are likely 'powered' by black holes. Redshift is a term used to describe the apparent shift toward longer wavelengths of spectral lines, in the radiation emitted by an object, caused by motion of the emitting object away from the observer. To measure this effect the spectral lines, which are light given off at a specific frequency by an atom or molecule, around the event horizon will be analyzed[41]. Questions that scientists hope to answer from this data are: what is the nature of space and time, and what powers super massive black holes[42]?

[39] http://constellation.gsfc.nasa.gov/docs/main.html
[40] https://conxproj.gsfc.nasa.gov/
[41] http://universe.gsfc.nasa.gov/program/observatories.html
[42] http://constellation.gsfc.nasa.gov/docs/science/about.html

The study of the formation of super massive black holes and the tracing of their evolution with cosmic time would allow scientists to discover what roles black holes play in the evolution of galaxies and how much total energy the universe outputs[43].

The tracing of visible matter throughout the universe and constraining the nature of dark matter and dark energy is another objective of Constellation-X. Dark matter's existence has been deduced from the analysis of galaxy rotation curves and other indirect evidence but dark matter has so far escaped direct detection. Dark energy is residual energy in empty space which is causing the expansion of the universe to accelerate[44]. Research focused on this objective would help to discover what the universe is made from and how it evolves.

In addition, the study of the life cycles of matter and energy and the subsequent understanding of the behavior of matter in extreme environments is another objective scientists plan to pursue using the Constellation-X telescope. NASA hopes to discover new forms of matter and uncover how the chemical composition of the universe evolves[45]. From these discoveries, scientists intend to be closer to understanding the structure and evolution of the universe.

2.5.3 Launch Date

Constellation X was formulated in 1996; many launch dates have been projected based on the progression of the design, construction, and funding of the project. The current tentative launch schedule calls for the four satellites to be launched in two separate launches with the first launch scheduled for 2013[46].

2.5.4 Launch Vehicle

Currently, from information provided by Mr. Jeff Stewart, a Constellation X project engineer at GSFC, the launch vehicle will most likely be the Delta IV Heavy, favored for its large payload capacity. This unmanned rocket is made by Boeing and was designed with input from several government organizations and commercial enterprises that use this vehicle[47]. The Delta rockets have a long history of delivering satellites and telescopes into space. Delta rockets were derived from the Thor ballistic missile in the 1950s, in response to the Soviet space effort. The first successful Delta rocket launch carried the Echo 1A satellite in 1960. The Delta IV program was developed in 1996 and the first launch using the

[43] http://constellation.gsfc.nasa.gov/docs/science/about.html
[44] http://universe.gsfc.nasa.gov/program/conx.html
[45] http://constellation.gsfc.nasa.gov/docs/science/about.html
[46] http://universe.gsfc.nasa.gov/program/conx.html
[47] http://www.boeing.com/defense-space/space/delta/delta4/delta4.htm

rocket was in November of 2002. The Delta IV Heavy rocket is large enough to encase two of the Constellation-X satellites without requiring extensive collapsing of the satellites[48].

Figure 3 displays cutaway and expanded views of the cargo fairing for the Delta IV Heavy rocket. As a result of the large fairing size, approximately 19 m tall and 5 m in diameter, and large payload capacity, up to 12,757 kg, the Delta IV Heavy is suitable for carrying two Constellation-X satellites in one launch.

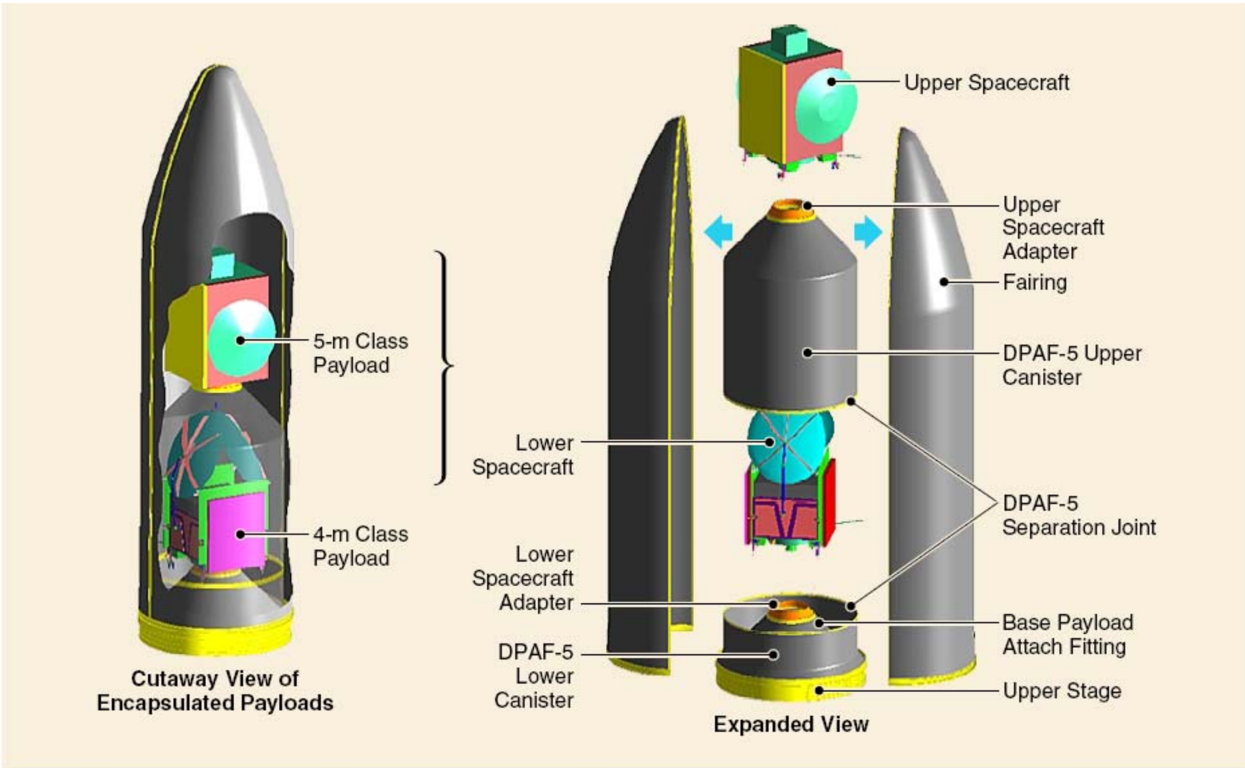

Figure 3 Delta IV Heavy Dual Payload Cargo Fairing[49]

2.5.5 Involved Groups, Researchers, and Engineers

NASA Goddard is the leader of the Constellation-X project and Mr. Jeff Stewart, the Mechanical Systems Manager, is currently the Constellation-X mentor for WPI students. Please refer to Appendix A for a complete list of the Constellation-X team at GSFC.

2.5.6 Description of the Constellation-X Satellites

The main components of the Constellation X telescope are the Spectroscopy X-ray Telescope (SXT) and the Hard X-ray Telescope (HXT). X-rays enter either the SXT or the HXT, which share similar optical designs, and are directed to a focal point at the end of the telescope, where data is retrieved. The other major components of the satellites include the Reflective Grating Spectrometer

[48] http://www.boeing.com/defense-space/space/delta/history.htm
[49] http://www.boeing.com/defense-space/space/delta/docs/Delta_IV_PPG_Update_Revised_Nov_2002.PDF

(RGS) and the X-ray Microcalorimeter Spectrometer (XMS), along with a variety of CCD detectors and cooling systems for the CCD detectors to help prevent thermal noise. Figure 4 shows a computer model of the current Constellation-X satellite design, with the major component structures indicated. The SXT is contained within the Flight Mirror Assembly (FMA).

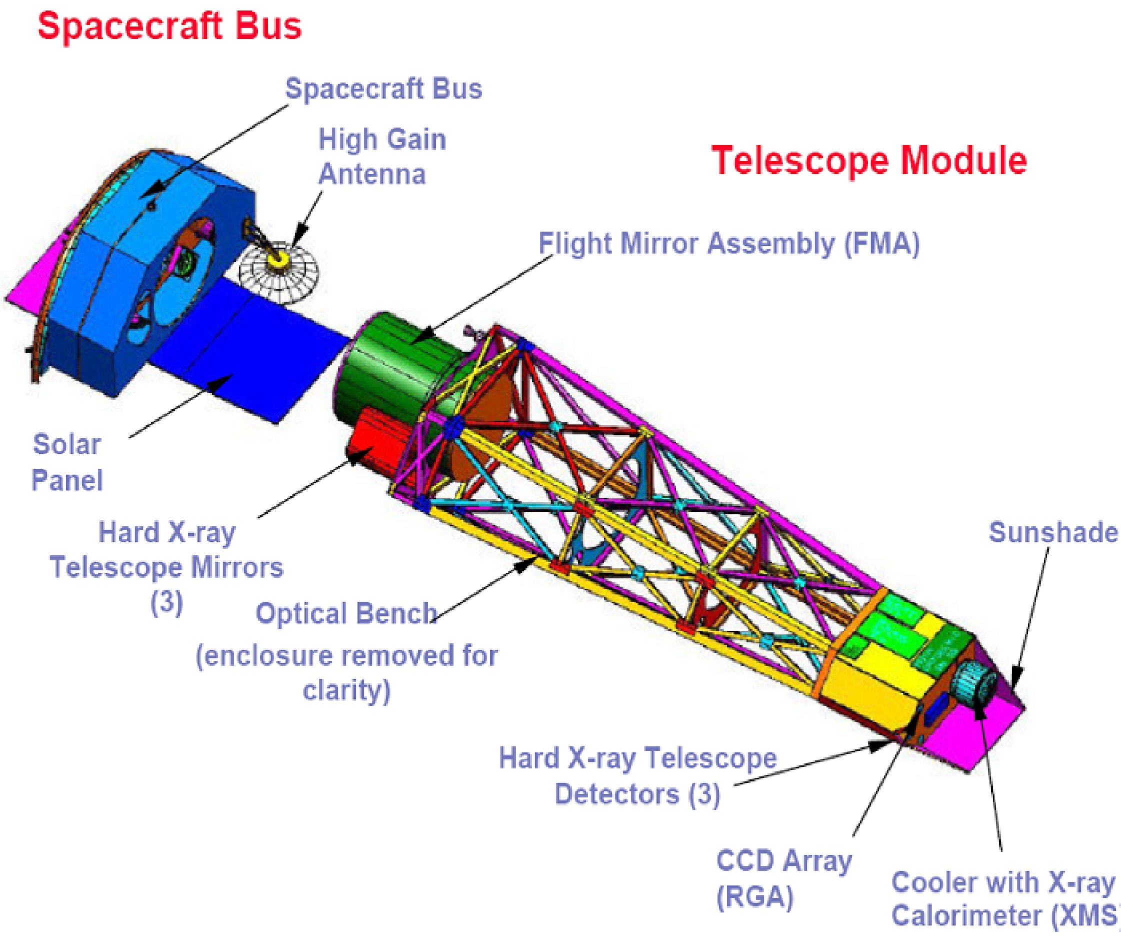

Figure 4 Constellation-X Satellite[50]

2.5.7 Spectroscopy X-Ray Telescope

The Spectroscopy X-ray Telescope (SXT) is the main focus of the 2004 WPI project. The SXT portion of each satellite is made up of approximately four thousand parabolic and hyperbolic reflectors in a cylindrical formation. The formation is divided into separate sections or modules holding approximately 160 reflectors with approximately 1-2mm of space between each reflector. Figure 5 depicts the current SXT design, including its overall dimensions. The individual reflector sub-modules can be seen at the cutout on the bottom of the figure.

[50] Figure taken from: SXT FMA Industry Pre-Bidders Conference presentation

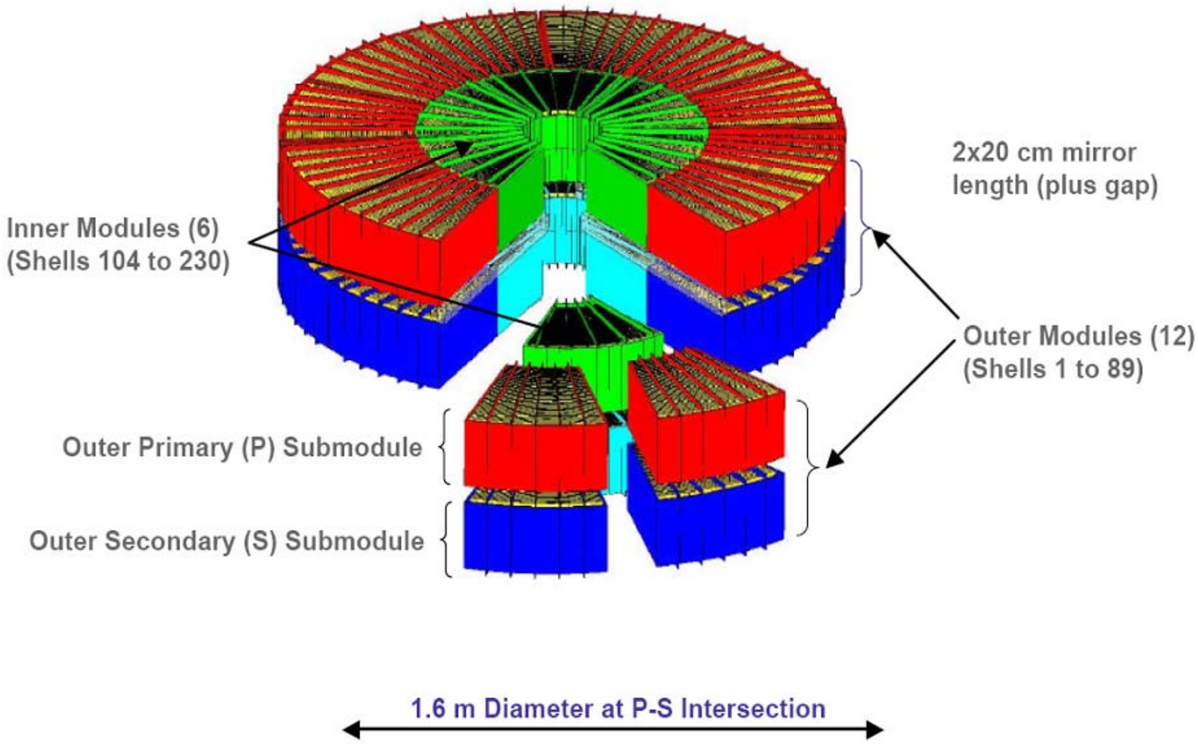

Figure 5 SXT Assembly[51]

The reflectors are formed from D263 glass, which was chosen for its extreme flatness and high light transmission[52]. The coefficient of thermal expansion (CTE) of D263 is used as the baseline CTE for selecting materials for use in the support structure of the SXT. During the forming process of each reflector a coating of epoxy and gold is applied to the reflector. This coating serves as the reflecting surface for X-rays. The current major problem in testing the D263 glass reflectors is the fragility of the reflectors. Engineers at NASA are researching either methods to strengthen the glass or suitable alternative reflector materials[53].

2.6 Overview of Previous Constellation-X Project Work

WPIs involvement in the Constellation X project at GSFC is in its third year. Although the 2004 WPI project at GSFC is a continuation of past WPI projects, the Constellation-X project continues to change as NASA engineers progress on the overall Constellation-X project design.

---

[51] Figure taken from: SXT FMA Industry Pre-Bidders Conference presentation
[52] http://www.eriesci.com/custom/d263-tech.aspx
[53] Stewart, Jeffrey. Personal interview. 11 August 2004.

2.6.1 Constellation-X Mirror Assembly Trade Study and Design (2002)

The 2002 WPI project team established the following goals:

1. Create a conceptual design and model for the Constellation-X reflector assembly,
2. Perform a trade study on these designs and make recommendations,
3. And design and manufacture composite reflector prototypes.

Their work involved extensive research regarding X-ray technology and the reflector assemblies of the recently launched Chandra X-ray telescope and the XMM Newton telescope. The 2002 WPI team worked with their mentors at GSFC to evaluate concepts and designs for the reflector assembly. The team helped to work on the design and construction of the reflector assembly and the reflector modules that would be used to house the different segments of the reflector assembly.

At the time of the 2002 project the plan was to align each reflector individually using the Centroid Detector Alignment (CDA) tool which employs lasers to determine proper alignment. The use of small combs, being placed between the exactly spaced teeth to help reduce the alignment time for the reflectors, was also considered. Concerns were raised regarding these combs however, because alignment would be required on the nanometer scale.

The trade study conducted by the project team was for the purpose of evaluating the different conceptual designs for the reflector assembly. These conceptual reflector assembly designs included a design where the separate reflector would be included in the final reflector assembly design and bonded together, a reflector assembly that would be a large overall composite structure (OCS) and include no modules at all, as well as a design where the modules would be made to fit within the OCS and held using wall braces or kinematic mounts.

At that time there were also concerns that the D263 glass possessed a coefficient of thermal expansion (CTE) that was too high to allow for a strong enough material to be used in the construction of the OCS, because the CTEs of both of these two items would have to match so as to ensure failure would not occur at a lower temperature. Their project team examined other materials which could possibly replace D263 glass, such as “Borofloat” or fused silica.

The 2002 project team also examined different ways of forming the reflectors. When the reflectors were shaped over the mandrels they became frail and brittle, sometimes shattering upon handling. For this reason the team investigated other reflector forming techniques including: a process known as electroforming, the use of titanium to replace the reflectors, as well as the use of supportive struts. The team also helped to design the titanium modules that would be used to house the reflectors and the selection of the composite material which would be used for this module.

The 2002 project team made the final recommendation that a Module Hybrid Design be used. This design would be a combination of the No Modules and Full Modules design. This design would allow for easier fabrication of the modules and also be helpful in the event of reflector breakage because each module would be isolated.

2.6.2 Constellation-X Mirror Alignment and Automation (2003)

The 2003 project team set their main goal to be reflector alignment automation. At the time of the project it was decided that individual alignment of the reflectors would be too time consuming because of the large number of reflectors. Within the goal of alignment automation the team tasked themselves with making the Production Alignment Robotic Assembly Tool (PARAT) operational. They would then test the accuracy of this tool and design a staging setup to align the reflectors using the PARATs.

The team's first task was to make the PARAT operational. The PARAT is a system involving four components: an uninterrupted power supply (UPS), a robot controller, a flexure assembly, and an ST Robotics R16 robot. The PARAT could be programmed for the automated alignment of one reflector. The PARAT grasps the reflector with the flexure assembly, which includes a flexure arm, linear positioner, and voice coil actuator (VCA). The flexure assembly was used to precisely align the reflector in the vertical z-axes. The flexure arm was developed by NASA engineers specifically for this project and is a system of levers with a 6:1 input reduction ratio. The VCA is a small device capable of applying precise linear forces and used essentially to "shake" the reflectors into place. The VCA itself consists of small magnets inside a cylinder that create an axial force when a current is applied.

Once the PARAT had aligned the individual reflector the precision of the PARAT could be tested using a coordinate measuring machine (CMM) which uses probes to collect data in the x, y and z axes. The centroid detector assembly (CDA) can then be used to check the alignment of the reflectors. The CDA sends out a laser beam which is reflected back to the CDA and the deviation of the laser beam from its original path determines the alignment of the reflector.

The project team then designed a staging set-up which utilized PARATs to align all of the reflectors in a specific module. Five of the robots were setup above the module and five were setup below. A closed loop feedback system was then designed to align all of the reflectors within the module. This system incorporated the use of ten PARATs and the use of the CMM to check the precision of the alignment.

2.7 Current State of Relevant Constellation-X Development

One of the obstacles faced by those working on the Constellation X mission is the precision alignment of the large number of reflectors which will be used in the telescope. Each reflector must be aligned precisely, within the order of magnitude of 0.1 μm, and manually aligning the reflectors has been deemed too tedious and time consuming. Therefore, developing a method for automated alignment of the reflectors has been suggested to keep the Constellation-X mission on schedule. There are several aspects that will be involved in the design of an automated alignment system for the reflectors. The following section will provide background information on some of the key components of the reflector alignment process.

2.7.1 Piezo Electric Materials and Applications

Piezoelectric materials include single crystals, manufactured ceramics, and different types of polymers as well as composite materials[54]. These materials have the ability to transform mechanical energy into electrical energy and vice versa. A piezoelectric material is one in which the positive and negative charges are separated from one another but evenly distributed, resulting in a state of neutrality. However this state of neutrality can be disrupted when a physical deformation is applied to the material.

In 1880 a phenomenon known as the piezoelectric effect was discovered by Pierre and Jacques Curie[55]. They found that when a mechanical stress was applied to one of the crystals they were working with an electrical polarization was generated. This phenomenon occurs when a mechanical deformation alters the existing neutrality of charge in a piezoelectric material with the resulting asymmetry of charges generating a voltage. The inverse of this phenomenon is known as the reverse piezoelectric effect. During reverse piezoelectricity an applied electric field affects the different points of separated charge within the crystal and result in a physical distortion[56]. The exact amount of mechanical deformation depends upon the type of material that is used as well as this materials geometry, but typical deformations are about a few nanometers per applied volt.

The exact way in which a piezoelectric material will behave depends upon many factors such as the material's density, Young's Modulus, piezoelectric coefficient, and Curie temperature. The piezoelectric coefficient describes relates the amount of excursion per applied voltage. If a ceramic piezoelectric material is heated beyond its Curie temperature it will lose its polarization and therefore also lose its piezoelectric properties. Piezoelectricity occurs naturally in the form of several types of crystals but can also be created artificially. Ceramics that are polarized by being cooled in the presence of an electric field will gain the property of piezoelectricity[57]. Some of these materials can be seen in Figure 6.

---

[54] http://www.electrostatic.com/rosen.htm
[55] http://en.wikipedia.org/wiki/Piezoelectricity
[56] http://en.wikipedia.org/wiki/Piezoelectricity
[57] http://www.e-bastelu.de/index_m.htm

Figure 6 Piezoelectric Actuators[58]

Some applications of piezoelectric materials include their use in sonar devices, acoustic transducers, and clocks and watches. Acoustic transducers use piezoelectric materials to convert acoustic sound waves into electric fields or vice versa. These can be found in telephones, stereo systems and musical instruments. Piezoelectric materials are also used in clocks and watches because an oscillating electric field causes the crystals to resonate at their natural frequency and these vibrations are counted to keep the watch on time[59].

Piezoelectric materials, or simply "piezos", were chosen for this project because of their precision when producing a mechanical deformation from an applied electric field. Presently, at GSFC, a technique, illustrated in Figure 7, is being developed in which bending piezo actuators will be inserted into a strut and used to grasp the reflectors which have been put in a position of gross alignment[60]. By then applying a voltage to the piezos in the strut a precision alignment of the reflector can be made on the nanometer scale. After the precision alignment is made an adhesive would be injected to lock the aligned reflector in place.

[58] http://www.physikinstrumente.de/products/section1/link1.php
[59] http://www.mse.cornell.edu/courses/engrill/piezo.htm
[60] Stewart, Jeffrey. Personal interview. 10 August 2004.

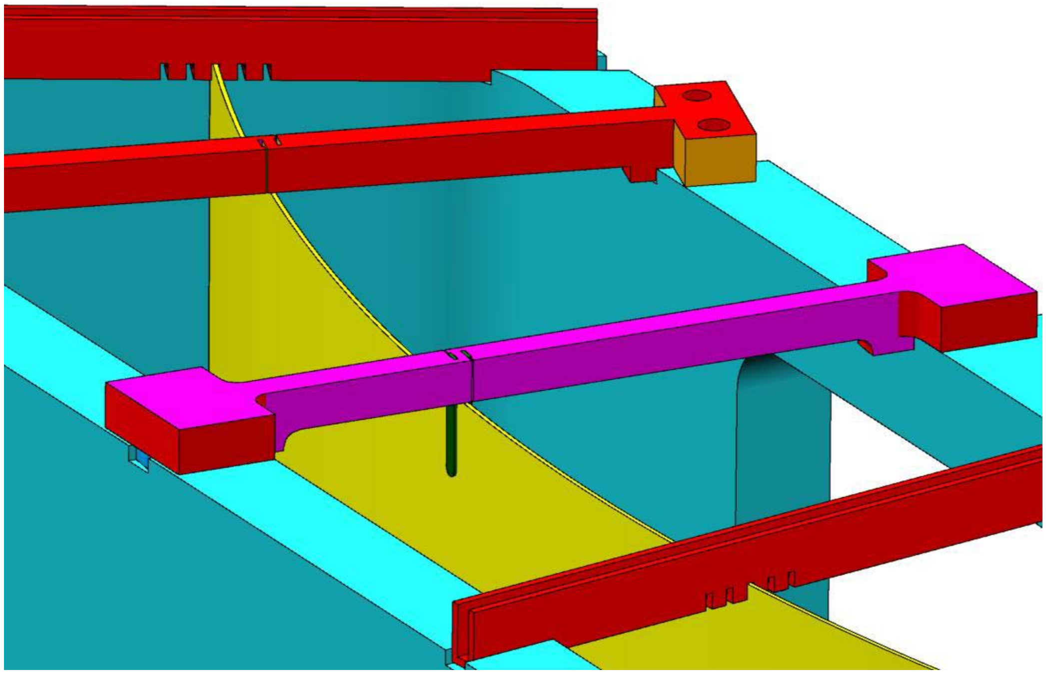

Figure 7 Alignment of Reflector Using Piezos[61]

In Figure 7 the long purple object is the strut that the piezo actuators are attached to. The small, flat, black objects perpendicular to the strut are the piezo actuators themselves which will be used to precisely align the reflectors. The curved yellow surface is a reflector which, once aligned, will be bonded in place by the use of an adhesive.

The engineers at GSFC are currently searching for a manufacturer of suitable piezo actuators. The exact type of material that will be used for the piezos has yet to be determined but some of the properties which the piezos must exhibit have been determined. The material which is chosen must meet outgassing requirements for materials to be used in space[62]. Also the piezos must be capable of generating enough force to bend the reflectors into the shape that is required for proper alignment. Engineers at GSFC have determined through recent calculations that the force required for this is in the range of 0.4 Newtons to 2.4 Newtons.

2.7.2 Adhesives and the Bonding Process

Presently it is undecided what type of adhesive will be used to bond the reflectors in place. Many types of adhesives have been researched and at this time two specific adhesives are under consideration: Norland 123 and Masterbond EP65HT-1, both of which are UV cure adhesives[63]. It would be desirable

[61] Photo Courtesy of Jeff Stewart
[62] Stewart, Jeffrey. Personal interview. 10 August 2004.
[63] Stewart, Jeffrey. Personal interview. 16 August 2004.

for the bonding process to be done as rapidly as possible because this would improve the overall efficiency of the automated process as well as ensure that thermal changes in the lab will not alter the reflector alignment.

UV cure adhesives have been considered because they exhibit some desirable properties. These adhesives contain photoinitiators that are activated when the adhesive is cured under intense UV light in a certain wavelength range. The curing times of UV cure adhesives can be accurately calculated and minimized. The curing time for UV cure adhesives is generally shorter than conventional adhesives. A UV cure adhesive would be preferable to heat activated adhesives as UV curing does not require a thermal change in the lab, a change which could affect other aspects of the reflector alignment[64].

These light-cure adhesives may also need to be combined with a structural adhesive. Presently it is also undecided which structural adhesive will be used for this purpose but so far Stycast has been used to bond the reflectors. Stycast is a versatile adhesive which has excellent low temperature properties, provides good electrical insulation, low cure shrinkage and low thermal expansion as well as high resistance to chemicals[65].

Whatever adhesive is chosen will need to be able to undergo rapid curing at a constant temperature. It must also be strong enough to hold the reflectors in place, have a coefficient of thermal expansion that is compatible with the reflectors, and meet NASA's outgassing requirements.

2.7.3 Reflector Production

A total of approximately 16,000 reflectors (4,000 per satellite) will be used in the Constellation X telescope. An additional 4,000 reflectors may also be manufactured as spares in case some reflectors become damaged. D263 glass has been selected as the substrate material for the reflectors. D263 glass is a borosilicate glass that is produced by melting pure raw materials. It has a large range of standard thicknesses but will be used in 0.44 mm sheets for the Constellation-X project. D263 is highly resistant to chemical attack. D263 glass is also extremely flat and has excellent surface quality, or smoothness[66]. D263 will be formed on a mandrel into the parabolic and hyperbolic shapes required through a process known as slumping. Slumping is where the glass substrate is placed on a forming mandrel and then heated to the annealing point of the glass, at which point the glass takes the shape of the mandrel. To add a reflective surface to the glass substrates the forming mandrels are coated with a layer of gold .2 μm thick and the glass substrates are coated with 10 μm of Epotek 301-2 epoxy. The glass is then slumped over the mandrel by heating it in an oven at 557° C. During the slumping process the layer of gold becomes bonded to the glass substrate. This gold layer will serve as the reflective surface for incoming X-

[64] http://www.hoenle.com/pdf/en/UV-Klebstoff_(adhesive)_A4_e.pdf
[65] http://www.lakeshore.com/temp/acc/am_epoxypo.html
[66] http://www.pgo-online.com/intl/jse/frameroute/genericset.html?Content=/intl/katalog/D263.html

rays. Multiple forming mandrels will be required to form the various radial diameters of glass required for the different sections of the SXT[67]. Several replication mandrels have already been manufactured by Carl Zeiss International for testing at GSFC.

Engineers at GSFC are also considering laminating the reflectors, similar to the way windshields are laminated, so that if a reflector were to break it would remain held together by the lamination and not damage any other reflectors[68]. In the alignment process it can be expected that some of the reflectors may fracture. This possibility poses a problem because if a sheet were to fracture the broken pieces could damage other sheets of glass that have already been put into place and this could slow the automated alignment process. The benefits of laminating the glass would be that the lamination would hold the pieces of broken glass in place in the case of a fracture and prevent them from damaging other reflectors. Lamination would also allow for much easier removal and replacement of a damaged reflector. Presently a polycarbonate lamination is being considered by the engineers at GSFC[69]. Polycarbonate lamination is also used in the production of bulletproof glass but in much thicker layers than will be used on the reflectors in this project. Polycarbonate is a light weight plastic material that is easily machined[70]. The polycarbonate lamination would also be done using the mandrels. Engineers at GSFC are presently working with two companies that specialize in polycarbonate lamination and have sent these companies each a mandrel to work with.

2.7.4 Vacuum Chuck Prototype

Another obstacle in the reflector alignment process is maintaining the relationship between adjacent parabolic and hyperbolic reflectors. Since a single replication mandrel is used to create each parabolic and hyperbolic reflector pair simultaneously the reflectors are most precisely aligned to each other when they are still on the replication mandrels. Unfortunately, the present technique of peeling the reflectors from the mandrels does not permit taking advantage of the reflector relationship because peeling could not be performed if the reflectors were aligned and bonded while still attached to the mandrel. A concept that has been proposed to take advantage of the parabolic-hyperbolic relationship of the reflectors while on the mandrels, but still allow for the bonding of the reflectors, is the use of a device known as a vacuum chuck. Ideally the vacuum chuck will have the same surface accuracy as the replication mandrels and can be used to align and install the reflectors to the required precision. The vacuum chuck could potentially allow for the process of aligning reflectors to the desired precision to be much less involved than the piezo prototype solution. Other advantages of the vacuum chuck prototype include the reduction in the amount of handling needed to align and bond the reflectors, which would

[67] http://conxproject.gsfc.nasa.gov/docs/meetings/fstsept02/HXT_RPetre_WZhang_FChristensen.pdf
[68] Stewart, Jeffrey. Personal interview. 10 August 2004.
[69] Stewart, Jeffrey. Personal interview. 11 August 2004.
[70] http://www.opticalfilters.co.uk/products/standardfilters/polycarbonate.htm

allow the reflectors to retain greater strength, the reduction or elimination of the radial struts required to hold the reflectors, which would allow for increased throughput of X-rays, and the elimination of the need to do any bonding in the area between the parabolic and hyperbolic reflectors.

A prototype vacuum chuck has already been created and tested. The prototype model was for the largest parabolic reflector in the outer module and was created from ULTEM. ULTEM is a high strength amorphous thermoplastic that is transparent, heat resistant, chemically resistant, and is easily machined[71]. The surface of the vacuum chuck prototype contains several grooves that are 1/16 inches wide and approximately 0.08 inches deep. The grooves separate the surface of the chuck into a grid of 36 rectangles 0.55 inches by 0.67 inches in size. The vacuum chuck is also narrower than the reflector it holds so as to allow for bonding the sides of the reflector.

The goal of the vacuum chuck is to install the reflectors in their proper alignment to the necessary degree of precision in a systematic installation process beginning with the largest reflector and proceeding down to the smallest reflector without requiring any physical handling of the reflectors.

2.8 Summary

This chapter has detailed the research the project team performed as background to the overall project. The background information presented includes: a brief background of NASA and GSFC, an overview of the electromagnetic spectrum and of X-rays, a description of X-ray telescopes, an overview of the Constellation-X mission and hardware, a review of the work performed by previous WPI Constellation-X project teams, and a description of the current state of relevant portions of the Constellation-X project.

[71] http://www.geplastics.com/resins/materials/ultem.html

3 Problem Statement

The goal of our project was to develop new methods of precision reflector installation for the SXT portion of the Constellation-X telescope. This chapter presents the problem statement of our project, along with the overall goal of our project team. Further, objectives that needed be met to accomplish the overall goal are presented, along with the specific tasks that were required to accomplish each objective. Each objective was designed to meet certain project requirements, as outlined by our GSFC mentors. This chapter presents an overview of the goal structure for our project team.

3.1 Problem Statement and Project Goals

One of the primary issues being addressed by the NASA engineers working on the Spectroscopy X-ray Telescope (SXT) portion of the Constellation-X satellite is that of accurately and quickly aligning and bonding the SXT reflectors. Although at least one method for manually aligning the reflectors is available, due to the large number of reflectors (approximately 4,000 reflectors per satellite) the engineers are attempting to develop a method to will both speed up the reflector alignment process and be suitable for automation. Further, once the reflectors are correctly aligned they must be permanently bonded to the telescope to insure that they do not move out of alignment during launch or operation.

Therefore, our project goal can be constrained by one main Constellation-X requirement: rapid alignment. The goal for our project was: **to develop methods of reflector placement and alignment that would provide accurate reflector placement and alignment on a sub-micrometer scale and be suitable for large volume implementation to speed the assembly process.**

3.2 Objectives and Tasks

To achieve the project goal the team had to complete a variety of objectives which in turn involved a variety of tasks. To achieve the final goal of precise reflector alignment through pursuing different alignment techniques and tools the team outlined several objectives. The objectives are as follows:

1. Develop a method or tool to grasp reflectors,
2. Develop a method or tool that will maintain the integrity of the reflector prescription,
3. Pursue the possibility of maintaining the relationship between the parabolic and hyperbolic reflectors that exists on the replication mandrel,
4. Develop a method or design that will allow rapid placement and replacement of reflectors.

As noted in this list, the first objective in designing a method of aligning reflectors is to be able to grasp the reflectors securely without breaking or weakening them. One of the problems with using D263 glass is the brittleness of the glass and the fragility that brittleness imparts in the .44 mm thick reflectors. Current estimates suggest that the reflectors will withstand 8 ksi of force, although imperfections in the glass may reduce that to roughly 1 ksi in localized areas of reduced strength. As a result of this fragility the reflectors must be handled with care to avoid crack propagation that might reduce the strength of the reflectors or fracture them.

The second objective was to develop a method for holding the reflectors during alignment that will prevent fluctuations of the reflector shape. Another problem that arises from the use of D263 is that the reflectors are prone to fluctuations in shape from vibrations, atmospheric changes such as heat and wind, and even gravitational forces. These fluctuations make it difficult to accurately align the reflectors.

The third objective in developing alignment methods was to consider ways to maintain the parabolic-hyperbolic relationship as it exists on the replication mandrels. When aligning the reflectors, not only must each individual parabolic and hyperbolic reflector be properly aligned relative to the optical axis of the satellite, but each parabolic-hyperbolic reflector in a pair must be precisely aligned to one another. Since each parabolic-hyperbolic pair is formed together on a single replication mandrel the parabolic-hyperbolic relationship exists when the reflectors are still on the replication mandrel.

The fourth and final objective was to develop a method of installing and replacing reflectors rapidly. The current designs that have been prototyped segment the SXT into sections of approximately 160 reflectors. One of the adverse results of this design choice is that the reflectors must be aligned individually in tight confines; the reflectors are less than 2 mm apart radially and the separation between the parabolic sections and the hyperbolic sections is approximately 50 mm axially. Therefore, a design where the reflectors are grouped in packs of approximately 10-20 reflector pairs allows for these reflector packs to be installed, aligned, and, if necessary, removed with improved efficiency versus installing and aligning individual reflectors in larger modules.

Our project team had to undertake a variety of tasks to complete our objectives. One of our initial tasks was to familiarize ourselves with the designs that are currently being pursued for the SXT. Being familiar with the work currently being done allowed our team to iterate new designs more effectively.

Another task our team had to accomplish was becoming familiar with the major pieces of hardware and software that the SXT team employs. Familiarity with hardware allowed our team to work more productively with other engineers on the SXT team and also guided us to work within realistic constraints for fabrication and testing. As a result of the close tolerances required for the SXT, many pieces of hardware, such as the coordinate measuring machine that is accurate to the order of 10 μm, may not have enough accuracy for final reflector alignment. Further, familiarizing ourselves with the software that the SXT team members use for design, such as I-deas and ProEngineer CAD software, allowed us to more easily trade ideas with other SXT team members.

3.3 Summary

This chapter has described, broadly, the goal for the 2004 Constellation X project as developing methods for precision reflector placement in the SXT portion of the Constellation-X satellites. The objectives and tasks necessary in achieving this goal along with some of the major difficulties present in achieving the goal are also described.

4 Methods and Designs

This chapter provides a description of the team's methods in pursuing our project goal at GSFC. Briefly, preliminary work involved researching background information on X-rays and the Constellation-X mission along with reviewing the work that had been performed by previous WPI project teams. Once at GSFC the team worked closely with our mentor Jeff Stewart and several other members of the SXT team to generate design constraints and iterations. After the bed of nails and glass-pack designs had been suitably constrained the team undertook modeling, prototyping, and testing of the designs.

4.1 Mirror Placement Design Specification

Although prior to the 2004 WPI project several methods of SXT reflector alignment had already been prototyped, none had been fully tested or fully developed to the stage where they could be considered suitable for satellite production. As such, the SXT team had proposed several alternative methods not only for reflector alignment but also for reflector grasping and placement. Current methods called for extensive human handling of the reflectors between production stages. SXT team brainstorming sessions prior to and during the time that our project team was at GSFC provided a rough outline for the proposed bed of nails design and glass-pack design. Research and modeling by our team provided data to continue testing of alternative methods.

4.1.1 Bed of Nails Design

At the start of the 2004 project in August, the bed of nails design was still in the concept stage. The idea proposed by Jeff Stewart was to have a tool that could take and hold the shape of a reflector as it was still attached to the replication mandrel. A related design had been pursued by another team with the vacuum chuck prototype, which attached to the front side of a reflector. The primary difference between attaching a tool the back side of the reflector instead of the front (or pristine) side lay in that the back surface is not a known or uniform surface and thus cannot be modeled to create a rigid gripping chuck. The primary advantages of gripping the back surface of the reflector are that the current replication mandrel design would be retained and the gripping chuck would not be in danger of damaging the pristine side of the reflector.

Initial brainstorming sessions with Jeff Stewart served to refine the overall concept of the bed of nails design. As a result of these sessions the concept called for a tool that could take the shape of the back surface of a reflector as the reflector was still attached to the replication mandrel. Further, the tool would need to either have the strength to maintain the mandrel prescription as the reflector was removed from the mandrel or have the ability to map the back of the reflector and respond dynamically to any changes in reflector shape after it was removed from the mandrel.

The current method for removing a reflector from the replication mandrel is to peel the reflector, started by lifting a corner of the reflector. As it is unknown how much force would be required to lift a reflector straight off of the mandrel instead of peeling it off, or whether such a process would damage the reflector, no specific load bearing specifications were given to the bed of nails.

Following these sessions research was conducted for bed of nails design ideas, including soliciting input from several of external suppliers. The goal of this research was to determine the general feasibility of the bed of nails design based on alignment, assembly, and cost constraints. Once a suitable design had been decided upon the design was presented for funding consideration to allow construction of a prototype for further testing.

4.1.2 Glass-pack Design

The telescope design assembly design that had been developed prior to the 2004 WPI project period called for the overall SXT diameter to be decomposed into several smaller segmented modules, with separate module layers for the parabolic and hyperbolic reflectors. Although this design had been prototyped and was continuing to be modified and tested, difficulties in telescope assembly and alignment prompted GSFC engineers to pursue developing alternative telescope designs.

The intent of the glass pack design was that it would be used in conjunction with the bed of nails design or a similar tool, such as the vacuum chuck. As such, brainstorming, research, and design of the glass-pack was undertaken concurrently with the bed of nails. The purpose of this concurrent engineering was to allow the unique constraints of one design influence the other design early in the development process.

The initial tasks the team undertook in designing the glass pack were brainstorming sessions with Jeff Stewart and researching what work had already been performed on the glass pack. At the start of our project the glass pack had already been proposed and a CAD mockup had been created to demonstrate the concept. Our team undertook to brainstorm potential design configurations and to research the feasibility creating a glass pack design based on material and reflector constraints.

Once a suitable design had been decided upon the team tasked itself with generating an accurate CAD model as an initial test of the design. Because of the complexity of the reflector figure and assembly geometry this required not only employing our knowledge of ProEngineer but also consulting several manuals and working with files imported from I-deas, the primary alternative CAD software at GSFC. The purpose of this CAD model was to aid in refining the overall design and also to assist in material selection for a prototype and for the final design.

4.2 Summary

This chapter presented the methods that our team used to achieve the goal for our project. These methods included working closely with GSFC engineers and supporting personnel in developing and refining design concepts, as well as developing prototypes. Our team also worked with commercial firms to source and select suitable components for designs. Further, the team worked with several software platforms that allowed us to model, refine, and test our designs.

5 Results

This chapter presents the results of our team's work at GSFC. The methods discussed in Chapter 4 were employed and the work was divided into two main areas: research and design relating to the bed of nails design, and research and design relating to the glass-pack reflector assembly (GRA). Our team created an initial design specification for the bed of nails that was submitted with a request for funding. Further, we created a GRA design that was modeled using rapid prototyping and pursued work in designing and testing a composite support structure for each parabolic-hyperbolic reflector pair.

5.1 Bed of Nails

The goal of the bed of nails design was to develop a tool that would conform to or map the back surface of a reflector while the reflector was still on the replication mandrel and then maintain that shape or have the ability to actuate the reflector back into that shape once the reflector had been removed from the replication mandrel.

Initially the team considered constructing the bed of nails out of a single piece of gel or silicone that could be molded onto the back of a reflector and then held in place or actuated dynamically. The impetus for this design was that a single section of moldable material pressed onto the back of the reflector would theoretically have an infinite number of attachment points to the reflector. An example of such a dynamic substance is a polymer hydrogel, which can be designed to react locally to changes in pH, solvent, or electric fields. Hydrogels have been used in creating linear actuators to simulate biological muscle tissue[72]. Unfortunately, hydrogels rely on fluid to operate, a parameter that was deemed unsuitable, and further research by the team did not uncover another more suitable material.

The team then decided that a bed of nails design with a finite number of unique mapping, actuating, and gripping points would be suitable. A similar effort was being pursued by another SXT team with the piezo prototype design, the most well developed design as of September 2004. The piezo prototype called for ten piezo electric bender actuators (piezos) to manipulate each reflector. Figure 8 shows a CAD mockup of the piezo prototype applied to the Optical Alignment Pathfinder 2 (OAP-2) module prototype. The OAP prototypes were used for production and alignment testing. Figure 8 also illustrates the difficulty of designing the piezo prototype so that the piezos will fit between the reflectors while the reflectors sit in the reflector slots. The gap between each reflector once they are installed in the module is less than 2 mm. Once situated between the reflectors the piezos must also have clearance to move through their effective actuation range without contacting any adjacent reflectors.

---

[72] http://www.ai.mit.edu/projects/muscle/papers/icim94/paper.html

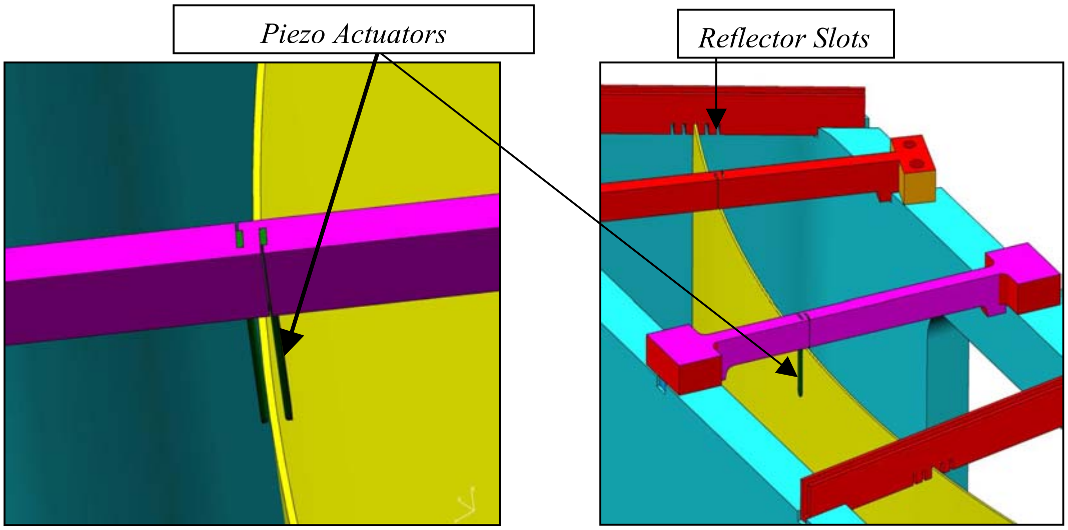

Figure 8 Piezo Prototype Showing Close-up[73]

The concept of designing the bed of nails to have a finite number of mapping, actuating, and gripping points was investigated as a compromise between the piezo prototype and a moldable tool with an effectively infinite number of mapping and gripping points. The piezo prototype was intended to be able to manipulate each reflector to remove any shape imperfections or to alter the reflector prescription. Using rigid actuators the bed of nails would ideally be able to both maintain the shape of each reflector and modify the prescription of each reflector if necessary, thus replacing the piezo prototype.

Several meetings with Jeff Stewart concluded that a bed of nails design using a relatively small number of discrete contact points would be suitable for developing a prototype for further testing. Since the piezo prototype called for ten piezo actuators, Jeff Stewart and our team decided that a bed of nails design using between twenty and thirty contact points would be suitable, resulting in an active contact point increase ranging from 100 → 200% over the number of active contact points in the piezo prototype.

As a result of the high level of precision required in assembling and aligning the reflectors, the mapping and actuating contact points on the bed of nails were required to have a high degree of resolution. Sub-micron (10^{-7} m) precision was considered the minimum acceptable resolution for mapping sensors or actuators based on the resolution of the alignment equipment, primarily the Centroid Detector Assembly (CDA). Further, the actuators needed to have a range of actuation on the order of tens of microns (10^{-5} m).

The team conducted research into actuators and position sensors with sub-micron resolution. Several solutions for position sensors were found to have suitable resolution, including capacitive position sensors, Linear Variable Differential Transformer (LVDT) sensors, and strain gauge sensors. The

[73] CAD model: Bobby Nanan. Source: *Piezo Plan 4* presentation

only actuators the team found with suitable resolution were piezo actuators. Piezo actuators are available from a variety of suppliers, in a variety of actuation configurations, and are also available with integrated position feedback sensors. This allowed the team to explore a variety of design configurations, including using piston actuators, bender actuators, and piezo linear position actuators. The team decided the most suitable configuration would be to use piston type piezo actuators with integrated feedback sensors (closed loop piezos). Since the control hardware for closed loop piezos was commercially available, this simplified the design process as no custom control hardware would have to be specified and built.

The decision to use closed loop piston type piezos was also based on the space constraints of the prototype reflectors at GSFC. The replication mandrel that is being used at GSFC to create test reflectors produces parabolic reflectors with a perimeter that is 257.82123 X 200 mm, equal to 51564.24594 mm^2. Figure 9 shows a CAD model of a reflector pair. The parabolic reflector is marked with a "P."

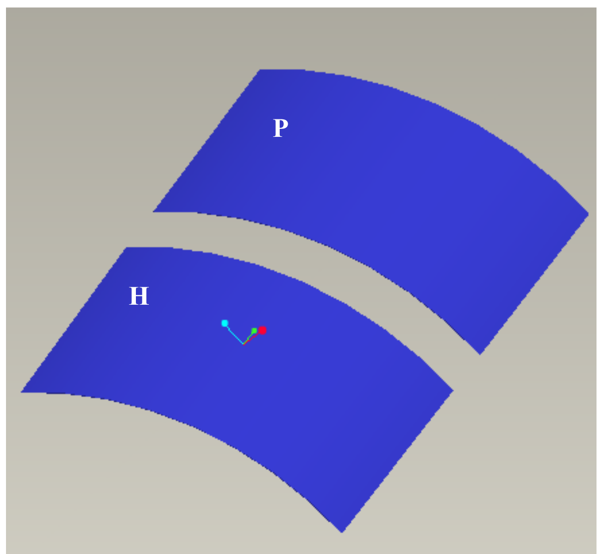

Figure 9 CAD Example of Reflector Pair

Because of the restraints of piezo electric material, there are limitations on the how much displacement can be achieved with a given quantity of material, type of material, and at a given voltage. Figure 10 depicts the relationship between voltage and displacement with the parallel expansion equation $\mathbf{\Delta T = Yd_{33}}$, where $\mathbf{Y}$ is the Young's modulus of the material, and $\mathbf{d_{33} = K^T{}_3\varepsilon_0 g_3}$. $\mathbf{K^T{}_3}$ is the relative dielectric constant of the material in the polar direction (parallel to the direction of polarization) with no mechanical clamping (constant stress), $\boldsymbol{\varepsilon_0}$ is the permittivity of free space, and $\mathbf{g_3}$ is the voltage coefficient[74].

[74] http://www.piezo.com/appdata.html

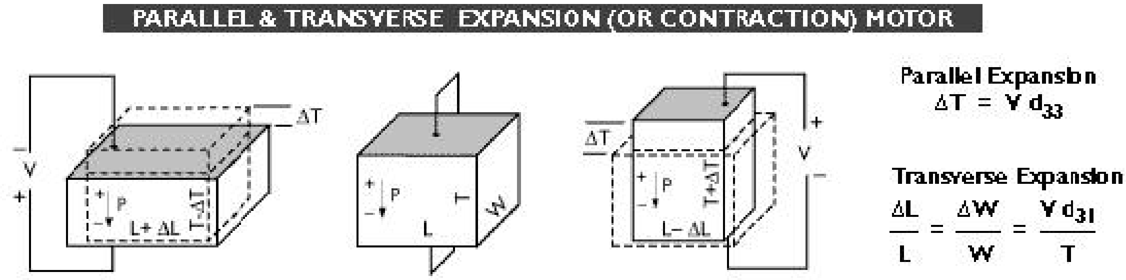

Figure 10 Piezo Motion Transducer Relationships[75]

The parallel expansion equation in Figure 10 illustrates the importance of material selection in controlling the characteristics of piezo actuators. While custom designed piezo actuators are available, the team decided that the increased cost and production lead time, particularly with a low volume order and with the need for an integrated position sensor, of a custom piezo actuator would be unsuitable for an initial design and prototype. The possibility of using custom piezo actuators was explored and rejected by the SXT team while designing the piezo prototype and their insight was also factored by our team in rejecting custom piezos.

At the time our team was designing the bed of nails the SXT team was working with Physik Instrumente (PI), a company based in Germany working in nanopositioning and nanomechanics, on positioning tools for use with the vacuum chuck. PI has a large variety of nanopositioning solutions and as a result of the SXT team's prior positive experience with PI, our team decided to investigate PI products more closely. Our team worked closely with Mark Wood, a PI representative, to select suitable positioning components and controllers.

After investigating a variety of closed loop piezo actuators available from PI our team decided to specify the P841.60 closed loop piston type piezo actuator. Figure 11 shows several P841/840 series piezo actuators with a diagram depicting the case dimensions (P840 actuators are open loop actuators sharing the same design and specifications of the P841 actuators). The P841.60 has a 122 mm long case[76].

[75] http://www.piezo.com/motor.html
[76] http://www.physikinstrumente.de/products/prdetail.php?secid=1-16

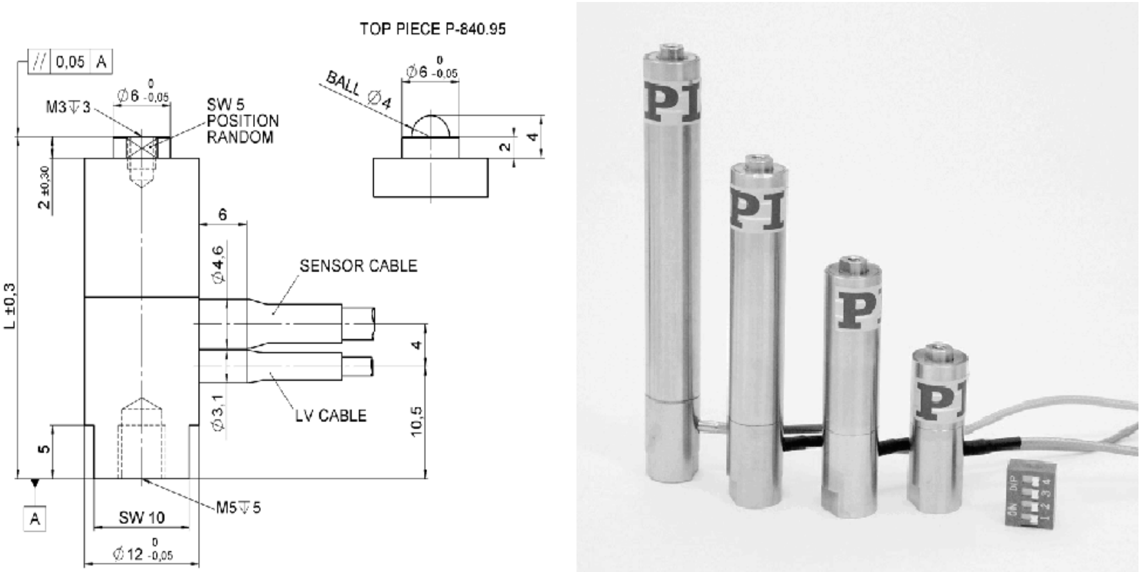

Figure 11 P841/840 Actuator Series with Dimensions[77]

The P841.60 was the only actuator that met all of our requirements for resolution and travel. The P841.60 is capable of 90 µm of travel with 1.8 nm of closed loop position and actuation resolution using an integrated strain gage position sensor. The P841.60 is also capable of exerting up to 1000 N of push force, which can be controlled through the voltage input to the piezo. Since the controller solutions available from PI required our team to have an accurate figure of the number of piezos we would be using, we needed to generate a rough model to visualize placement of piezos and suction cups.

A rough CAD design was used to assist in selecting piezo and vacuum components. Figure 12 shows the rough placement configuration sketch for suction cups, piezos, and mounting hardware that was used for the bed of nails design. Figure 13 shows the full CAD model that our team developed for design visualization.

[77] http://www.physikinstrumente.de/products/prdetail.php?secid=1-16

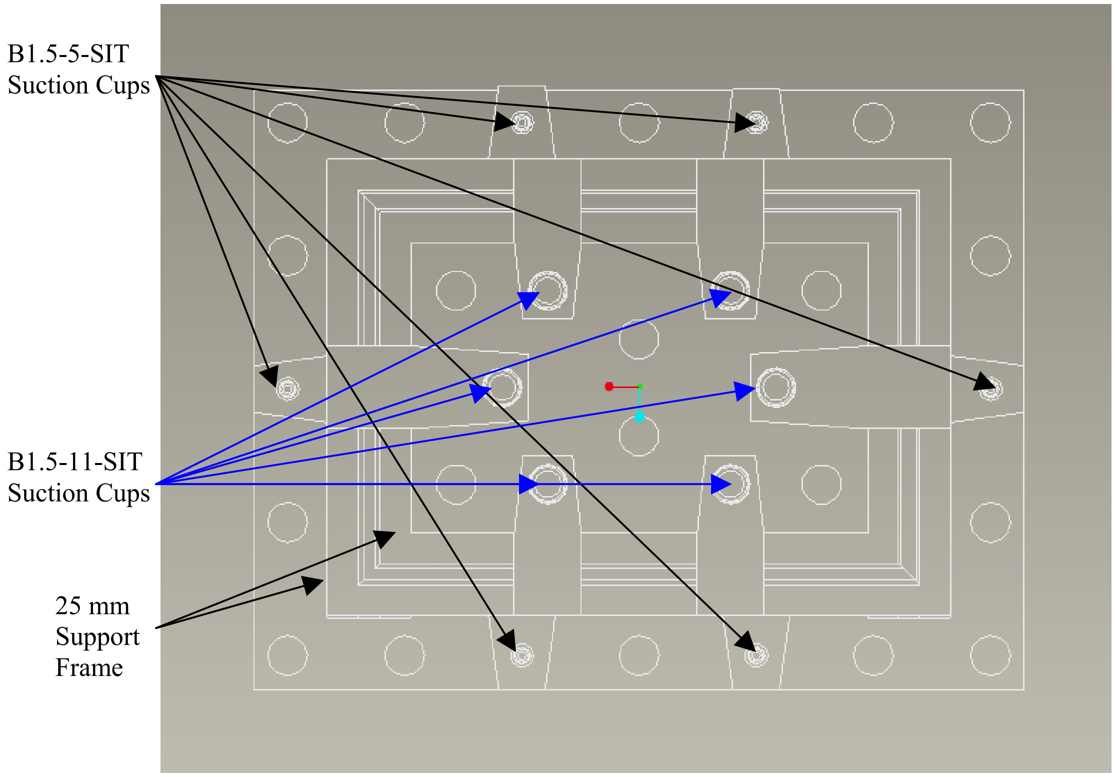

Figure 12 Bed of Nails Sketch

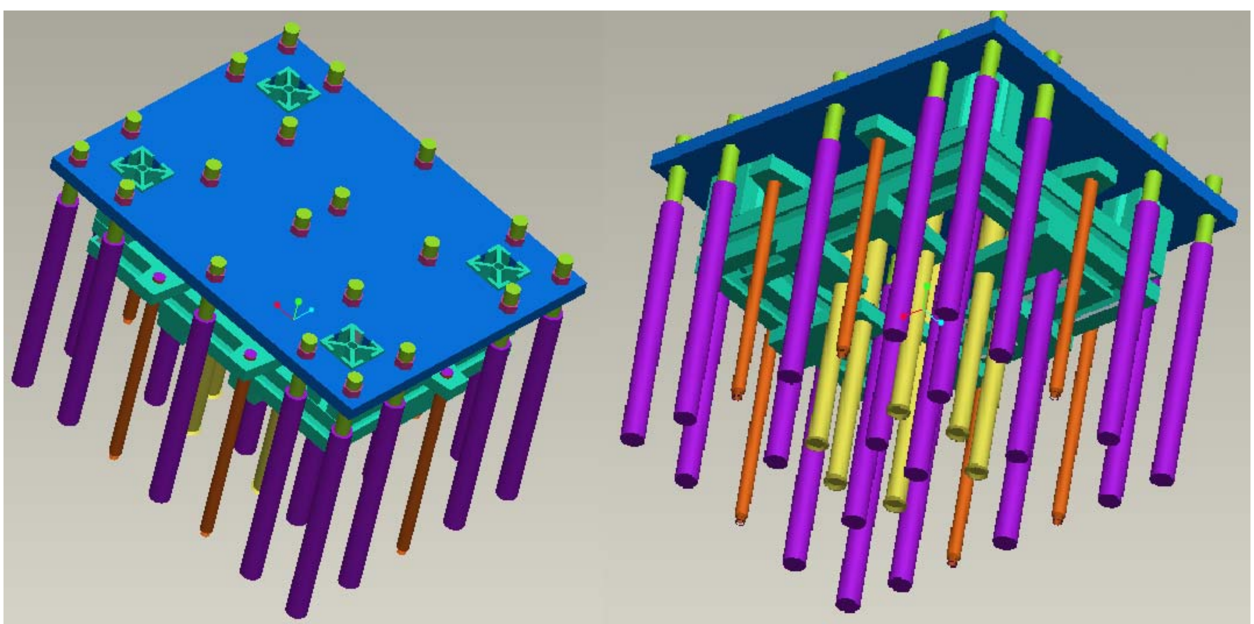

Figure 13 Bed of Nails Configuration Mockup

The purpose of Figure 12 was to determine a suitable configuration of actuators and suction cups that could be fit onto a test reflector. The only replication mandrel available for forming test reflectors generates reflectors at an average radial diameter of 492.40227766 mm (492 mm). Therefore, the specifications for the bed of nails design was based on the assumption that testing would be performed using the 492 mm diameter reflector. The overall telescope assembly called for each cylindrical parabolic or hyperbolic reflector to be divided into segments at 60° intervals, creating six smaller curved reflectors at each reflector diameter specification. Therefore, to specify the perimeter dimensions of a test reflector we performed calculations based on a reflector diameter of 492.40227766 mm, with the reflector comprising 60° of a total cylinder. Figure 14 depicts the geometry that was used to calculate the reflector arc length. The top vertex, vertex C, of the triangle in Figure 14 represents the optical axis of the SXT. The average radius to the reflector is set as the dimension of segments CA and CB, which intersect the optical axis, forming a 60° angle.

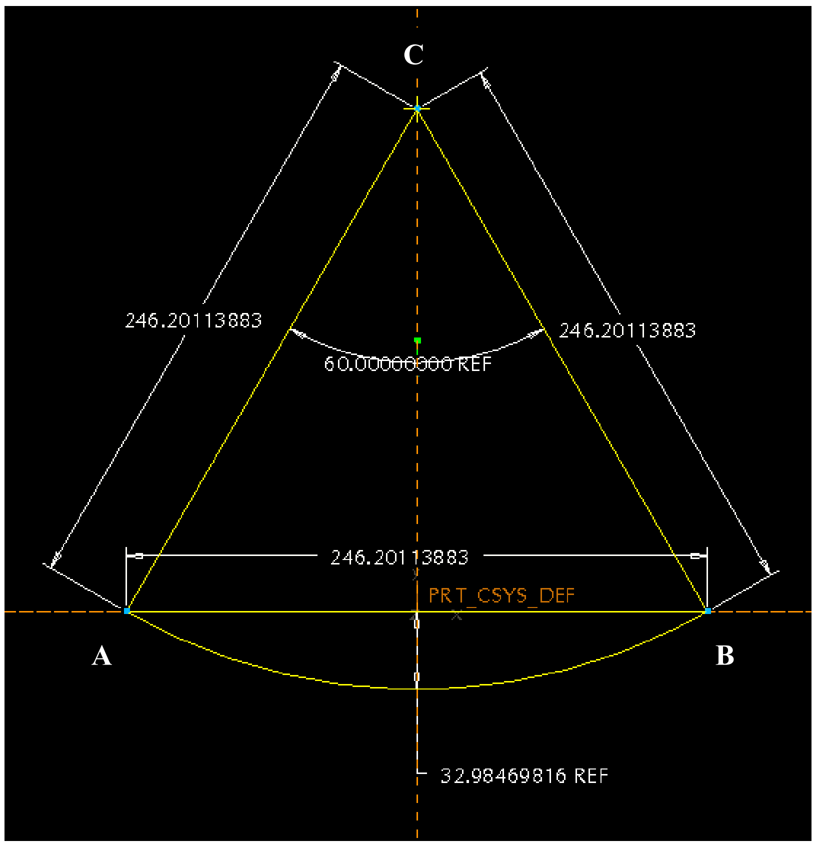

Figure 14 Reflector Dimension Geometry (units: mm)

Calculating the length of the arc shown from vertex A to B, and given the uniform reflector axial dimension of 200 mm, results in a reflector with a perimeter dimension of 257.82122968458 x 200 mm. This perimeter dimension was used as the outer boundary in Figure 12.

Given the time and cost restraints for the project, our team worked to select readily available components for the bed of nails design from vendors where NASA or the SXT team had a pre-existing relationship. To specify the gripping components of the bed of nails design our team chose to select components from Anver, a Hudson, Massachusetts based company specializing in vacuum components. As with PI, Anver was chosen as a supplier based on a prior successful relationship within the SXT team.

Stock Anver components allowed our team to specify a vacuum gripping mechanism that would be able to adapt to a variety of reflector curvatures. Using 1.5 bellows silicone suction cups, each attached to an individual level compensating suspension, the gripping mechanism would be able to compensate for reflector curvature across the suction cup diameter and across the entire bed of nails tool.

Further, the team chose to specify 80/20 as the supplier for support frame components. 80/20 is a company specializing in extruded aluminum frame systems and has a variety of extruded aluminum profiles available, along with a diverse array of fasteners, joints, and accessories. 80/20 was suggested as a supplier by our mentor, Jeff Stewart. To minimize reflector surface that would be blocked by the bed of nails support structure the team chose to specify 80/20 25 mm square aluminum tubing, the smallest available from 80/20, in a simple rectangular configuration. The boundaries of the support frame are outlined in Figure 12.

With the support frame overlaid on the reflector perimeter the remaining reflector surface area was populated with piezo and suction cup vertical profiles. The casing diameter of the P841.60 closed loop piezo is specified as 12 mm by PI. An inner and outer perimeter of piezo profiles were overlaid on the reflector/support sketch. Next, inner and outer perimeters of suction cups were overlaid on the reflector/support sketch. Figure 12 shows the suction cup profiles are offset from the support frame to allow clearance for their suspension and for the mounting plates connecting each suspension to the 25 mm frame. Mounting hardware shown in Figure 12 was modeled assuming that custom mounting hardware would be machined for the bed of nails prototype.

The team selected suction cups and suspension systems that were readily available from Anver. The smallest bellows suction cup available from the Anver catalog was part number B1.5-5-SIT. This is a 1.5 bellows silicone suction cup, with a cup diameter of 5.5 mm and a body diameter of 7 mm. B1.5-5-SIT suction cups were used to populate the outer perimeter of suction cups. The inner perimeter of suction cups was populated with Anver part number B1.5-11-SIT, a 1.5 bellows silicone suction cup with an 11.4 mm cup diameter and 12 mm body diameter. B1.5-5 and B1.5-11 are available in either silicone or nitrile (SIT stands for translucent silicone in Anver's naming scheme). Silicone was chosen because of its low durometer allowing the cup to mold more easily, high heat resistance to allow for gripping a hot reflector, and lack of dye that might leach or outgas onto the reflector. Figure 15 shows the dimensions of the B1.5-11 and B1.5-5 suction cups, including cup diameter and body diameter.

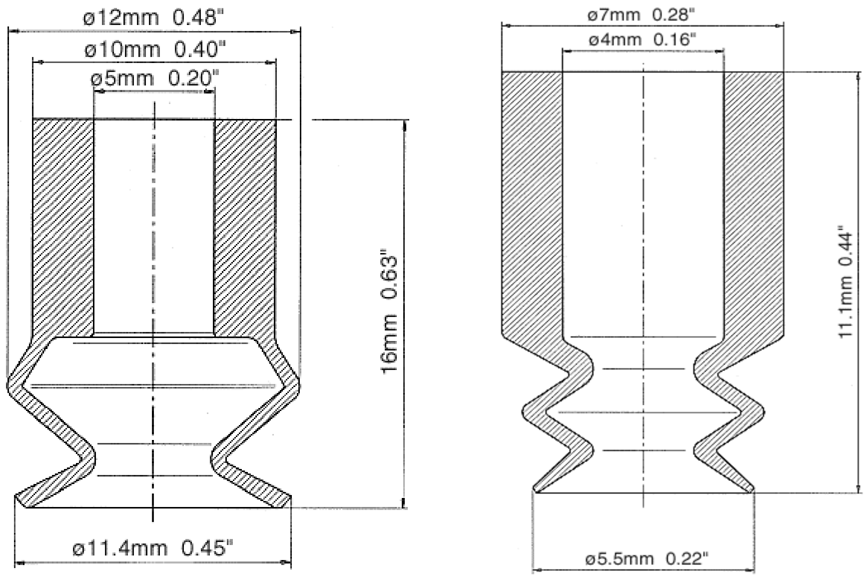

Figure 15 B1.5-11 and B1.5-5 Dimensions[78]

Suspension systems for the suction cup were selected from those available from the Anver catalog, based on the dimensions of the 492 mm diameter reflector. The team calculated that the suspension would need a range of 32.98469816 mm to compensate for reflector curvature from the lowest point on the reflector to the highest point. This distance is shown in Figure 12. The most compact suspension system available from Anver is the SLSA-1 system, which is available in a variety of suspension travel configurations, the largest of which allows for 30 mm of suspension travel (part number SLSA-130NR), less than the required 32.98469816 mm. The team made a rough calculation, assuming a linear reflector slope, and determined that the center point of the SLSA-130NR suspension would have to be mounted 11.139045186243 mm in from the lowest edge of the reflector to operate within the suspension's 30 mm travel range. Figure 16 shows the reflector perimeter dimensions, along with the relative position of a B1.5-5-SIT suction cup offset 11.14 mm from adjacent reflector edges. As Figure 16 makes clear, 11.14 mm represents a relatively small distance from the edge of the reflector as compared to the overall dimensions of the reflector.

[78] http://www.anver.com/document/vacuum%20components/vacuum%20cups/B1-5%20Cups/b1_5-11-sit!.htm *and* http://www.anver.com/document/vacuum%20components/vacuum%20cups/B1-5%20Cups/b1_5-5-sit!.htm

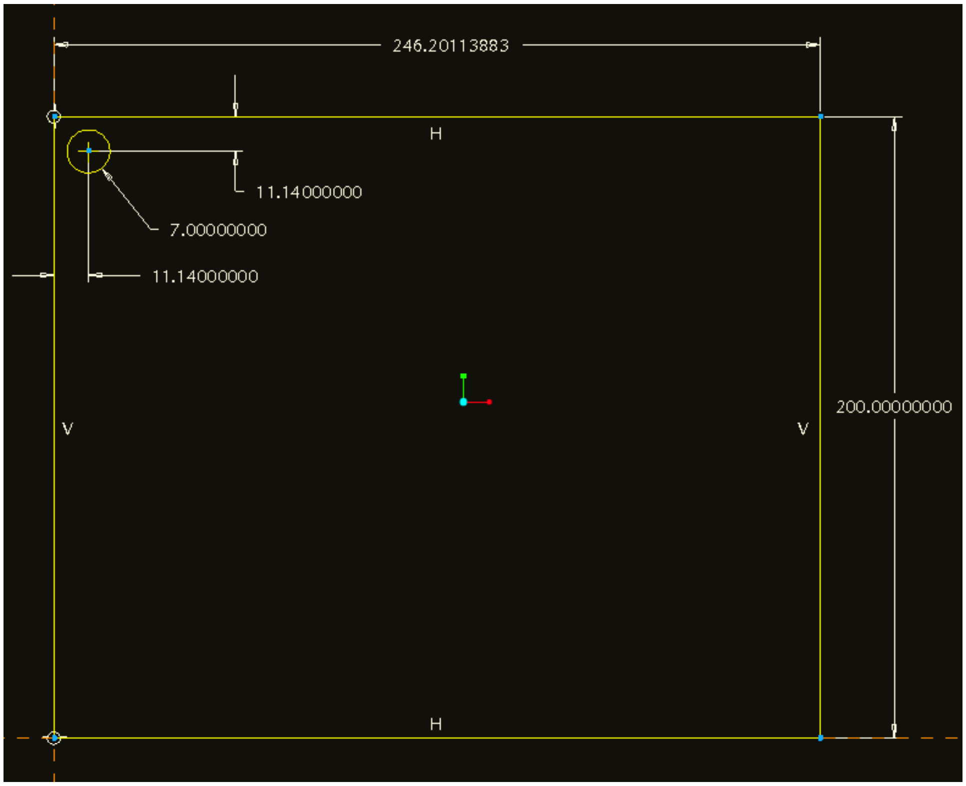

Figure 16 Suction Cup Edge Offset

Based on the visual diagram in Figure 16 the team decided that the 11.14 mm offset was acceptable for testing and thus that the SLSA-130NR suspension would be suitable for both the outer perimeter of B1.5-5-SIT suction cups and the inner perimeter of B1.5-11-SIT suction cups.

Using the same linear reflector slope that we used to estimate the suction cup edge offset, our team also performed a rough calculation of the amount of reflector curvature that would have to be compensated for by the bellows in the suction cups. Assuming that the center of a B1.5-5-SIT suction cup was placed at 11.139045186243 mm from the edge of the reflector, the bellows would have to account for .602885682961 mm of position change across the cup radius of 2.25 mm or a total of 1.205771365922 mm across the cup diameter. The dimensions of the B1.5-5-SIT, shown in Figure 15, indicate that this is a suitable range of compensation for the bellows.

The configuration shown in Figure 12 calls for a total of twelve suction cups, six B1.5-5-SIT and six B1.5-11-SIT. Using a safety factor of 2, the Anver catalog specifies the lift capacity of the B1.5-5-SIT as .07 kg and the B1.5-11-SIT as .24 kg. This results in a total lift from the Figure 12 configuration of 1.86 kg. Using D263 glass substrate dimensions of 258 X 200 mm (slightly larger than the actual reflector dimensions), a substrate thickness of .44mm (slightly thicker than the actual substrate thickness), an Epotek 301-2 epoxy thickness of 10 μm (representing the upper bound of epoxy thickness), and a gold thickness of 2000 Angstroms, we calculated the reflector mass to be 55.1807 g. At this mass the reflector would exert approximately .541141 N of force. 1.86 kg of suction cup lift could overcome 18.2405 N of force. Given that the figure of 1.86 kg of lift is calculated using a factor of safety of two, the Figure 12 suction cup configuration should be able to allow 17.6993 N of actuation force from the piezos without danger of dropping the reflector. The SXT team assumes that roughly .25 N of actuation force would be required by a single piezo to affect a localized shape alteration. Using this figure of .25 N, the Figure 12 configuration should be able to allow all twenty piezos to be active simultaneously and while still retaining a sufficient grip on the reflector.

Based on the space constraints of the test reflector and the Figure 12 configuration sketch the team decided to specify twenty P841.60 closed loop actuators for the bed of nails prototype. Twenty piezos represent a 100% increase in active contact points over the piezo prototype. Once our team had decided on the number of closed loop piezos we wanted to specify, the team worked with Mark Wood to outline a controller configuration. The controller configuration for twenty P841.60 closed loop piezos called for the following parts:

Item	Qty	Part Number	Description	Price	Ext. Price
1	20	P-841.60	Preloaded Closed Loop LVPZT Translator, 90µm	$2,221.00	$44,420.00
2	4	E-500K012	Controller Chassis, 19", 6-channel	$2,251.00	$9,004.00
3	7	E-503.00	LVPZT Amplifier Module -20 to 120V, 3 Channels	$2,202.00	$15,414.00
4	7	E-509.S3	Sensor/Controller Module, Strain Gage Sensor, 3 Channels	$2,610.00	$18,270.00
5	1	E-516.I3	Display, Interface Module 20 Bit, IEEE488/RS232, 3 Channels	$3,054.00	$3,054.00
				Total	**$90,162.00**

Table 1 Closed Loop Piezo Parts List[79]

The controller configuration shown in Table 1 allows for adding a single additional P841.60 closed loop piezo without the need to purchase additional E-503.00 amplifiers or E-509.S3 position controllers. If necessary, this additional piezo could be placed in the Figure 12 configuration at the center of the reflector.

Once the controller configuration had been specified and quoted by PI, the team requested a quote on hardware from Anver. The quote from Anver is as follows:

Item	Qty	Part Number	Description	Price	Ext. Price
1	6	B1.5-5-SIT	Suction cup	$3.50	$21
2	6	B1.5-11-SIT	Suction cup	$4	$24
3	12	BM5	Barbed fitting	$1	$12
4	12	SLSA-130NR	Suspension	$26.49	$317.88
5	12	BTC-114T	Vacuum Fitting	$2.75	$33
6	12	72300040	Bracket Hanger	$55	$660
				Total	**$1,067.88**

Table 2 Anver Suction Cup Parts List[80]

[79] Wood, Mark. "PI Quotation." E-mail to Devin Brande. 13 Sept., 2004.

As no detailed support frame specification was drawn up beyond the 25 mm square extruded aluminum tube frame, our team was not able to request an official quote from 80/20 for the support frame. However, the team generated the following rough cost estimate:

Item	Qty	Part Number	Description	Price	Ext. Price
1	892 mm	25-2525	Extruded profile	$.008/mm	$7.14
2	4	25-4107	Joining plate	$3.20	$12.80
3	4	25-4108	Corner bracket	$2.60	$10.40
				Total	**$30.34**

Table 3 80/20 Frame Structure Parts List

The final step our team took in the bed of nails design was to pursue funding for the hardware necessary to create a bed of nails prototype. Our team's initial goal had been to test the bed of nails using a single P841.60 closed loop piezo would provide results that would indicate whether or not it was worth the cost and effort of pursuing a full specification prototype. However, difficulties in securing funding or obtaining demonstration parts from PI caused a series of delays in pursuing the bed of nails. Further, our mentor Jeff Stewart suggested that testing with a single piezo might not provide conclusive data as to the feasibility of the bed of nails. Therefore, an Independent Research and Development (IRAD) funding proposal was drawn up, using our specifications and cost information, for the bed of nails project by Andrew Carlson, a graduate student working on the SXT. This proposal requested funding to allow the purchase of all the components in the Figure 12 specification and was submitted for review in the second half of September, 2004. The full bed of nails IRAD proposal is located in Appendix B. The IRAD proposal represents the end of our team's contribution to the bed of nails design.

5.2 Composite Support Sheet

After progress on the Bed of Nails device was halted awaiting further funding an alternative composite support sheet or composite draping design was proposed. The composite draping design was meant to serve the same purpose as the proposed bed of nails design; the purpose was to maintain the shape and prescription of the reflectors after they are removed from the replication mandrel. The composite draping design was proposed as a structural element that would be attached to the back surface of a reflector pair to increase the strength and rigidity of the reflectors. The draping structure would be attached to the reflector pair while the reflectors were still on the replication mandrel. The draping would either be co-cured with the reflectors during the slumping process, utilizing the pre-existing adhesive in the composite material, or pre-cured separately and attached using additional adhesive, after the reflectors

[80] Laycox, Mark. No Subject. Email to Devin Brande. 13 Sept., 2004.

had been completely formed. Once the draping was attached to the reflector pair both the reflectors and the draping structure attached to the reflectors would be peeled off of and removed from the mandrel.

In the current process of peeling the reflectors from the mandrel the shape and prescription of the reflectors is not maintained. The composite draping element would serve to provide the reflectors with enough structural rigidity that reflector shape and prescription would be preserved during and after the process of peeling the reflectors from the mandrel. Ideally, the structural support provided by the composite draping would be significant enough to prevent any shape deformation during the reflector removal process. Given maximum thickness requirements for a reflector (0.44 mm including draping), our team speculates that some shape deformation could occur in the reflector during the peeling process and that a certain amount of shape memory would have to exist in the composite draping to account for deformation. These speculations illustrate the importance of testing the composite draping structure. A valuable measurement would be the amount of shape deformation that occurs in the reflector after it is peeled from the mandrel and comparing this amount of deformation to a reflector that is peeled from the mandrel without a composite draping structure.

To conduct initial research into composite materials our team was referred by Jeff Stewart to Ben Rodini, a composites expert working for SWALES Aerospace Company, and Janet Squires, a SWALES employee working on the SXT with composite materials knowledge. During a September 23rd meeting with our team Ben Rodini provided us with general information on composites, information specifically regarding a composite material suggest by Jeff Stewart, M55J, and also offered his thoughts on how we might create the composite draping structure. One of Mr. Rodini's primary suggestions was that a pre-cured composite sheet would likely be more effective than a co-cured composite sheet. This suggestion matched that of Janet Squires from a September 22nd email. Mr. Rodini told us that M55J composite material has a modulus of 15 million psi (msi), as compared to 3.5 msi for Epotek 301-2 and 10 msi for D263, tensile/compression strength of +/- 100 ksi and a survival temperature of +/- 50° C. In an email correspondence Janet Squires discussed having performed analysis assuming a uni-directional ply thickness of 0.001 inches[81]. Mr. Rodini suggested that we should plan on using unidirectional composite plies at least 0.002 inches thick as 0.001 inch thick layers of composite are more difficult to find and are more expensive. Mr. Rodini also suggested that we consider using sheets of M55J woven composite fabric as the layers of the draping structure. According to Mr. Rodini this woven fabric is available in 0.003 inch thick sheets with a 0°/90° weave and offers the advantage of having the ability to contour to different shapes, meaning it could take the shape of the reflectors more easily as compared to uni-direction composite plies[82].

[81] Squires, Janet. "RE: Reflector support thickness." Email to Devin Brande. 22 September 2004.
[82] Rodini, Ben. Personal Interview. 23 September 2004.

Following our team's meeting with Ben Rodini we met with Jeff Stewart and decided that at least three different composite layups should be tested. The first two tests would use a pre-cured composite sheet bonded to a reflector pair and the third test would use a co-cured composite sheet. The first pre-cure layup would consist of uni-directional layers of composite material (at least .002 inches per layer), the second of woven fabric layers of composite (0.003 inches per layer), and the third test would be a co-curing test to determine if a composite sheet could be bonded to the reflector pair using only the adhesive that exists within the composite material, without the need for an additional adhesive layer.

The theory behind testing a co-cure layup was that during the composite curing process, which takes place under approximately 100 psi of pressure and at 250 to 350° F[83], any excess resin adhesive used in creating the composite sheet would be pressed out and cured onto the reflector pair, thereby bonding the reflectors and composite sheet together. One difficulty in implementing a co-cure process would be that because an adhesive may not form a suitable bond to the smooth reflector surface, etching of the glass surface may be required in order to bond the composite to the reflector.

With the uni-directional composite ply test the composite plies would be laid up at an angle to one another to add strength in all directions and in a symmetrical fashion to give the composite sheet a homogenous structure. Therefore, any layup using unidirectional plies must use an even number of plies. Further, given the maximum thickness requirement for a reflector there would be a limit to the number of plies of a given ply thickness that could be applied. Several layup patterns that were suggested include a 0°, 60°, -60°, -60°, 60°, 0° layup using 0.002 inch thick plies or a 45°, 45°, 0°, 90°, 90°, 0°, 45°, 45° layup using 0°/90° two layer composite weave[84].

Unfortunately, because only one replication mandrel exists at GSFC for creating test reflectors our group was not allowed to use this mandrel for composite draped testing, as the testing could damage the replication mandrel. However, since we only wanted to test the major effects of a composite draping on reflector shape it was not necessary that we use the precise replication mandrel. A less precise mandrel could be machined, measured using a tool such as a CMM, and used for testing by comparing the shape of a reflector pair with a composite sheet attached to the shape of the test mandrel.

We decided that an aluminum test mandrel for the third reflector pair of our five could be designed and machined and would be able to serve all of the purposes that would be necessary for testing the composite draping structure. This mandrel was designed using the prescription of the existing replication mandrel. Our team designed the mandrel using ProEngineer and this model was used by SXT machinist Chris Kolos to machine an aluminum test mandrel. The CAD model of the mandrel needed to provide an extra 1/8 inch (0.125) of thickness on all sides to allow for damage that was expected to occur from the tools used to machine the mandrel. This additional 1/8 inch was incorporated into the design of the test mandrel and an image of the ProEngineer design can be seen in Figure 17.

83 Rodini, Ben. Personal Interview. 23 September 2004.
84 Rodini, Ben. Personal Interview. 23 September 2004.

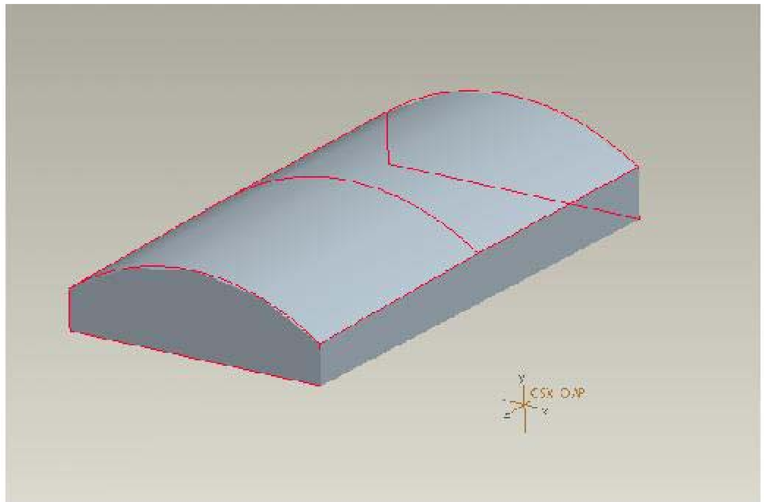

Figure 17 Aluminum Test Mandrel

One of primary design consideration for the test mandrel was whether to add a raised rib structure in the area of the mandrel where the parabolic and hyperbolic conic sections come together. The purpose of the additional rib structure would be to prevent a composite sheet from sagging in the 50 mm gap between the parabolic and hyperbolic reflectors. In testing the composite sheets any changes in shape that could cause the composite sheet to fold should be avoided because as this could adversely affect the strength of the composite draping and its ability to maintain the shape of the reflector. However, we decided that the design of the aluminum mandrel should not feature this rib structure because it would also require approximately 1/8” of extra material on each side of the rib and that this error in machining might result in the rib having inaccurate dimensions. This rib structure would need to fill the gap between the reflectors exactly; any overlapping or clearance between the rib and the reflectors could result in an inaccurate shape or prescription of the reflector/composite structure or sagging of the composite structure into the gap. Figure 18 shows the final machined aluminum mandrel.

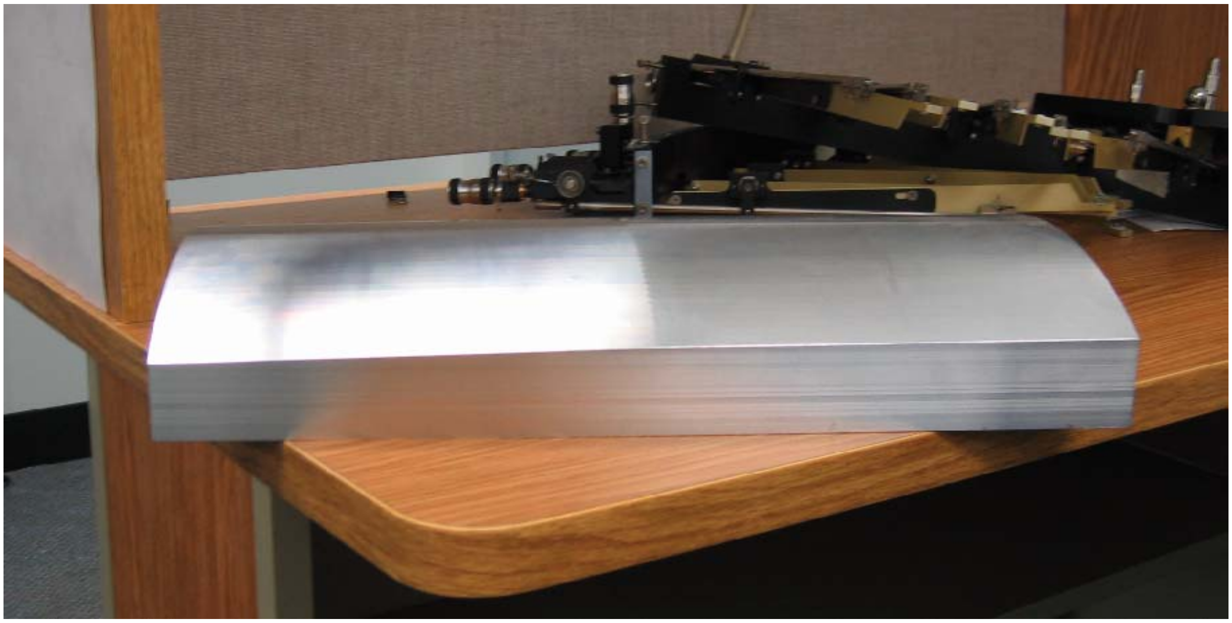

Figure 18 Aluminum Test Mandrel

The concept of having a structure separate from the mandrel that could be used to fill the gap was also considered. This separate structure would be placed on the mandrel to fill the 50 mm gap between reflectors and would prevent the composite structure from sagging while it is attached to reflectors. A CAD model of the mandrel with the added rib structure outlined and the separate rib alone is shown in Figures 19 and 20 respectively.

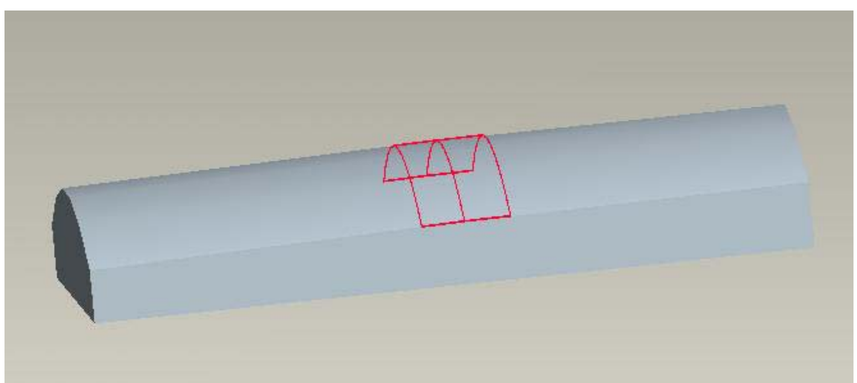

Figure 19 Test Mandrel With Added Rib Structure

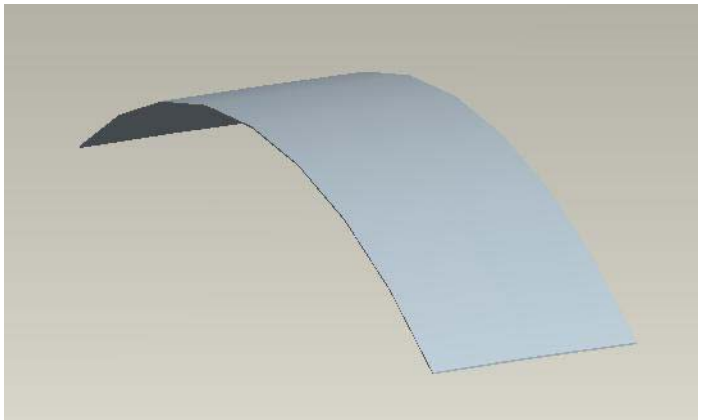

Figure 20 Separate Rib Structure

Unfortunately, due to time constraints our project team was unable to test the composite draping structure. The technicians in the composites lab were unable to schedule time during the time remaining in the 2004 WPI project period to assist our team in constructing the composite test sheets for composite draping design testing. As a result of the scheduling conflict with the composites shop our team was unable to perform any testing of the composite draping structure. Composite draping testing will be continued by the SXT team at GSFC.

5.3 Glass-pack

The goal of the glass-pack design was to develop a simplified Spectroscopy X-ray Telescope (SXT) Flight Mirror Assembly (FMA) design as an alternative to the design prototypes that were being pursued concurrently during our project. The purpose of a simplified alternate design would be to speed up the FMA assembly process primarily through the elimination of reflector alignment stages.

The team's first step in pursuing the glass-pack design concept was to examine the design prototypes that existed at the beginning of the project period and to meet with the two individuals primarily involved with working on the glass-pack at that time: Jeff Stewart and Bobby Nanan, an engineer working on CAD modeling for Constellation-X. The primary SXT FMA design that was being pursued prior to the start of our project was the Optical Assembly Alignment (OAP) design, which consisted of two prototypes, OAP-1 and OAP-2. The OAP-1 prototype was the predecessor to OAP-2; OAP-1 had been disassembled and modified for use with OAP-2 before the start of our project. Figure 21 shows a CAD model of the modified OAP-1 prototype with the OAP-2 prototyped, containing one reflector, attached.

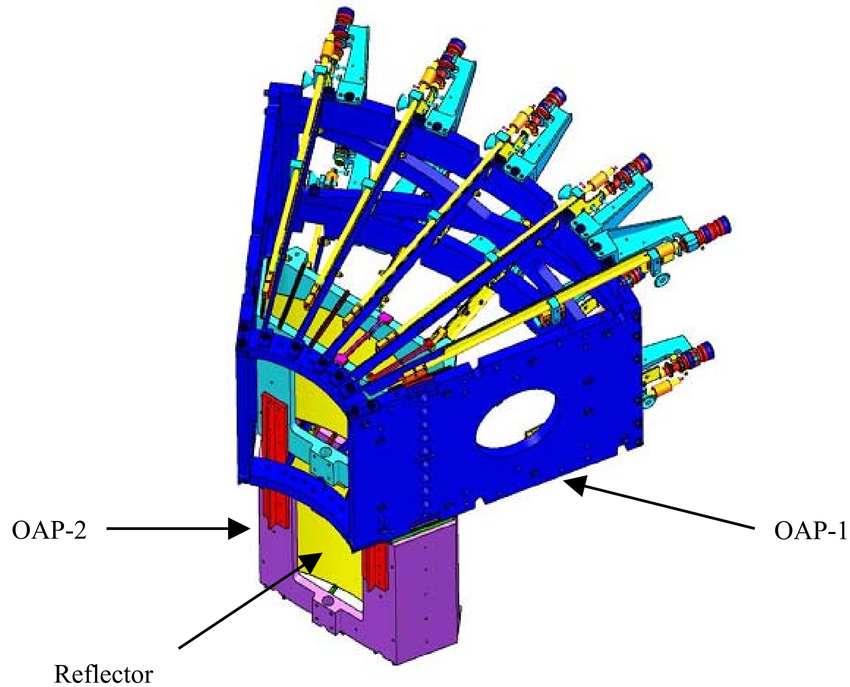

Figure 21 OAP Modules[85]

The design of the OAP modules called for parabolic and hyperbolic reflectors to be installed, aligned, and bonded separately. Further, the structure of the OAP modules not only required developing installation, alignment, and bonding methods that would be precise and able to work in the confines of the module housings, but also was a large contributor to X-ray obscuration in the SXT. Figure 22 shows a close-up CAD view of the OAP-2 module showing the reflector support struts with five reflectors installed. The OAP-2 module has a total of six reflector support struts that run perpendicular to the X-ray path, across the top and bottom of the reflectors. Each strut is .125 inches (3.175 mm) wide, resulting in .75 inches (19.05 mm) of obscuration. The piezo strut shown in Figure 22 is part of the piezo prototype, which was in the process of being fabricated during our project, and was not factored in the obscuration calculation.

[85] Model from: Piezoplan 4 presentation.

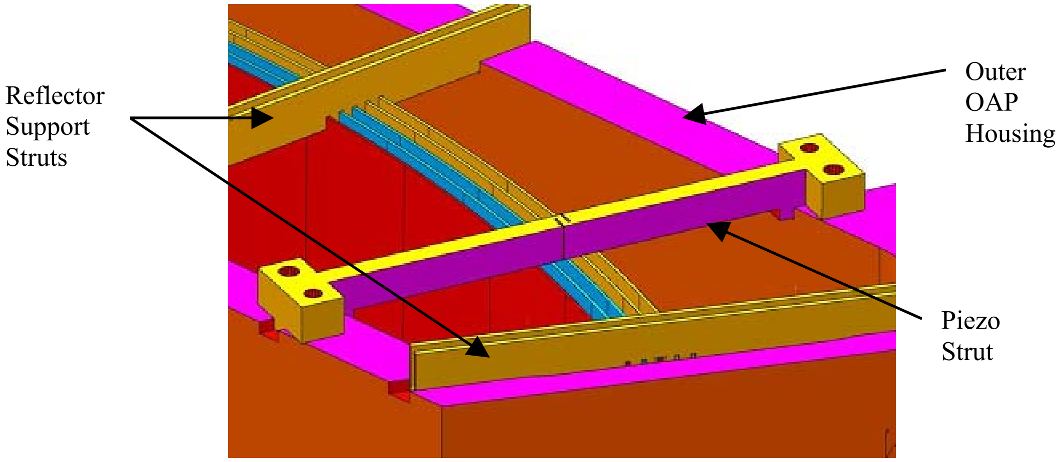

Figure 22 OAP-2 Housing w/ Reflectors[86]

In meeting with our mentor, Jeff Stewart, our team learned that the SXT team was looking for a method of telescope assembly that would eliminate as many of reflector alignment steps as possible and simplify the development of an alignment method by employing a more open reflector assembly structure. The OAP modules required three major alignment steps:

- Aligning each parabolic reflector to the SXT optical axis,
- Aligning each hyperbolic reflector to the SXT optical axis,
- Aligning each parabolic-hyperbolic pair to each other.

The process of aligning each parabolic-hyperbolic (P-H) reflector pair to each other was established as the primary process to try to eliminate. Each P-H pair is fabricated on a replication mandrel as a pair and in the correct P-H alignment. However, the reflectors were being removed from the mandrel individually, which took the reflectors out of the proper P-H relationship, and then installed in the OAP modules. One of the considerations in designing the glass-pack then became creating a design that would allow a P-H pair to be installed and aligned as a single unit.

Prior to our team's arrival, Jeff Stewart and Bobby Nanan pursued the glass-pack concept and developed a mockup glass-pack design to demonstrate some of the glass-pack concepts and how the glass-pack could be incorporated with other tools that were being developed, primarily the vacuum chuck. The numbered sequence in Figure 23 depicts the glass-pack concept, the implementation of the vacuum chuck in the assembly of the glass-pack, and the installation of a complete glass-pack into an outer telescope support structure (wagon wheel). The initial glass-pack concepts called for a core of several reflector pairs to be built up using support struts that would attach to the axial, or side, edges of the reflectors. Two pairs of reflectors would then be aligned and attached to each other outside of the glass-pack core using several vacuum chucks, as shown in Figure 23 panel 1, and then slid over the core and

---

[86] Model from: Piezoplan 4 presentation

bonded, as shown in panel 2. Panel 3 shows a complete glass-pack attached to two vacuum chucks. Panel 4 shows the glass-pack in relation to the wagon wheel telescope structure.

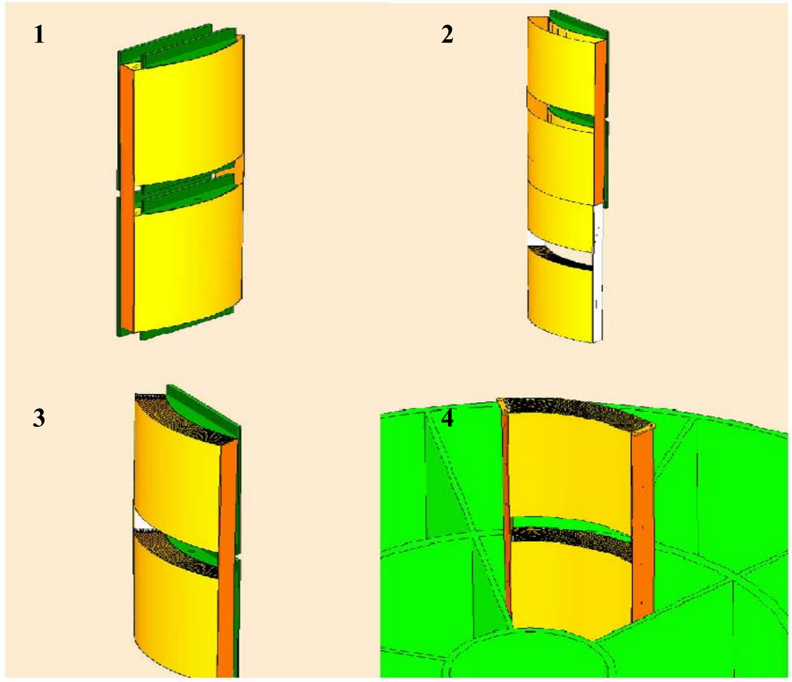

Figure 23 Glass-pack Mockup[87]

Figure 24 shows a detail of a vacuum chuck pair in panel 1 and the first reflector pair being installed in a the glass-pack reflector core.

1

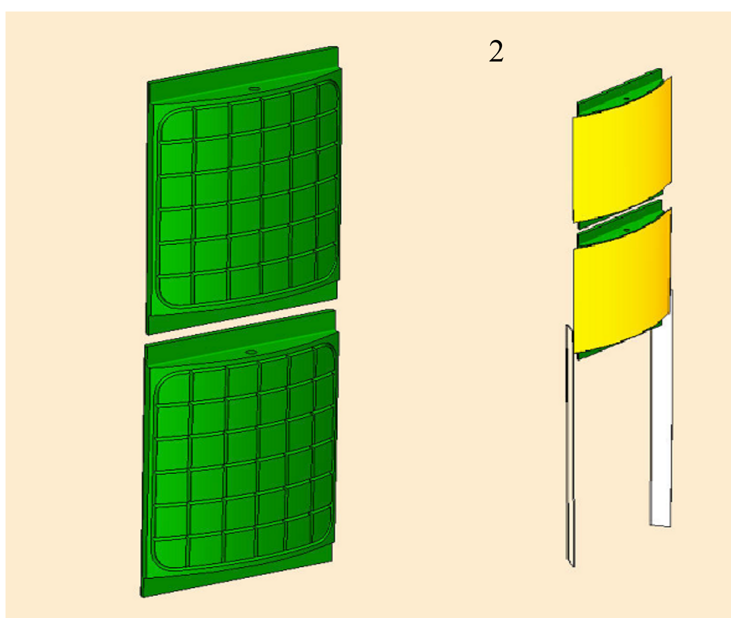

Figure 24 Vacuum Chuck Pair and Glass-pack Core[88]

[87] Models created by: Bobby Nanan

The team's next step in designing a complete glass-pack reflector assembly (GRA) was to collect all of the necessary reflector CAD and data files. This included a variety of I-deas CAD files generated by Bobby Nanan, to use in CAD modeling, which contained complete reflector cylinders, as well as radially cut reflectors. We also obtained several documents that provided an overview of the SXT optical geometry and detailed the geometry of each reflector diameter. These documents are presented in their entirety in Appendices C and D.

Our initial step in the design of the GRA was to familiarize ourselves with the reflector pair CAD files we received from Bobby Nanan. Jeff Stewart recommended we design the glass-pack to contain on the order of tens of reflector pairs as compared to the hundreds of pairs that the OAP modules would hold. Because of the precise prescription (reflector micro-roughness is specified at 4 Å rms over 1 mm[89]) and the parabolic-hyperbolic shape and relationship of the reflectors, creating and working with CAD models of reflector pairs is a difficult process. Bobby Nanan had precisely modeled only a small number of reflector pairs, and our team would thus have to model any additional or different reflector pairs. Therefore, our team decided initially to work with only ten reflector pairs, and later to work with five pairs, to speed up the process of designing and iterating the GRA.

In familiarizing ourselves with the reflector CAD files our goal was to record as much information as we could about the ten reflector pairs we were working with. We used the CAD models (converted as STEP files from I-deas to ProEngineer) that were provided to us by Bobby Nanan to obtain much of this data. These CAD models of the reflectors were designed to micron accuracy, which was acceptable for the purposes of our project because the reflectors cannot yet be cut, nor can the GRA struts be machined, with micron precision. The initial GRA was designed to work with reflector pairs 167 through 178 of 230 (refer to Appendix C for reflector data). The nomenclature for the reflectors dictates that as the reflector number increases, its distance from the optical axis decreases; meaning the highest numbered reflector (230) will be the one closest to the optical axis while the lowest numbered reflector (1) is the farthest away.

Prior to taking the measurements of each reflector, the different attributes of the reflectors had to be identified in the CAD models using a uniform method for each reflector to make it simple to understand where each measurement came from and also to standardize our measurement system for all reflector models. "Datum Plane 1" was created on each model to pass through the smaller curved edge of the reflector while "Datum Plane 2" passed through the larger curved edge. Points were created at each of the eight corners of the reflector and Datum Axes were created at each of the four corner edges. Points 0 through 3 and Datum Axes 1 and 3 were created to lie within Datum Plane 2 while points 4 through 7 and Datum Axes 2 and 4 were created to lie within Datum Plane 1. This naming convention can be seen in Figure 25.

---

[88] Models created by: Bobby Nanan
[89] "Con-X SXT FMA Requirements Document"

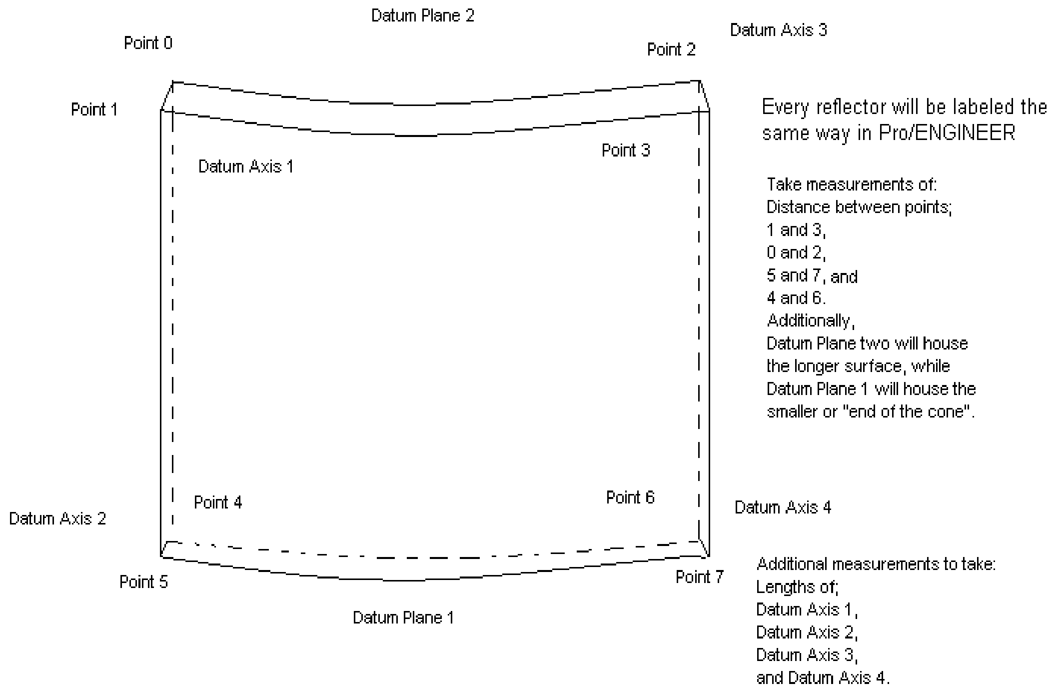

Figure 25 Reflector Dimension Naming Scheme

Measurements were then taken of these models using an analysis measurement tool within the Pro-Engineer software to collect data that was needed to build the GRA. The straight line distance between the points on the corners of the reflectors was measured for each reflector as well as the lengths of the corner edges for each reflector. These measurements were used to identify design parameters for the GRA as well as to calculate other additional information about the reflectors. These measurements can be found in Appendix E.

As a result of converting Bobby Nanan's reflector CAD files from I-deas to ProEngineer as STEP files our team encountered difficulty in working with and modifying the geometry of the reflector files. We worked with Bobby Nanan, who works with I-deas, and James Sturm, another engineer who works with ProEngineer, to attempt to work around the difficulties. We speculated that the difficulty in working with the files was a result of the STEP files used to transfer the reflectors from I-deas to ProEngineer not containing the complete original model data. The files that Bobby Nanan sent us contained complete, 360° reflector cylinders, designed to serve as a foundation to allow cutting any desired radial reflector segment out of a complete cylinder. When we encountered difficulty in manipulating the cylinder files Bobby Nanan also sent us files containing reflectors that were cut radially from the cylinders. Despite the assistance of Bobby Nanan and James Sturm, we were unable to determine a way to adequately manipulate the reflector files.

Thus, while files from Bobby Nanan were suitable for obtaining reflector data, our team decided to construct our own reflector CAD files in ProEngineer to use for GRA modeling. Given the complexity of modeling our own struts, in addition to the limited project time, our team decided to step down from working with ten reflectors to working with five reflector pairs. In meeting with Jeff Stewart it was agreed that a functional GRA design using five reflector pairs would be sufficient and could be extrapolated to work with more reflector pairs, in the range of ten to twenty.

Figure 26 depicts reflector shell 168 as an example of the CAD models our team constructed. In Figure 26 panel 1, the dotted line axis A3 was inserted to clarify the P-H relationship. The P-H reflectors are separated by a 50 mm axial gap, and are at an axial angle with respect to each other. This angle is characterized roughly by the relationship **$\beta = 3\alpha$**, where the parabolic reflector is inclined from the optical axis at an angle, α, and the hyperbolic reflector is inclined at an angle from optical axis, β, that is roughly three times greater than the angle of the parabolic reflector. This rough relationship is based on the data in Appendix E. For shell 168, the parabolic reflector is at α = 0.49672418° and the hyperbolic reflector is at β = 1.24238402°. Axis A3 in Figure 26 panel 1 serves to clarify angles α and β.

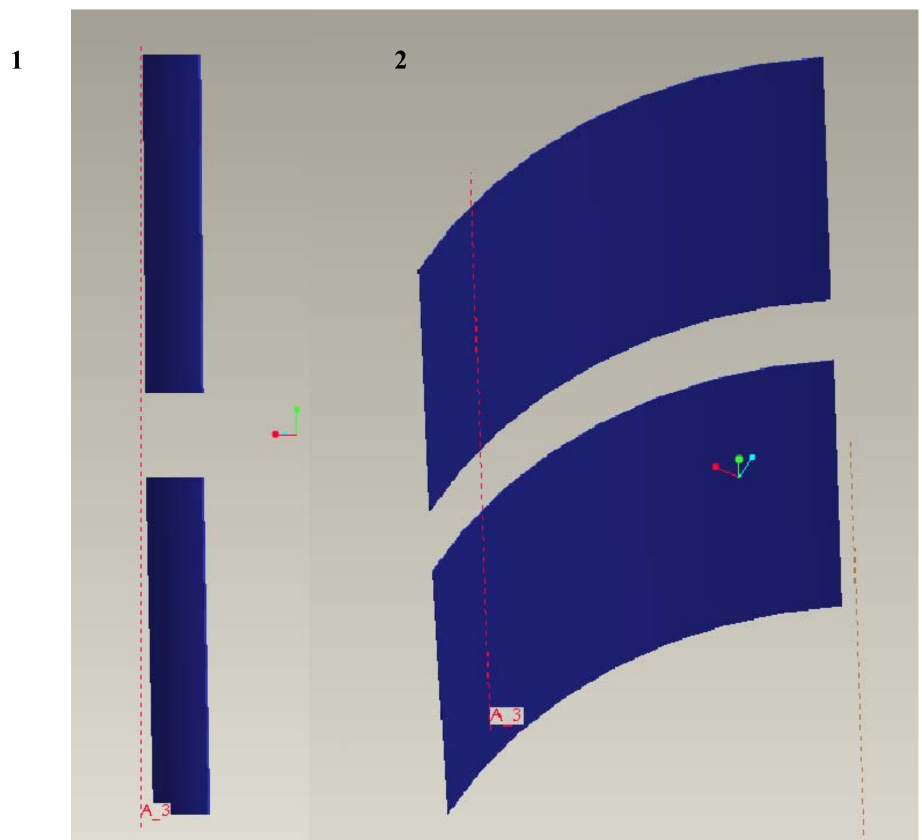

Figure 26 Reflector Model with P-H Relationship

Once our team completed modeling our own reflector pairs, we began work on modeling a GRA design. Concurrent with our work on the bed of nails and on modeling reflector pairs, our team had been having regular brainstorming sessions with Jeff Stewart, including a larger brainstorming session involving several other SXT team members; Bobby Nanan, Air Force graduate students Andrew Carlson, Josh Schneider, and Thomas Meagher, and Swales engineers Burt and Janet Squires.

Our initial designs drew heavily on inspiration from the OAP-2 module with the idea that the OAP style module design could be modified to meet the requirements of the GRA design. One of the basic principles of the OAP module design was to have a self-supporting module structure into which individual reflectors would be installed. This self-supporting module structure would provide support for the reflectors, would be either interconnected with other modules or installed into a wagon wheel type structure, and would be launched as flight hardware. Our initial designs sought to simplify the module design while retaining the module's self-supporting quality. Figure 27 shows one of our designs for an external structure GRA.

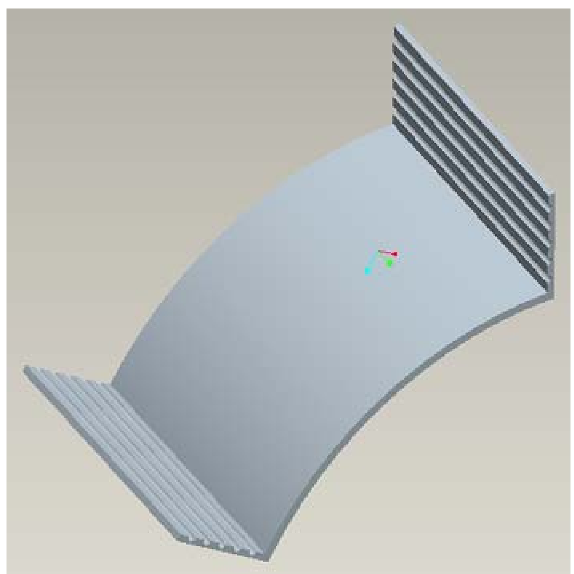

Figure 27 GRA Design: External Structure

The primary advantage of an external structure design was that it did not require any additional structure be attached to the reflectors. The concept called for the bed of nails or a similar tool to grasp the reflectors on the replication mandrel, move them within the GRA structure to where the reflectors could be aligned using a precision alignment tool such as a Physik Instrumente Hexapod, and finally the reflectors would be bonded.

There were, however, several disadvantages to an external structure design. First, the P-H angle between reflectors required that the reflectors be installed radially, beginning with the inner-most reflector pair, from the outside of the GRA structure. Reflector pairs could not be slid into the GRA structure in the axial direction. Second, because casting and machining tolerances could not match the alignment tolerances for the reflectors, the reflectors would have to be held in place entirely by epoxy through a method known as liquid shim. The liquid shim method calls for a part to be held in a structure by an external tool while epoxy is used to bond the part to the structure. The purpose of liquid shim is to prevent any rigid contact between part and structure that might induce stress. Further, liquid shim can account for slight variations in tolerance as the liquid shim method requires at least .005 inches (.127 mm) of clearance for the epoxy. No rigid part of the GRA structure could be used for final location of the reflectors as tolerance stack-up would cause mis-alignment. The slots shown in the structure in Figure 27 were intended to hold epoxy for the liquid shim process. Third, and finally, because the shape of each reflector and spacing between each reflector is not a constant, it would not be possible to design a generic external structure GRA module.

After several brainstorming sessions it was decided that, based on the disadvantages of the external structure GRA design and the delays experienced with the bed of nails design, our team should dismiss an external structure GRA design and pursue a GRA design where generic size individual structure elements would be attached to each reflector pair. Further, these individual structure elements would be connected to adjacent reflector pairs, thereby building up a GRA structure.

The advantages of an individual structure GRA design were outlined as follows:

- Individual structure elements would provide local support to each reflector pair,
- The lack of an external structure would allow easier access for alignment tools,
- Individual structure elements would allow a variable number of reflector pairs in a glass-pack versus a number defined by the size of an external structure,
- Reflector pairs could be installed radially or axially,
- And using liquid shim bonding between reflector pairs could add tolerance for mis-alignment would not require the same precision machining or casting as and external structure design.

The disadvantages of an individual structure GRA design were outlined as follows:

- A generic size support structure element would only fit a limited range of reflectors as a result of the P-H angle; several different structure elements would have to be designed to accommodate the full range of reflector diameters,
- Additional structure elements would be required to attach a glass-pack to the overall telescope wagon wheel structure,
- And there is limited space between reflector pairs in which any structure element can be placed.

Once our team had decided to pursue an individual structure GRA design we worked to design and model a complete support structure for our five reflector pair CAD models, shells 173 through 177.

One of the early design parameters that we decided on was that the individual structure elements would be attached to the back side of each reflector to reduce the chance of damaging the pristine reflective side. We also decided that we wanted a significant reduction in obscuration as compared to the OAP-2 module, which had 19.05 mm of obscuration.

As the gap between each reflector pair is very small (less than 2 mm) and varies at each reflector shell diameter, we were restricted in how thick we could make any aspect of the support structure that attached to the back surface of a reflector. The smallest gap between reflectors is .7 mm. Thus, we decided to specify the portion of our support structure that would fit into the gap between reflectors at .5 mm thick. By designing this thickness to accommodate the smallest reflector gap, the only part of the support structure design that would have to be changed to accommodate different reflector diameters would be the support structure angle that allows is to mate to both parabolic and hyperbolic reflectors.

Our next step was to design the overall shape of the individual support structure elements. In the interest of simplifying manufacturing of the support structure, we designed an element with a basic, "L" shaped cross section. Since the support structure was intended to be a generic size that could apply to several different reflector diameters, we designed the support structure to follow the profile of reflector shell 175, the middle shell in our five shell pack.

Since the angle variation from shell 173 to shell 177 is small, .03165344° for the parabolic reflectors and .09471087° for the hyperbolic reflectors, the resulting variation in radial position is small. The delta between the position of hyperbolic shell 173 and hyperbolic shell 177 is approximately .35 mm. The angle difference between hyperbolic shell 175 and 173 is .01708678° and the difference between hyperbolic shell 175 and 177 is .0169137°. These angles result in a position delta of .0596441 mm between shells 173 and 175 and .05903995 mm between shells 175 and 177. As the reflector gap between adjacent reflectors in the range of shells 173 to 177 is relatively large, 1.5494709 mm between shells 173 and 174, the position delta between reflectors is not large enough to cause the support structure to interfere with any reflectors. The small gaps created by the position deltas will be filled with epoxy Thus, while a generic support structure size will only be suitable for a small number of reflectors in the portions of the telescope where reflector gaps are in the range of .7 mm, in areas where the gap approaches 2 mm a generic size will apply to a larger number of reflectors.

Figure 28 shows three views of the individual support structure strut we designed based on the profile of shell 175.

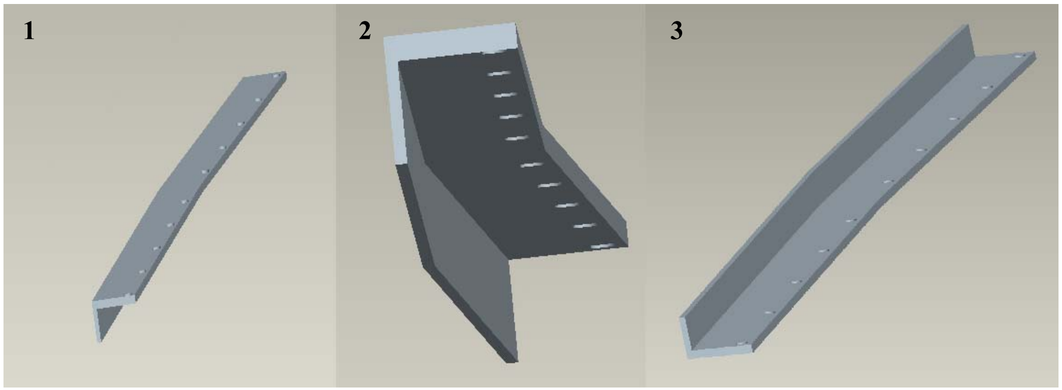

Figure 28 Individual Support Strut Showing Cross Section and P-H Angle

Figure 29 shows the basic cross section of the strut design with the dimensions, in mm.

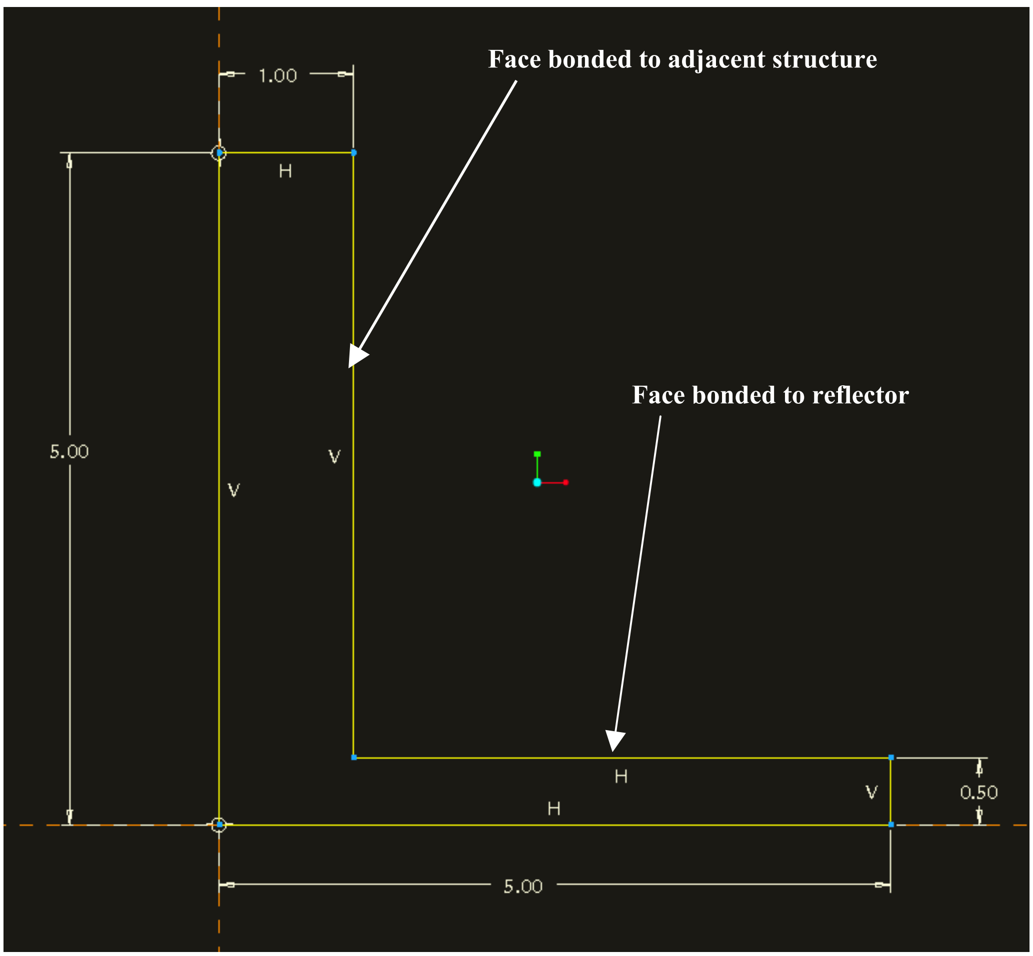

Figure 29 Individual Support Strut Cross Section w/ Dimensions (mm)

Initially our team designed the support strut to be used with a UV cure adhesive. During the strut design process another SXT team member, Thomas Meagher, was testing several UV cure adhesives from Norland Products, specifically Norland 88 and Norland 123. Both of these epoxies are low outgassing, UV cure, single part adhesives. The holes shown in Figure 28 were designed to allow the injection and curing of a UV cure adhesive. Thus, the length of strut where the holes were located needed to be significant enough to allow casting or drilling of holes no less than 2 mm in diameter, the minimum space required for curing the Norland adhesives according to testing by Thomas Meagher.

Our team performed rough calculations, assuming the use of Norland 123, to determine the proper sizing for the support strut. Using strut dimensions as shown in Figure 29, we determined that each reflector would have .001824 m^2 of bonded area between adjacent structure (assuming two struts are bonded to each reflector, one on either side). Assuming a reflector mass of 55.1807 g, equivalent to .541141 N of force, a reflector would exert roughly 296.678 Pa (.043 psi) of force on the adhesive. Norland Products states a tensile strength of 3,000 psi and a modulus of elasticity of 50,000 psi for their 123 adhesive[90], several orders of magnitude greater than the load imposed by a reflector.

The dimensions of the surface bonded to the reflector were determined based on the requirement to have a significant reduction in obscuration as compared to the OAP-2 prototype. Using the dimensions from Figure 29, the support structure for our individual support GRA design will cause 10 mm of obscuration, roughly a 48% reduction in obscuration from 19.05 mm of obscuration caused by the OAP-2 prototype.

Once we had an initial individual structure GRA design modeled in ProEngineer we began work on creating a prototype to test fitment and also to use as a visual demonstration of our GRA design. We initially contacted the composites shop at GSFC to pursue having the support struts machined out of composite. However, we were unable to work out a satisfactory schedule with the composite shop that would allow us to have a complete model by the end of the project period.

Our next contact for creating a prototype model was Applied Rapid Technologies Corporation (ART). ART is a company that specializes in rapid design development, offering rapid prototyping using epoxy resin material. The SXT team had explored using the services of ART in development of the piezo prototype and Jeff Stewart recommended that we contact ART to produce our GRA prototype. We contacted ART initially with our GRA models to determine if their rapid prototyping capabilities were suitable for the tolerances of our GRA models. Our primary concerns were whether or not they would be able to prototype the .44 mm thick reflector models and whether or not they could prototype the 450 mm long support struts in a suitable time frame. ART's website states that their primary rapid prototype envelope is a 10 inch cube (1000 cu. in.), and that they have access to a 9600 cu. in., 20 X 20 X 24 inch prototype envelope. Further, ART specifies a minimum build layer thickness of .006 inches (.1524 mm)[91]. Since our 450 mm struts were larger than the 10 inch cube envelope, we wanted to be sure ART could deliver our struts before the end of the project period. After several communications it was determined that they could prototype our models within our time constraints.

[90] https://www.norlandprod.com/adhesives/NEA%20123.html
[91] http://www.artcorp.com/rapidprototyping.htm

After sending ART the final set of CAD models for the GRA design, we received the rapid prototyped pieces and assembled the GRA model using Norland 88 UV cure epoxy. Figure 30 shows two views of the assembled GRA model. Due to the fact that several of the rapid prototyped reflectors we received from ART were not the correct size the reflector shape is not correct in the assembled model and the model reflectors appear warped. The rapid prototyped model was, however, successful as a visual model in demonstrating the feasibility of our GRA design.

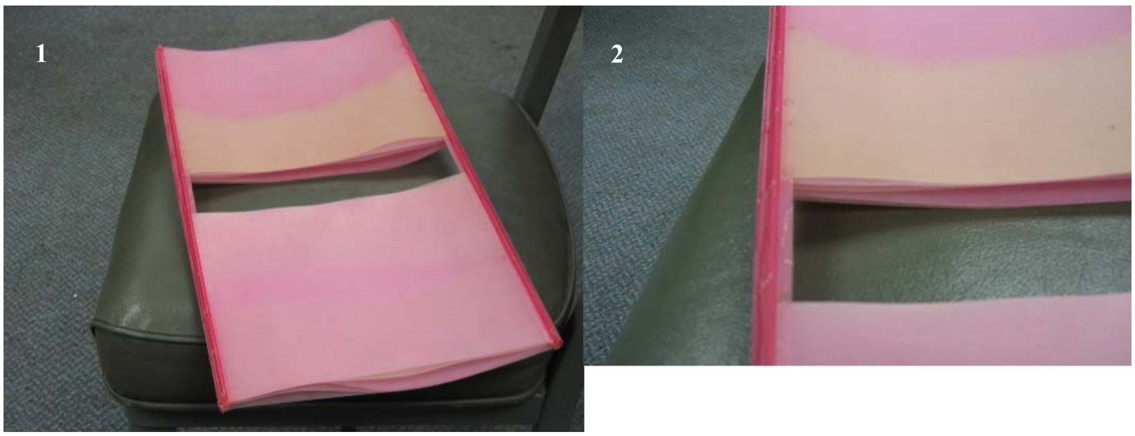

Figure 30 Rapid Prototype GRA Model

While our team was communicating with ART, we also began work on developing the composite support draping that would be bonded to the back surface of a reflector pair while the reflectors were still on the replication mandrel. This composite draping was intended to be an alternative to the bed of nails design, which had encountered funding delays. In meetings with Jeff Stewart it was decided that we wanted to have the option of testing the composite draping using a D263 glass reflector or using an ART rapid prototype reflector.

As the composite draping would have to be created using a reflector mandrel we altered our GRA design to be centered on the reflector prescription that was being used to create D263 test reflectors. This required modeling five new reflector pairs and a new individual support strut. The data we calculated for modeling the five new, final reflector prescriptions is presented in Appendix F.

The final support strut file that was sent to ART for rapid prototyping was also modified to assist in assembly the resin GRA model. Figure 31 shows the assembly alignment step that was added to the support strut file. Since our rapid prototype model will be assembled by hand, Jeff Stewart suggested that we add a step to the support strut to assist in radially spacing reflectors with support struts attached.

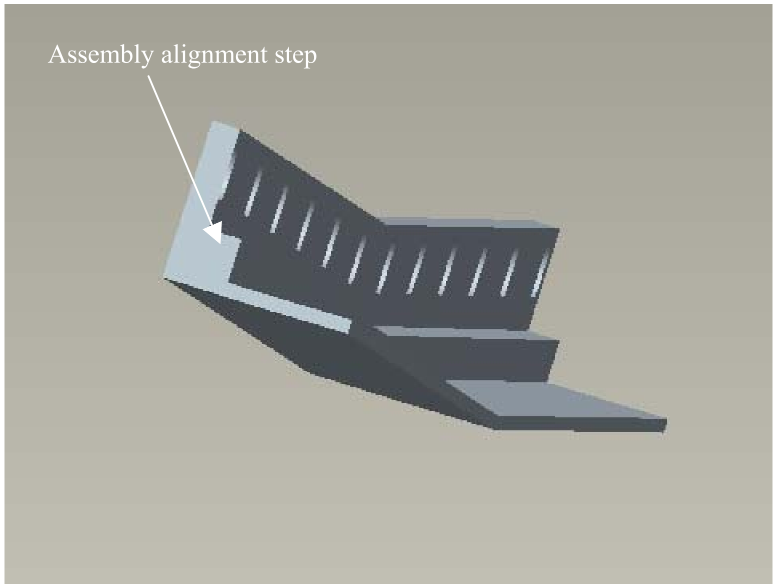

Figure 31 Individual Support Strut Showing Assembly Step

Figure 32 shows the dimensions of the support strut with the assembly alignment step, dimensions are in mm. As the rapid prototype model was designed to be a visual model, the spacing between each reflector will be a fixed value based on the dimension of the alignment step. The dimension of the alignment step was based on extruding a .5125° portion of the total radial 60° of the reflectors plus allowing .017 mm of clearance on all sides for implementing the liquid shim method.

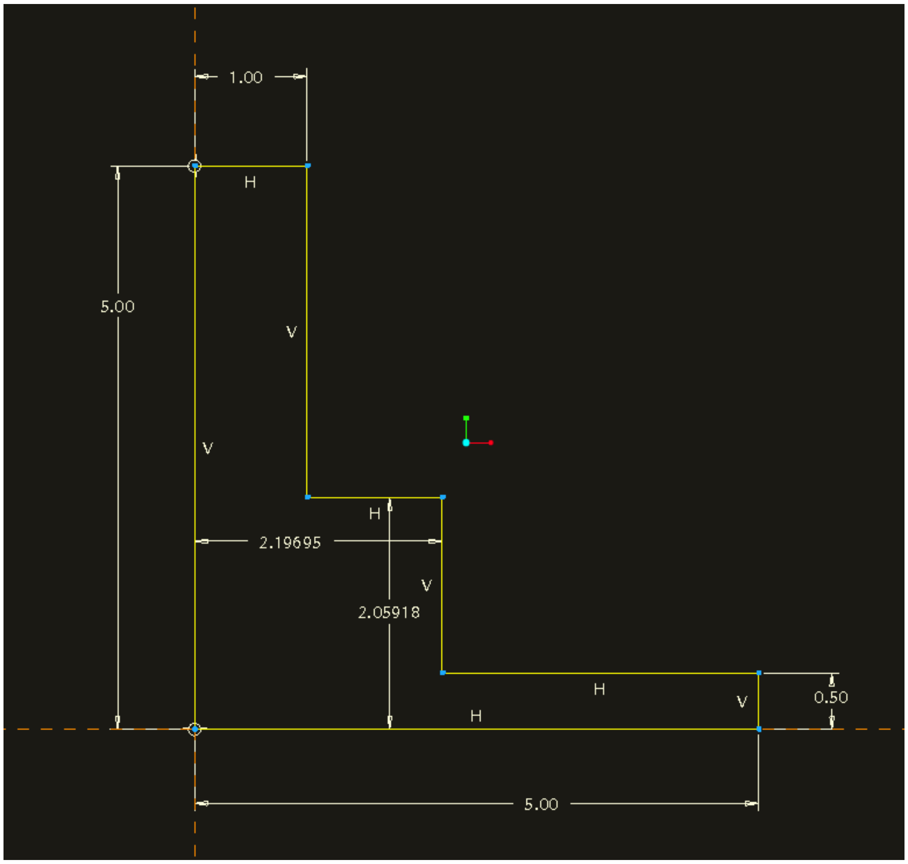

Figure 32 Individual Support Strut Assembly Step Dimension (mm)

After modeling the final set of reflector prescriptions and the modified GRA support strut we delivered the files to ART for prototyping. Figure 33 shows the assembled individual support strut GRA design that was sent to ART, with the strut assembly alignment steps added.

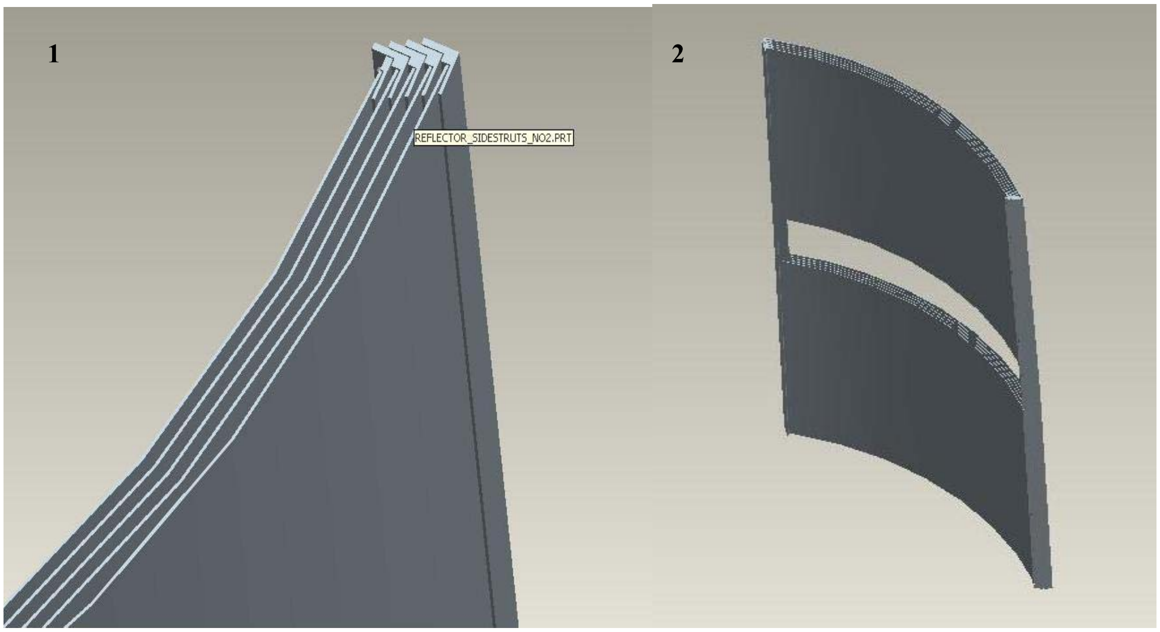

Figure 33 Individual Support Strut GRA Assembly w/ Alignment Step

The final step our team took with the GRA design was to design and model a method of attaching a glass-pack to an outer wagon wheel telescope structure. Although there was no set design or specification for the wagon wheel structure, we received a mockup wagon wheel model from Bobby Nanan to use in developing an attachment method. Figure 34 shows the CAD mockup of the wagon wheel that Bobby Nanan created.

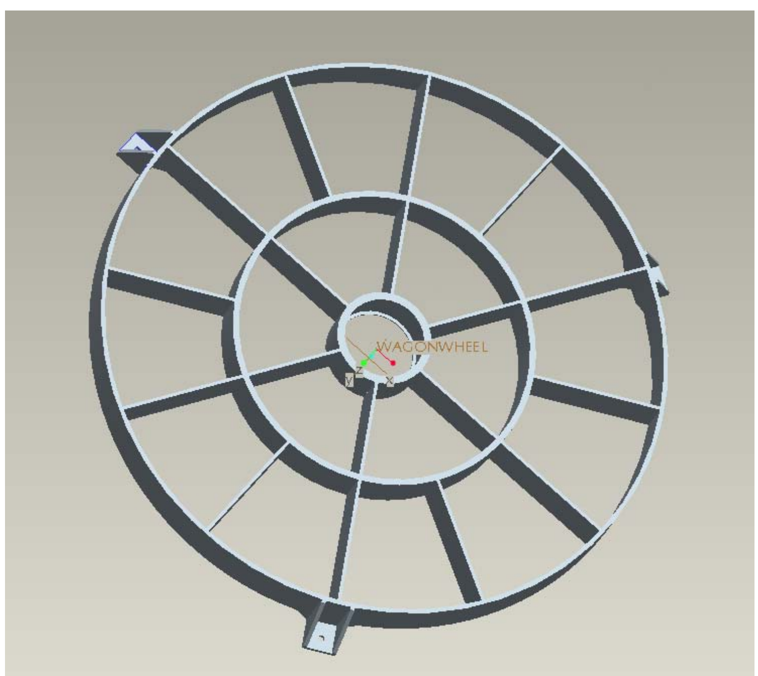

Figure 34 Wagon Wheel Mockup[92]

[92] Model created by: Bobby Nanan

For our mockup GRA mounting struts our team decided to model a strut that would be bonded using an adhesive to the individual support struts in the GRA. Attaching the mounting strut to the GRA support strut allows for the largest bonded area between the mounting struts and the GRA structure without having to attach additional structure to the reflectors. Our team also decided to design the mounting struts to attach to the top face of the wagon wheel ribs using rigid fasteners (such as a screw or bolt). Attaching the mounting struts to the top rib face as opposed to bonding the struts to the inner module faces allows the use of rigid fasteners that would allow an individual glass-pack to be removed from the wagon wheel without having to dissolve an adhesive. Figures 35 and 36 show the top of the mounting strut. Figure 36 shows the adhesive bond profile between the mounting strut and the GRA support struts.

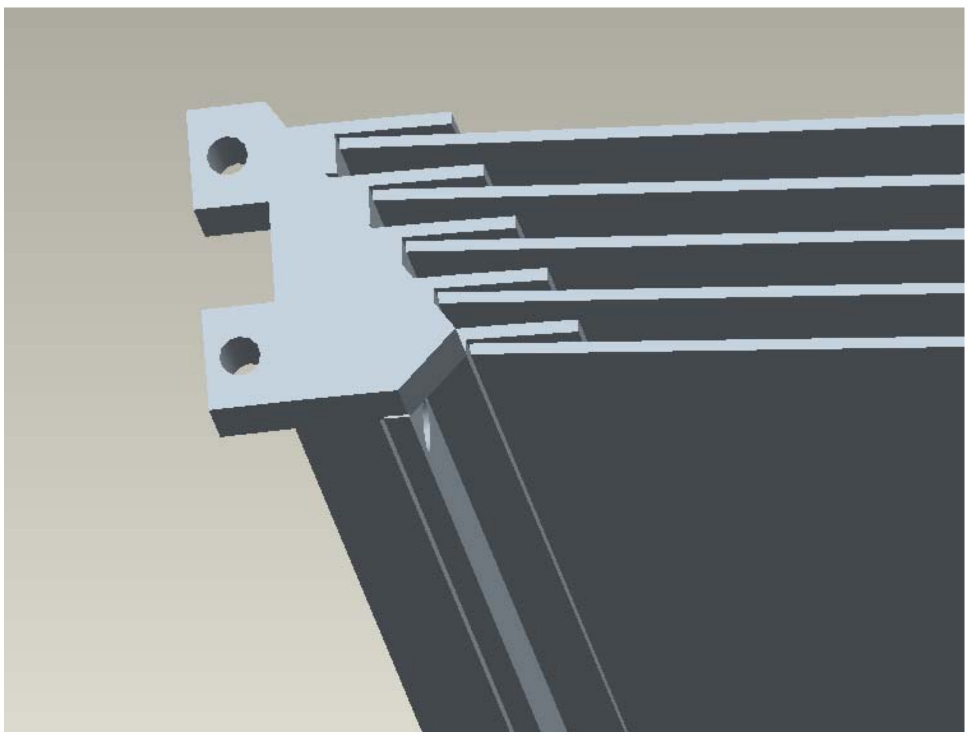

Figure 35 GRA to Wagon Wheel Mounting Strut

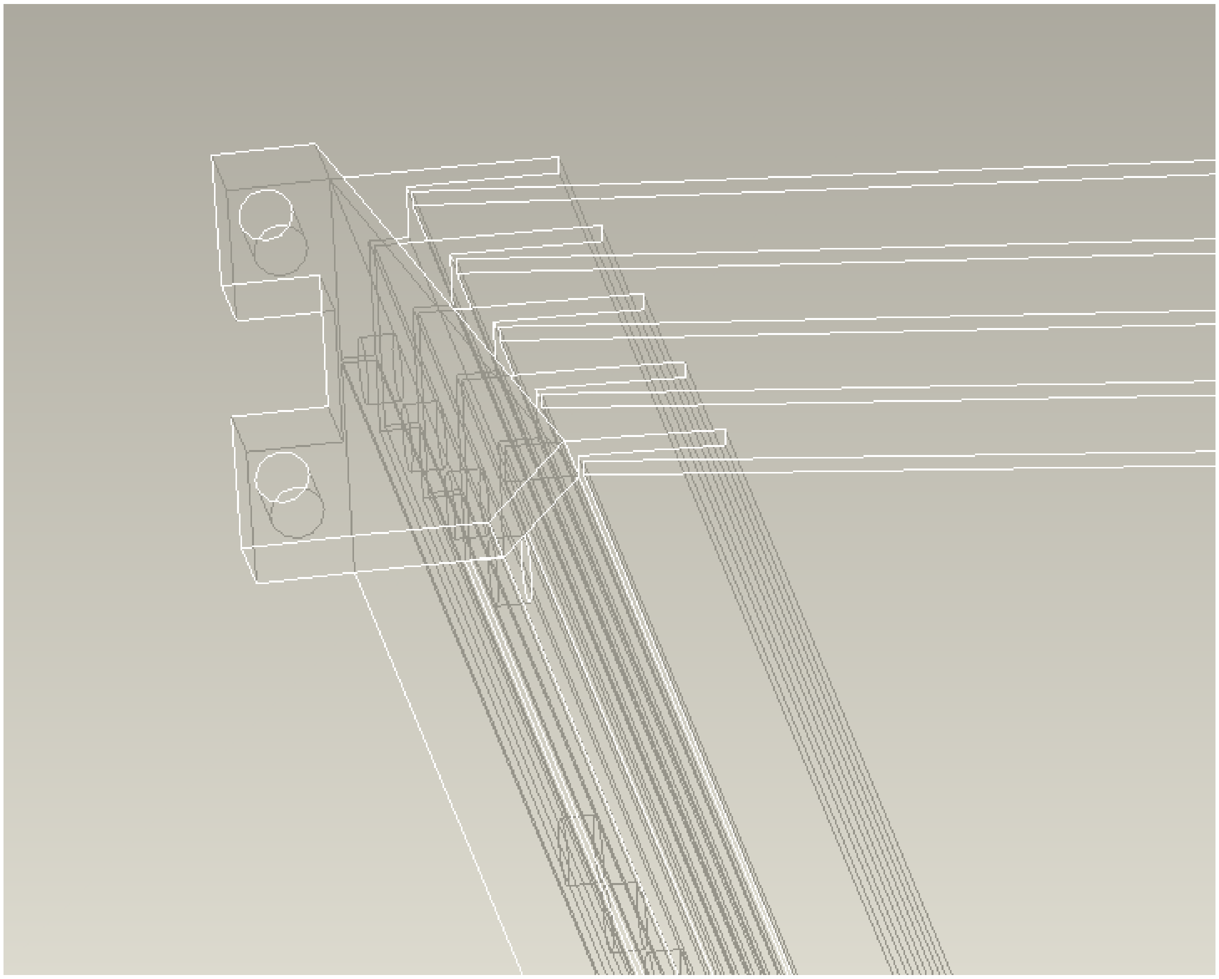

Figure 36 GRA to Wagon Wheel Mounting Strut Showing Step Detail

Because there is no definite wagon wheel design or specification, the GRA to wagon wheel mounting strut design is intended only as a demonstration of a potential method of attaching a glass-pack into the overall SXT structure. Figure 37 shows our GRA model attached to a wagon wheel section using our mounting strut design.

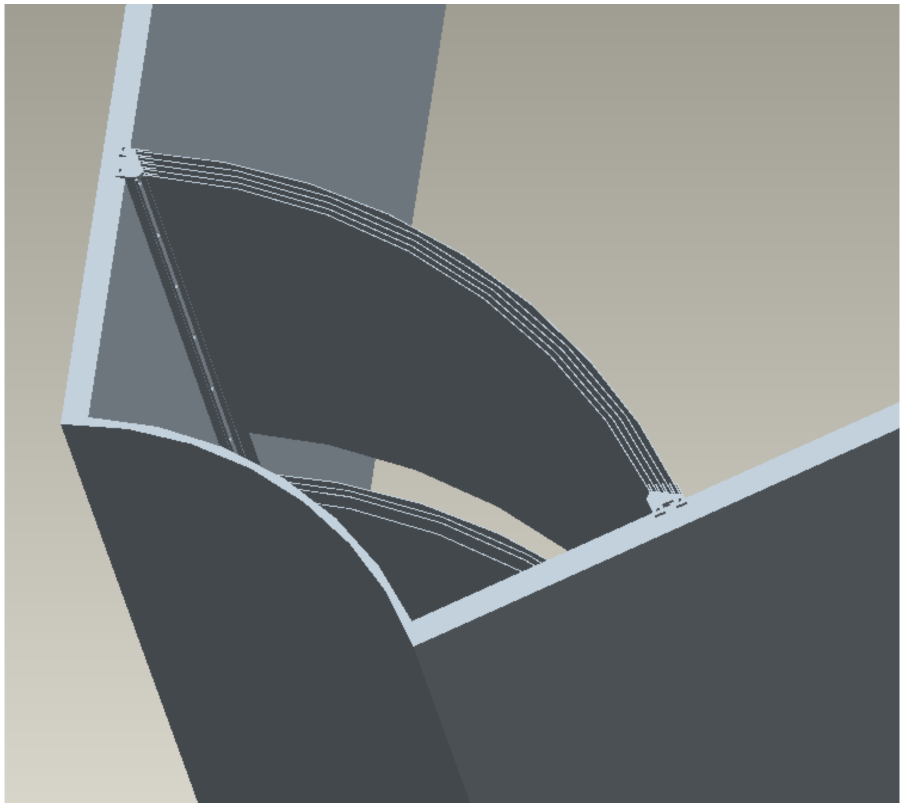

Figure 37 GRA Mounted to Wagon Wheel Section

Due to time constraints our team was unable to pursue the mounting strut design further or to have a prototype piece manufactured.

5.4 Summary

This chapter detailed the work performed by our project team. We researched, designed, and pursued funding for a potential reflector gripping and prescription controlling tool: the bed of nails design. We researched an alternative design to the bed of nails in the form of a composite reflector draping and performed initial support for testing of the composite draping design. Finally, we developed the glass-pack design and the GRA as a method of assembling the SXT using small packs of reflectors.

6 Summary and Conclusions

This chapter presents a summary of the work our team performed at GSFC including how well our team was able to complete our objectives and to meet our goal. The overall goal of our project was to develop new methods of reflector installation in the Constellation-X Spectroscopy X-ray Telescope (SXT). Our team pursued that goal by developing the glass-pack SXT structure and assembly design, by pursuing the bed of nails reflector gripping and prescription control design and the composite reflector support draping design. The purpose of the three major designs our team worked on was to simplify the SXT assembly process, in theory reducing the telescope assembly time.

6.1 Project Summary

To achieve our project goal, our team worked on three different designs: the bed of nails design, the composite reflector support draping, and the glass-pack design. Because each design was in early stages of development at the beginning of our project our team worked primarily on researching and modeling each design. We were unable to perform testing on any of the designs. Each design was presented as a potential component in constructing the SXT.

The bed of nails design was proposed as a vacuum gripping tool to grip SXT reflectors that would also have the capability to control the prescription of a reflector. The bed of nails is intended to be used for removing reflectors from the replication mandrels that form the reflectors while maintaining the prescription of each reflector using piezo actuators with integrated strain gage position sensors. Further, the closed loop piezo actuators are intended to allow precision (nm scale) modification of the reflector prescription.

The gripping component of the bed of nails was specified using vacuum suction cup components from Anver. Using a vacuum suction cup gripping design allows precise control over the total weight capacity of the bed of nails by changing the number and size of the specified suction cups. Further, Anver is able to supply a level compensating suspension for their suction cups. This level compensating suspension, along with using 1.5 bellows design suction cups, will allow the bed of nails to compensate for reflector curvature. Due to the high cost of constructing a bed of nails prototype (~$129,100), work was halted on the bed of nails design to await funding.

Our team then worked to research and develop the composite reflector support draping as an alternative to the bed of nails design. The purpose of the composite draping was to tie each parabolic and hyperbolic reflector pair together while the pair remained on the replication mandrel and to add strength to each reflector. The goal of the composite draping was to maintain the parabolic-hyperbolic (P-H) relationship of each reflector pair and prevent fluctuations in reflector prescription after the reflectors are removed from the replication mandrel. Our team had an aluminum test mandrel machined to use in testing the composite draping. However, due to time constraints and scheduling difficulties with the GSFC composites shop our team was unable to perform testing on the composite draping design.

Our team also researched and developed the glass-pack design and modeled our glass-pack reflector assembly (GRA). The glass-pack design was intended to be an alternative method of constructing and assembling the SXT. The assembly prototype that was being tested during our project called for individual parabolic and hyperbolic reflector module sections to hold large numbers of reflectors (roughly 160 reflectors). The glass-pack design called for small packs of ten to twenty reflector pairs to be installed into a large wagon wheel structure. The purpose of the glass-pack design was to simplify and reduce the time for the reflector alignment process by eliminating the P-H alignment step. Further, the glass-pack design would allow an individual pack to be removed for repair or replacement instead of requiring the removal of a larger reflector module.

Our team's three designs were developed to simplify and reduce the time required for SXT construction primarily through removing reflector alignment steps required for other designs. These designs allowed our team to meet our goal of developing new methods of reflector installation and are intended to meet the goal of the GSFC SXT team of reducing the time required for constructing the SXT.

6.2 Assessment and Future Work

While our team was able to successfully develop and model our designs, the challenging scientific goals set forth for the Constellation-X mission and for the SXT specifically present an array of difficulties in designing and manufacturing the telescope. The primary difficulty is the small size and close proximity of the SXT reflectors that is required to meet throughput and resolution requirements. Also, since the reflectors are so fragile they require a robust support structure. Further, the design of an X-ray telescope requires precisely aligned reflectors. However, the proximity of the reflectors to each other makes the task of designing a structure and outlining an alignment methodology difficult.

Therefore, much of our team's design work was focused on maintaining as much structure strength with as little structure material as possible. We also worked to eliminate as much alignment work as possible to simplify the overall reflector alignment process. We believe our designs were successful in meeting the goals of the project and present feasible methods for constructing the SXT.

Our team's primary recommendation for work should follow is that each design; the bed of nails, the composite draping, and the glass-pack, should be fully prototyped and tested to determine if the designs are fully suitable for implementation into the overall SXT design. Testing will primarily center on the ability of the bed of nails and the composite draping to control reflector shape and on the difficulty of assembling and installing GRA packs.

If funding is secured for the bed of nails, a full bed of nails design would need to be assembled and tested. The main challenge in testing the bed of nails design will be to coordinate the closed loop piezos using the controller hardware to work individually using data input from all of the piezos. Since one of the goals of the bed of nails is to not only maintain but modify the prescription of a reflector, it will need to be determined what portion of a reflector a single piezo effects and what data is required from surrounding piezos.

Testing for the composite draping will primarily involve fabricating a variety of composite layups, either by pre-curing a layup using the test mandrel or by co-curing a layup with reflectors on the test mandrel. Once the composite layups have been created and attached to the reflectors, a precision measuring tool, such as a CMM, could be used to measure the prescription surface of the mandrel and the prescription surface of the reflector pair to determine of the composite draping can maintain the prescription imposed by the test mandrel.

The next major step in testing the glass-pack design will be to do material and manufacturing research to determine a suitable material and manufacturing method for the individual support struts and for the GRA to wagon wheel mounting struts. Once a material has been selected a full size prototype should be fabricated to allow reflector installation and alignment using precision alignment equipment, such as the CDA.

6.3 Conclusions

The three designs for SXT construction pursued by our project team met the project goal outlined at the beginning of the project period. Our team worked primarily to research and model our designs and we were able to overcome difficulties in SXT visualization and data calculation. Further, although we encountered delays in several designs, our team was able work around the delays or to develop or present alternative designs. The primary work that needs to follow from our project is prototyping and testing of our designs.

7 References

Introduction

This chapter presents a complete list of references used for this report, including data files that are used for reference. The list is presented in the order each reference appears in the main text. Each reference number corresponds to the appropriate footnote in the main text.

1. http://astrosun2.astro.cornell.edu/academics/courses//astro201/interferometer.htm
2. http://constellation.gsfc.nasa.gov/
3. http://constellation.gsfc.nasa.gov/
4. http://www.hq.nasa.gov/office/pao/History/factsheet.htm
5. http://www.hq.nasa.gov/office/pao/History/factsheet.htm
6. http://history.nasa.gov/brief.html
7. http://www.hq.nasa.gov/office/pao/History/x1/appendixa1.html
8. http://history.nasa.gov/brief.html
9. http://history.nasa.gov/brief.html
10. http://www.nasa.gov/pdf/55583main_vision_space_exploration2.pdf
11. http://www.gsfc.nasa.gov/about_mission.html#content
12. http://www.gsfc.nasa.gov/indepth/about_facilities.html
13. http://www.gsfc.nasa.gov/mission.html
14. http://eos-chem.gsfc.nasa.gov/
15. http://swift.gsfc.nasa.gov/
16. http://www.gsfc.nasa.gov/GSFCStrategicPlanCharts.pdf
17. http://health.howstuffworks.com/x-ray1.htm
18. http://www.lbl.gov/MicroWorlds/ALSTool/EMSpec/
19. http://www.lbl.gov/MicroWorlds/ALSTool/index.html#electromagspec
20. http://www.lbl.gov/MicroWorlds/ALSTool/EMSpec/EMSpec2.html
21. http://health.howstuffworks.com/x-ray.htm
22. http://imagers.gsfc.nasa.gov/ems/xrays.html
23. http://imagine.gsfc.nasa.gov/docs/science/know_l1/emspectrum.html
24. http://chandra.harvard.edu/xray_astro/history.html
25. http://chandra.harvard.edu/xray_astro/history.html
26. http://chandra.harvard.edu/xray_astro/history.html

27. http://chandra.harvard.edu/xray_astro/history.html
28. http://imagine.gsfc.nasa.gov/docs/science/how_l2/xtelescopes_systems.html
29. http://imagine.gsfc.nasa.gov/docs/science/how_l2/xtelescopes_systems.html
30. http://imagine.gsfc.nasa.gov/docs/science/how_l2/xtelescopes_systems.html
31. *Revealing the Universe*; Wallace and Karen Tucker: Harvard University Press; Cambridge, Massachusetts; London, England 2001 (p.24-26).
32. http://chandra.harvard.edu/xray_astro/history.html
33. http://heasarc.gsfc.nasa.gov/docs/uhuru/uhuru.html
34. http://www.hao.ucar.edu/public/research/mlso/Skylab/sky_about.html
35. http://chandra.harvard.edu/xray_astro/history2.html
36. http://heasarc.gsfc.nasa.gov/docs/einstein/heao2.html
37. http://harris.roe.ac.uk/~jcm/thesis/node41.html
38. http://chandra.harvard.edu/xray_astro/history4.html
39. http://constellation.gsfc.nasa.gov/docs/main.html
40. https://conxproj.gsfc.nasa.gov/
41. http://universe.gsfc.nasa.gov/program/observatories.html
42. http://constellation.gsfc.nasa.gov/docs/science/about.html
43. http://constellation.gsfc.nasa.gov/docs/science/about.html
44. http://universe.gsfc.nasa.gov/program/conx.html
45. http://constellation.gsfc.nasa.gov/docs/science/about.html
46. http://universe.gsfc.nasa.gov/program/conx.html
47. http://www.boeing.com/defense-space/space/delta/delta4/delta4.htm
48. http://www.boeing.com/defense-space/space/delta/history.htm
49. http://www.boeing.com/defense-space/space/delta/docs/Delta_IV_PPG_Update_Revised_Nov_2002.PDF
50. Figure taken from: SXT FMA Industry Pre-Bidders Conference presentation
51. Figure taken from: SXT FMA Industry Pre-Bidders Conference presentation
52. http://www.eriesci.com/custom/d263-tech.aspx
53. Stewart, Jeffrey. Personal interview. 11 August 2004.
54. http://www.electrostatic.com/rosen.htm
55. http://en.wikipedia.org/wiki/Piezoelectricity
56. http://en.wikipedia.org/wiki/Piezoelectricity
57. http://www.e-bastelu.de/index_m.htm
58. http://www.physikinstrumente.de/products/section1/link1.php
59. http://www.mse.cornell.edu/courses/engrill/piezo.htm
60. Stewart, Jeffrey. Personal interview. 10 August 2004.

61. Photo Courtesy of Jeff Stewart
62. Stewart, Jeffrey. Personal interview. 10 August 2004.
63. Stewart, Jeffrey. Personal interview. 16 August 2004.
64. http://www.hoenle.com/pdf/en/UV-Klebstoff_(adhesive)_A4_e.pdf
65. http://www.lakeshore.com/temp/acc/am_epoxypo.html
66. http://www.pgo-online.com/intl/jse/frameroute/genericset.html?Content=/intl/katalog/D263.html
67. http://conxproject.gsfc.nasa.gov/docs/meetings/fstsept02/HXT_RPetre_WZhang_FChristensen.pdf
68. Stewart, Jeffrey. Personal interview. 10 August 2004.
69. Stewart, Jeffrey. Personal interview. 11 August 2004.
70. http://www.opticalfilters.co.uk/products/standardfilters/polycarbonate.htm
71. http://www.geplastics.com/resins/materials/ultem.html
72. http://www.ai.mit.edu/projects/muscle/papers/icim94/paper.html
73. CAD model: Bobby Nanan. Source: *Piezo Plan 4* presentation
74. http://www.piezo.com/appdata.html
75. http://www.piezo.com/motor.html
76. http://www.physikinstrumente.de/products/prdetail.php?secid=1-16
77. http://www.physikinstrumente.de/products/prdetail.php?secid=1-16
78. http://www.anver.com/document/vacuum%20components/vacuum%20cups/B1-5%20Cups/b1_5-11-sit!.htm *and* http://www.anver.com/document/vacuum%20components/vacuum%20cups/B1-5%20Cups/b1_5-5-sit!.htm
79. Wood, Mark. "PI Quotation." E-mail to Devin Brande. 13 Sept., 2004.
80. Laycox, Mark. No Subject. Email to Devin Brande. 13 Sept., 2004.
81. Squires, Janet. "RE: Reflector support thickness." Email to Devin Brande. 22 September 2004.
82. Rodini, Ben. Personal Interview. 23 September 2004.
83. Rodini, Ben. Personal Interview. 23 September 2004.
84. Rodini, Ben. Personal Interview. 23 September 2004.
85. Model from: Piezoplan 4 presentation.
86. Model from: Piezoplan 4 presentation
87. Models created by: Bobby Nanan
88. Models created by: Bobby Nanan
89. "Con-X SXT FMA Requirements Document"
90. https://www.norlandprod.com/adhesives/NEA%20123.html
91. http://www.artcorp.com/rapidprototyping.htm
92. Model created by: Bobby Nanan

Appendix A: Contact Sheet for Overall Constellation-X Team

Introduction

The following table is a contact and information sheet for the majority of persons working on the Constellation-X mission. This table is provided as a reference for anyone wishing to contact a specific member of the Constellation-X project team and as a reference for the scope of the Constellation-X mission in the number of persons working closely with the project.

Constellation-X Team

Last Name	E-mail	Affiliation	Phone	Fax	Technology/Title	Team
Beckman, Mark	Mark.Beckman@nasa.gov	GSFC/Code	301 286-8866	301 286-0369	Flight Dynamics Lead (Observatory)	Observatory
Bolt, Richard	Richard.B.Bolt@nasa.gov	GSFC/Code	301-286-3784		Safety	Observatory
Bookbinder, Jay	jbookbinder@cfa.harvard.edu	SAO	617-495-7058	617-496-7577	Mission Scientist	
Boyd, David	dboyd@cfa.harvard.edu	SAO	617-495-7396	617-495-7098	Thermal/Systems	
Boyle, Rob	Rob.Boyle@nasa.gov	GSFC/Code 552	301 286-7185	301 286-0389	Cryocooler Technology	XMS
Burdine, Robert	Robert.V.Burdine@nasa.gov	MSFC	256-544-4648			SXT
Butterworth, Bruce	Bruce.R.Butterworth@nasa.gov	GSFC/Code 500	301-286-6185		GSFC Review	
Cabrera, Blas	cabrera@leland.stanford.edu	Stanford	650-723-3395	650-725-6544		XMS
Caldwell, David	dcaldwell@cfa.harvard.edu	SAO	617-496-7591	617-497-7708	Optical/Mechanical	
Cash, Webster	Webster.Cash@Colorado.edu	U of Colorado	303-492-4056	303-492-5941	Off-plane grating/Reflector technology	RGS
Chalmers, Rob	Rob.Chalmers@nasa.gov	GSFC/Code 545	301 286-6071	301 286-1704	Con-X Thermal Engineer	Observatory
Chan, Kai-Wing	kwchan@milkyway.gsfc.nasa.gov	GSFC/Code 662	301 286-6238	301 286-1684		SXT
Christensen, Finn	finn@dsri.dk	DSRI	3532 5734	3536 2475	Astrophysics	Science
Cohen, Lester	lcohen@cfa.harvard.edu	SAO	617-495-7368	617-496-7708	Optics	SXT
Content, Dave	David.A.Content@nasa.gov	GSFC/Code 551	301-286-7382	301-286-0204	Optics, Gratings	SXT
Craig, William	craig1@llnl.gov	LLNL				HXT
Davis, William	wdavis@cfa.harvard.edu	SAO	617-496-7990x157	617-496-7708	Optics	SXT
Deere, Kay	kdeere@pop400.gsfc.nasa.gov	CSC/GSFC Code 494	301-286-2655	301-286-4940	Con-X Project Support	Project
DiMenco, Paul	Paul.A.Deminco@nasa.gov	GSFC/Code 101	301 286-0840	301-286-0329	SEU Program Integration Manager	
Doty, John	jpdoty@mit.edu	MIT			CCD Technology	RGS
Edmond, Jerry	Jerry.P.Edmond@nasa.gov	GSFC/Code 210.Y	301-286-8772	301-286-0530	Contracts	
Egle, Wilhelm	egle@zeiss.de	Zeiss			Manager of Mandrel Effort for Zeiss	SXT
Engelhaupt, Darrell	engelhd@email.uah.edu					
Farley, Rodger	Rodger.E.Farley@nasa.gov	GSFC/Code 543	301 286-2252	301 286-1658	GSFC Mechanical Engineer	
Figueroa, Enectali	Enectali.Figueroa-1@nasa.gov	GSFC/Code 662	301 286-1249	301-286-1684	Laboratory for High Energy Physics	SXT
Flanagan, Kathy	kaf@space.mit.edu	MIT	617-258-7324	781-910-1320	RGS IPT Lead	RGS
Freeman, Mark	mfreeman@cfa.harvard.edu	SAO	617-495-7106	617-495-7098	Thermal Systems Engineer	
Friedrich, Stephan	stephan@pts.llnl.gov	LLNL				XMS

Gadwal, Govind	Govind.R.Gadwal.1@gsfc.nasa.gov	GSFC/Code 594	301-286-6511	301-286-4940	Technology Systems Engineer	Observatory
Garcia, Mike	garcia@cfa.harvard.edu	SAO	617-495-7169	617-495-7356	SAO Science Lead	
Geary, John	jgeary@cfa.harvard.edu	SAO	617-495-7431			
Geithner, Paul	paul.geithner@nasa.gov	NASA HQ/Code S	202 358-4422	202 358-3096	Beyond Einstein Program Executive	
Glenn, Paul	paul@bauerinc.com	Bauer, Inc.	781-235-8775 x172			SXT
Gorenstein, Paul	pgorenstein@cfa.harvard.edu	SAO	617-495-7250	617-495-7356		SXT
Grady, Jean	Jean.F.Grady@nasa.gov	GSFC/Code 494	301-286-9345	301-286-4940	Project Manager	Management
Harms, Richard	harms@rjhsci.com					
Harrison, Fiona	fiona@srl.caltech.edu	CalTech	626-395-6601	626-449-8676	Hard X-ray Telescope IPT Lead	HXT
Heilmann, Ralf	ralf@space.mit.edu	MIT				SXT
Henderson, Stephen	henderson@milkyway.gsfc.nasa.gov	GSFC/Code 662	301 286-9471		USRA scientist in code 660	
Hertz, Paul	Paul.L.Hertz@nasa.gov	NASA HQ/Code S	202 358-0986	202 358-3096	SEU Theme Director	
Hilton, Gene	hiltong@boulder.nist.gov	NIST				
Hinkle, Ken	Raymond.K.Hinkle@nasa.gov	GSFC/Code 540	301 286-5051	301-286-1717	GSFC Review	Observatory
Houghton, Martin	Martin.Houghton@nasa.gov	GSFC/Code 571	301 286-0694	301 286-1718		SXT
Irwin, Kent	irwin@boulder.nist.gov	NIST				
Johnson, W. Neil	johnson@osse.nrl.navy.mil	NRL	202-767-6817	202-767-6473	Silicon Strip Detector Lead	
Jones, William	William.D.Jones@nasa.gov	MSFC	256-544-3479	256-544-2659		SXT
Kahn, Steve	skahn@astro.columbia.edu	Columbia University	212-854-3099	212-854-8121	RGS IPT Lead	RGS
Kaluzienski, Lou	louis.j.kaluzienski@nasa.gov	NASA HQ/Code S	202-358-0365	202-358-3096	Discipline Sci High Engy Astrops	
Katz, Charles	ckatz@pop700.gsfc.nasa.gov	GSFC (Retired)	301-286-2791	301-286-1766	Instrument Systems	SXT
Kelley, Richard	Richard.L.Kelley@nasa.gov	GSFC	301-286-7266	301-286-1684	X-Ray Calorimeter IPT Lead	XMS
Kilbourne, Caroline	Caroline.A.Kilbourne@nasa.gov	GSFC/Code 662	301-286-2469	301-286-1684	GSFC Microcalorimeter Lead	XMS
Kim, Charles	Charles.K.Kim@nasa.gov	GSFC/Code 542	301-286-8893	301 286-0204	S/C Subsystem (Mechanical)	Observatory
Kirchman, Frank	Frank.J.Kirchman@nasa.gov	GSFC/Code 556	301-286-1218	301 286-1348	GSFC Review	Observatory
Kolodziejczak, Jeff	Jeffery.Kolodziejczak-1@nasa.gov	MSFC/SD31	256-961-7775	256-961-7215	MSFC's Lead Test Scientist	SXT
Kraft, Ralph	rkraft@cfa.harvard.edu	SAO	617-496-7709			SXT
Lecha, Maria	Maria.C.Lecha@nasa.gov	GSFC/Code 567	301 286-9276	301 286-1750	S/C Subsystem (Communications)	Observatory
Lehan, John	lehan@lheapop.gsfc.nasa.gov	GSFC/Code 662	301-286-0671	301-286-1215	Research Scientist - X-ray Telescopes	SXT
Lewis, Jon	Jon.M.Lewis@nasa.gov	GSFC/Code 574	301-286-2200	301 286-1719	S/C Subsystem (Propulsion)	Observatory
Liu, Jane	Jane.L.Liu@nasa.gov	GSFC/Code 490	301-286-2468	301 286-4940	Business Manager	Project
Luers, Phil	Philip.J.Luers@nasa.gov	GSFC/Code 490	301-286-5777	301-286-1765	S/C Subystem (C&DH)	Observatory
Marshall, Frank	Francis.E.Marshall@nasa.gov	GSFC/Code 662	301-286-5279	301-286-1684	Science Team	
McCracken, Jeff	Jeff.E.Mccracken@nasa.gov	MSFC	256 961-4473	256-544-2367	Lead Test Engineer	SXT
Meyers, Gary	Gary.F.Meyers@nasa.gov	GSFC/Code 581	301-286-5840	301-286-5719	S/C Subsystem (Ground Operations)	Observatory
Nanan, Bobby	bnanan@pop700.gsfc.nasa.gov	GSFC/Code 543	301 286-6802	301 286-1658		SXT
Nguyen, Diep	Diep.T.Nguyen-1@nasa.gov	GSFC/Code 556	301-286-1410	301-286-4940	SXT Instrument Manager	SXT
Niemeyer, Lee	William.L.Niemeyer@nasa.gov	GSFC/Code 547	301 286-5251	301-286-1649	GSFC Review	Observatory
Odell, Curtis	Curtis.E.Odell@nasa.gov	GSFC/Code 663	301-286-4479	301-286-1684		SXT
O'Dell, Steve	Stephen.L.Odell@nasa.gov	MSFC/SD50	256-961-7776	256-961-7215	Optics	SXT
Osterman, Steve	osterman@origins.colorado.edu	U of Colorads				
Owens, Scott	Scott.M.Owens@nasa.gov	GSFC/Code 551	301-286-1592			SXT

Petre, Robert	Robert.Petre-1@nasa.gov	GSFC/Code 662	301-286-3844	301-286-1684	Mission Scientist/SXT IPT Lead	SXT
Pilar, Joy	Pilar.Joy@nasa.gov	GSFC/Code 541	301 286-8622	301 286-1646		SXT
Podgorski, William	wpodgorski@cfa.harvard.edu	SAO	617-495-7363	617-496-7708	Technology Systems Engineer	SXT
Porter, Scott	Frederick.S.Porter@nasa.gov	GSFC/Code 662	301-286-1684	301 286-5016		SXT
Ramsey, Brian	Brian.D.Ramsey@nasa.gov	MSFC	256 961-7784	256-544-7754		SXT
Randy McEntaffer	randy@bogart.colorado.edu	U of Colorado				
Rasche, Robert (Mon&Wed)	rrasche@cfa.harvard.edu	SAO	617-496-7774	617-495-7040	Technology Development Leader	Management
Rasche, Robert (Tues&Thurs)	rrasche@maine.rr.com	Home office (Wells, ME)	207-641-2212	207-641-2217		
Rasmussen, Andy	arasmus@astro.columbia.edu	Columbia University	212-854-8126			RGS
Reid, Paul B.	preid@cfa.harvard.edu	SAO	617-495-7233	301-286-1600	SAO Optics Lead	SXT
Reynolds, Chris	chris@astro.umd.edu	University of MD				
Ricker, George	grr@space.mit.edu	MIT			RFC	RGS
Romaine, Susan	sromaine@cfa.harvard.edu.	SAO				
Ryschkewitsch, Michael	Michael.G.Ryschkewitsch@nasa.gov	GSFC/Code 500	301-286-6422		GSFC Review	Observatory
Saha, Timo	Timo.T.Saha@nasa.gov	GSFC/Code 551	301-286-2863	301 286-0204		SXT
Savage, Robert	Robert.M.Savage@nasa.gov	GSFC/Code 502	301-286-1849	301-286-4940	Constellation-X Technology Manager	Management
Schattenburg, Mark	marks@space.mit.edu	MIT	617-253-3180		RGA	RGS
Shipley, Ann	Ann.Shipley@colorado.edu	U of Colorado	303-492-1875		Off-plane grating/Reflector technology	RGS
Shirron, Peter	Peter.J.Shirron@nasa.gov	GSFC/Code 552	301 286-7327	301 286-0389	ADR IPT Lead	ADR/XMS
Silver, Eric	esilver@cfa.harvard.edu	SAO	617-496-7858	617-496-7577	NTD/Ge Technology	XMS
Smith, Scott	W.S.Smith@nasa.gov	MSFC	256 544-5175			
Soong, Yang	soong@lheavx.gsfc.nasa.gov	GSFC/Code 660	301-286-6318	301 286-1684		SXT
Spitzer, Thomas	Thomas.J.Spitzer@nasa.gov	GSFC/Code 563	301-286-4383	301-286-1751	Power	XMS
Stewart, Jeffrey	Jeffrey.W.Stewart@nasa.gov	GSFC/Code 543	301-286-3218	301 286-0241	Extendible Optical Bench	SXT
Tananbaum, Harvey	ht@cfa.harvard.edu	SAO	617-495-7248	617-495-7356	Facility Science Team Chair	Management
Thienel, Julie						
Ulmer, Melville P.	m-ulmer2@nwu.edu	Northwestern U	847-491-5633	847-491-3135	Hard X-ray Optics	HXT
Wainio, Lisa	lisa.a.wainio@nasa.gov	NASA HQ/Code SZ	202 358-0995	202 358-3096	Constellation-X Program Executive	
Weaver, Kim	Kimberly.A.Weaver@nasa.gov	GSFC/Code 662	301-286-4256	301-286-1684	Dep Proj Scientist/Mission Science Coord	Science
Weisskopf, Martin	Martin.C.Weisskopf@nasa.gov	MSFC	256 544-7740	256-544-7754		
Whitaker, Ann	Ann.F.Whitaker@nasa.gov	MSFC	256 544-2481	256-544-5877		
White, Nicholas	Nicholas.E.White@nasa.gov	GSFC/Code 660	301-286-8443	301-286-0250	Project Scientist	Science
Whitehouse, Paul	Paul.L.Whitehouse@nasa.gov	GSFC/Code 490	301-286-8378	301-286-0389	Cryocooler IPT	Cryocooler/XMS
Woodhall, Clyde	Clyde.H.Woodall@nasa.gov	GSFC/Code 420	301-286-7114	301 286-0232	Launch Vehicle Interface	Observatory
Zhang, William	William.W.Zhang@nasa.gov	GSFC/Code 662	301-286-6230	301-286-1684		SXT

Appendix B: Bed of Nails IRAD Proposal

Introduction

This document is the complete bed of nails IRAD proposal as written by Andrew Carlson and submitted to the NASA GSFC IRAD review panel for FY05 funding. This document represents the final stage of development for the bed of nails design that was reached by the 2004 WPI project team.

Goddard Space Flight Center
FY05 IRAD Proposal
Advanced Telescopes and Interferometric Systems
Bed of Nails Technique for Precision Alignment of Optics

Wolter type x-ray telescopes require demanding tolerances in the alignment of parabolic and hyperbolic x-ray reflecting optics. One of the major challenges facing the scientific and engineering communities is finding a material that will meet smoothness, figure, and strength requirements. NASA scientists see gold-coated thin glass as the only feasible material to complete x-ray missions in conception. This decision poses a serious tradeoff with glass strength. The NASA Constellation X SXT Mechanical Systems Engineering Team developed a three-step technique to structurally reinforce the glass optics, align them in a structural housing, and then bond them in place with minimal movement due to epoxy shrinkage. The x-ray reflecting optic is in its most perfect shape while on the replication mandrel; this is where thin composite sheets with ribbing will be attached to the backs of the primary and secondary reflectors. This process will take place in an oven under vacuum. In addition to structurally reinforcing the glass to survive launch loads, this process simultaneously aligns and constrains the primary reflector to the secondary reflector thus sparing an additional and potentially costly alignment step. The second step is to remove the reinforced reflectors from the mandrel using a bed of nails technique. This system will consist of many suction cups, position sensors, and actuators that attach themselves to the back (non-pristine) side of the reflector and measure its shape. The bed of nails will further ensure the reflectors maintain their shape off of the mandrel until they are aligned within the structural housing. Any deviation in shape due to lifting the reflectors off of the mandrel will be corrected with the bed of nails actuators. Coupled with the bed of nails will be a hexapod to nano-position the reflectors into the structural housing. The last step of the three-step process will be the bonding of the reflectors into the structure using an ultraviolet curing system. The advantages of this system are quick cure time, favorable mechanical properties of the adhesive and minimal out-gassing of the epoxy. The future of x-ray telescopes lies in the ability to precisely align and launch systems with large collecting areas. The Constellation X mission consists of over 16,000 x-ray reflectors that must be aligned to within submicron tolerances. Not only is this three-step process feasible, but its success may prove revolutionary in the telescope community. The three-step process will significantly decrease production time and also focuses on the reusability of alignment hardware, which will reduce costs. In addition to saving money, the structural reinforcement will improve mission reliability and feasibility. The skills and knowledge learned by building and testing the three-step alignment process will be invaluable to future x-ray missions posed by NASA and other space agencies.

Principal Investigator

Name: **Josh Schneider**

Organization: NASA-GSFC-543

Telephone: (301) 286-4070

E-mail: jschneider@mscmail.gsfc.nasa.gov

☐ **GSFC "New Innovator" Candidate**
Check here if PI has less than five year's professional experience

Division/Laboratory Chief Concurrence

Name: **Jeffrey W. Stewart, Dr. William W. Zhang, and Timo Saha**

Organization: 543, 662, and 551

Signature:

Technical Objectives and Approach

Technical Objectives

1. Provide NASA projects with the technology and processes required for the precision alignment of x-ray reflecting optics.
2. Work to eliminate the tradeoff between precision, smoothness, and figure with strength and mass by incorporating composite reinforcements.
3. Progress the alignment system into an assembly line scenario using robots already available to the engineering team in a closed loop environment.
4. Develop an alignment system that will significantly reduce production time and costs while increasing mission reliability.
5. Develop industry partners that will continue to improve the capabilities of precision alignment techniques, so that spacecraft systems may also progress.

Approach

1. Utilize available precision mandrels of Zerodur.
2. Design and machine a laminate of composite material to sufficiently drape over the existing shape on the back (non-pristine) side of the reflectors when they are on the mandrel, in conjunction with strips (ribs) as structural reinforcement.
3. Complete finite element modeling of the interface between the composite, adhesive, and glass.
4. Test the attachment of composite materials and ribs to the x-ray reflectors in an oven under vacuum.
5. Design and build the bed of nails alignment system, which will also incorporate closed loop feedback and control.
6. Integrate the bed of nails alignment system to a hexapod and test by lifting a reflector off of the mandrel and aligning it within a structural housing.
7. Bond the reflector into the housing using a UV curing system coupled with a ST Robotics R17 robot already available to the team.
8. Test the alignment, bonding, and integration of multiple primary and secondary x-ray reflector pairs.

Justification & Benefits – What future missions, opportunities will be enabled?

Reducing the volatility of the precision, smoothness, and figure tradeoff with mass and strength is of great interest over a vast range of programs. This technology would be most helpful to those attempting to design, build, and launch x-ray telescopes. Solving challenges currently posed by the scientific and engineering community involves taking a systems perspective and looking at the entire alignment process from reflector replication to bonding. Success will prove revolutionary to world of cutting edge telescopes. By taking a process oriented view, production time and costs will also be reduced, which is of the greatest importance in an era where science missions have suffered sever budget cuts. The lessons learned regarding the use of composites, adhesives, glass and other materials will prove useful across many engineering disciplines.

Budget-

	Engineering And Labor	Tooling and Fixturing
Design and machine composite reinforcements	$5,000.00	$5,000.00
Design and machine bed of nails aluminum frame		$100.00
Develop software to link UV cure system to robot	$8,000.00	
Bed of nails suction cups and supporting hardware		$1,200
20 P841.60 piezo actuators		$44,500.00
4 E500.00 Controller Chassis		$9,100.00
7 E503.00 Amplifier Module		$15,500.00
7 E509.S3 Controller Module		$18,300.00
E 516.i3 Display/interface module		$3,100.00
UV Cure System		$7,300.00
Test active alignment system	$5,000	
Disseminate findings throughout NASA, academia and scientific publications		$7,000
Total (Non-Civil Service):		**$129,100**
Civil Service Management		0.3
Civil Service Fabrication of the composite		0.1
Civil Service Software		0.15
Civil Service Fabrication of the Bed of Nails		0.2
Civil Service Integration		0.2
Full Time Equivalent		0.95
Grand Total:		**$129,100**

Technical Equipment Requirements and Dependencies-

All additional equipment not available to the investigator is listed in the budget section. The Zerodur mandrels of 662 and the ST Robotics R17 of 543 will be available for use.

Appendix C: Constellation-X SXT Design Data

Introduction and Abstract

This document, written by Timo Saha, is provided as one of the two primary documents that our team used for reflector geometry and generating reflector CAD models. This document contains the complete SXT optical geometry data as of 21 May 2002. Further, the document provides information regarding the calculations used for the design of a Wolter Type I telescope and insight regarding the scope and magnitude of the SXT design. The full text of this document can be found in the file *CSX_SXT_designs_200_and_300.doc* on the project CD.

May 21, 2002

TO: SAO/Bob Rasche
FROM: 551/Timo Saha

SUBJECT: CSX/STX telescope design data for 200 mm and 300 mm long mirrors

This memo describes the updated telescope designs for the Constellation-X/SXT project. The most important change is to limit the mirror axial length to a range from 200 mm to 300 mm. The design data are listed in Tables 1 and 2 and the on-axis effective area in the SXT energy range is plotted in Figure 1 and listed in Tables 3 and 4.

Appendix D: Constellation-X Design Parameters and Data

Introduction and Abstract

This document is an SXT optical data write-up by GSFC engineer Timo Saha and serves as a complement to Appendix C. This document is an optical design data sheet created prior to the document in Appendix C. It presents data for a limited selection of reflectors, including data related to the replication mandrel used for creating the test reflectors our designs were based on (shell number 3). This document, in conjunction with Appendix C, served as the basis for many of our reflector geometry calculations. The full text for this document can be found in the file *CSX_eng_mdl_design4.doc* on the project CD.

October 26, 2001

TO:CSX team
FROM: /551Timo Saha

Subject: Design Parameters and Data for Constellation-X Engineering Model Telescope (version 4)

This memo describes the changes we have made in the engineering model telescope design for Constellation-X. The design data and parameters of the version 4 design are listed in the Tables 1, 2, 3, and 4.

Appendix E: Reflector Data for Shells 167→178

Introduction

This appendix presents the data that our team calculated regarding reflectors 167 through 178 (refer to Appendix C for baseline geometry data). The purpose of the data was to serve in modeling GRA components and to assist in generating our own reflector CAD models.

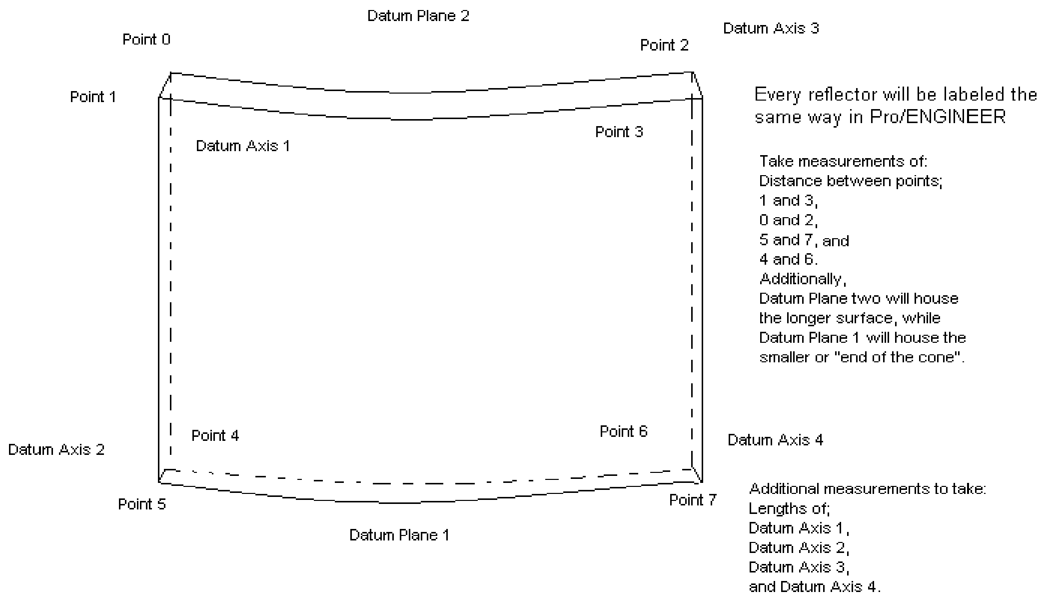

Figure 1 Reflector Dimension Naming Scheme

Figure 1 is a copy of Figure 25 from Section 5.2. Figure 1 outlines the reflector points and datums that were used in measuring each reflector. Tables 4 and 5 present the data and calculations we collected for each reflector shell that served to define the reflector shape for modeling.

Mirror	Dist Pt 0 to 2 (mm)	Dist Pt 1 to 3 (mm)	Dist Pt 4 to 6 (mm)	Dist Pt 5 to 7 (mm)	Length of mirrors (mm)	Avg diff btw Pts 0 to 2 & Pts 4 to 6 (mm)	Avg diff btw Pts 1 to 3 & Pts 5 to 7 (mm)	Angle btw Pts 0 to 2 & Pts 4 to 6 (deg)	Angle btw Pts 1 to 3 & Pts 5 to 7 (deg)
	Parabolic or Primary Mirror Measurements and Calculations								
No. 167	241.125	241.566	239.820	240.261	200.000	0.653	0.653	0.186928	0.186928
No. 168	239.056	239.497	237.761	238.202	200.000	0.648	0.648	0.185495	0.185495
No. 169	236.998	237.438	235.713	236.154	200.000	0.642	0.642	0.184063	0.183920
No. 170	234.950	235.390	233.675	234.116	200.000	0.637	0.637	0.182631	0.182487
No. 171	232.912	233.353	231.647	232.088	200.000	0.633	0.633	0.181198	0.181198
No. 172	230.885	231.326	229.630	230.071	200.000	0.627	0.627	0.179766	0.179766
No. 173	228.868	229.308	227.623	228.063	200.000	0.623	0.623	0.178333	0.178333
No. 174	226.861	227.302	225.626	226.066	200.000	0.617	0.618	0.176901	0.177044
No. 175	224.864	225.305	223.639	224.080	200.000	0.612	0.612	0.175469	0.175469
No. 176	222.877	223.318	221.662	222.103	200.000	0.608	0.608	0.174036	0.174036
No. 177	220.901	221.342	219.695	220.136	200.000	0.603	0.603	0.172747	0.172747
No. 178	218.934	219.375	217.739	218.179	200.000	0.597	0.598	0.171171	0.171315

Table 4 Reflector Data for Parabolic Shells 167→178

Parabolic or Primary Mirror Measurements and Calculations

Mirror	Length of Axis 1 (mm)	Length of Axis 2 (mm)	Length of Axis 3 (mm)	Length of Axis 4 (mm)	Width of Epoxy Layer (mm)	Length of Epoxy Layer (mm)	Depth of Epoxy Layer (mm)	Overlap width of Epoxy layer on Axis 1 (mm)	Overlap width of Epoxy layer on Axis 2 (mm)	Overlap width of Epoxy layer on Axis 3 (mm)	Overlap width of Epoxy layer on Axis 4 (mm)
No. 167	0.440534	0.440502	0.440865	0.440918	0.60	200.000	0.20	0.079733	0.079749	0.079568	0.079541
No. 168	0.440541	0.440510	0.440869	0.440921	0.60	200.000	0.20	0.079730	0.079745	0.079566	0.079540
No. 169	0.440549	0.440518	0.440873	0.440925	0.60	200.000	0.20	0.079726	0.079741	0.079564	0.079538
No. 170	0.440557	0.440526	0.440877	0.440929	0.60	200.000	0.20	0.079722	0.079737	0.079562	0.079536
No. 171	0.440565	0.440535	0.440882	0.440933	0.60	200.000	0.20	0.079718	0.079733	0.079559	0.079534
No. 172	0.441204	0.440543	0.440447	0.441193	0.60	200.000	0.20	0.079398	0.079729	0.079777	0.079404
No. 173	0.441121	0.440552	0.440205	0.440783	0.60	200.000	0.20	0.079440	0.079724	0.079898	0.079609
No. 174	0.441124	0.440561	0.440218	0.440789	0.60	200.000	0.20	0.079438	0.079720	0.079891	0.079606
No. 175	0.441127	0.440570	0.440231	0.440796	0.60	200.000	0.20	0.079437	0.079715	0.079885	0.079602
No. 176	0.441130	0.440579	0.440244	0.440803	0.60	200.000	0.20	0.079435	0.079711	0.079878	0.079599
No. 177	0.441133	0.440589	0.440257	0.440810	0.60	200.000	0.20	0.079434	0.079706	0.079872	0.079595
No. 178	0.441137	0.440598	0.440270	0.440817	0.60	200.000	0.20	0.079432	0.079701	0.079865	0.079592

Table 5 Reflector Epoxy Data for Parabolic Shells 167→178

Hyperbolic or Secondary Mirror Measurements and Calculations

Mirror	Dist Pt 0 to 2 (mm)	Dist Pt 1 to 3 (mm)	Dist Pt 4 to 6 (mm)	Dist Pt 5 to 7 (mm)	Length of mirrors (mm)	Avg diff btw Pts 0 to 2 & Pts 4 to 6 (mm)	Avg diff btw Pts 1 to 3 & Pts 5 to 7 (mm)	Angle btw Pts 0 to 2 & Pts 4 to 6 (deg)	Angle btw Pts 1 to 3 & Pts 5 to 7 (deg)
No. 167	239.167	239.607	235.234	235.675	200.000	1.967	1.966	0.563370	0.563227
No. 168	237.113	237.554	233.211	233.652	200.000	1.951	1.951	0.558929	0.558929
No. 169	235.070	235.510	231.199	231.640	200.000	1.935	1.935	0.554489	0.554345
No. 170	233.037	233.478	229.196	229.637	200.000	1.921	1.921	0.550191	0.550191
No. 171	231.015	231.455	227.204	227.645	200.000	1.905	1.905	0.545894	0.545751
No. 172	229.002	229.443	225.222	225.663	200.000	1.890	1.890	0.541453	0.541453
No. 173	227.000	227.441	223.250	223.690	200.000	1.875	1.876	0.537156	0.537299
No. 174	225.008	225.449	221.288	221.728	200.000	1.860	1.861	0.532858	0.533002
No. 175	223.026	223.467	219.336	219.776	200.000	1.845	1.846	0.528561	0.528704
No. 176	221.054	221.495	217.393	217.834	200.000	1.831	1.831	0.524407	0.524407
No. 177	219.092	219.533	215.902	215.461	200.000	1.595	2.036	0.456939	0.583281
No. 178	217.140	217.580	213.538	213.979	200.000	1.801	1.801	0.515955	0.515812

Table 6 Reflector Data for Hyperbolic Shells 167→178

Hyperbolic or Secondary Mirror Measurements and Calculations

Mirror	Length of Axis 1 (mm)	Length of Axis 2 (mm)	Length of Axis 3 (mm)	Length of Axis 4 (mm)	Width of Epoxy Layer (mm)	Length of Epoxy Layer (mm)	Depth of Epoxy Layer (mm)	Overlap width of Epoxy layer on Axis 1 (mm)	Overlap width of Epoxy layer on Axis 2 (mm)	Overlap width of Epoxy layer on Axis 3 (mm)	Overlap width of Epoxy layer on Axis 4 (mm)
No. 167	0.440541	0.440520	0.440869	0.440926	0.60	200.000	0.20	0.079730	0.079740	0.079566	0.079537
No. 168	0.440548	0.440528	0.440873	0.440930	0.60	200.000	0.20	0.079726	0.079736	0.079564	0.079535
No. 169	0.440556	0.440536	0.440877	0.441192	0.60	200.000	0.20	0.079722	0.079732	0.079562	0.079404
No. 170	0.440564	0.440545	0.440881	0.440777	0.60	200.000	0.20	0.079718	0.079728	0.079560	0.079612
No. 171	0.441203	0.440554	0.440446	0.440784	0.60	200.000	0.20	0.079399	0.079723	0.079777	0.079608
No. 172	0.441121	0.440563	0.440205	0.440790	0.60	200.000	0.20	0.079440	0.079719	0.079898	0.079605
No. 173	0.441123	0.440572	0.440217	0.440797	0.60	200.000	0.20	0.079439	0.079714	0.079892	0.079602
No. 174	0.441126	0.440581	0.440230	0.440804	0.60	200.000	0.20	0.079437	0.079710	0.079885	0.079598
No. 175	0.441129	0.440590	0.440243	0.440811	0.60	200.000	0.20	0.079436	0.079705	0.079879	0.079595
No. 176	0.441133	0.440600	0.440256	0.440819	0.60	200.000	0.20	0.079434	0.079700	0.079872	0.079591
No. 177	0.441136	0.440610	0.440269	0.441585	0.60	200.000	0.20	0.079432	0.079695	0.079866	0.079208
No. 178	0.441140	0.440620	0.440282	0.441341	0.60	200.000	0.20	0.079430	0.079690	0.079859	0.079330

Table 7 Reflector Epoxy Data for Hyperbolic Shells 167→178

Mirror	Primary Front (dm) Distance from the Optical Axis	Primary Back (dm) Distance from the Optical Axis	Thickness (mm)	Distance between Front and Back (dm)	Distance between Front and Back (mm)	Distance between Front and Back without the thickness (mm)
No. 167	2.6307289679	2.6176921670	0.441291	0.0130368009	1.30368009	0.86238909
No. 168	2.6100624851	2.5971280558	0.440495	0.0129344293	1.29344293	0.85294793
No. 169	2.5895011284	2.5766685509	0.440504	0.0128325775	1.28325775	0.84275375
No. 170	2.5690443615	2.5563131188	0.440512	0.0127312427	1.27312427	0.83261227
No. 171	2.5486916510	2.5360612286	0.440520	0.0126304224	1.26304224	0.82252224
No. 172	2.5284424663	2.5159123523	0.440529	0.0125301140	1.25301140	0.81248240
No. 173	2.5082962794	2.4958659645	0.440538	0.0124303149	1.24303149	0.80249349
No. 174	2.4882525651	2.4759215427	0.440547	0.0123310224	1.23310224	0.79255524
No. 175	2.4683108009	2.4560785668	0.440556	0.0122322341	1.22322341	0.78266741
No. 176	2.4484704670	2.4363365196	0.440565	0.0121339474	1.21339474	0.77282974
No. 177	2.4287310462	2.4166948865	0.440575	0.0120361597	1.20361597	0.76304097
No. 178	2.4090920240	2.3971531554	0.440585	0.0119388686	1.19388686	0.75330186

Table 8 Reflector Shell Angle Data for Parabolic Reflectors (1 of 2)

Length of mirrors (mm)	Primary Front Distance from the Optical Axis (mm)	Distance between Front and Back with the thickness (mm)	Distance between Front and Back with the thickness divided by the length (mm)	Angle of the Primary Mirror (Alpha) from the Optical Axis (radians)	Angle of the Primary Mirror (appr. Alpha) from the Optical Axis (degrees)
200.000	263.07289679	1.74497109	0.00872486	0.00872463	0.49988471
200.000	261.00624851	1.73393793	0.00866969	0.00866947	0.49672418
200.000	258.95011284	1.72376175	0.00861881	0.00861860	0.49380914
200.000	256.90443615	1.71363627	0.00856818	0.00856797	0.49090862
200.000	254.86916510	1.70356224	0.00851781	0.00851761	0.48802283
200.000	252.84424663	1.69354040	0.00846770	0.00846750	0.48515199
200.000	250.82962794	1.68356949	0.00841785	0.00841765	0.48229574
200.000	248.82525651	1.67364924	0.00836825	0.00836805	0.47945400
200.000	246.83108009	1.66377941	0.00831890	0.00831871	0.47662670
200.000	244.84704670	1.65395974	0.00826980	0.00826961	0.47381376
200.000	242.87310462	1.64419097	0.00822095	0.00822077	0.47101541
200.000	240.90920240	1.63447186	0.00817236	0.00817218	0.46823127

Table 9 Reflector Shell Angle Data for Parabolic Reflectors (2 of 2)

Mirror	Secondary Front (dm) Distance from the Optical Axis	Secondary Back (dm) Distance from the Optical Axis	Thickness (mm)	Distance between Front and Back (dm)	Distance between Front and Back (mm)	Distance between Front and Back without the thickness (mm)
No. 167	2.6111659637	2.5718875589	0.440419	0.0392784048	3.92784048	3.48742148
No. 168	2.5906531082	2.5516832066	0.440428	0.0389699016	3.89699016	3.45656216
No. 169	2.5702445985	2.5315816323	0.440438	0.0386629662	3.86629662	3.42585862
No. 170	2.5499399025	2.5115823117	0.440448	0.0383575908	3.83575908	3.39531108
No. 171	2.5297384907	2.4916847233	0.440457	0.0380537674	3.80537674	3.36491974
No. 172	2.5096398363	2.4718883483	0.440467	0.0377514880	3.77514880	3.33468180
No. 173	2.4896434152	2.4521926703	0.440477	0.0374507449	3.74507449	3.30459749
No. 174	2.4697487062	2.4325971760	0.440487	0.0371515302	3.71515302	3.27466602
No. 175	2.4499551906	2.4131013544	0.440498	0.0368538362	3.68538362	3.24488562
No. 176	2.4302623523	2.3937046973	0.440508	0.0365576550	3.65576550	3.21525750
No. 177	2.4106696781	2.3744066989	0.440519	0.0362629792	3.62629792	3.18577892
No. 178	2.3911766572	2.3552068563	0.440530	0.0359698009	3.59698009	3.15645009

Table 10 Reflector Shell Angle Data for Hyperbolic Reflectors (1 of 2)

Length of mirrors (mm)	Secondary Front Distance from the Optical Axis (mm)	Distance between Front and Back with the thickness (mm)	Distance between Front and Back with the thickness divided by the length (mm)	Angle of the Secondary Mirror (Alpha) from the Optical Axis (radians)	Angle of the Secondary Mirror (appr. 3 Alpha) from the Optical Axis (degrees)
200.000	261.11659637	4.36825948	0.02184130	0.02183783	1.25121522
200.000	259.06531082	4.33741816	0.02168709	0.02168369	1.24238402
200.000	257.02445985	4.30673462	0.02153367	0.02153035	1.23359794
200.000	254.99399025	4.27620708	0.02138104	0.02137778	1.22485647
200.000	252.97384907	4.24583374	0.02122917	0.02122598	1.21615909
200.000	250.96398363	4.21561580	0.02107808	0.02107496	1.20750616
200.000	248.96434152	4.18555149	0.02092776	0.02092470	1.19889717
200.000	246.97487062	4.15564002	0.02077820	0.02077521	1.19033189
200.000	244.99551906	4.12588162	0.02062941	0.02062648	1.18181039
200.000	243.02623523	4.09627350	0.02048137	0.02047850	1.17333187
200.000	241.06696781	4.06681692	0.02033408	0.02033128	1.16489669
200.000	239.11766572	4.03751009	0.02018755	0.02018481	1.15650435

Table 11 Reflector Shell Angle Data for Hyperbolic Reflectors (2 of 2)

Appendix F: Reflector Data for Final Design Shells

Introduction

This appendix presents the data that our team used to model the reflectors and GRA support structure designs that were used in the final GRA design. The final reflectors were modeled assuming a constant reflector thickness. The baseline data for the reflector geometry can be found in Appendix D.

Measurements for the 5 Mirrors

Shell Number	Primary Front	Primary Center	Primary Back	Primary-Secondary Intercept	Secondary Front	Secondary Center	Secondary Back
	(mm)	(mm)	(mm)	(mm)	(mm)	(mm)	(mm)
1	242.11876275	241.40686927	240.69287024	240.50688300	239.99151151	237.84279077	235.69186734
2	244.33441856	243.61601380	242.89548424	242.70779600	242.18770931	240.01933008	237.84872801
3	246.56361670	245.83866096	245.11156106	244.92216200	244.39733075	242.20917301	240.01877215
4	248.80644023	248.07489356	247.34118325	247.15006200	246.62045817	244.41240116	242.20208063
5	251.06297269	250.32479490	249.58443387	249.39158000	248.85717439	246.62909661	244.39873478

Shell Number	Circumference Primary Front	Circumference Primary Center	Circumference Primary Back	Circumference Primary-Secondary Intercept	Circumference Secondary Front	Circumference Secondary Center	Circumference Secondary Back
	(mm)	(mm)	(mm)	(mm)	(mm)	(mm)	(mm)
1	1521.27705270	1516.80409405	1512.31790583	1511.14931354	1507.91113897	1494.41032838	1480.89567789
2	1535.19842873	1530.68455850	1526.15733776	1524.97805777	1521.71025672	1508.08592820	1494.44763316
3	1549.20489373	1544.64986248	1540.08135907	1538.89132968	1535.59371768	1521.84511712	1508.08242262
4	1563.29696958	1558.70052630	1554.09048846	1552.88963823	1549.56203922	1535.68840786	1521.80055438
5	1577.47518118	1572.83707334	1568.18524779	1566.97351119	1563.61574171	1549.61631614	1535.60253946

Shell Number	59.3 degrees Primary Front	59.3 degrees Primary Center	59.3 degrees Primary Back	59.3 degrees Primary-Secondary Intercept	59.3 degrees Secondary Front	59.3 degrees Secondary Center	59.3 degrees Secondary Back
	(mm)	(mm)	(mm)	(mm)	(mm)	(mm)	(mm)
1	250.58813674	249.85134105	249.11236616	248.91987304	248.38647372	246.16259020	243.93642694
2	252.88129673	252.13776200	251.39202814	251.19777452	250.65949506	248.41526539	246.16873513
3	255.18847277	254.43815790	253.68562387	253.48959958	252.94640961	250.68170957	248.41468795
4	257.50975082	256.75261447	255.99323879	255.79543207	255.24730257	252.96200718	250.67436910
5	259.84521734	259.08121791	258.31495887	258.11535893	257.56225968	255.25624319	252.94786275

Table 12 Final Reflector Data Calculations (1 of 6)

Shell Number	1.1 degrees Primary Front	1.1 degrees Primary Center	1.1 degrees Primary Back	1.1 degrees Primary-Secondary Intercept	1.1 degrees Secondary Front	1.1 degrees Secondary Center	1.1 degrees Secondary Back
	(mm)	(mm)	(mm)	(mm)	(mm)	(mm)	(mm)
1	4.64834655	4.63467918	4.62097138	4.61740068	4.60750626	4.56625378	4.52495902
2	4.69088409	4.67709171	4.66325853	4.65965518	4.64967023	4.60804034	4.56636777
3	4.73368162	4.71976347	4.70580415	4.70216795	4.69209192	4.65008230	4.60802962
4	4.77674074	4.76269605	4.74860983	4.74494056	4.73477290	4.69238125	4.64994614
5	4.82006305	4.80589106	4.79167715	4.78797462	4.77771477	4.73493874	4.69211887

With Uniform Thickness at .44 mm, The Points at the Back of the Reflector From the Optical Axis

Shell Number	Primary Front	Primary Center	Primary Back	Primary-Secondary Intercept	Secondary Front	Secondary Center	Secondary Back
	(mm)	(mm)	(mm)	(mm)	(mm)	(mm)	(mm)
1	241.67876275	240.96686927	240.25287024	240.06688300	239.55151151	237.40279077	235.25186734
2	243.89441856	243.17601380	242.45548424	242.26779600	241.74770931	239.57933008	237.40872801
3	246.12361670	245.39866096	244.67156106	244.48216200	243.95733075	241.76917301	239.57877215
4	248.36644023	247.63489356	246.90118325	246.71006200	246.18045817	243.97240116	241.76208063
5	250.62297269	249.88479490	249.14443387	248.95158000	248.41717439	246.18909661	243.95873478

With Uniform Thickness at .5 mm, The Points at the Back of the Side Struts and Composite Rib

Shell Number	Primary Front	Primary Center	Primary Back	Primary-Secondary Intercept	Secondary Front	Secondary Center	Secondary Back
	(mm)	(mm)	(mm)	(mm)	(mm)	(mm)	(mm)
1	242.17876275	241.46686927	240.75287024	240.56688300	240.05151151	237.90279077	235.75186734
2	244.39441856	243.67601380	242.95548424	242.76779600	242.24770931	240.07933008	237.90872801
3	246.62361670	245.89866096	245.17156106	244.98216200	244.45733075	242.26917301	240.07877215
4	248.86644023	248.13489356	247.40118325	247.21006200	246.68045817	244.47240116	242.26208063
5	251.12297269	250.38479490	249.64443387	249.45158000	248.91717439	246.68909661	244.45873478

Table 13 Final Reflector Data Calculations (2 of 6)

Measurements for the 5 Mirrors

With the Length of the Composite Outer Struts at 5 mm, the Distance from the Optical Axis

Shell Number	Primary Front	Primary Center	Primary Back	Primary-Secondary Intercept	Secondary Front	Secondary Center	Secondary Back
	(mm)	(mm)	(mm)	(mm)	(mm)	(mm)	(mm)
1	236.67876275	235.96686927	235.25287024	235.06688300	234.55151151	232.40279077	230.25186734
2	238.89441856	238.17601380	237.45548424	237.26779600	236.74770931	234.57933008	232.40872801
3	241.12361670	240.39866096	239.67156106	239.48216200	238.95733075	236.76917301	234.57877215
4	243.36644023	242.63489356	241.90118325	241.71006200	241.18045817	238.97240116	236.76208063
5	245.62297269	244.88479490	244.14443387	243.95158000	243.41717439	241.18909661	238.95873478

Shell Number	Circumference Primary Front	Circumference Primary Center	Circumference Primary Back	Circumference Primary-Secondary Intercept	Circumference Secondary Front	Circumference Secondary Center	Circumference Secondary Back
	(mm)	(mm)	(mm)	(mm)	(mm)	(mm)	(mm)
1	1487.09652463	1482.62356598	1478.13737776	1476.96878547	1473.73061090	1460.22980031	1446.71514982
2	1501.01790066	1496.50403043	1491.97680969	1490.79752969	1487.52972865	1473.90540013	1460.26710509
3	1515.02436566	1510.46933441	1505.90083100	1504.71080161	1501.41318961	1487.66458905	1473.90189455
4	1529.11644151	1524.51999823	1519.90996039	1518.70911016	1515.38151115	1501.50787979	1487.62002631
5	1543.29465311	1538.65654527	1534.00471972	1532.79298312	1529.43521364	1515.43578807	1501.42201139

Table 14 Final Reflector Data Calculations (3 of 6)

Difference in the Circumferences of the Front of the Struts to the Front of the Mirrors

Shell Number	Primary Front	Primary Center	Primary Back	Primary-Secondary Intercept	Secondary Front	Secondary Center	Secondary Back
	(mm)	(mm)	(mm)	(mm)	(mm)	(mm)	(mm)
1	34.18052807	34.18052807	34.18052807	34.18052807	34.18052807	34.18052807	34.18052807
2	34.18052807	34.18052807	34.18052807	34.18052807	34.18052807	34.18052807	34.18052807
3	34.18052807	34.18052807	34.18052807	34.18052807	34.18052807	34.18052807	34.18052807
4	34.18052807	34.18052807	34.18052807	34.18052807	34.18052807	34.18052807	34.18052807
5	34.18052807	34.18052807	34.18052807	34.18052807	34.18052807	34.18052807	34.18052807

Shell Number	59.3 degrees	59.3 degrees	59.3 degrees	59.3 degrees	59.3 degrees	59.3 degrees	59.3 degrees
	Primary Front	Primary Center	Primary Back	Primary-Secondary Intercept	Secondary Front	Secondary Center	Secondary Back
	(mm)	(mm)	(mm)	(mm)	(mm)	(mm)	(mm)
1	244.95784420	244.22104851	243.48207361	243.28958050	242.75618118	240.53229766	238.30613440
2	247.25100419	246.50746946	245.76173560	245.56748197	245.02920252	242.78497285	240.53844259
3	249.55818023	248.80786536	248.05533133	247.85930704	247.31611707	245.05141703	242.78439541
4	251.87945828	251.12232193	250.36294625	250.16513953	249.61701003	247.33171464	245.04407656
5	254.21492480	253.45092537	252.68466633	252.48506639	251.93196714	249.62595065	247.31757021

Shell Number	1.1 degrees	1.1 degrees	1.1 degrees	1.1 degrees	1.1 degrees	1.1 degrees	1.1 degrees
	Primary Front	Primary Center	Primary Back	Primary-Secondary Intercept	Secondary Front	Secondary Center	Secondary Back
	(mm)	(mm)	(mm)	(mm)	(mm)	(mm)	(mm)
1	4.54390605	4.53023867	4.51653088	4.51296018	4.50306576	4.46181328	4.42051851
2	4.58644359	4.57265120	4.55881803	4.55521467	4.54522973	4.50359983	4.46192727
3	4.62924112	4.61532297	4.60136365	4.59772745	4.58765141	4.54564180	4.50358912
4	4.67230024	4.65825555	4.64416932	4.64050006	4.63033240	4.58794074	4.54550564
5	4.71562255	4.70145055	4.68723664	4.68353412	4.67327426	4.63049824	4.58767837

Table 15 Final Reflector Data Calculations (4 of 6)

Shell Number	Primary Front	Primary Center	Primary Back	Primary-Secondary Intercept	Secondary Front	Secondary Center	Secondary Back
	Measurements for the 5 Mirrors						
	(mm)	(mm)	(mm)	(mm)	(mm)	(mm)	(mm)
1	242.11876275	241.40686927	240.69287024	240.50688300	239.99151151	237.84279077	235.69186734
2	244.33441856	243.61601380	242.89548424	242.70779600	242.18770931	240.01933008	237.84872801
3	246.56361670	245.83866096	245.11156106	244.92216200	244.39733075	242.20917301	240.01877215
4	248.80644023	248.07489356	247.34118325	247.15006200	246.62045817	244.41240116	242.20208063
5	251.06297269	250.32479490	249.58443387	249.39158000	248.85717439	246.62909661	244.39873478
Gap							
1 and 2	1.77565581	1.76914453	1.76261400	1.76091300	1.75619780	1.73653931	1.71686067
2 and 3	1.78919814	1.78264716	1.77607682	1.77436600	1.76962144	1.74984293	1.73004414
3 and 4	1.80282353	1.79623260	1.78962219	1.78790000	1.78312742	1.76322815	1.74330848
4 and 5	1.81653246	1.80990134	1.80325062	1.80151800	1.79671622	1.77669545	1.75665415
Gap - 0.5							
1 and 2	1.27565581	1.26914453	1.26261400	1.26091300	1.25619780	1.23653931	1.21686067
2 and 3	1.28919814	1.28264716	1.27607682	1.27436600	1.26962144	1.24984293	1.23004414
3 and 4	1.30282353	1.29623260	1.28962219	1.28790000	1.28312742	1.26322815	1.24330848
4 and 5	1.31653246	1.30990134	1.30325062	1.30151800	1.29671622	1.27669545	1.25665415
Clearance							
1 and 2	243.05876275	242.34686927	241.63287024	241.44688300	240.93151151	238.78279077	236.63186734
2 and 3	245.27441856	244.55601380	243.83548424	243.64779600	243.12770931	240.95933008	238.78872801
3 and 4	247.50361670	246.77866096	246.05156106	245.86216200	245.33733075	243.14917301	240.95877215
4 and 5	249.74644023	249.01489356	248.28118325	248.09006200	247.56045817	245.35240116	243.14208063

Table 16 Final Reflector Data Calculations (5 of 6)

Clearance + 0.17							
1 and 2	243.22876275	242.51686927	241.80287024	241.61688300	241.10151151	238.95279077	236.80186734
2 and 3	245.44441856	244.72601380	244.00548424	243.81779600	243.29770931	241.12933008	238.95872801
3 and 4	247.67361670	246.94866096	246.22156106	246.03216200	245.50733075	243.31917301	241.12877215
4 and 5	249.91644023	249.18489356	248.45118325	248.26006200	247.73045817	245.52240116	243.31208063
Location + 1.28							
1	243.39876275	242.68686927	241.97287024	241.78688300	241.27151151	239.12279077	236.97186734
2	245.61441856	244.89601380	244.17548424	243.98779600	243.46770931	241.29933008	239.12872801
3	247.84361670	247.11866096	246.39156106	246.20216200	245.67733075	243.48917301	241.29877215
4	250.08644023	249.35489356	248.62118325	248.43006200	247.90045817	245.69240116	243.48208063
Location + 0.78							
1	242.89876275	242.18686927	241.47287024	241.28688300	240.77151151	238.62279077	236.47186734
2	245.11441856	244.39601380	243.67548424	243.48779600	242.96770931	240.79933008	238.62872801
3	247.34361670	246.61866096	245.89156106	245.70216200	245.17733075	242.98917301	240.79877215
4	249.58644023	248.85489356	248.12118325	247.93006200	247.40045817	245.19240116	242.98208063
Location + 1.78							
1	243.89876275	243.18686927	242.47287024	242.28688300	241.77151151	239.62279077	237.47186734
2	246.11441856	245.39601380	244.67548424	244.48779600	243.96770931	241.79933008	239.62872801
3	248.34361670	247.61866096	246.89156106	246.70216200	246.17733075	243.98917301	241.79877215
4	250.58644023	249.85489356	249.12118325	248.93006200	248.40045817	246.19240116	243.98208063
5	252.84297269	252.10479490	251.36443387	251.17158000	250.63717439	248.40909661	246.17873478
Location + 0.61							
1	242.72876275	242.01686927	241.30287024	241.11688300	240.60151151	238.45279077	236.30186734
2	244.94441856	244.22601380	243.50548424	243.31779600	242.79770931	240.62933008	238.45872801
3	247.17361670	246.44866096	245.72156106	245.53216200	245.00733075	242.81917301	240.62877215
4	249.41644023	248.68489356	247.95118325	247.76006200	247.23045817	245.02240116	242.81208063
5	251.67297269	250.93479490	250.19443387	250.00158000	249.46717439	247.23909661	245.00873478
Location + 1.11							
1	243.22876275	242.51686927	241.80287024	241.61688300	241.10151151	238.95279077	236.80186734
2	245.44441856	244.72601380	244.00548424	243.81779600	243.29770931	241.12933008	238.95872801
3	247.67361670	246.94866096	246.22156106	246.03216200	245.50733075	243.31917301	241.12877215
4	249.91644023	249.18489356	248.45118325	248.26006200	247.73045817	245.52240116	243.31208063
5	252.17297269	251.43479490	250.69443387	250.50158000	249.96717439	247.73909661	245.50873478
Location - 4.56							
1	237.55876275	236.84686927	236.13287024	235.94688300	235.43151151	233.28279077	231.13186734
2	239.77441856	239.05601380	238.33548424	238.14779600	237.62770931	235.45933008	233.28872801
3	242.00361670	241.27866096	240.55156106	240.36216200	239.83733075	237.64917301	235.45877215
4	244.24644023	243.51489356	242.78118325	242.59006200	242.06045817	239.85240116	237.64208063
5	246.50297269	245.76479490	245.02443387	244.83158000	244.29717439	242.06909661	239.83873478

Table 17 Final Reflector Data Calculations (6 of 6)

Appendix G: Executive Summary

Introduction

This appendix presents the executive summary of our report to serve as a brief overview and summary of the full report.

Project Code: FJL-CONX

Constellation-X SXT Assembly Design

Executive Summary

A Major Qualifying Project

Submitted to:

The Faculty of Worcester Polytechnic Institute

In partial fulfillment of the requirements for the degree of Bachelor of Science

Project Team:

Devin Brande
branded@wpi.edu

Monika Goodrich
cbwb07@wpi.edu

Michael Planka
mplanka@wpi.edu

Advisors:

Fred Looft, PhD
fjlooft@wpi.edu

Stephen Bitar
sjbitar@wpi.edu

conx04@wpi.edu

Introduction

The Constellation-X mission is a long term NASA project designed to develop, manufacture, and implement a satellite array X-ray telescope. One of the goals of the Constellation-X mission is to allow scientists to continue to study in depth the structure and evolution of the universe (SEU). The science objectives for Constellation-X primarily involve the study of super massive black holes, dark matter, and matter cycling and recycling in the universe[93]. In order to achieve the science objectives for the Constellation-X mission, the Constellation-X telescope has been designed to be roughly 100 times more powerful than any other X-ray telescope[94].

The 2004 WPI Constellation-X project team was assigned to assist the NASA Goddard Space Flight Center (GSFC) team working on the Spectroscopy X-ray Telescope (SXT) portion of the Constellation-X satellites. The WPI project team's work was centered on assisting in development of SXT design and assembly techniques for the roughly 4,000 X-ray reflectors in each of four Constellation-X satellites.

Background

The hardware design for the Constellation-X mission centers on a four satellite orbiting telescope array. The four satellites will operate together, focusing on a single object. To achieve the science goals of the Constellation-X mission, the four satellites combined must have 15,000 cm^2 of on-axis effective area at 1.25 keV, 6,000 cm^2 at 6 keV, and 1,500 cm^2 at 40 keV, with 15 arc sec. angular resolution and >5 arcmin. field of view from 0.25 to 10 keV and 1 arc min. angular resolutions and >8 arcmin. field of view from 10 to 40 keV[95].

To achieve the on-axis effective area, angular resolution, and field of view requirements for the Constellation-X mission, each satellite incorporates several telescope and detector components. Figure 1 shows an individual Constellation-X satellite with the major components labeled.

[93] http://constellation.gsfc.nasa.gov/science/about.html
[94] http://constellation.gsfc.nasa.gov/
[95] SXT FMA Industry Study Pre-Bidders Conference presentation, pp. 33

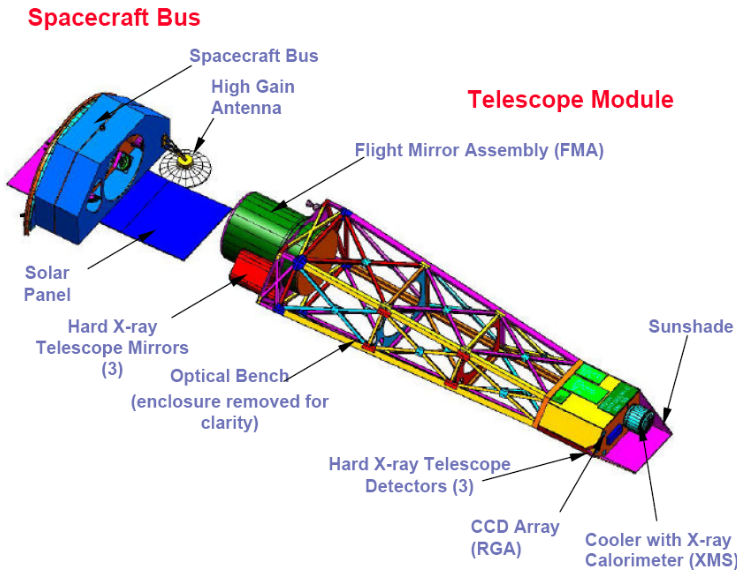

Figure 1 Constellation-X Satellite (exploded view)[96]

The SXT is located in the Flight Mirror Assembly (FMA) portion of each Constellation-X telescope. Figure 2 shows the SXT with several reflector modules exploded. The SXT employs a Wolter Type I telescope design is composed of approximately 4,000 parabolic and hyperbolic reflectors, designed to simulate 230 cylindrical reflectors, installed into a support structure.

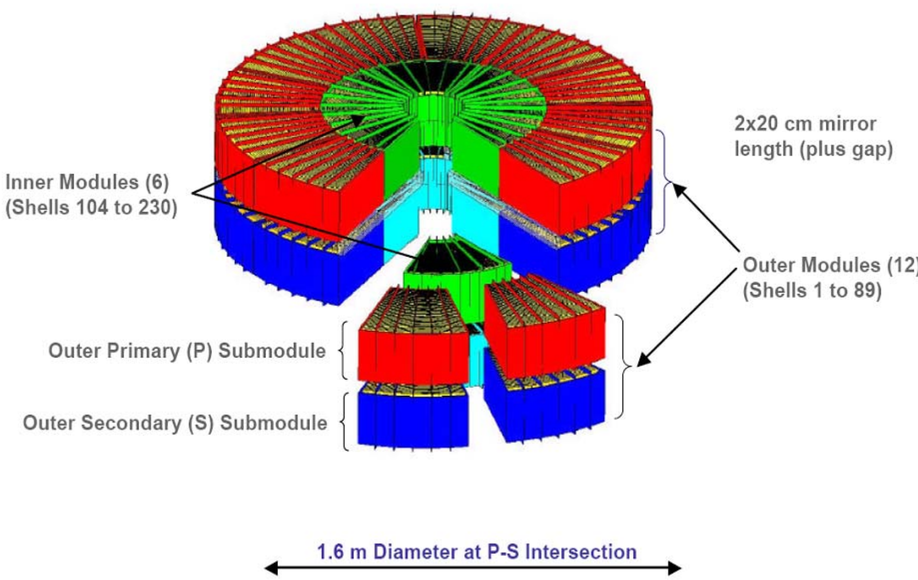

Figure 2 Constellation-X SXT (exploded view)

[96] SXT FMA Industry Study Pre-Bidders Conference presentation, pp. 8

The reflectors in the SXT are constructed using a 0.4 mm D263 glass substrate that is slumped over a replication mandrel that creates the cylindrical reflector shape and the parabolic and hyperbolic reflector prescriptions required for a Wolter Type I design. A 2000 Å thick layer of gold is bonded to the reflector using a 5 to 10 μm thick layer of Epotek 301-2 epoxy during the slumping process. This gold layer serves as the reflecting surface for incoming X-rays.

As of early October 2004 a final design for the SXT had not been decided on. Some of the primary difficulties GSFC engineers were dealing with included: reflector installation, reflector alignment, and reflector bonding. Several functional prototypes have been developed, including the Optical Alignment Pathfinder (OAP) 2 module show in Figure 3.

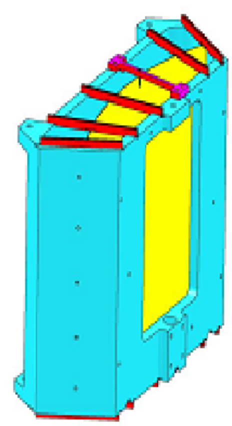

Figure 3 OAP-2 Parabolic Reflector Portion

Project Statement

The goal of the 2004 WPI Constellation-X project was to develop new methods of precision reflector installation in the SXT portion of the Constellation-X satellites. This goal involved developing both telescope structure designs and reflector gripping and alignment designs. Precision installation required sub-micron scale control of reflector prescriptions for alignment and sub-mm scale bonding control.

The objectives for the 2004 project were to:

- Develop a method or tool to grasp reflectors,
- Develop a method or tool that will maintain the integrity of the reflector prescription,
- Pursue the possibility of maintaining the relationship between the parabolic and hyperbolic reflectors that exists on the replication mandrel,
- Develop a method or design that will allow rapid placement and replacement of reflectors.

Methods

In order to develop new SXT structure and reflector gripping designs the 2004 project team worked closely with the GSFC engineers assigned to work on the SXT. The overall SXT team was a powerful resource in soliciting information and design ideas. The team met frequently with our mentor, Jeff Stewart, along with team members Bobby Nanan, Burt Squires, Janet Squires, and Air Force graduate students Thomas Meagher and Josh Schneider for structure and gripping tool brainstorming sessions. Following brainstorming sessions the 2004 team performed research and worked closely with several commercial product suppliers for parts and visualization assistance.

The primary modeling software that the 2004 team employed was the ProEngineer CAD software. The team used ProEngineer to model a variety of structure designs and also used ProEngineer to assist in creating a gripping tool specification.

Results

The 2004 project team performed development work on two new designs to be implemented in SXT assembly: the "bed of nails" reflector gripping and actuation tool and the "glass-pack" reflector assembly design. The team developed the bed of nails design from the concept phase to creating a detailed funding request and developed the glass-pack design from the concept phase through a small scale physical model and working CAD models. The bed of nails and glass-pack designs were presented as alternatives to the existing gripping and assembly prototypes.

The bed of nails design is a vacuum gripping tool with dynamic position and actuation capabilities that will attach to the back (non-reflective) surface of a reflector using an array of six, 5.5 mm diameter silicone suction cups and six, 11.4 mm diameter silicone cups. The twelve suction cups will be individually mounted to level compensating suspensions. The bed of nails design will also employ piston type piezo electric actuators with integrated strain gage sensors to allow the back surface of a reflector to be mapped and to allow the bed of nails to modify the reflector prescription if necessary. To achieve nanometer scale position and actuation control twenty Physik Instrumente P841.60 closed loop piezo actuators with strain gage position sensors were specified with appropriate controller hardware to allow individual control of the piezos. The P841.60 is capable of 90 μm of piston travel with 1.8 nm closed loop resolution[97]. Figure 4 shows the design sketch that the team used to assist in selecting bed of nails components along with a potential configuration for the components. Due to the high cost of creating a bed of nails prototype (~$130,000), the final stage of development that our team undertook was to submit a detailed list of components that was included as part of an Independent Research and Development (IRAD) funding proposal.

Due to the funding delay with the bed of nails design the team also began work on researching and designing a composite support sheet or draping as an alternative to the bed of nails design. The team

[97] http://www.physikinstrumente.de/products/prdetail.php?secid=1-16

consulted several resources, primarily engineers with composite design experience, to lay the groundwork for fabricating and testing a composite support sheet. The team also had an aluminum testing mandrel machined for use in composite testing.

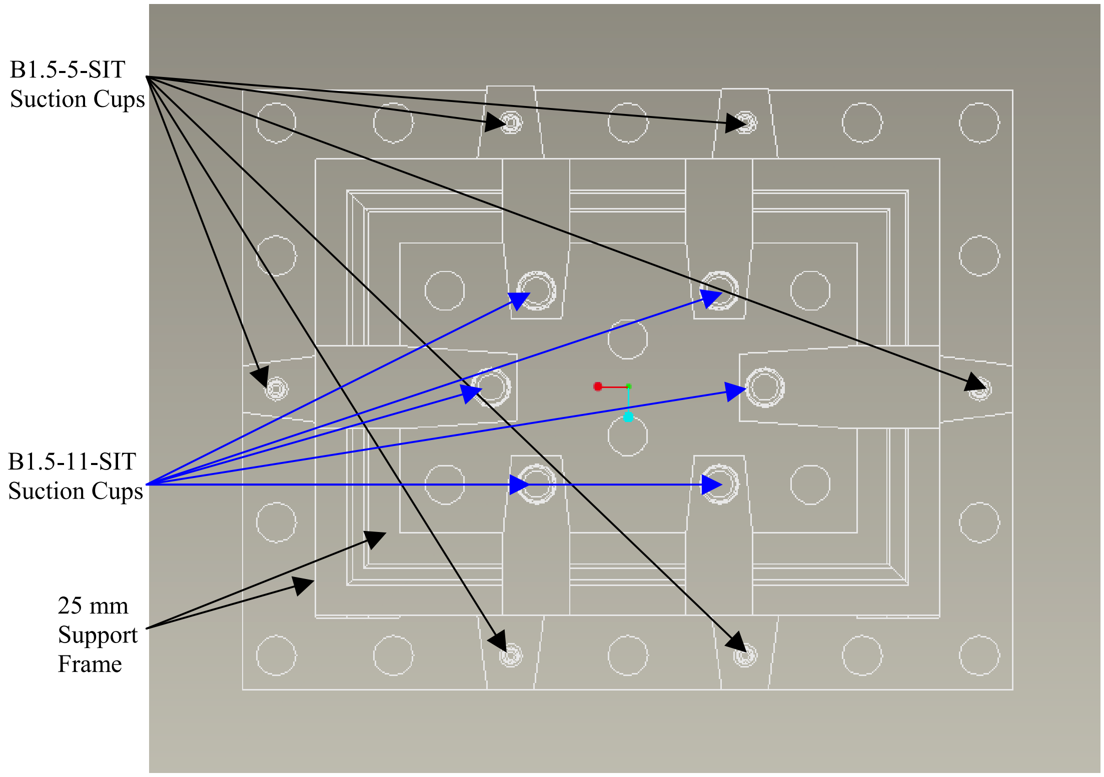

Figure 4 Bed of Nails Sketch

The glass-pack design is an SXT assembly prototype based on having individual structure elements (struts), attached to each parabolic-hyperbolic (P-H) reflector pair, which are bonded to struts attached to adjacent reflector pairs. The individual strut design allows an overall structure to be built up through the process of aligning and bonding each reflector pair. Additionally, the individual strut design, in conjunction with a tool such as the bed of nails, also simplifies the alignment of reflectors, as compared to other prototypes, by eliminating the need to align each parabolic reflector to its accompanying hyperbolic reflector. Finally, the glass-pack design simplifies the alignment methods by allowing unobstructed access for precision alignment tools such as a Centroid Detector Assembly (CDA), an interferometer, or a Physik Instrumente hexapod. Figure 5 shows the CAD model of the final Glass-pack Reflector Assembly (GRA) design. Figure 5, panel 1 shows the GRA attached to an outer SXT structure or "wagon wheel." Panel 2 shows the GRA without the wagon wheel attachment strut to detail the individual reflector support struts.

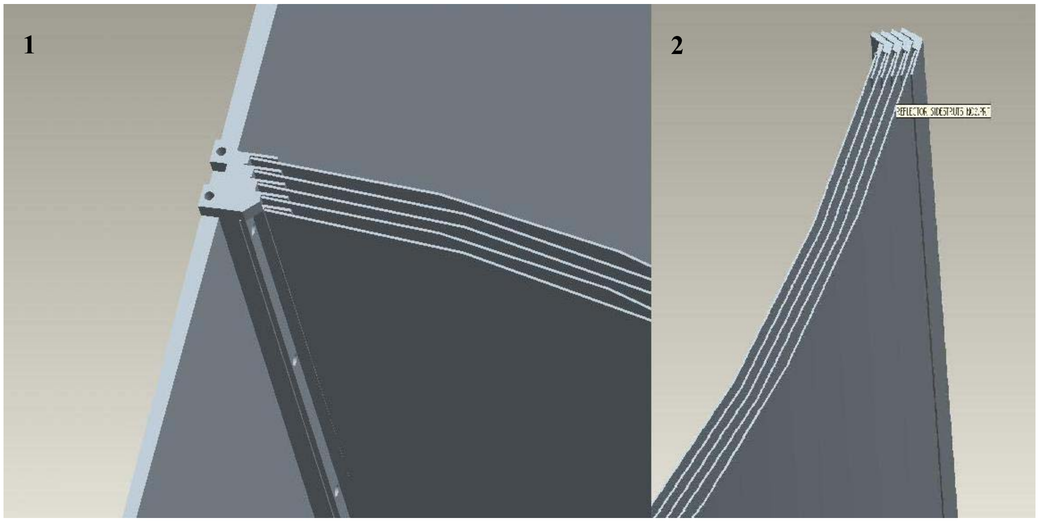

Figure 5 GRA Assembly

Summary and Conclusions

The 2004 WPI project team worked to develop several new designs for SXT assembly: the glass-pack SXT structure design and the bed of nails reflector alignment tool design. The bed of nails design was researched, specified, and brought to the funding stage. The next step for the bed of nails design is to construct and test a prototype. The next step for the alternative composite support sheet design is to fabricate and test, using a Coordinate Measuring Machine (CMM), several composite support sheet designs. The glass-pack design was researched, modeled, and prototyped. The next step is to determine if the GRA design is a suitable alternative to current prototypes and to do materials research for further prototypes. The 2004 team met their goal of developing new, alternative methods of reflector installation in the SXT. Complete details can be found in the full report.

References

1. http://constellation.gsfc.nasa.gov/science/about.html
2. http://constellation.gsfc.nasa.gov/
3. SXT FMA Industry Study Pre-Bidders Conference presentation, pp. 8, 33
4. http://www.physikinstrumente.de/products/prdetail.php?secid=1-16