Comments on Swales Aerospace Report: "Plan for the Fabrication, Assembly, and Alignment of Replicated Reflectors for the Constellation-X Spectroscopy X-ray Telescope."

The study documented in the attached report was conducted to generate a point of reference for Constellation-X project planning and, in particular, planning for reflector fabrication. The study has been successful in this regard and has been extremely useful. For this particular study a number of assumptions were made, some regarding the technical aspects of the mirror itself, others programmatic in nature, such as schedule. Notes of interest regarding some of the assumptions and concepts are discussed below:

1. The study is based the use of 20 cm (axial length) reflectors. For purposes of production planning, this is a "worst case" in terms of both the number of forming and finish mandrels needed and the total number of glass reflectors to be produced.

2. The study assumed a mission development schedule consistent with a first launch in 2010. The current plan is for first launch in 2013. The lengthening of the schedule change may affect how to optimally phase sub-elements of the SXT FMA development.

3. The plan set forth in the study is driven by an assumed mandrel delivery that was provided to Swales early in their study. Subsequent assessment of mandrel production indicates that these assumptions may be pessimistic and mandrels may be produced faster than what was assumed for the study).

4. The study assumes that a "stand-alone" facility will be acquired. While the Constellation-X Project accepts that special facilities will be required to carry out the reflector production, the study is not entirely in the spirit of FAR 45.102, which states that the Government's policy is that contractors are ordinarily required to furnish all property necessary to perform a Government contract. Furthermore, some of the items identified in the Swales study may be able to be made available at the start of contract, thus shortening the estimated "facility acquisition" time. Examples of such items include employee lounge/kitchen, office space, lavatories, etc. However, the analysis of floor space requirements for all items in Chart 3.0-1 of the Swales report is considered representative and therefore useful for planning.

5. Finally, the assembly/alignment concept put forth in Section 7 of the Swales report is provided only as a concept and is not really germane to the reflector production study. The concept is provided only as a possible concept, requires modification and improvement, and has neither been rejected nor endorsed by the Constellation-X Project.

PLAN FOR THE FABRICATION, ASSEMBLY, AND ALIGNMENT OF REPLICATED REFLECTORS FOR THE CONSTELLATION-X SPECTROSCOPY X-RAY TELESCOPE

March 13, 2003

STATUS REPORT

PLAN FOR THE FABRICATION , ASSEMBLY AND ALIGNMENT OF REPLICATED REFLECTORS FOR THE CONSTELLATION-X SPECTROSCOPY X-RAY TELESCOPE

CONTRIBUTORS TO THIS REPORT:

Swales Aerospace:

Jim Heaney
Qian Gong
Wayne Sours
Brian Amiss
Steve Derdeyn

NU-TEK:

Robert Bupp

CONTENTS

1.0 SUMMARY

The Constellation-X Spectroscopy X-Ray Telescope (SXT) will ultimately be comprised of 4 individual telescope assemblies free-flying in orbital formation. In one design concept, that will be used as the reference design in the study reported in this document, an individual telescope consists of about 230 nested shells with a total of about 4100 reflector elements arranged in a Wolter I configuration. This report addresses the facility requirements for producing reflector elements in a replication process, verifying their surface figure and roughness, assembling and aligning the reflector elements to compose an individual telescope, and the associated labor and materials costs, and schedule.

Key ingredients in this proposed plan are the delivery of the 460 figured forming mandrels (230 ‘primary’ or parabolic and 230 ‘secondary’ or hyperbolic) that will be used to impart the desired curvature to the estimated 30,000 glass blanks that will be required to yield sufficient reflectors for 4 telescope assemblies plus spares; and the 230 finishing mandrels that are required to apply the reflecting coating (gold in this study) to the shaped reflectors. The plan assumes that 1 finishing, or replicating, mandrel can be used to apply the coating to 2 reflector elements.

This plan treats mandrels as government furnished equipment (GFE) and will accept their delivery schedule as a given, pacing item. Reflector production rate and associated manpower are adjusted to fit the mandrel delivery rate.

The plan assumes that there will be a certain starting date, or ‘time zero’, when contracts will be awarded simultaneously for the purchase of mandrels and for the acquisition of a facility for reflector production. This is not a constraining assumption, because both activities will occur independently and reflector production estimates are presented in this report on a timeline of ‘years from date of start’ and can be adjusted forward or backward to accommodate the mandrel procurement schedule. Using a ‘time zero’ start date, the plan estimates that it will require about 18 months to acquire a production facility and get it up and running to produce reflectors. Mandrel production is estimated to require about 1 year to get up and running. Therefore, there will be a number of mandrels ready and waiting when the time comes to produce reflectors. From then onward, the reflector production schedule has been adjusted with the assumption that mandrels are always available when needed.

As reflectors emerge from the production facility, some are directly installed into 2 telescope assemblies that are being erected simultaneously and in parallel with reflector production. Remaining reflectors are stored until needed to assemble the final 2 telescopes in the year following the end of reflector production activity.

This planned approach has produced results, summarized as follows:

Duration	starting at 'time zero', the entire reflector production, test, assembly and alignment activity will extend into a 7^{th} year, for 4 telescopes.

Facility Size	a facility sized to about 40,000 sq. ft will be required, if all activities are housed under one roof.

Within the scope of this report, certain items are considered to be GFE, such as the mandrels, and any mechanical structures and mechanisms, such as the telescope module structures, the Optical Assembly Pathfinder prototyping, and similar mechanical features. This subsystem interface area can become a source of confusion, omission, or overlap and is not addressed as part of this report.

The estimated duration is determined by applied labor assumptions, including shift work and hours per week, as will be discussed in the report. Consequently, the estimate of 6+ years is somewhat flexible, contingent upon how much labor is brought to bear on reflector production.

Details are discussed in the following report.

2.0 INTRODUCTION

The Constellation-X Spectroscopy X-Ray Telescope will use a Wolter Type I design of nested, grazing-incidence X-ray mirrors to focus X-rays. Although the design uses many more mirror shells than Chandra (AXAF), the optical figure requirement is much lower.[1] An experimental prototyping effort is in progress to evaluate replication techniques as a means of forming and coating individual parabolic (primary) and hyperbolic (secondary) reflector elements of the Wolter I configuration. In the approach studied in this report, the reflector segments of a mirror shell are made of glass with figure imparted by thermal forming over a precisely shaped mandrel.[2] This has the advantage that many mirror elements can be made from the same mandrel thus reducing costs.

A sketch of one SXT concept, with its nested shells viewed end-on, is presented in Figure 2.0-1. The outer annulus is composed of 12 segments each subtending 30 degrees. The inner annulus has 6 segments of 60 degrees. The transition from 30 degree to 60 degree segments occurs at the radius where the largest inner reflector is equal in arc length to the largest outer reflector. This occurs at a diameter of 0.8 m which is half the outer diameter of 1.6m.

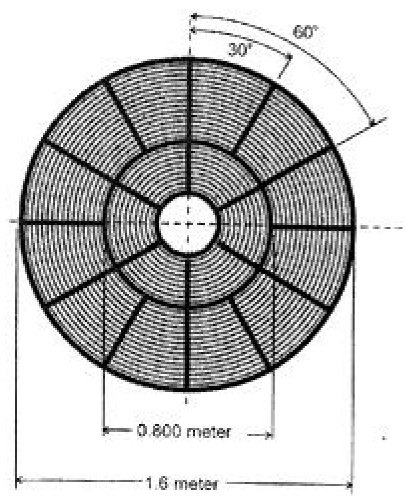


Figure 2.0-1. Sketch of an end-on view of the Constellation –X SXT segment mirror organization.

Each segment shown in Figure 2.0-1 is a separate module containing stacked pairs of parabolic and hyperbolic glass reflectors, each with figures imparted in the mandrel shaping process and coated with a reflecting surface – gold in this study, with platinum as a possible alternate. Typical reflector stacks are sketched in Figure 2.0-2.

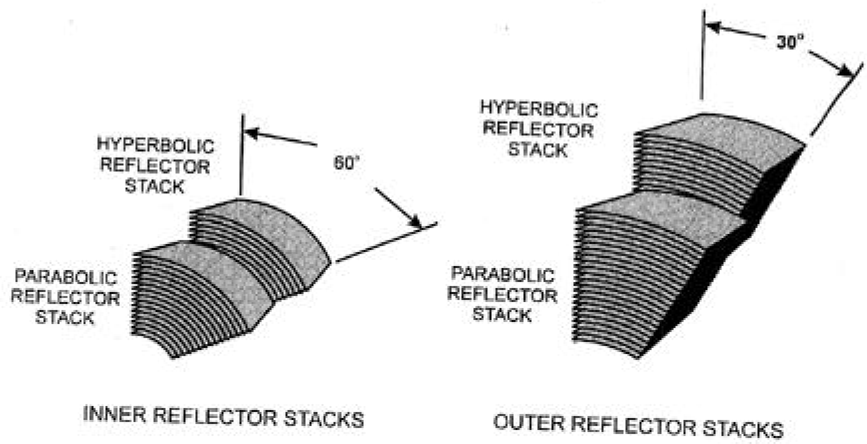


Figure 2.0-2 A sketch of inner- and outer-shell parabolic (primary) and hyperbolic (secondary) reflectors.

The largest reflector arc length is about (1.6m x π)/12 = ~42cm. For the study reported here, the width of each parabolic and hyperbolic reflector is given as 20cm, derived from the SXT dimensions pictured in Figure 2.0-3. Other telescope design concepts may consider alternate reflector dimensions, but the fabrication plan formulated in this study will use the reflector dimensions stated above.

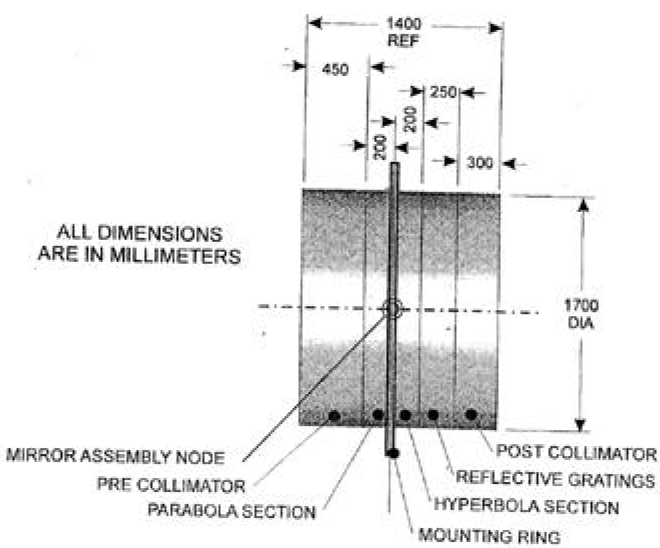


Figure 2.0-3 The SXT mirror assembly with gratings and collimators.

Reflector prototyping development has selected a glass thickness of 0.4mm. The planned approach will start with pre-cut glass sheets, 0.4mm thick and slightly larger than the final reflector dimensions, e.g. about 42cm x 20cm x 0.4mm for the largest reflector. Final cutting to the exact dimensions needed for telescope assembly will be done as one of the sequenced fabrication steps discussed in the detailed report that follows.

In this conceptual concept, the SXT will require about 4100 reflectors per telescope, or about 20,500 flightworthy reflectors for 4 telescopes plus 1 set of spares.

The report will outline:

- the requirements of a 'stand-alone' facility – building and equipment – needed to manufacture about 20,500 flightworthy glass reflectors;
- the processing steps associated with preparing the delivered mandrels prior to glass forming;
- the processing steps associated with producing shaped and coated glass reflectors;
- the metrology activities and associated equipment requirements needed to verify reflector acceptability;
- a plan for assembling and aligning the reflectors into a delivered telescope housing;
- a schedule for the production, verification, assembly and alignment of finished reflectors for 4 SXTs plus 1 set of spares, derived from the constraints imposed in this study.

It is not within the scope of this study to consider issues related to the mechanical structure of the telescope or its development, or the detailed interface requirements between the individual reflectors and their mounting structure.

3.0 FACILITY ACQUISITION

This study will assume that a 'stand-alone' facility will be acquired that will house all activities associated with reflector shaping and coating, part verification, assembly and alignment. However, it is quite possible to partition the various activities such that they can be performed in separate facilities and locations.

Chart 3.0-1 presents an itemized listing of the specialized compartments of a proposed facility for producing 20,500 replicated reflectors and assembling them into 4 aligned telescopes.

	REFLECTOR SEGMENT MANUFACTURING FACILITY						
		DIMENSIONS	**CLEANLINESS**				
ITEM	**DESCRIPTION**	**(SQ.FT.)**	**LEVEL**				
1	Loading Dock	200	Ordinary				
2	Parts receiving & storage	3000	Ordinary				
3	Cart, dolly storage	300	100000				
4	Transition & cleaning room	200	100000				
5	Clean dressing room	100	100000				
6	Cleaned part storage	2500	100000				
7	Very clean part storage	1000	10000				
8	Oven Room	1000	10000	(Est. about 15 ovens)			
9	Oven utility room	1000	Ordinary				
10	Precision Cutting Room	300	10000				
11	Glass strenghtening area	2000	Ordinary/Vented				
12	Epoxy spraying room	500	10000/vented				
13	Replicating/refurbishing room	1000	10000	(Est. about 2 replicating/refurbishing chambers)			
14	Replicating utility room	1000	Ordinary				
15	Replication curing room	500	10000	(Ultimately need space for about 30 mandrels)			
16	Refurbishing utility room	1000	Ordinary				
17	Mandrel prep. Facility	1000	<10000	1 vac chamber; 1 oven; vented work area			
18	Inspection room/metrology	1500	<10000				
19	Clean storage room	1500	<10000				
20	Telescope Assembly/Align.	2000	1000	For 2 telescopes at a time.			
21	Small Machine shop	500	Ordinary				
22	Conference room	500	Ordinary				
23	Data collection room	500	Ordinary				
24	Employee lounge/kitchen	800	Ordinary				
25	Reception area	300	Ordinary				
26	Office Space	2000	Ordinary	For about 20 employees.			
27	Lavatories	600	Ordinary	1 set with clean room access. 2 sets total.			
28	Chemical retaining area	200	Ordinary				
29	Building Utility space(HVAC)	1000	Ordinary				
30	Maintenance space	500	Ordinary				
31	Hallways (20% of total)	5700	Mixed				
32	Contingency (20% of total)	5700	100000				
	TOTAL AREA :						
	(Sq. Ft..)	39900					
	(Sq. Yds.)	4,433					
	Parking area for 50 vehicles						
	******************************	**************	*****************	***************	**************	**************	
	CLEAN ROOM AREA (Sq. Ft.)						
	Class (100,000 - 10,000)	11,650					
	Class (< 10,000)	13,150					
	Ordinary area	15,100					
	TOTAL:	39,900					

Chart 3.0-1 – An itemized listing of the specialized compartments of a reflector segment manufacturing facility, with estimated dimensions and cleanliness levels.

Cleanliness levels are assigned to each area in accordance with the activity that will occur in that area. Dust is an enemy in the reflector fabrication process and extraordinary measures will have to be taken to eliminate this problem when the facility is established. Room air filtering will be a structural challenge. Special non-shedding wall paints will be recommended. This affects room modification costs.

Some of the processes, such as mandrel cleaning, glass plate strengthening, epoxy application, etc. will involve the use of hazardous chemicals and their storage and ultimate disposal. This will require special venting in certain rooms and designated disposal and storage rooms.

Machinery such as forming ovens, vacuum coating chambers, mandrel refurbishing instrumentation and the like will be installed such that the utility portions of the machinery – pumps, electrical wiring, coolant circulators, etc. – will be housed behind a sealed wall, in an ordinary ambient environment. The business end of these instruments will open into a class 10,000 or better clean area. This arrangement is typical in production plants of this type.

Chart 3.0-2 below presents a functional flow of the reflector segment shaping, coating, inspection, assembly and alignment processes.

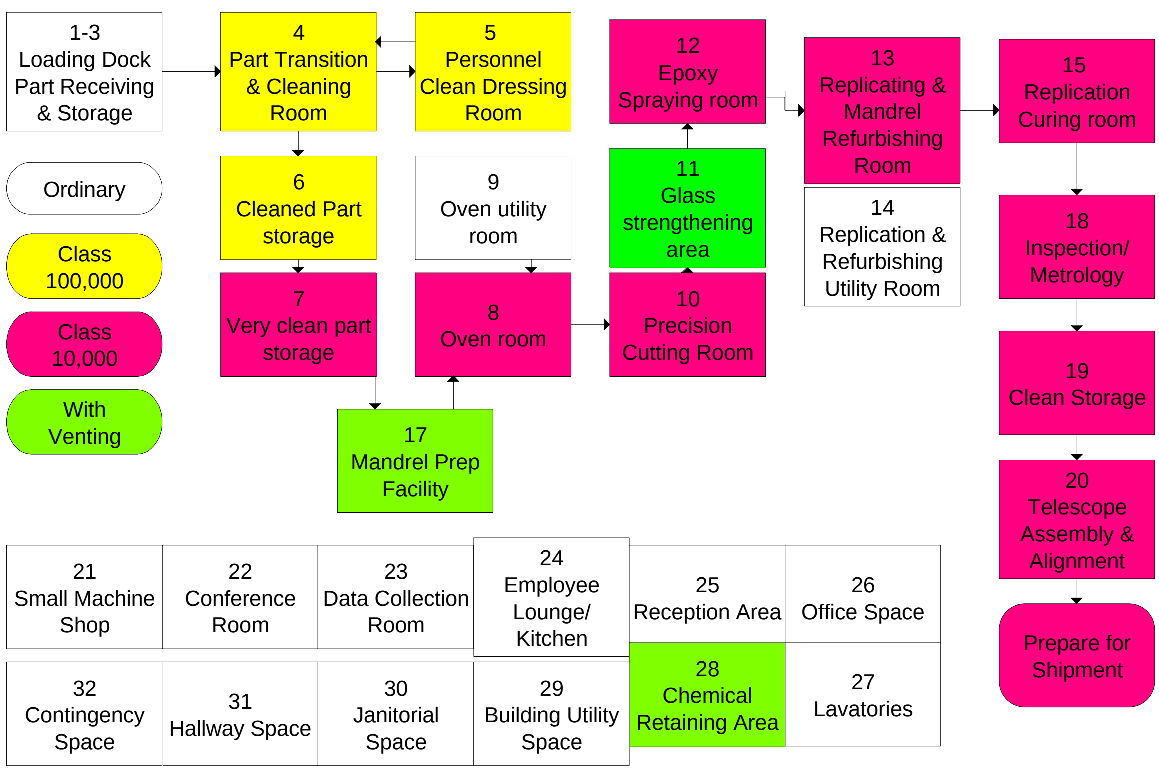
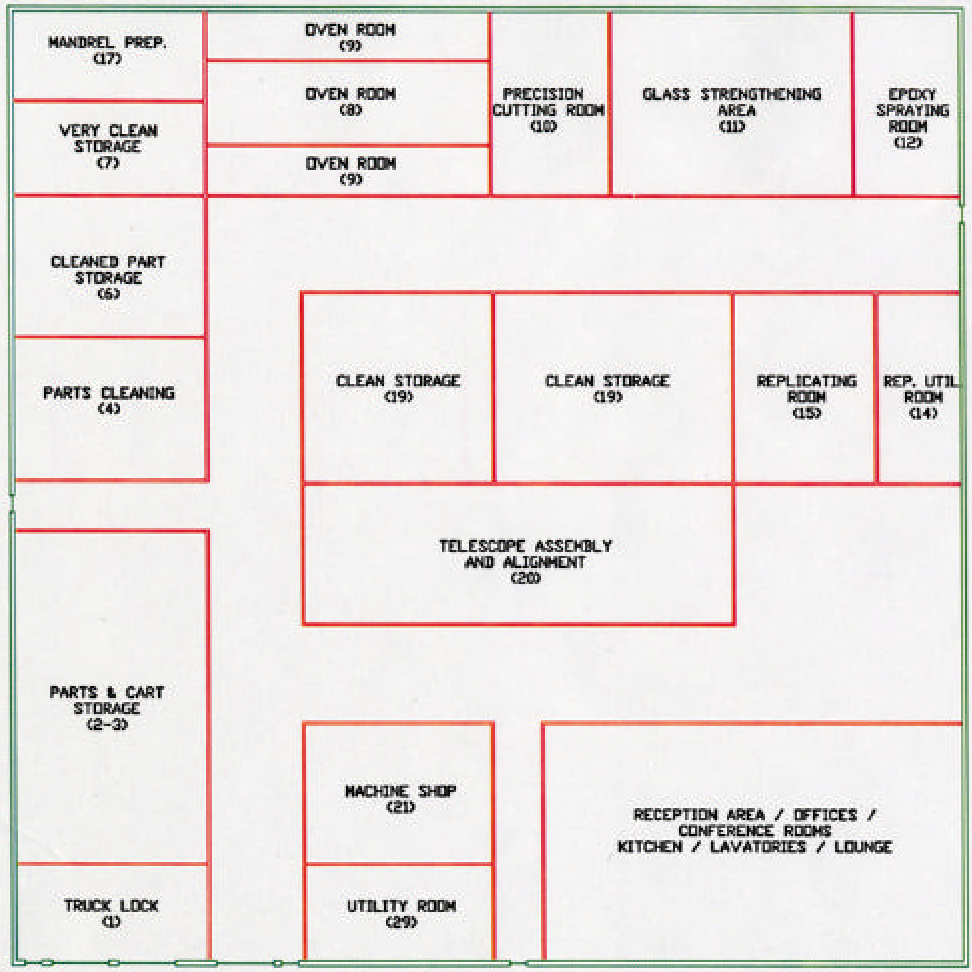


Chart 3.0-2 A correlation of facility needs with reflector manufacturing process.

Figure 3.0-1 Sketch of a suggested 40,000 sq. ft. replication facility with functional areas identified.



The numbers at the top of each block in Chart 3.0-2 correlate with the numbers in Chart 3.0-1 and the parenthetical numbers in Figure 3.0-1. They serve to connect the process flow with facility space requirements.

Figure 3.0-1 above is a sketch of the suggested floor plan of a 200 ft. x 200 ft. (40,000sq. ft., approximately to scale) replication facility with space assigned for each of the functional areas identified in the preceding Chart 3.0-2. In order to minimize dust contamination and preserve room cleanliness levels, utility functions are assigned exterior wall locations and critical areas are near the building center. Hallways are sufficiently wide and high to accommodate fork lift transport of heavy items.

The assigned square footage in Chart 3.0-1 is derived from experience with large assembly and shop areas, such as those at various NASA installations, coating vendors, and other aerospace houses.

The estimated space requirements can also be affected by utilizing an existing manufacturing plant of a major optical or glass production house that has been made available to this project. The numbers presented in Chart 3.0-1 are intended to serve as a useful baseline when generating a total cost estimate for the SXT activity.

A simple ordering of the reflector forming and replication process goes as follows.

1. A replication facility is either established or acquired that can perform some, or all, of the separate steps.

2. Forming and replicating mandrels are ordered approximately at the same time as facility acquisition begins. Mandrel delivery begins about 6 months prior to the availability of the replication facility. It is assumed that outer shell mandrels arrive first. Then the replication process can begin with the forming of all reflectors needed for the SXT's outermost shell.

3. Glass is also ordered at this time.

4. Upon delivery, mandrels are first stored, then opened for inspection. Each mandrel will be accompanied by its own unique 'basket' or 'automated transport apparatus' that contains holding features, or tabs, to be used in various semi-automated replication process steps. At this point, forming mandrels are cleaned and transferred to the mandrel preparation facility where a surface coating is applied that will aid in glass release after the forming process. This is a time consuming process, estimated to require about 18.5 hours of elapsed time to prepare 2 forming mandrels. This estimate may change with experience. See Chart 4.0-1.

5. Glass pieces that will be formed are cleaned and delivered to the forming room.

6. Cleaned and prepared mandrels are delivered to the forming room.

7. A single mandrel and a piece of glass are inserted into the forming oven and heated.

8. After several hours, the glass will slump into the desired shape. The mandrel and shaped glass are allowed to return to room temperature slowly. This is also a time consuming process, estimated to extend for about 12 hours per formed sheet. Again, experience with cooling techniques may shorten this time estimate.

9. The formed glass is removed from the oven and taken to the glass strengthening area where it is exposed to an etching or related process, plus inspection, to insure that the glass was not weakened during the forming process. An elapsed time of 3 hours has been assigned to this process step and it is assumed that more than one piece of glass can be processed in parallel. This step is assigned a success rate of 85%.

10. At the same time, the forming mandrel is removed from the oven, inspected, and inserted for the next forming episode, with no additional treatment. It is assumed that a forming mandrel can be used for 10 formings before it has to be returned to the mandrel preparation area for re-application of a release coating. See Chart 4.0-1. An individual mandrel may be used as many as 60 times.
Also assume that forming mandrels are never harmed to a degree that would require a surface re-polishing.

11. After strengthening, the formed glass moves to the precision cutting station where it is trimmed to the exact final reflector dimensions. This step is assigned a success rate of 85%.

12. Next, epoxy is applied to the formed glass, with an assumed success rate of 95%.

13. The glass then moves to the automated replication facility where it is placed in contact with the gold-coated finishing mandrel for the coating replication process.

14. After coating transfer from the finishing mandrel to the formed glass, the coated reflector is placed in a temperature controlled curing room. The elapsed curing time is assumed to be about 12 hours, but this is an almost labor free activity.

15. After the replication process, the finishing mandrel must be inspected and have a new gold coating applied to prepare for the next replication transfer. The proposed plan is to use an automated coating facility, with chambers separated by vacuum interlocks, such that the finishing mandrel is re-coated in an almost fully automated process. Hence the need for some kind of mandrel ‘tabs’ or ‘basket’ that can connect with the automated machinery to move mandrels along the process line.

16. When the curing is complete, finished reflectors are moved to the inspection and metrology station where their figure, surface roughness, and general condition are verified for future flight use.

17. Upon completion of the inspection stage, qualified reflectors are sent either to a telescope assembly and alignment area, or are placed in a clean storage facility until needed for telescope installation.

18. Telescope assembly and alignment may occur in the same facility in which replication occurs, or in another distant location. These details are discussed in Section 7.0.

4.0 MANDREL PREPARATION

This plan begins with the recommendation that every mandrel, forming and finishing, be provided with its own tray or basket for ease in transportation and installation into automated forming, coating, and refurbishing processes. The trays will have tabs or other appendages that will permit the installation of holes, clips, etc., that cannot be installed on the glass mandrels. These features will mate with their partners in the automation process.

Another key assumption in this plan is that mandrels are never harmed to an extent that would require that they be shipped back to their manufacturer for replacement or refurbishing. All necessary mandrel cleaning, recoating, etc. will occur only in the reflector manufacturing facility.

See Chart 4.0-1 – Mandrel Preparation, Processing

As the forming mandrels are delivered to the established reflector processing facility, they are inspected, cleaned, and coated with platinum to facilitate the subsequent release of the glass after the forming process. This is a labor intensive activity and Chart 4.0-1 addresses that, separate from other process steps. The plan estimates that one full-time senior technician, with one full-time technician assistant, and the part-time involvement of a skilled professional, who may spend another part of his time participating in replication process steps, will be sufficient to perform this task, at the rate at which forming mandrels will be arriving.

The entire mandrel preparation process may take many days. (18.5 hrs. is the estimated elapsed time, but experience may alter this estimate.) As long as the elapsed time does not exceed the mandrel delivery rate, i.e. about 2 forming mandrels per week, this team should be able to prepare mandrels as fast as they are needed by the reflector facility.

Certain process steps involve some risk, as indicated in Chart 4.0-1. A process yield less than 100% has been assigned to those steps, for an ultimate estimated process yield of 85%. I.e., 15% of the time, this process will have to be repeated.

Each telescope outer shell forming mandrel is used 60 times to shape glass for 60 reflectors (12 for each of 4 telescopes plus 1 spare set of 12). Some process steps are done just once and need not be repeated throughout 60 uses of that mandrel. Other steps, such as those involved with the application and treatment of a release agent, may have to be done an unknown number of times. Experience will ultimately establish that number. For the sake of this study, we assumed that a forming mandrel can be used to shape 10 pieces of glass before the release agent has to be replaced. Then, this replacement step must be done 60/10 or 6 times for an outer shell mandrel, 3 times for an inner shell mandrel. As indicated in the notes of Chart 4.0-1, this effectively leads to the preparation and processing of forming mandrels 1017 times.

MANDREL PREPARATION AND PROCESSING

STEP	TASK	Profess. Labor 1	Tech 1 Labor 2	Tech Asst.1 Labor 3	Yield	Elapsed Time (Hrs.)	NOTES
1	Personnel preparation	0.5	0.5	0.5		0.5	
2	Unload, inspect 2 forming mandrels	0.5	0.5	0.5	1	0.5	(1)
3	Wash 2 mandrels; prep for coating		0.5	0.5	1	0.5	(2)
4	First coating of 2 forming mandrels		0.5	0.5		2	
5	Inspect mandrels	0.25	0.25	0.25	0.95	0.25	
	Sub-Totals:	1.25	2.25	2.25		3.75	
6	Additional coating of 2 mandrels		2	2		2	(3)
7	Inspect mandrels	0.25	0.25	0.25	0.95	0.25	
8	Mandrel coating treatment		2	2		12	
9	Final mandrel inspection	0.25	0.25	0.25	0.95	0.25	
10	Delivery (2) to replication process		0.25			0.25	
	Sub-Totals	0.5	4.75	4.5		14.75	
	Column Totals:	1.75	7	6.75	85%	18.5	(4)

NOTES:

(1) Assume mandrels are never harmed. Yield refers to process success and indicates rate of repeat.
(2) Assume that steps 1 - 4 are done once for each mandrel. The total number of forming mandrels is 460 = 230 'P' + 230 'H'. Therefore steps 1 - 4 are repeated 460 times as mandrels are delivered over a 30 - 36 month period.
(3) Assume that steps 6 - 9 are repeated after each 10 uses of a forming mandrel. Of the 230 mandrels of each type, 109 are outer shell and 121 are inner shell. Each outer shell mandrel is used 60 times. Each inner shell is used 30 times. Therefore, steps 6 - 9 are applied to each outer shell mandrel 60/10 = 6 times; each inner shell mandrel 30/10 = 3 times. That sums to 654 outer shell + 363 inner shell = 1017 forming mandrels that experience steps 6 - 9.
(4) Elapsed time: This team can prep 2 forming mandrels in approximately one 8 hr. shift. The 18.5 hr. elapsed time includes chamber, annealing time., etc.

Chart 4.0-1 A process flow, with associated elapsed time, and yield for the preparation of mandrels prior to use in shaping reflector glass.

5.0 DETAILED STEPS INVOLVED IN THE PRODUCTION OF A REFLECTOR SEGMENT

Reflector Replication Process Flow

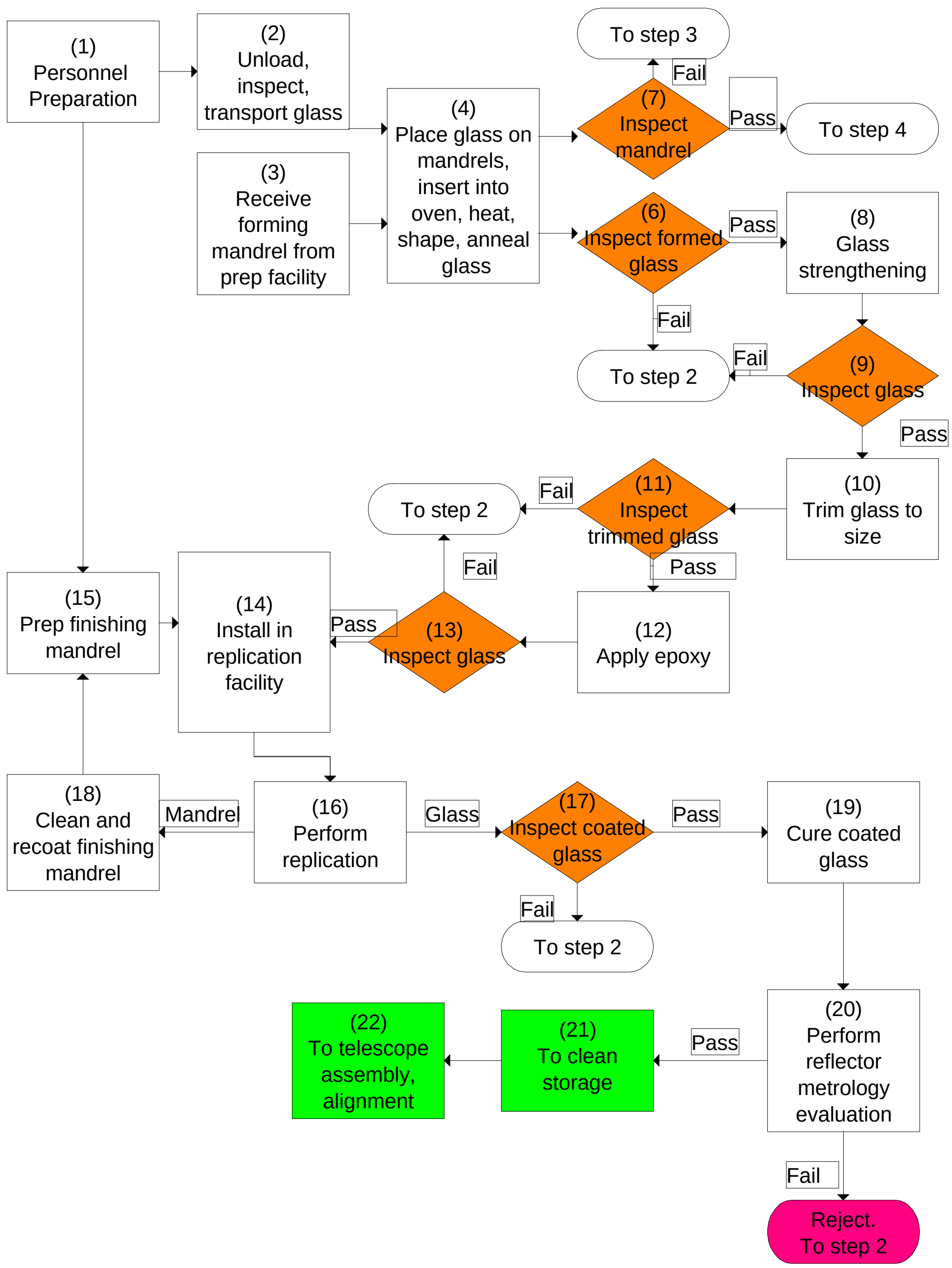


Chart 5.0-1 is a flow diagram of the process steps for reflector production.

The detailed process steps in Chart 5.0-1 refer specifically to the reference concept telescope design that is the model used in this study. That is, the fabrication of 20,500 gold coated glass substrate reflectors, shaped to parabolic and hyperbolic figures in a slumping and controlled annealing process, and gold coated in a mirror replication coating transfer process. Further evolution of the SXT design concept may differ from the process outlined in Chart 5.0-1.

Two key items in Chart 5.0-1 are the glass forming and annealing (step 4) and the replication cure time (step 19). These steps consume a lot of elapsed time, but are not labor intensive.

Step 8, the glass strengthening treatment process will require an exact amount of time that has not yet been established.

Certain steps, as indicated in the chart's inspection points, have a yield less than 1. The necessity to repeat these steps will have to be factored into the time and labor cost data.

Step 3, the mandrel treatment process, has been discussed in Section 4.0 above.

Step 22, telescope assembly and alignment, will be discussed in Section 7.0 of this report.

6.0 METROLOGY – INSPECTION AND REFLECTOR VERIFICATION

As the reflector segments emerge from the production process, their figures and surface roughnesses will be evaluated in a prepared metrology facility. The detailed design and prototyping of the required metrology instrumentation has evolved to the point where individual equipment and labor needs can be estimated.[3]

These are identified in Chart 6.0-1 below.[3]

Alignment requirements are included in the metrology facility needs outlined in Chart 6.0-1 because the current SXT plan will employ the same equipment and personnel skills to accomplish both tasks as an integrated x-ray optics activity.

A more detailed concept of the SXT assembly and alignment concept is provided in the next section

METROLOGY/ALIGNMENT: equipment & personnel				
METROLOGY				
Equipment	**Quantity**		**Personnel**	**Number**
Interferometer	2		Metrology technicians	8
Coordinate measuring machine	1		Lead metrology engineer	1
laser scanner (multi axis)	2		Process engineer	1
roughness profiler	1		s/w & analysis support	1
midfrequency measuring profiler	1			
fixturing for automated metrology	2			
inspection station	2			
atomic force microscope	1			
subtotal				
***				
ALIGNMENT				
Equipment	**Quantity**		**Personnel**	**Number**
Interferometer	2		alignment technicians	8
Coordinate measuring machine	1		alignment optical engineer	2
laser scanner (multi axis)	2		alignment mechanical engineer	2
x ray pencil beam	2		materials engineer	1
inspection station	2		x-ray science / liason	1
subtotal			systems engineering	2
			contamination engineering	1

Chart 6.0-1 - Estimated STX metrology and alignment facility requirements.

7.0 ASSEMBLY AND ALIGNMENT

7.1 ASSEMBLY

The current study assumes that the modules of two telescopes will be built up simultaneously, in parallel with the reflector production process. Reflectors that are not needed immediately will be housed in a clean, controlled environment.

The assembly and alignment will occur in a class 1000 clean work area.

A telescope module assembly and bonding apparatus, the Optical Assembly Pathfinder (OAP),pictured below in Figure 7.0-1, is being developed by the structural engineers of the Goddard Space Flight Center.

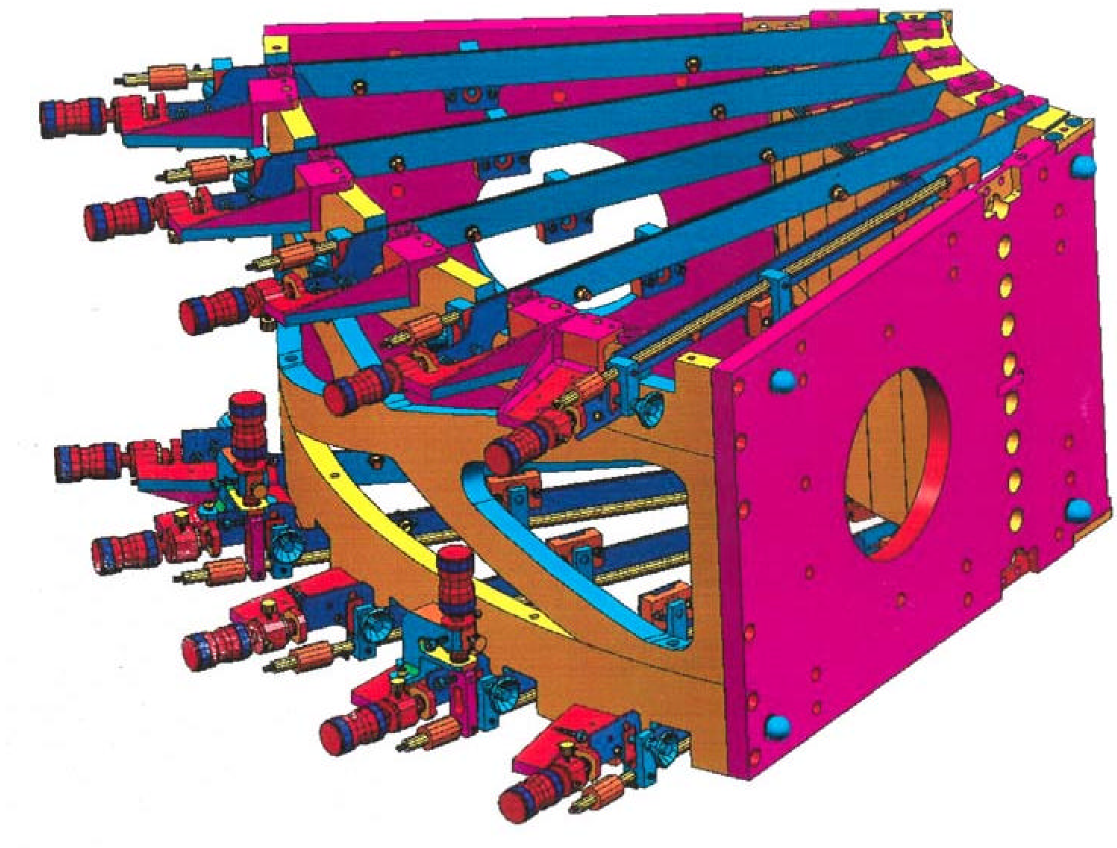


Figure 7.1-1 The Optical Assembly Pathfinder

This conceptual plan calls for the OAP to integrate with the 'robotic arm for automated mirror alignment'.[4] This combination will have the ability to automate the adjustment of reflector segments as they are installed and prepared for final bonding, and will interface with the alignment process discussed below.

7.2 ALIGNMENT

The basic tool for the current alignment plan is the Centroid Detector Assembly (CDA) (Bauer Associates). The CDA is an optical instrument that provides a laser beam (HeNe @ 633nm) with its position and angle under precise control. It is designed and aligned in such a way that the output beam arising from a point source can be directed at different angles. When aligning the SXT primary reflectors, this point should be located at the foci of the primary shells. See the concept sketched in Figure 7.2-1.

In this concept, the beam from the CDA is first reflected off the primary. It is then reflected off a flat mirror. The normal of the flat mirror is parallel to the primary reflector axes. The beam reflected from the flat mirror should return along the incident beam path and finally back to the focus of the primary reflector, if the primary is well aligned. However, the SXT mirror shells do not have a common focus. Consequently, the CDA must move to different focal positions. From the metrology point of view, this CDA movement will be difficult to accomplish within the assigned alignment error budget. One way to overcome this difficulty is to use two CDAs.

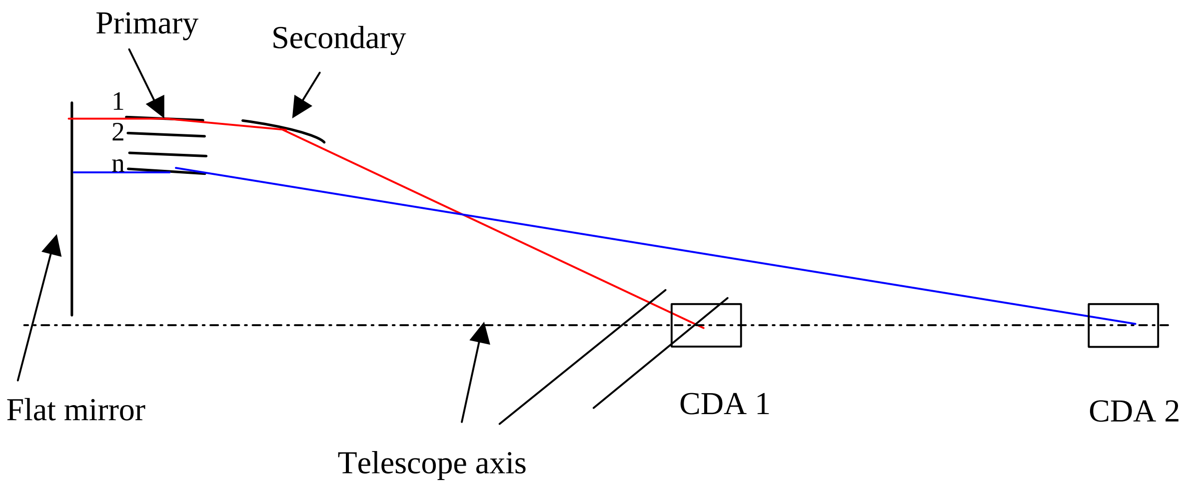


Figure 7.2-1. The CDA mirror alignment concept.

However, this alignment difficulty is eased somewhat by the fact that:

1. all telescope shells (primary and secondary pair) are confocal;

2. the CDA works exactly as a single ray trace. Although the primary shells do not have the same focus, the returned beams at that plane can be predicted with the help of ray trace software. If the mirror alignment procedure is automated, the pre-calculated return position can be integrated into the software, which will greatly simplify the single mirror alignment and effectively minimize human error.

One optional procedure for aligning the mirror shells of each segment is as follows:

1. use metrology to set up the telescope axis;

2. place the CDA #1 and CDA #2 in such a way that the point sources of both CDAs are on the telescope axis with the pre-selected separation;

3. align the flat mirror in such a way that the normal of the flat mirror is parallel to the telescope axis;

4. align the axis of the telescope frame to a pre-defined axis (see Figure 2);

5. start the reflector alignment from the outmost shell:
   a. use CDA #2 to align primary reflector #1 to #3*
   b. use CDA #1 to align primary and secondary pair
   c. move to the next pair and continue.

*(This assumes that the first pair is finished before moving on to the next pair. However, the first secondary shell will block the beam from CDA #2 and prevent it from hitting the next adjacent primary. This is avoided by aligning two more primary shells in advance.)

Note: If experience shows that the primary reflector positioning error can be largely corrected by the secondary reflector alignment, then the stand-alone primary alignment may be eliminated. In that alternative, one CDA with fixed location is sufficient. This should be determined by experiment.

The proposed assembly and alignment plan requires access through the mechanical structure by inserting reflectors into alternate telescope wedges, as indicated in Figure 7.2-2 below. This approach will result in the completion of a single wedge first.

The flat mirror and the telescope frame are mounted on the same table, as shown in Figure 7.2-2. The frame can rotate 360 degrees about the telescope axis. The setup has two major functions: 1) use CDAs to align each telescope reflector; 2) use a UV source (wavelength as short as can be tolerated without suffering from severe absorption in the air) and an off-axis parabola to check the CDA alignment – each telescope wedge and two adjacent wedges with all shells in place.

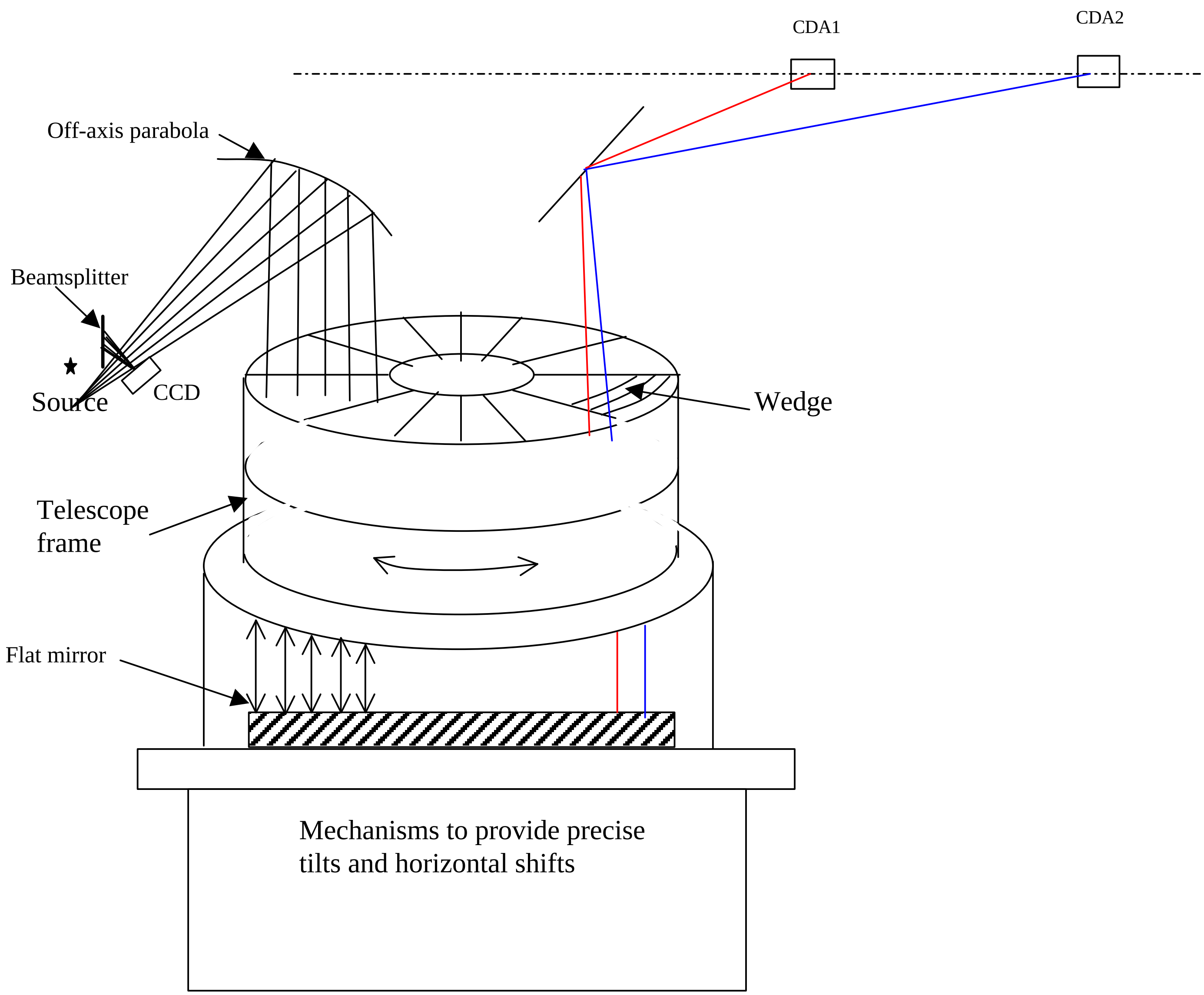


Figure 7.2-2. SXT reflector sub-assembly alignment plan

This arrangement has the advantage in that alignment can start as soon as the first reflector segment of the outmost shell is produced. While waiting for the reflectors for the next shell, we can continue to align other reflectors in the same shell. It also provides a way to store some of the completed reflectors.

7.2.1 Gravity Effects

A finite element analysis indicates that the individual reflectors must be aligned and bonded in a unique direction that minimizes the effect of gravity. To accommodate this, the alignment setup is placed on a table that has precise horizontal tilt adjustment capability. Experimentation is in progress to verify the analytical prediction and the necessity for an offsetting correction.

8.0 SCHEDULE

Chart 8.0-1 below presents an estimated schedule for the production, testing, assembly and alignment of 20,500 glass replicated reflectors into 4 telescopes.

There are a few key assumptions that drive the schedule.

a) Mandrels are treated as government furnished equipment with the assumption that they will be produced in a timely manner, such that their delivery begins about 6 months or so before the production facility is ready for them. Consequently, production proceeds with the assumption that there will be no delays due to a lack of available mandrels.

b) The true duration of certain time-critical production steps listed in Chart 5.0-1, such as mandrel preparation for forming, glass forming and strengthening, and curing time after coating with gold in the replication process, will require further prototyping experimentation in order to become better defined.

c) Similar duration uncertainties can also be applied to metrology issues, assembly and alignment.

d) The replication process scheduling assumes two work shifts per day, 260 work days per year.

SCHEDULE for REFLECTOR PRODUCTION									
ASSEMBLY & ALIGNMENT									
YEARS FROM START:	**-1**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	
ACTIVITY									
Establish Production Facility		XXXX	XX						
GSFC Prototyping		XXXX	XXXX	XX					
Order Production Equipment		XXXX	XX						
Order Materials, incl. Glass		XXXX	XXXX	XXXX	XX				
Forming Mandrel delivery(1680 days)	XX	XXXX	XXXX	XXXX	XXXX	X			
Finishing Mandrel Delivery (1380 days)	XX	XXXX	XXXX	XXXX	X				
Reflector production (20,500)		XX	XXXX	XXXX	XXXX	XXXX			
First two telescope modules		X	XXXX	XXXX	XXXX	XXXX			
First two telescopes complete							**XX**		
Second two telescopes complete							**XX**	**XX**	
NOTES:									
(1) The year -1 is the time before 'time zero'. This assumes an early mandrel order.									

Chart 8.0-1 Schedule estimate for producing 20,500 replicated reflectors, and testing, assembling and aligning them into 4 SXTs.

Having recognized these imbedded assumptions, it should also be noted that replication and metrology prototyping efforts underway at present at the Goddard Space Flight Center have enabled bounded estimates to be placed on the time duration of key tasks. There are no insurmountable difficulties.

9.0 ACKNOWLEDGEMENTS

This report was prepared with the active participation of the Goddard Space Flight Center's SXT team. Significant help was provided by Goddard's Rob Petre, Jean Grady, Will Zhang, Diep Nguyen, Dave Content, Curtis O'Dell, Scott Owen and Jeff Stewart; and Bob Rasche of the Smithsonian Astrophysical Observatory.

10.0 **References**:

1. See: http://constellation.gsfc.nasa.gov/
2. M. A. Jimenez-Garate, et al. "Thermal forming of glass microsheets for x-ray telescope mirror segments", *Applied Optics 42*, pp. 724-734, Feb. 2003.
3. D. Content, Goddard Space Flight Center, private communication.
4. R. Farley, Goddard Space Flight Center, "Robotic Arm for automated mirror alignment", private communication, Jan. 2003

END