Opto-mechanics of the Constellation-X SXT Mirrors: Challenges in Mounting and Assembling the Mirror Segments

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ABSTRACT

The Constellation-X Spectroscopy X-Ray Telescopes consists of segmented glass mirrors with an axial length of 200 mm, a width of up to 400 mm, and a thickness of 0.4 mm. To meet the requirement of < 15 arc-second half-power diameter with the small thickness and relatively large size is a tremendous challenge in opto-mechanics. How shall we limit distortion of the mirrors due to gravity in ground tests, that arises from thermal stress, and that occurs in the process of mounting, affixing and assembling of these mirrors? In this paper, we will describe our current opto-mechanical approach to these problems. We will discuss, in particular, the approach and experiment where the mirrors are mounted vertically by first suspending it at two points.

Keywords: Constellation-X, Spectroscopy X-Ray Telescopes, Lightweight optics, Mirror mount, Opto-mechanics

1. INTRODUCTION

The Constellation-X Spectroscopy X-Ray Telescopes (SXT) aim to make significant discoveries in astrophysics with high-resolution spectroscopy[1,2], by combining high-resolution detector with telescopes with large effective area over the soft x-ray band (of over 10^4 cm^2 at 1.5 keV.) To achieve this with grazing incidence Wolter type I optics, the mirror surface area and mass permitted by the spacecraft require an areal density of roughly 1 kg/m^2. Using glass as the substrate (with density ~ 2.5 x 10^3 kg/m^3), the thickness of these mirrors is limited to approximately 0.4 mm. This is indeed the baseline thickness of the SXT.

This thickness (or thinness) requirement of the mirrors presents an opto-mechanical challenge in mounting them without compromising their figure for focusing. The mission requirement on imaging of the telescopes is 15 arc-seconds, measured in half-power-diameter (HPD). The thin mirrors are therefore to be aligned and mounted, in the telescope housing, with precision at a level of a micrometer. Given that the baseline design of mirrors has an axial length of 200 mm, 1 micrometer error peak-to-valley in low order axial figure error, for example, in sag, results in an error of 2 arc-seconds in the mirror's axial slope, 4 arc-seconds in reflected rays, which is further compounded, in a double-reflection, with a similar error from the secondary mirror. The limit on the amplitude of figure distortion is even more stringent for error of higher spatial frequency.

We are faced with many challenges in building these telescopes[3-5], for instance, the survival of the thin glass shell under launch load. A substantial area of concern is how the mirror figure is distorted due to various stresses. These include residual stress of the mirror from the thermal treatment during the fabrication process, coating stress from the deposition of the metal layer for x-ray reflection, thermal stress on the mirrors from the telescope housing due to material incompatibility, etc. We also need to understand gravity distortion in ground testing, alignment and assembly, and their subsequent relaxation when the telescope is launched into space. Gravity distortion in ground tests limits our ability to qualify the performance of the mirror. Imposing better boundary conditions on the mirror by, for example, affixing the mirrors at more points or more strategic positions will reduce the gravity distortion, but will exacerbate the thermal stressing of the mirror arising from incompatibility of coefficients of thermal expansion (CTE) with the telescope housing. In fact, even with a CTE match material, the environmental thermal gradients, coupled with the different thermal masses between the mirror and module housing, is not negligible.

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In this paper, we will focus on the discussion of gravity-induced distortion and its trade space with thermal distortion. To discuss in concrete terms, we will illustrate the issues associated with mounting distortion typical of a mirror with a nominal diameter of 485 mm, and an angular span of about 55 degrees. The angular size reflects the typical size of the mirrors currently in fabrication for technology development. The arc length of this mirror is about 224 mm (with slight differences, due to the conical geometry, between the fore and aft ends of the mirror, and between primary and secondary mirrors). With a 200 mm axial length, the mirror is actually not too different from a square when viewed from the front surface. The ideal axial sag of this mirror, for focusing, by design, is about 1.1 micrometers.

To facilitate discussion, we shall use the following nomenclature. We shall refer to the three dimensions of a mirror in its natural cylindrical terms: axial, azimuthal and radial. When orthogonal coordinates are used, we choose to take axial direction as the z-axis, the direction towards the center of the mirrors as the x-axis, and the orthogonal direction (nearly across the face of the mirror) as the y-axis. If the segment were part of the imaginary cone, the cone axis will coincide with the z-axis, with the cone apex in the negative z direction. The boundaries in different axial positions are referred to as axial ends, or simply, ends. The end with a larger radius, where the incident x-ray enters, is the fore end; while the one with a smaller radius, where x-ray exits, is the aft end. The boundaries in the azimuthal direction is referred to as azimuthal edges, or simply, edges. Generally, there is no distinction between the two edges. For the purpose of this paper, we will focus mostly on the axial sag (second order term) of the mirror figure but not on distortion with higher spatial frequency. In this context, there will also not be specific distinction between a hyperbolic or parabolic axial figure, for mirrors in the primary or secondary stage.

2. DISTORTIONS OF MOUNTED MIRRORS

2.1 Considerations on gravity sag

Depending on the orientation and specific ways of supporting it, a typical Constellation-X glass mirror, supported by a small number of fixed boundary points, will suffer gravity sag of different magnitude. For example, the magnitude of gravity sag for a horizontal beam (or flat plate) with rectangular cross-section, supported at or near the ends, is $\Delta = \frac{f}{32}\frac{\rho g}{E}\frac{L^4}{\tau^2}$, where Δ is the maximum sag near the middle of the plate. The other notations have their usual meanings: ρ is the density of the material, g the acceleration due to gravity, E the Young's modulus of the material, L the length and τ the thickness. The factor g can be effectively smaller with a sine factor, if the beam is not horizontal. The factor f is typically of the order of unity, and it depends on the types of supports and the locations of the supports. For example, f is 1 and 5, respectively, for a horizontal beam fixed and simply supported at the two ends, and -0.5 and 0.1875, respectively, for a beam simply supported and fixed symmetrically at a quarter of its length from the ends. (Negative sag indicates that the shape of the beam is convex instead of concave upward.) Using a typical length or width of the SXT mirror of 200 mm, and a Young's modulus of about 70 GPa for the glasses under studied for the Constellation-X SXT, the gravity sag is about $f/10$ mm. This magnitude of sag is generally too large for our application even for a small value of f value such as ~ 0.1. (To show the contrast, we compare this to the designed second order amplitude of the mirror of about 0.001 mm.) We should also note that with a small bond line that is desirable for the bonding, the boundary conditions at the bonds are closer to a simple support with little constrain in the local rotation of the mirror, than a fixed support. Thus, a very small f value, compared to unity, is not justified. This kind of gravity sag from a beam illustrates the order of magnitude of the sag of mirror supported at two or a small number of points in the azimuthal direction where the approximation of a cylindrical or conical mirror to a plate is reasonable in terms of elastic deformation. The approximation is not good for axial sag near the middle of the mirror, as it cannot be bent like a beam without anticlastic reaction from the rest of the mirror. Nevertheless, such consideration is consistent, in orders of magnitude, with finite-element modeling. To reduce the gravity distortion without violating other constraints such as the dimension and thickness (from mission science requirement, as explained above), or the choice of material (for practical mirror forming), we are left with the options of optimizing the strategic locations and numbers of the bonds, and the orientation of the mirror. We will, in this paper, concentrate on the orientation of the mirror, and discuss the process of mounting the mirror in a vertical fashion, in the section 3 below.

2.2 Considerations for thermal distortion

A thin mirror bonded at various points or edges to a structure with different material will suffer from thermal stress due to a CTE mismatch, if placed at a different temperature. For example, a thin beam, if constrained at both ends, will tend to buckle if temperature rises. Assuming the beam preserves its length (that is, hypothetically, not compressed), the transverse deviation (sag) is $\Delta \approx \sqrt{3\varepsilon/8}L$, where ε is the strain, in this case due to thermal expansion ε = α δ*T*, and *L* the length. This is generally an over-estimate as the beam is shortened by compressive stress. Taking that into the account, and assuming uniform load and temperature for a simple column, it will buckle when the load exceeds the Euler load $W_c = \pi^2 EI/L^2$, where *E* is the Young's modulus, *I* is the cross-sectional moment of inertia. For a rectangular plate, the cross-sectional moment of inertia is $I = b\tau^3/12$, where *b* is the beam's width, and τ is its thickness. The critical strain is, therefore, $\varepsilon_c = (\pi^2/12)(\tau/L)^2$. Putting in typical dimensions of the Constellation-X mirror of τ = 0.4 mm, *L* = 200 mm, the critical strain is $\varepsilon_c = 3.3 \times 10^{-6}$, which is comparable to (and exceeded by) the thermal strain of the glass in just 1°C. The first buckling mode for a simply supported beam will have a transverse deflection[6] of $\Delta = (2L/\pi)\sqrt{\varepsilon - \varepsilon_c}$. For the glass with coefficient of thermal expansion of $\alpha = 4.5 \times 10^{-6}$ /°C, and for 1°C temperature change, the maximum deflection is still very large, Δ = 140 μm.

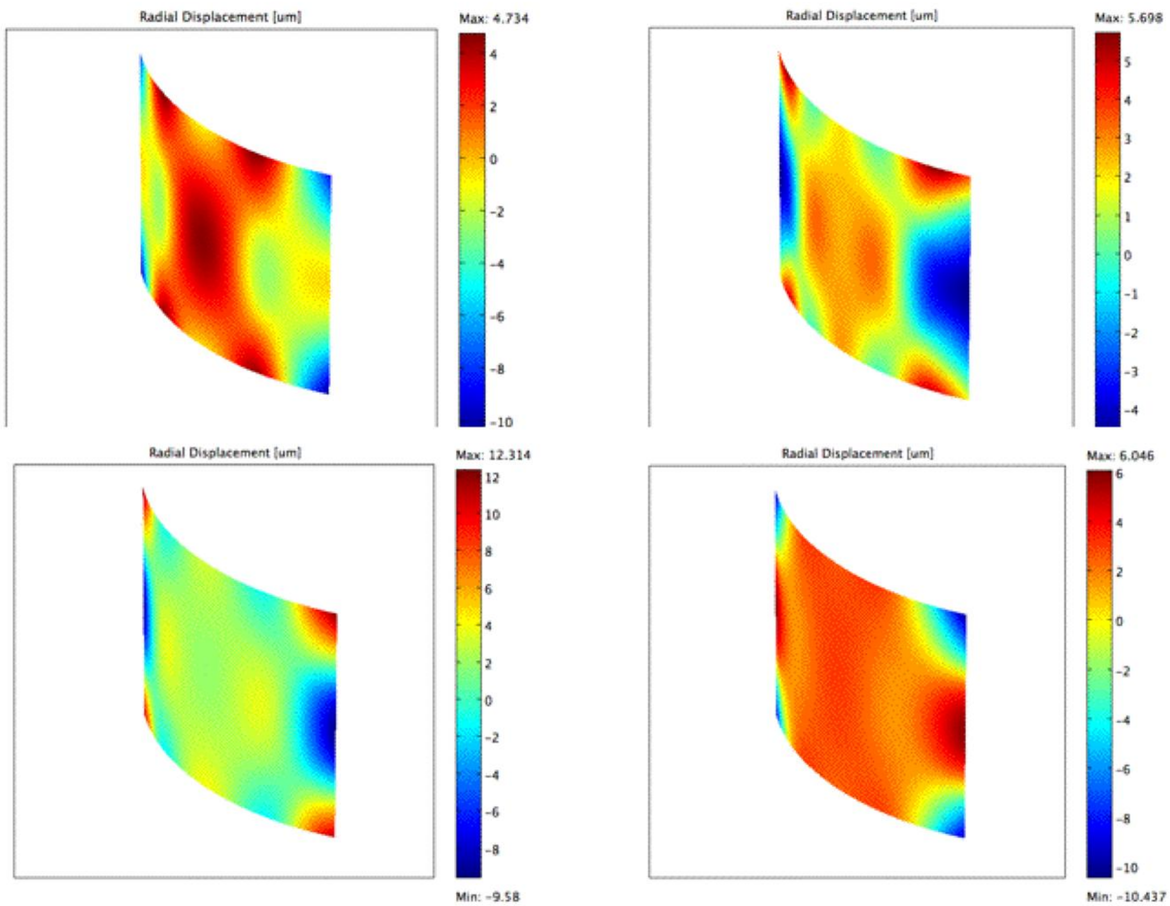

Fig. 1. Finite element model of a curved piece of mirror, for a temperature difference of +1°. The dimension of the model are: radius 242.5 mm, thickness 0.4 mm, axial length 200 mm and an angular span of 60°. The bond points are located axially at 50 mm (¼ of the axial mirror length) from the mirror ends, and azimuthally at ±15°, ±20°, ±25° and ±30° (the central meridian is defined as at azimuthal 0°). The data show the radial component of the displacement.

A finite element model of a plate, constrained at the two end by just boundary lines (but not the full boundary surfaces) that allows rotational degrees of freedom for the boundary surface, gives a maximum deflection at the middle of the plate as Δ = 85 μm/°C. For constrains only at two points, rather than the whole edges, the deflection is further reduced because the stress can be re-distributed to its neighboring region, relieving the stress along the sector joining the two points. Finite element model for a square plate constrained at two points at the end of the middle sector gives a maximum deflection along the sector of Δ = 37 μm/°C. These are therefore very significant distortions that need to be addressed.

More representative finite element models (see also ref. 7) of a curved piece of glass attached only at 4 points, at various locations, are shown in figure 1 above. These models are for mirrors with fixed dimensions (radius = 242.5 mm, thickness = 0.4 mm, axial length of 200 mm, and angular span of 60°). The bond points are idealized points fixed in 3 translational degrees of freedom, and their positions are 50 mm from the ends and azimuthally at ±15°, ±20°, ±25° and ±30°, which are at the edges of the mirrors. Since we are concerned with thermal distortions, gravity is turned off in these models. The axial profiles at different azimuths show a variation from concave to convex, depending on the location of the bond points. The maximum radial distortions are about 5-12 μm/°C for these bond configurations. This is a significant scale that implies a requirement on temperature homogeneity between the mirror and its mount is of the order of a fraction of a degree.

To investigate the thermal deformation further, we set up a glass mirror with a typical radius of 242.5 mm, a length of 200 mm, a width of about 125 mm and a thickness of 0.4 mm. This was then bonded to a strong back made of the same glass, for CTE compatibility, at 4 rectangular points, each at a distance from the boundaries, both in length and width, of about a quarter of the full dimensions. The bonding was done with small beads of epoxy on steel studs of equal length. It is assumed that any extensions of the studs due to thermal variation are identical and are essentially perpendicular to the plane of the surface, and did not involve any lateral strain. Lateral strain tangential to the mirror surface may buckle the mirror. The combination was then subjected to a higher temperature, about 6°C above room temperature at which the mirror was bonded. The mirror and the glass mount combination were then removed and they allowed to cool in the laboratory. The experimental parts and instrument were enclosed in a plastic tent to minimized forced convection. The temperature of the glass mount is monitored *in situ* with thermocouples. To get around the problem of distorting the mirror with thermocouple directly placed on it, an identical mirror + mount article was arranged near the test article to monitor the temperature of the mirror. Both the thermocouples and the articles under tests are calibrated before hand. The cooling time scale for the thin mirror was determined to be about 2 minutes in the laboratory condition without forced convection. The glass mount, due to its mass, cooled more slowly. The temperature difference between the glass mount and the mirror is reduced to about 5% in 2 hours. The mirror surface was, during this period, measured interferometrically, to obtain its axial profiles as functions of azimuths. The dependence of average sag on temperature is shown in the figure below. The sensitivity is shown to be 3.3 μm/°C, quite consistent with models.

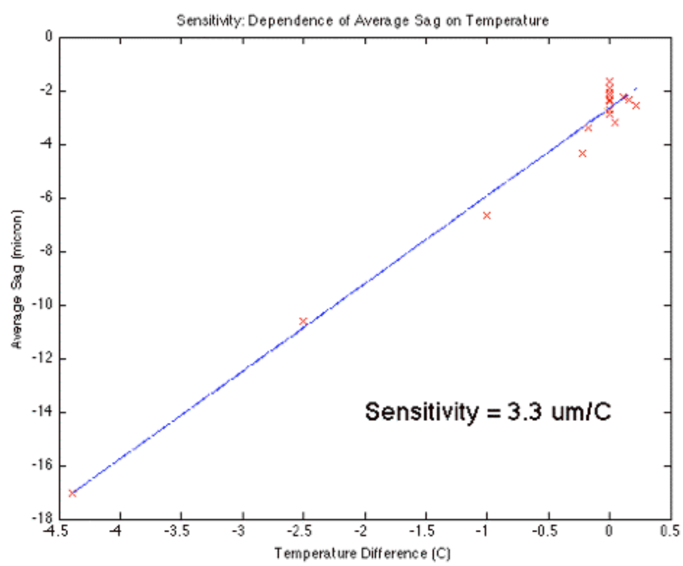

Fig. 2. Dependence of average axial sag on temperature difference, as measured on a 0.4 mm glass bonded at 4 points on a glass plate of the same material. The sensitivity is measured to be 3.3 μm/°C.

The experiment also reveals the fact that, even with a perfect CTE-matching material for the mount, temperature variation coupled with latency of thermal response, can effectively produce a temperature difference. For example, in our laboratory, there is a diurnal cycle of temperature due to the controls of the ventilation. The temperature peaks in the afternoon and bottoms out early in the morning. Since it is a time scale of hours for the mount to reach thermal equilibrium, the mount's temperature therefore lags behind that of the mirror. It is estimated that the temperature difference could be as much as 0.2°C in the afternoon when the mirror is bonded. It was measured to be about 0.25°C (mount higher), and about -0.1°C in the morning when the mirror was taken for metrology (when the bonding strength is presumably completely realized). Assuming a linear change, the typical rate is ≈ 0.02°C/hr. Since the epoxy cures over a similar period of time, the average effective temperature difference during the epoxy curing period is ≈ 0.08°C. Coupled with sag's temperature sensitivity of 3-4 μm/°C, this shows that when the mirror + mount is at thermal equilibrium, the mirror will suffer an additional sag of ~ 0.3 μm. All these factors should be considered in the final design of the housing of the telescope module, where arc-second precision in the optics are required.

3. VERTICAL MOUNTS

3.1 General mounting schemes

In the following, we will address various mounting schemes, with a view towards final integration of the telescope. We will discuss the vertical mounting schemes, which minimize gravity sag and, in particular, discuss the result of a specific implementation that starts by suspending the mirror at 2 points at the top (fore) end.

In order to achieve final alignment and integration of mirrors in the telescopes, we are devising a step-by-step technology development plan from the fabrication of mirror segments to integration of telescope modules. A simplified flow diagram illustrating those steps is shown in figure 3.

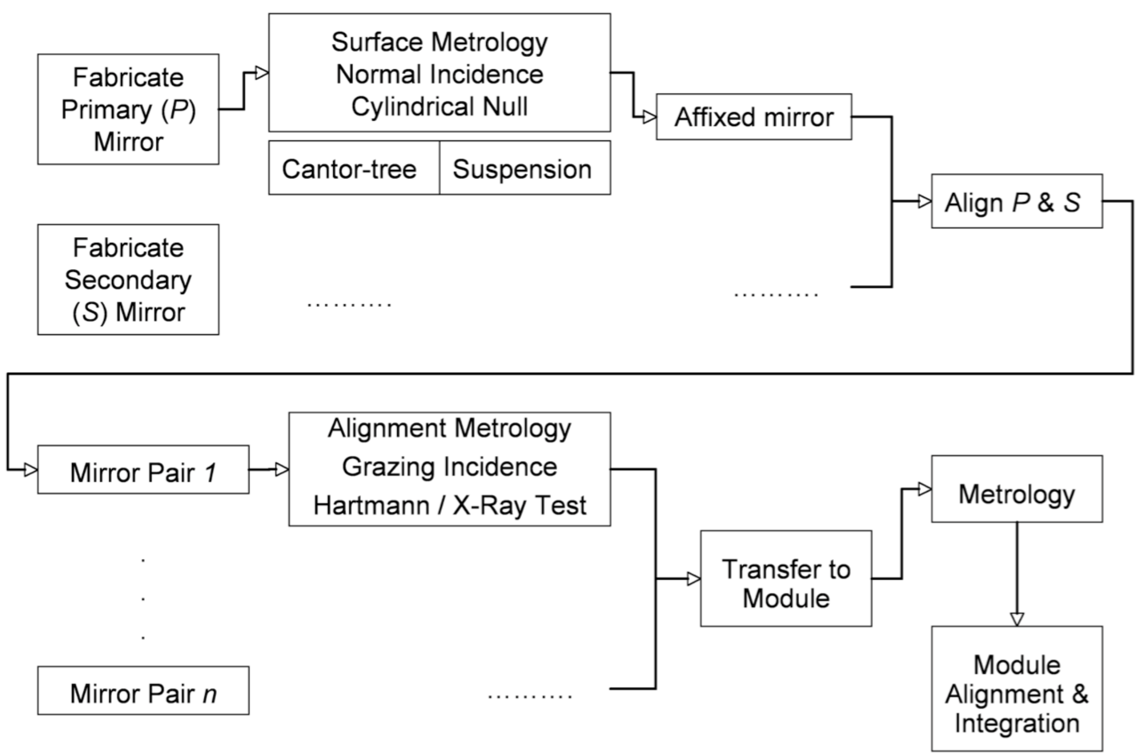

Fig. 3. Flow chart outlining the process for alignment and integration of mirrors.

Each step represents more or less a technology development area. The crucial installation of mirrors into the telescope housing is itself completed in a two-step process: first, by temporarily mounting an individual pair of mirrors into a "metrology mount", and subsequently, by "transferring" the mirrors into the telescope modules. This two-step process is necessary due to the fact that the access space of the telescope module housing is quite limited, and the inner-to-outer installing scheme, which is presently the default scheme, does not allow normal incidence metrology to be used. With limited space and metrology, we have to perform the basic mirror mounting and detailed metrology of specific mirrors in a separate mount, and transfer the mirror to the telescope module housing in separate procedure. This procedure will have to be separately qualified. The temporary metrology mount has all the space in front of the mirror surface and metrology available to it, and it is only mounted at the backside. This allows the individual mirror to be brought to the telescope module housing, where it is mounted into the housing by affixing it only at a number of points at the perimeter. The process can then be repeated for the mirror in the next shell, until the whole module is populated. Grazing incidence metrology is always available throughout the process. The final unit can then be qualified at the module level. The modular approach divides the risk of mirror integration into that of integrating the mirrors into the telescope modules and that of integrating the modules into a full telescope. Eighteen primary-and-secondary combined modules are needed for each telescope if the inner modules are 60 degrees wide and the outer modules are 30 degrees. Presently, the inner radius of the telescope is chosen to be 15 cm, and the outer radius 65 cm. The azimuthal dimension ranges from 15 cm to about 34 cm. The break between the inner and outer module is chosen to be at the radius of about 34 cm, so that the largest mirror in the inner modules are about the same size of those in the outer modules.

We have previously investigated gravity and other mirror distortions under both mirror "horizontal" and mirror "vertical" mounting configurations. The vertical and horizontal configurations refer to the general orientation of the optical axis of the mirror segment. These mounts are primarily metrology mounts but they serve also as a platform to transfer the mirror into a mounting in a permanent flight setting.

To minimize distortion, the vertical orientation is a more favorable configuration. The gravity sag is smaller as the force no longer acts perpendicular to the mirror surface. This has a distinct advantage in the alignment of mirrors and their integration into the telescope housing. Nevertheless, the horizontal orientation is imposed on us via experimental constraints. To test of mirrors in the x-ray beam, the mirror is presently required to be horizontal. We use a point x-ray source at a distance to create a near parallel x-ray beam at the mirror aperture. As of now, our facility has a beam line of 600m and it naturally demands a horizontal configuration. There are two possible configurations of a horizontal mount: one with the mirror surface facing up, and one with the mirror surface facing sideways. Either way, to minimize possible distortions due to gravity, we will have to support the mirrors at more strategic locations and model the mirror in more detail to remove those terms from our ground measurement. Issues concerning testing a mirror pair in the x-ray beam are discussed in separate papers in this volume.[8,9]

To approach mounting the mirror in a vertical (or near vertical) orientation, three approaches has been taken: An active adjustment approach implemented as the Optical Alignment Pathfinder (OAP), a self-adjusting mechanism called the Cantor-Tree mount, and a passive mounting scheme called the suspension mount. In OAP, a mirror is mounted in 10 slots, 5 at each end. These slots are themselves movable in the radial directions so that the mirror can be actively "tuned" at 5 azimuthal sectors, in an attempt to achieve the perfect radial positions and axial figure simultaneously[10]. The Cantor-Tree is a more passive approach, in which the slots come in pairs. Each pair sits on a swivel which itself forms a leg of the next lower level of a revolving structure. We constructed an 8-point tree (4 at each of the mirror ends) and have been using it for metrology[11,12]. By design, the mounting points are not externally adjustable, except that the mirror can be kinematically tilted. To take the passive approach to a stage where we can have the mirror rigidly bonded to a structure, we devise what is called the Suspension mount. In such a scheme, the mirror is first suspended in such a way that the central meridian is vertical (by pre-determining the suspension points and the mirrors center of gravity); the mirror is then bonded from the backside to a CTE-compatible strong back. This allows the mirror to be transferred elsewhere for metrology or integration. The approach, due to its passive nature, assumes a mirror fabricated into a figure that is acceptable (see, for example, ref. 13 for a discussion of the active vs. passive approaches.) In the following section, we will discuss some result from mounting the mirror in this fashion.

3.2 Suspension Mount

We evaluate the telescope mount/assembly concept with mirrors of a typical dimension (around 250 mm in radius, 0.4 mm in thickness, and 55 to 60 degree in angular span - the widths are therefore 226 mm to 245 mm across, somewhere in the mid-range between 150 and 340 mm.) The suspension mount is a simple concept where the mirror is first suspended so that it is essentially vertical along the axial direction, to minimize the effect of gravity sag. More precisely, since the mirror is not part of a perfect cylinder, only the middle meridian is vertical. This is achieved by suspending the mirror at pre-determined points. The mirror is then affixed at the back to a strong back by advancing the structure in from a larger radial position. The structure is itself mounted on stages with all 6 degrees of freedom so that the mounting posts can be aligned with the mirror. Presently the bulk of the mounting structure is made of same glass as the mirror, to minimize problems with CTE mismatch. The mounting posts, however, are made of stainless steel. These are adjustment screws with a fine 0.25 mm pitch (they have the same length to begin with.) Once the attachment screws are judged, visually, to make contact with the mirror, a small bead of epoxy is applied to the tip of each of them after retracting the whole strong back, before advancing it again to bond.

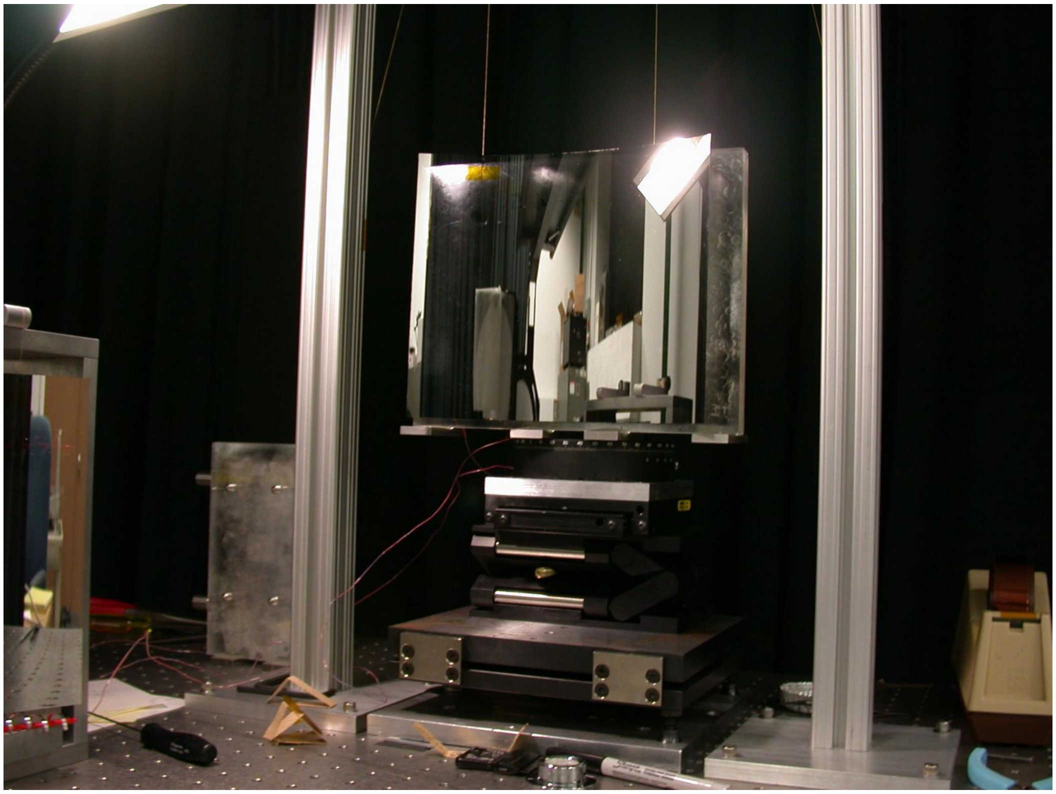

Fig. 4. Experimental set up of the suspension mount. The mirror, with cone opening upward, is suspended at two points at the top with Kevlar strings. The strings run parallel to the mounting mechanism at the top of the frame. The attachment points are determined such that the central meridian of the mirror is vertical. A strong back, made of the same glass, advances from the back to make contact at 4 posts. Contacts are made by adjusting the strong back's orientation and position. Additional fine adjustment is possible by advancing the fine-pitched adjustment screws. Temperatures of various components are monitored with thermocouples.

The suspension and bonding of the mirrors has proved be successful. We implemented a simple 2-point suspension scheme in which the center of gravity lies in a vertical plane containing the two suspension points. Basically, for a circular arc with radius R and angular span Θ, the center of gravity lies in the line of symmetry and is at a distance $x_c = R\ \mathrm{sinc}(\Theta/2)$, where the sinc function is defined as $\mathrm{sinc}(x) = \sin(x)/x$. For a conical surface, the radius varies linearly at different heights of the cone, so the center of gravity is essentially a weighted average over the radii: $x_c = (R_t + R_b)/2\ \mathrm{sinc}(\Theta/2)$, where R_t and R_b are radius at the top and bottom of the conical mirror. This is corrected for the non-zero thickness of the mirror. Further correction can be made to allow for a small error in cutting the mirror into precise dimension at the top and bottom of the mirror (thus the mirror may not have the same angular span from top to bottom.). The cutting precision is being improved but at the moment this error is not a limiting factor of the precision in the suspension scheme. Once the position of the center of gravity is determined, the positions of the two suspension points can be determined for any orientation of the mirror. The tilt of the suspended mirror is measured with a digital protractor with a precision of 0.01°.

For bonding, we implement a simple 4-point bond pattern. A 3-point kinematic mechanism would be simpler but it is less symmetric. For a 4-point mount, more adjustment in the yaw angle is needed in order to bring all 4 points in to contact with the mirror if the 4 points are fixed relative to the glass mount fixture. We also use a fixture that has retracting and advancing mechanism in the form of precision screws (fine 0.25 mm pitch), so that the 4 points can always be brought in to contact with the mirror by advancing or retracting those adjustment screws. Once that alignment is accomplished, the whole glass mount fixture is retracted, tack-bonding material added to the tip, and the fixture is brought back to its original position for the adhesion to take effect. From finite-element analysis, 0.1 degree in tilt is easily tolerated so that small error due to, for example, imperfection in the determination of the "contact", the effect from surface tension of the adhesive, etc., are not important in the procedure. The adhesive, in our case epoxies, are left to cure over a long time (~ 1 day) to minimize distortion due to rapid uneven epoxy shrinkage.

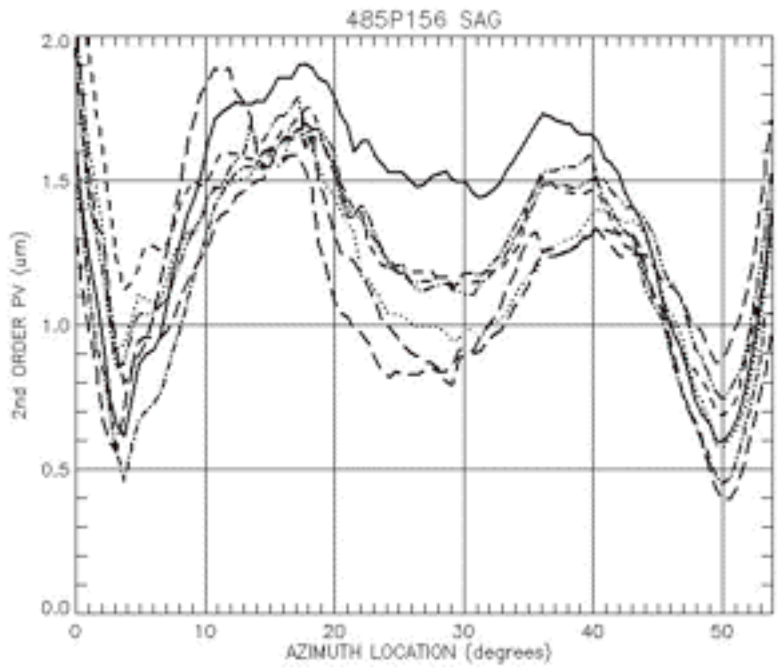

Fig. 5. Measurement of the axial sag of a mirror 485P156, in the suspension mount, and the dependence on azimuth. This is a test of mount and measurement repeatability. The solid line represents the measurement done with the mirror in the Cantor-tree mount, the dashed and dotted lines show those for six repeated experiments. For each experiment, the same mirror was de-bonded, and re-mounted before the measurement was taken.

4. DISCUSSION

Beyond mounting the mirror onto a simple strong-back, several processes are needed to complete the integration of the mirror into the module housings, and integration of modules into the telescopes, as outlined in figure 3. Looking into the future, we foresee important engineering processes that needed to be set up in detail. In this final section, we shall briefly address some of them, and outline viable approaches that one may take to establish them.

4.1 Challenges in Mirror Transfer, Module Alignment and Integration

Besides mounting a mirror onto a strong back, the mirror needed to be paired up to form a two-stage reflection system, and be transferred to a module housing.

Since vertical-mounting mechanisms depends on the principle of having the mirror vertical, it is natural to also have the mirror vertical during transfer of the mirrors into the mirror module. However, since the primary and secondary mirrors have different angles to the optical axis, they cannot simultaneously be vertical. Besides, even if they can be set minimally deviated from the vertical, the mirror module will then necessarily be tilted, for each shell of the mirrors (or a band of them) in the integration process. This is logistically quite inconvenient as the light source for monitoring the process, for example, need to be tilted, too. Alternatively, we can ask the question: Will the mirror hold its shape sufficiently well while it is tilted by is semi-cone angle, after it is fixed to the strong back at several points? Modeling shows that the 4-point bond in experimentation may not be sufficient for the largest mirrors in the secondary stage, which have the largest cone angles[14]. More bonding points may be needed. On the other hand, even though it is logistically complicated, the module, in principle, can be tilted. A compromise can be taken in that a range of mirrors can be accommodated to a single tilt setting of the module, so that the module needed not be titled every time a new shell is introduced.

Introducing more bonding points for better structural stability is not as trivial as it seems. More bond points mean more over-constraints of the mirrors, and any error in the bonding process exacerbates mirror deformation. The concern is especially true for the epoxy process. For instance, for a variation of epoxy bond size of 0.1 mm, 1% shrinkage implies 1 μm of radial variation, which may already be excessive depending on the spatial separations between the bonds. The thermal expansion is less of a problem, as the difference in lengths of the supporting posts are less than 1 mm, radial difference due to thermal expansion is expected to be less than 0.01 μm/ºC. More precisely controlled application of epoxy and its curing process will be needed to minimize the error in over-constraints. Some experimentation is already underway for a controlled application of epoxy.

Another component of the mirror transfer process that needs to be addressed is the bonding onto the module housing itself. The present concept is to have the mirror "encapsulated" in narrow slots. A series of experiments are in progress to demonstrate its feasibility in maintaining the local positions of the bonded regions. This is complicated by the precision required, tight spacing between mirrors, accessibility to bring in mirror into the module, and choices of CTE matching materials. Engineering design of the module housing to accommodate these requirement is still on going.

4.2 Summary

In summary, we have discussed the opto-mechanical challenges in building the Constellation-X telescopes and progress so far in understanding and solving some of them. In particular, we addressed mirror figure distortion due to gravity and thermal stress, their magnitudes and characteristics. We approached these problems both analytically and experimentally. We have not, in this paper, addressed other stresses such as the coating stress, or residual body stress from thermal forming of the mirror, or their relaxation. We have described experimental methods and current status of bonding a mirror in a vertical, and thus with minimal gravity, orientation, and outlined the processes following this stage of affixing the mirrors.

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