CFRP panel concept design study for the CCAT

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ABSTRACT

Under contract from the Cornell-Caltech Atacama Telescope Project (CCAT), Composite Mirror Applications, Inc. (CMA) has undertaken a feasibility design study for the use of Carbon Fiber Reinforced Plastic (CFRP) panels in forming the primary mirror surface. We review some of the past projects using CFRP panel technology for millimeter and submillimeter wavelength radio astronomy telescopes. Pros and cons of the technology are discussed. A particular panel configuration was proposed and computer modeled with finite element analysis (FEA). The technology of replicated CFRP panels for short wavelength radio astronomical telescopes is mature and cost effective. For shorter wavelengths into the IR and visible, it is becoming a very attractive alternative to traditional, heavy glass or metal technologies.

Keywords: CFRP, submillimeter, telescope, reflector panel

1. BACKGROUND

1.1. CFRP Sandwich Panel Technology

Composite reflector (or mirror) panels using CFRP face sheets and honeycomb aluminum core have been used on several high frequency (60-350 GHz), precision, radio telescopes since the early 1980's (Baars, et al. 1987). The subreflector for the IRAM 30m telescope was one of the early applications to explore this technology. The IRAM 15m (and SEST 15m) telescopes applied this technology to all of the primary and secondary reflector surfaces. Those panels, fabricated by MAN Technologie, were replicated on steel mandrels. The reflective surface layer was a film of teflon coated with a thin layer of aluminum. The teflon layer was bonded to the panel with the aluminum reflective layer protected by the teflon. Since these telescope are located outside and must withstand the elements, it was thought that the teflon would provide a protection to the reflective surface. This seems to have worked properly for the SEST telescope in Chile, but the layer did not survive for the IRAM telescopes in the French Alps where ice storm particles cut and penetrated the surface layer. Although the sandwich panel technology was sound, the surfacing problem presented a severe problem for the IRAM use.

In the late 1980's, the SMT (Submillimeter Telescope) project (Baars, et al. 1999) further refined this panel technology for higher precision telescope reflectors (frequency range 250-1000 GHz). The panel development results of that project are directly applicable to the CCAT requirements. Glass (pyrex) mandrels were fabricated at the University of Arizona and send to MAN Technologie who fabricated the primary and secondary reflector panels under contract to the Max-Planck-Institut fuer Radioastronomie. The mandrels were figured to an accuracy of 3 μm rms and the panels were fabricated to an accuracy of 6 μm rms. The SMT panels are trapezoidal with a dimension of 1.55m on the radial side. The SMT panels are attached to a CFRP backup structure at 5 or 6 points (depending on the ring). There is a slight warp to the panels (on the order of 10-30 μm) during fabrication which is taken out by the over constrained support of the CFRP tubular backup structure. This does not introduce problematic forces or moments to the panels nor the backup structure. The reflective layer of the SMT panels is a 40 μm thick aluminum foil which is bonded to the panel in the final replication step. The 10m SMT is the most precise radio telescope to

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date and was the first telescope to make ground based astronomical observations at frequencies above 1 THz (Tong, et al., 2000).

The SMT mandrels were not polished to provide optical, specular surfaces. However, the surface of the panels replicated are still of high enough quality to provide coherent reflection at 10 μm wavelength. During telescope fabrication, measurement tests were made on some of the SMT panels using a 10 μm laser interferometer system. Clean fringes were obtained across the reflective surface and panel surface figure could be evaluated using this method. It is not known what the reflective efficiency was at those wavelengths.

CMA supplied the tertiary, flat mirror panel for the SMT project in 1992. The 1m x 0.7m oval flat is also a CFRP-aluminum honeycomb sandwich panel. It was replicated on a glass flat and has an accuracy of 0.5 μm rms. This was verified using a 10 μm laser interferometer. The surface coated is vacuum deposited aluminum, similar to an optical glass mirror coating. The mirror was recoated in the mid-1990's after SMT construction was finished. It is still in normal service a decade later.

Figure 1. One of the IRAM 15m telescopes during assembly on site.

Figure 2. Submillimeter Telescope (SMT) on Mt. Graham, AZ.

Figure 3. SMT panel and pyrex mold during fabrication at MAN Technologie.

Figure 4. SMT panel testing on a 10 μm laser interferometer.

More recent projects have continued with CFRP surface panel technology. The 1.7m diameter AST/RO submillimeter telescope uses CFRP for the primary mirror reflector surface (Stark, et Al, 2001). An aluminum reflective layer is vacuum sputtered onto the surface. This telescope is located at the South Pole where the environmental conditions can be harsh. The extreme temperatures at this site are positive statement about the adhesion of the sputtered coating to the polymer surfaces on CFRP.

1.2. Composite Mirror Applications (CMA)

Composite Mirror Applications, Inc. (CMA) was founded in 1991 to design, prototype and manufacture custom lightweight optics. CMA has developed and optimized processes for producing ultra-smooth, high precision lightweight mirrors for use at mm-wavelength up through visible imaging applications and continues to advance mirror technology for UV and x-ray astronomy as well as LIDAR and partial physics applications (cf Chen et al 2000; Romeo, et al 2000; Romeo and Chen 2002a, 2002b).

There are a number of previous CMA projects which are relevant to the technology proposed for the CCAT Panel Study include. These include

- Secondary Mirrors for ALMA and APEX antennas (12m diameter submillimeter radio telescopes)
- CFRP/ Aluminum sandwich tertiary mirror for the SMTO
- CFRP secondary mirrors for CBI dishes (Caltech Cosmic Background Imager)
- 320mm diameter CFRP Cassegrain mirror telescopes for ASIAA (Academia Sinica Institute of Astronomy and Astrophysics) AMiBA (Array for Microwave Background Anisotropy) system.

Some of these projects are illustrated in the figures below. CMA has also been developing CFRP surfaces for use at optical wavelengths. CMA has advanced the CFRP mirror development to the point where the surface quality considerations are on the 10's of nm level not the μm level. Those projects are described elsewhere in these SPIE proceedings.

Figure 5. CFRP 0.75m diameter secondary mirror (built at CMA) for ALMA telescopes.

Figure 6. Two CFRP 320mm diameter Cassegrain systems built at CMA for the ASIAA AMiBA experiment on Mauna Loa, HI.

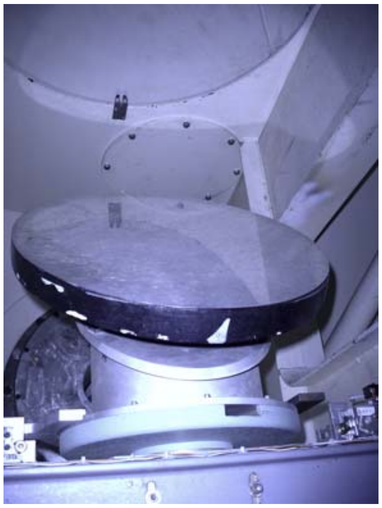

Figure 7. SMT tertiary mirror built by CMA and in service at the telescope. The surface was verified on a 10 μm interferometer.

2. CFRP PANEL STUDY

2.1. Scope of this Study

The scope of work for this design study was defined by the CCAT project office and included the following main tasks:

- Reviewing the reflector surface technical specifications.
- Develop a panel design (baseline concept).
- Analyze the panel design for performance under various environmental load conditions.
- Optimize the panel concept within the rough boundary conditions supplied.
- Develop a manufacturing plan for a complete set of surface panels.
- Develop a critical risk assessment of all areas related to the panel design and manufacture.
- Provide an initial cost estimate and schedule.
- Recommend steps to be taken in the further development and design of panels.

In this paper we discuss the panel concept, the analysis of the panel model, and risks related to this technology.

2.2. Specifications

The starting CCAT configuration specifications relevant to panel designs are summarized below.

- 25m diameter segmented primary mirror
- 3 m diameter central hole in primary
- f/0.6 primary mirror
- 6 or 7 rings of panels
- radial panel layout preferred
- 3 point mount for each panel.
- 5μm rms surface error under all operating conditions
- surface “specular” on smaller scale
- panel gaps of 5mm or slightly less
- panel areal density of less than 10 kg/m^2
- panel cost goal of less than \$10,000/m^2

2.3. Design approach and key tradeoffs

The feasibility of producing reflector/mirror panels to the CCAT specifications is proven by previous projects and current development underway at CMA. The challenge is to produce the panels at a reasonable cost and time scale.

Optical telescope mirrors developed at CMA use all CFRP, complex core structures. This provides the stiffness required for holding the optical telescope figure. However, it is an expensive process due to the material costs and the labor time involved. Alternately, we have considered a thin (meniscus) mirror panel bonded to a space frame structure to hold the figure. This would be lightweight but would be fairly labor intensive.

Our approach for the CCAT panel design has been to follow a similar design to previous submm radio telescope projects. We propose fabricating sandwich panels with carbon fiber (CFRP) face sheets and honeycomb aluminum core. The panels will be replicated on glass molds. This approach is proven technology, as discussed in the background section of this paper. Our approach is a refinement and reasonable extension of those 15-20 year old developments. The technical feasibility of producing a CFRP mirror panel meeting the specifications has been established to a relatively high degree. Processes are well in hand, that are traceable to producing 5 μm panels at an areal density of $\leq$10 kg/m^2. Producing over 60 mirrors from a single mandrel has been demonstrated and contributes to the cost effective nature of surface transfer or replication process. Amortizing the cost of the mandrels over high numbers of parts/mandrel creates a low non-recurring engineering, NRE, when compared to the overall project cost.

This technological approach has low, acceptable risk. Similar products have been field tested in various environmental conditions. Manufacturing using this technology has been successful.

The challenge for this CCAT panel concept study has been “value engineering”. How can we maximize the performance, reduce the cost, and reduce the overall weight.

2.4. Baseline Panel Concept and Design

2.4.1. Segmentation Scheme

The panel size and shape will be particularly important for the panel support points, panel thickness, areal density, performance and cost. We have studied panels appropriate to 3 different segmentation schemes for the primary mirror surface. The first 2 segmentation schemes use trapezoidal shaped panels laid out in 6 and 7 rings of panels total. For these layouts, we have aimed (a) to have the panel shape aspect ratio symmetric when possible and avoid long narrow panels, (b) keep panel dimensions under 2m in size, and (3) maintain 12-fold symmetry in the layout when possible. We investigate other panel shapes and sizes to investigate those influences on performance and cost.

The layout for 7 rings of panels leads to panel shapes which are slightly better in aspect ratio. The sizes of 6-ring segmentation are 1.83m radial and those of 7-ring segmentation are 1.57m radial. The 7-ring panels are all less than 1.5m (60") in width. We expect that there will be some significant tooling expenses associated with handling panel sizes with widths over 1.5m (60"). The availability of key machines (coating chambers, CMM machines, etc) decreases as one crosses the 1.5m (60") boundary. For example, the availability of a coordinate measuring machine (CMM) up to 60"x80" is significantly better than larger machines at measurement specialty shops.

For a comparison in panel shapes, we have also generated a hexagonal segmentation. The 3 point support requirement for the panels leads one to naturally investigate panel shapes with 3-fold symmetry rather than 4-fold symmetry. Thus, we also have briefly investigated this panel shape.

2.4.2. Panel Design

Our baseline panel concept is a CFRP aluminum core sandwich panel for the ring segmentation schemes. Both the front and back surfaces of the panel will be curved and concentric. The front face sheet will be slightly larger than the core and back face sheet. This will provide close continuity of the front surface while allowing clearance for tip tilt adjustment of the individual panels without mechanical interference with adjacent panels. Face sheets of 1.5mm thickness will be used for both the front and rear surfaces. For the CFRP face sheets, we have chosen high modulus carbon fibers with a cyanate ester resin system. This unidirectional prepreg will be layed up as a 12 ply sheet using $[0/60/-60]_{2S}$ layup schedule. This will yield a quasi-isotropic sheet in x,y with high stiffness. Material choice is critical for the face sheets.

The 5056 aluminum honeycomb core will use 1/4" cell size and 0.001" foil. Aluminum 5056 is chosen over 5052 or commercial grade because of its higher stiffness and strength. This is the material of choice for critical applications in the aerospace industry (5052 is used for less critical aerospace applications). In our design, this choice will allow us to create a design with lower areal density (highest stiffness for lowest density). We will use a vented core configuration. The aluminum will be pre-treated for corrosion. A core tag of NB-101 glass reinforced film adhesive, 0.06" will be used between the aluminum core and the CFRP face sheets to prevent galvanic corrosion. The thickness of the aluminum core layer will depend on the panel size, shape and attachment points. This is discussed further in the next sections.

Our process utilizes a unique fabrication of the final surface over the glass, polished mandrel. The result is a precise large scale figure accuracy and nearly 1:1 surface roughness replication. For the symmetric, optical mirrors being fabricated at CMA, there is no astigmatism or other large scale error induced during the replication process.

2.4.3. Mirror Coating

Candidate coatings for the mirrors are available for the panels, including aluminum and gold thin films. Over-coatings must be investigated thoroughly to yield the required reflectivity across the entire wave band of interest. SiO and SiO_2 over-coatings are likely to meet the requirements for durability and antireflection. Aluminized coatings have been used over CFRP surfaces in several projects and appear to be more durable than coatings applied to glass surfaces.

3. FINITE ELEMENT ANALYSIS (FEA)

3.1. Parametric Analysis

CMA does the modeling and drafting in *SolidWorks*, a 3D design software. The FEA analysis is done with *Cosmos*, a package which integrates with *SolidWorks*. A key element of the FEA analysis is using the accurate material properties. This is especially critical and difficult for composite material design projects since the CFRP material properties can be highly dependent on the layup schedule and the fabrication. The values we have used in our analysis do have basis in testing done with past projects. In addition, we are currently doing extensive materials testing to verify the material values we assume. We have fabricated CFRP and sandwich composite samples which are currently being tested at Northern Arizona University. NRL (Naval Research Lab) is the funding agency for these studies.

Our initial baseline model was a panel for the 6 ring segment configuration. We have used a panel from the 5th ring (second to outside ring). This was chosen for its near square aspect ratio. For this panel we have optimized the location of the 3 point mount. The primary deviations under gravity are the inside corners where there is only support from single support point along the central axis. This is to be expected. We have investigated reinforcement with support beams on the back side but this is not a recommended solution. Simply making the panel thicker with the core material is the most direct means of creating a stiffer panel. This is also the most cost effective solution consistent with mass production manufacturing. The result is that a panel can be made which meets the technical requirements. Figure 8 is a representation of the panel under gravitational distortion for a 140mm thick core panel. These distortions would be acceptable under the CCAT specifications. This panel would have an areal density of 9.75 Kg/m^2 (excluding mounting point hardware).

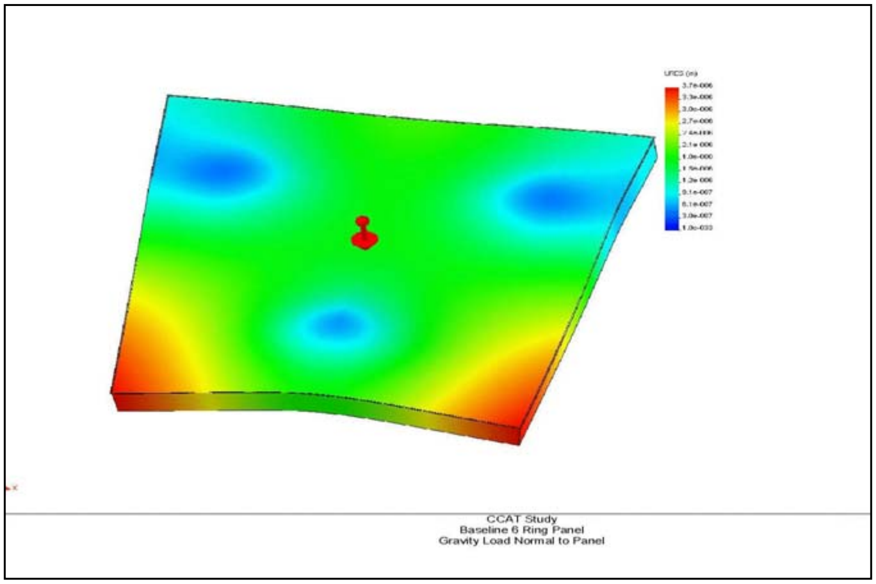

Figure 8. Deformations of 6 ring segmentation panel under gravitational loading.
Panel uses 140mm thick core. Plot scale is 0 to 3.7 μm.

The base model has been tested for loading under wind conditions. We assumed a test case of a 5m/s wind, applied head-on at 5,000m elevation. The pressure effect on the panel is much less than any gravitational effects. We feel that we can ignore the wind loading in the further analysis and concentrate on the gravitational distortion. Wind will, however, be a more significant effect on the mounting points and could be a concern when there is a gradient across the entire dish. The later effect will be particularly problematic for the pointing. The wind issue will be addressed again at a later time in the design process but was passed over for this preliminary phase.

We do not expect thermal loading to be a great concern for our panel design. The low CTE CFRP material will control the main figure of panel surface. The z-displacement will be significant due to the aluminum core. But this can be mitigated by choosing a mounting point through the panel and closer to the front face sheet. There are economical solutions to the z-direction thermal expansion if one wishes to implement them. For the current analysis, we have not taken thermal effects into consideration.

The CTE (coefficient of thermal expansion) of the CFRP sheets is similar to pyrex glass. However, CFRP has a much higher thermal conduction (between aluminum and steel in value). The result is that CFRP will thermalize rapidly. With the CFRP and aluminum core panel structure, we do not expect that there will be a significant thermal gradient across the panel under normal load conditions. This fact, combined with the low CTE, results in a structure which is relatively insensitive to thermal effects. Due to these considerations, we have not done an extensive analysis of the panel under thermal (gradient) loading at this stage. This complex analysis is left for later stages in the development. We also feel that it is more effective to test a sample panel under thermal load conditions rather than only analyze the predicted behavior with computer models.

After optimizing the baseline panel, we analyzed alternate panel sizes and shapes (the two alternate segmentation schemes). The first alternate case is a 7-ring panel. We chose the outermost panel for that analysis since it is the most difficult case. A panel of performance similar to the baseline panel can be fabricated more easily. A core thickness of 100mm can be used, with a resulting areal density of 8.25 Kg/m^2 for the panel. Figure 9 illustrates the deformations under gravity loading.

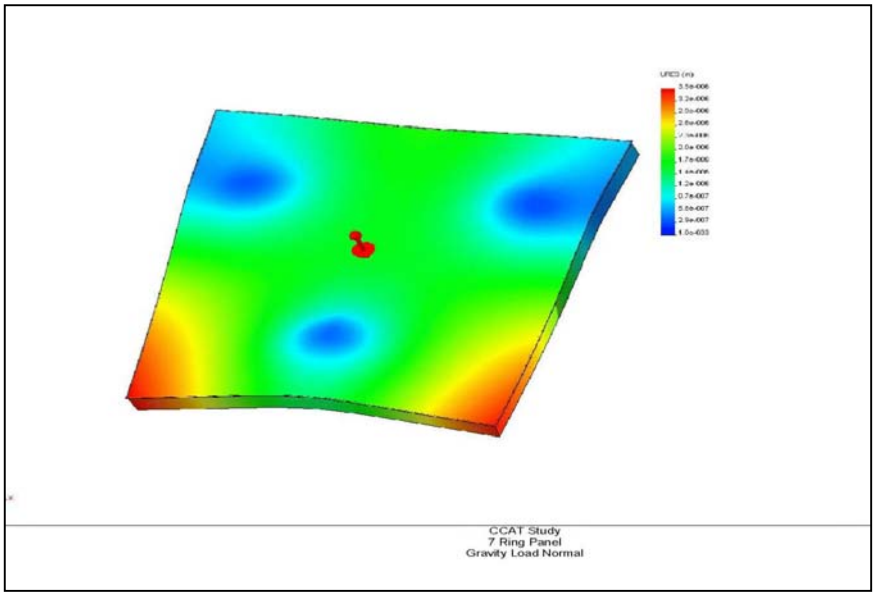

Figure 9. Deformations of 7 ring segmentation panel under gravitational loading.
Panel uses 100mm thick core. Plot scale is 0 to 3.5 μm.

A second alternate panel of hexagonal shape was also analyzed. The three point mount leads one to consider this shape. It is not surprising that this panel shape performs better than the trapezoidal shaped panels. To obtain the equivalent performance with this panel shape, we can reduce the panel core thickness to 65mm. This results in an areal density of 7 Kg/m^2. Figure 10 illustrates this panel under gravitational loading. The hexagonal segmentation scheme is not viewed favorably by the CCAT project because of the large number of independent panel shapes. But this issue can be mitigated by a judicious choice of molds for the fabrication shapes. We believe that we can reduce the number of molds needed for this segmentation scheme to roughly 8 shapes (of oversized molds).

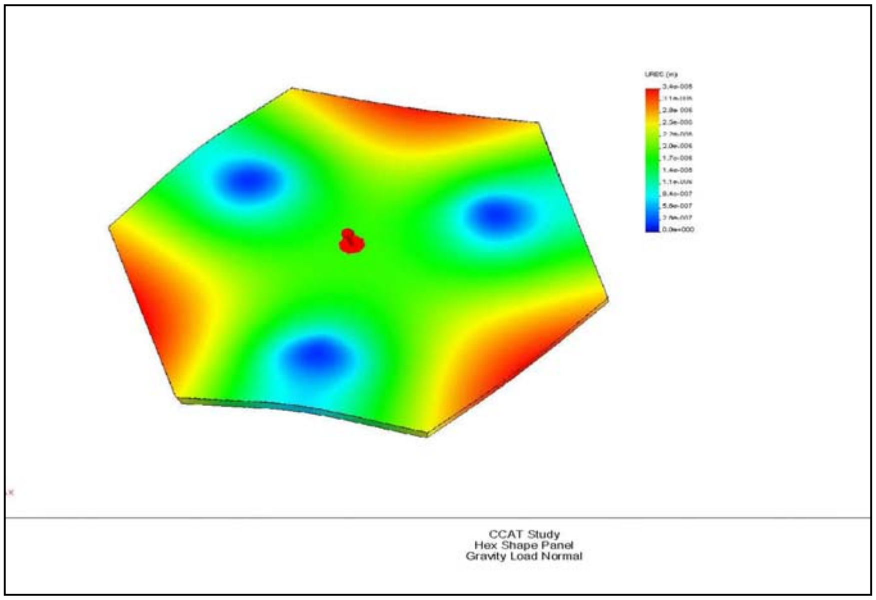

Figure 10. Deformations of hexagonal segmentation panel under gravitational loading. Panel uses 65mm thick core. Plot scale is 0 to 3.4 μm.

To further investigate the baseline (6-ring) panel design , we have tried constraining the panel at more than 3 points. A five point mounting system would do a much better job of supporting the trapezoidal shaped panel than a 3 point mount. In such a case, the panel thickness could then be reduced to about 100mm core thickness (and 8.25 Kg/m^2 areal density) for the large, 6-ring trapezoidal panels. The support then relies on the backup structure or active control. However, the CCAT primary mirror plans call for all reflector panels to be 3 point mounted and controlled, so this design solution is not applicable here.

3.2. Design Conclusions

A panel which meets the design constraints can be fabricated for any of the segmentation sizes and configurations considered. But the size and shape of the panels do have consequences in other areas. These consequences may influence other areas of the primary mirror design.

1) By reducing the panel size using 7 rings instead of 6 rings, it is possible to reduce the areal density by more than 15%. Further, a hexagonal panel scheme could reduce the areal density by 28% over the baseline 6 ring design. This could be a significant factor for the weight on the primary mirror truss structure and the dynamical performance of that primary mirror. A 2 Kg/m^2 difference in areal density of the panels results in a total weight change of 1 metric ton for the segmented primary mirror panel system.

2) The costs of these various panel configurations will scale similarly to the areal density. There is greater material costs and there is greater difficulty in fabricating a thicker panel. Additionally, the handling of larger panels requires more people (and labor cost), particularly when the total panel weight increases.

3) Molds for a 7-ring segmentation scheme would be of lower cost than for the 6-ring configuration due to the lower area of glass to be cast, handled, and polished.

4) Improved performance for the trapezoidal panel shapes can be achieved by using 4 or 5 points for support rather than 3 point supports. This is not as critical for the hexagonal panel shape. However, 3 point mounts are strongly favored for overall project considerations. There is a tradeoff between panel weight and performance versus more mounting points. The panel deformation errors are small and there would not be large stresses induced by the panels onto the backup structure in configurations of more than 3 mounting points. This is a design philosophy issue. Namely, whether to treat the backup structure and panels as an integrated structure or to treat them as separate elements (with the panels overly rigid on their own).

5) Costs will be higher for larger panel sizes (per area costs) because of the greater risks involved during fabrication of each panel component.

6) The hexagonal panel segmentation scheme offers some advantages in weight, symmetry to mounting points, and potential cost savings. It is worthwhile reviewing this option in the context of the rest of the reflector structure. It, of course, has large implications in other design areas.

7) The panel distortion plots (figures 8-10) indicate that it may be difficult to pick a representative position for edge sensors when trapezoidal panel shapes are used with 3-point mounts. This is understandable, given the mis-match between the panel shape and the support geometry. The hexagonal panel shape, however, offers clear choices on locating the edge sensors. This may be an important consideration if edge sensors are a key component to the primary mirror surface measuring and active control system.

Table 1: Summary of Design Conclusions

	Panel Segmentation Scheme		
	6 ring trapezoidal	7 ring trapezoidal	hexagonal
number of panels	162	228	210
areal density	9.8 Kg/m^2	8.3 Kg/m^2	7.0 Kg/m^2
total reflector mass	4740 Kg	4010 Kg	3390 Kg
shape & aspect ratio	worse	acceptable	good
attachments *	unnatural match to 3-point mount	unnatural match to 3-point mount	natural match to 3-point mountt
performance	acceptable	better	better
cost	baseline +20%	baseline cost	baseline -10%

* Multiple (>3) attachment points will improve performance and reduce the areal density for trapezoidal shaped panels (see text).

3.3. Error Budget

Based on our studies to date, we can estimate an error budget for our panel design as follows.

Error budget for all size scales greater than roughly 200 mm

Item	rms (μm)
mold	1
replication	1.5
gravitational	2
wind (5 m/s)	1
absolute temp change	1
Thermal gradient	0.5
aging	0.5
Total RSS	3.1
Current CCAT spec	5

Error budget for sub-aperture of less than 200mm diameter

Item	rms (μm)
mold	0.05
replication	0.10
thermal gradient	0.20
aging	0.30
Total RSS	0.38

For the sub-aperture use, we have assumed that z-adjustment errors of the panels will be accounted for with active control. Thus, the errors due to gravity, wind and absolute temperature change were not relevant. For the small sub-panel aperture, there will not be a gradient across the sub-aperture. It is anticipated that active panel adjustment will be used to compensate for those errors.

3.4. Other Design Concerns

Based on the experience of the SMT project, there is a concern about possible, large scale panel figure error during replication. The SMT panels showed a very slight warping of the panels after removal from the mandrels. These errors were small in all cases, of the order of 10-30 μm, and do not introduce hazardous residual forces or moments in the panel (or back up structure). For the SMT, this slight, large scale error is removed by supporting the panels on five or six adjustors (attached to the CFRP back-up structure) and the adjustment removes the warping error.

For a trapezoidal shaped panel, the weakest resistance to distortion will be a warping motion just like that observed in the SMT panels. It is difficult for us to computer model such warping which may result during the replication process. The CCAT specifications call for panel support at only 3 points, so removal of any potential warping is not possible with the support points. The CMA replication process is different than that used by MAN for the SMT panels. And, CMA has avoided these sorts of large scale errors during fabrication of other, large mirrors. However, the potential for slight, large scale warps is a concern for trapezoidal panels which should be explored further. We propose that a next step in development would be to fabricate a panel of similar shape using an existing mandrel to verify the CMA process for trapezoidal shapes.

4. CRITICAL RISK ASSESSMENT

We have evaluated the various risks of this technology for a potential project. The technology is well established and the risks are not great. The table below summarizes the 3 most important risks and approaches to mitigation.

Table 2: Critical Risk Summary

Rank & Trend	**Risk ID**	**Risk Description**	**Approach & Plan**	**Status**
1 Criticality: High	**CMA-1** Planned closure: PDR	**Potential Trapezoidal Panel Warp using 3-point mount** • There may be some residual warp in the trapezoidal panels due to lay-up and core design; This is not easy to computer model. • Trapezoidal panels are not optimal with 3-point mounts.	**Mitigate** • Make test panels in next design phase to investigate for potential problems. • Use alternate panel shapes with 3 fold symmetry. • Or, use more attachment points so that constraint symmetry matches panel symmetry	Propose test panels using existing mandrels which are similar in shape.
2 Criticality: Medium	**CMA-2** Planned closure: Complete fabrication with mandrels	**Handling of Glass Mandrel** • Potential for breakage in use and handling. Manufacture of mandrels is expected to be >12 month delivery and has a potential for significant delays (1 year). • Potential for damage in shipping of mandrel to panel manufacturer.	**Mitigate** • Care and adherence to procedures. • Propose alternate double replication approach which must be confirmed on a demonstrator or prototype panel. Potential cost saving on molds.	Propose evaluation panel to research alternate approach.
3 Criticality: Medium	**CMA-3** Planned closure: Delivery of panels	**Durability of Surface** • Probable that a new coating is needed compared to past submm panel projects. Similar to glass optical coating technology. Durability not known.	**Mitigate** • Study problem with tests in the prototype phase of the panel study. • Characterize durability of coatings.	Propose testing plans for next phase

5. CONCLUSIONS AND FURTHER STEPS

As a next step in the development, we recommend that a prototype (or demonstration) panel be fabricated using the same process anticipated for the CCAT panels. Ideally, this should be a full size panel with similar curvature to the anticipated CCAT surface. A prototype panel will do more than just verify the CMA fabrication process. The concerns about possible panel warpage can be studied. If necessary, the design could be modified to address any problems. Dynamic and static load testing of the panel will be compared with the FEA modeling and verify (and confirm) the design.

We recommend that additional, small sample panels be fabricated for environmental tests. These samples can be deployed in a test setup at the potential site in Chile. Additional samples can be subjected to accelerated aging tests. The surface layer treatment is of particular concern for this testing, not the fundamental panel structural integrity.

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