Khalai Kachwa

An Accessible Planetarium for Immersive Education and Entertainment

خلائی کچھوا

تعلیم اور تفریح کے لئے ایک گنبدِ افلاک نُما

Version May 22, 2023

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ABSTRACT

Section 1 of this manual introduces the user to the *Khalai Kachwa*, a 4.5 m diameter mobile planetarium made by PhysLab and the Khwawirmi Science Society. The manual consists of several sections. Section 2 will detail the various components which can be assembled to form the *Khalai Kachwa*. Section 3 will walk the user through chronological steps to assemble the *Khalai Kachwa*. Section 4 talks about our media library as well as the software required to project said movies. Section 5 discusses the Sphemir projection technique and components of the projection system.

This work has been funded by the National Centre for GIS and Space Applications, Pakistan.

1 Introduction

1.1 The Planetarium

A planetarium is a specialised facility that offers visitors an immersive experience in astronomy and space science. It typically features a large dome or curved screen onto which images of stars, planets, and other celestial objects are projected, providing an accurate simulation of the night sky. Planetariums are designed to provide an interactive and engaging learning environment, and often include multimedia exhibits, sound systems, and lighting effects.

The term ‘planetarium’ originally referred to a device that projected images of stars and planets onto a domed ceiling, allowing viewers to experience the appearance of the night sky from any location on Earth. Today, however, the term ‘planetarium’ is also used to describe the facility that houses such a device, as well as the programs and exhibitions that are presented therein. Planetarium technology has come a long way since the early days of simple projectors. Today, many planetariums use state-of-the-art digital projection systems that can display high-resolution images and even 3D visualisations of the universe.

Overall, planetariums play an important role in public outreach and education in astronomy and space science. They provide a unique opportunity for visitors to learn about the wonders of the universe and to be inspired by the mysteries and beauty of space.

1.2 What is the *Khalai Kachwa*?

The Khwarizmi Science Society began development on a portable planetarium in July 2022 in preparation for the 2022 **Lahore Science Mela**. The aims of this development were to construct a portable planetarium with a hemispherical dome, portable build, a system to flexibly position the dome, and a cohesive projection system providing a 180 degree immersive multimedia environment.

The Khwarizmi Science Society had previously developed the **LHC Interactive Tunnel**, a multimedia experience centred on particle Physics education built in collaboration with CERN. The LHC Interactive Tunnel includes equipment like high-power computers, ultra-short throw projectors, and Kinect sensors—all mounted on a metallic scaffolding. This makes the tunnel extremely difficult to transport in an assembled state. The entire project can, however, be disassembled and transported for short-period exhibits and *melas*. The *Khalai Kachwa* is built with similar operations in mind. The planetarium would need be robust and provide an immersive viewing experience while being portable.

The result is a portable planetarium with a 4.5 m diameter hemispherical dome, a high tensile steel wire and pulley positioning system, and a spherical mirror projection system. The *Khalai Kachwa*’s dome supported by its sanctioned supports reminded us of a tortoise shell, hence the name *Khalai Kachwa*. The planetarium was painted bright orange to emulate the Martian landscape, and has since become part of its identity.

Figure 1. *Top*: Our first visitor at the Eminabad Science Mela, March 2023. *Left*: The *Khalai Kachwa* viewed from the outside. *Right*: An internal view from one of our shows.

2 Parts

This section will go over the different components constituting the *Khalai Kachwa*. We will list parts, quantities, and brief descriptions of the components (an in-depth discussion of the components can be found in Section 5).

2.1 Dome

The *Khalai Kachwa*'s defining feature is the 4.5 m diameter, hollow, hemispherical dome. Images are projected upon the internal surface of this dome and viewers are seated under it. The dome consists of eight **carpels** (called such because of their similarity to the carpels in a citrus fruit). The carpels consist of a curved fibreglass surface joined to an iron support. Each carpel has a total of ten bolt holes (five on either side) to be joined adjacent to other carpels.

All eight carpels aren't identical though, as some have slight additions for functionality. There are three different types of carpels in total.

Click here for a video displaying all the different carpels which come with the *Khalai Kachwa*.

2.1.1 Plain Carpel 4x

Figure 2. Inner and outer views if a pain carpel.

One of the carpels is simply the plain carpel, which has no additional features compared with other carpels. A single plain carpel is pictured in Figure 2. The carpel has a slight cut-off at the tip at the very top for better mechanical joining, pictured in Figure 3.

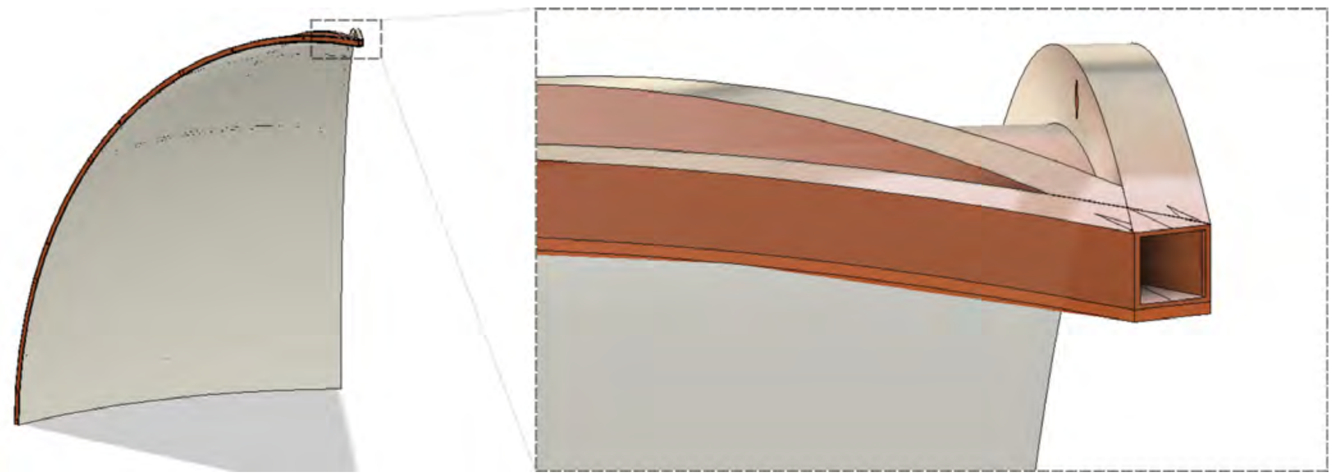

Figure 3. The very top of seven out of eight carpels ends in a cutoff, and not a point.

It is worth noting that one of these plain carpels is also considered to be the **projection carpel**. This projection carpel is called such because the mirror and projection systems are attached onto it. As such, this carpel has screw holes to accommodate the mirror system and bolt holes to accommodate the projection system. These holes and their positions are shown in Figure 4.

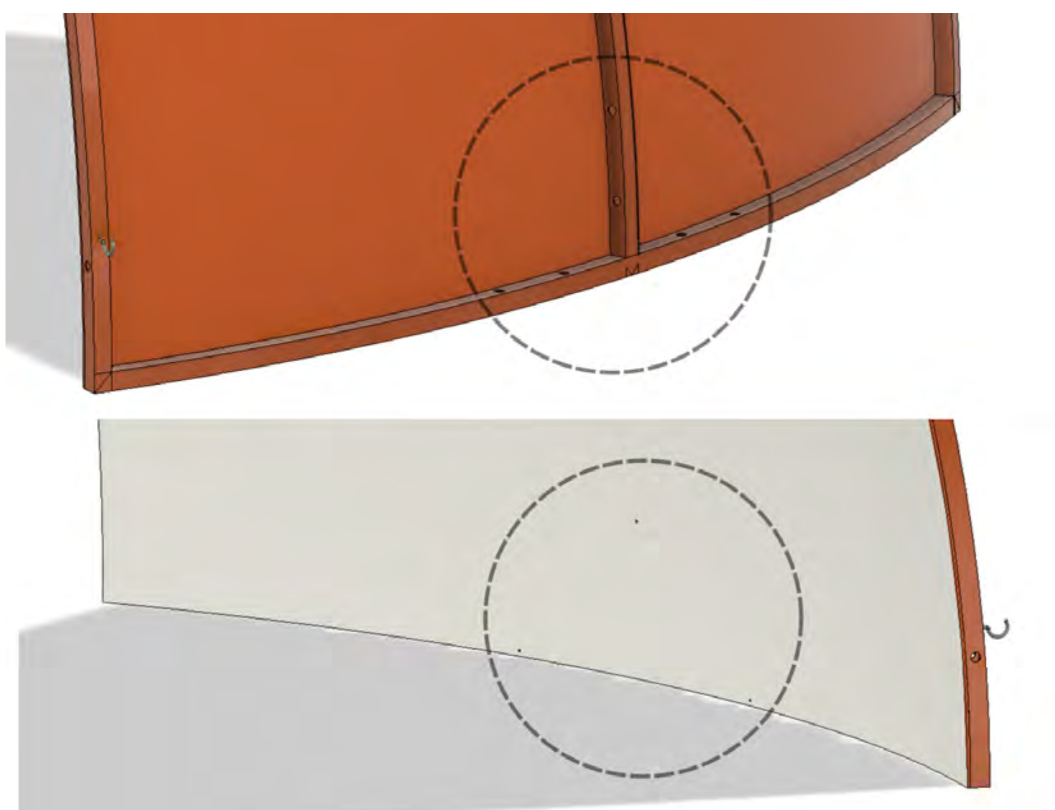

Figure 4. Screw holes (top image) and bolt holes (bottom image) used to attach the mirror system and the projection system to the projection carpel respectively.

2.1.2 Baseplate Carpel 3x

In addition to the plain carpel, we also have three baseplate carpels. These are identical to plain carpels, except for a small metallic plate on the outside of the carpel towards the bottom. This baseplate has a hole through which the high-tensile steel attaches with a clip hook. Figure 37 shows how a baseplate carpel looks.

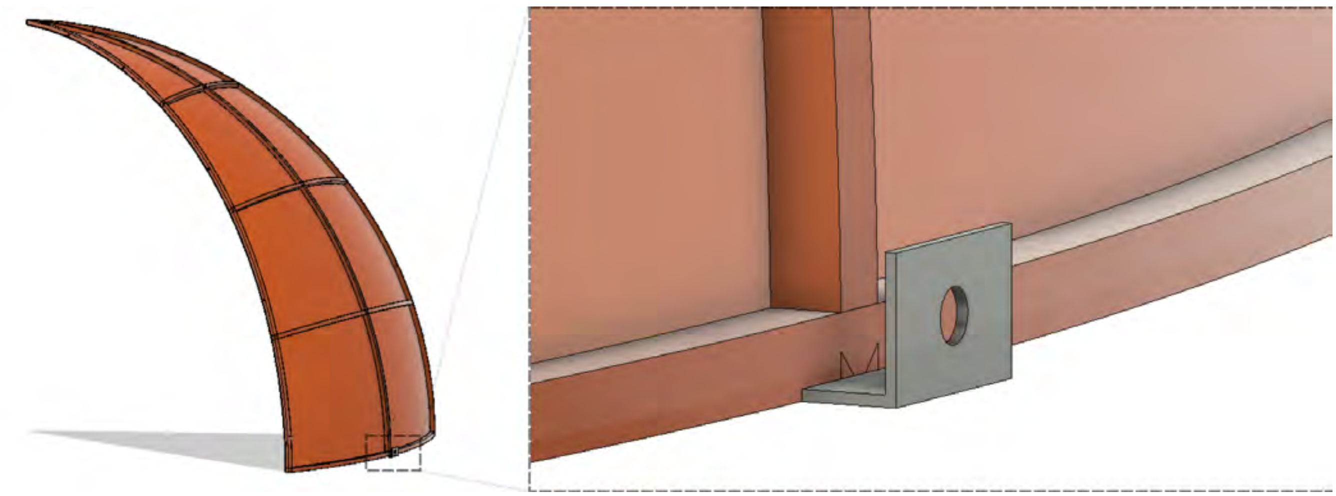

Figure 5. The baseplate is a feature on four of eight carpels.

2.1.3 Primary Carpel 1x

Finally we have the primary carpel, called so because it is recommended to begin dome assembly with this carpel. We will talk more about this later on in Section 3.4. This carpel has a baseplate identical to the one in Figure 37, but features a top at the upper tip. This top fills in the space left uncovered by the cutouts in the other seven carpels. Figure 6 shows what this top looks like. Note that the top isn't necessarily octagonal, and an additional screw-in top can cover any spaces.

2.1.4 Dome Nuts and Bolts 40x

Our eight carpels are joined to form our hemispherical dome through 40 pairs of nuts and 2.75" bolts.

2.2 Ring

the *Khalai Kachwa*'s dome sits atop a circular ring made from iron pipe. The ring is divided into four identical segments, which are bolted together to form the complete ring. Figure 7 shows these subrings which eventually come together to form the complete ring.

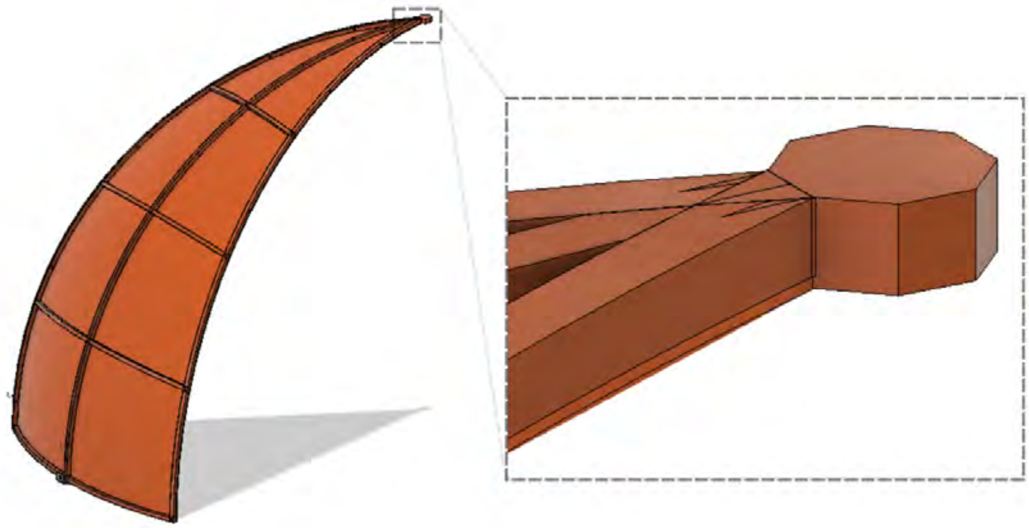

Figure 6. The top on the upper tip of the primary carpel.

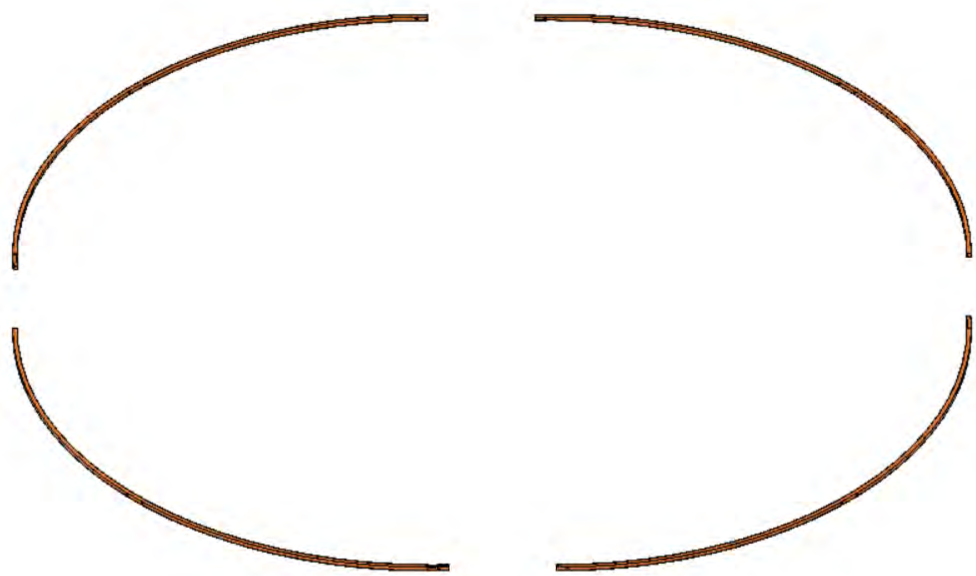

Figure 7. The four segments of the dome ring.

2.2.1 Subring 4x

Each subring has a segment made with a smaller pipe on one end, which slides into its adjacent subring. Figure 8 shows the two ends of a subring and their bolt holes.

Each subring also has two bolt holes in its centre which are used to join it to one of the poles (Section 2.3). Figure 9 shows what these holes look like.

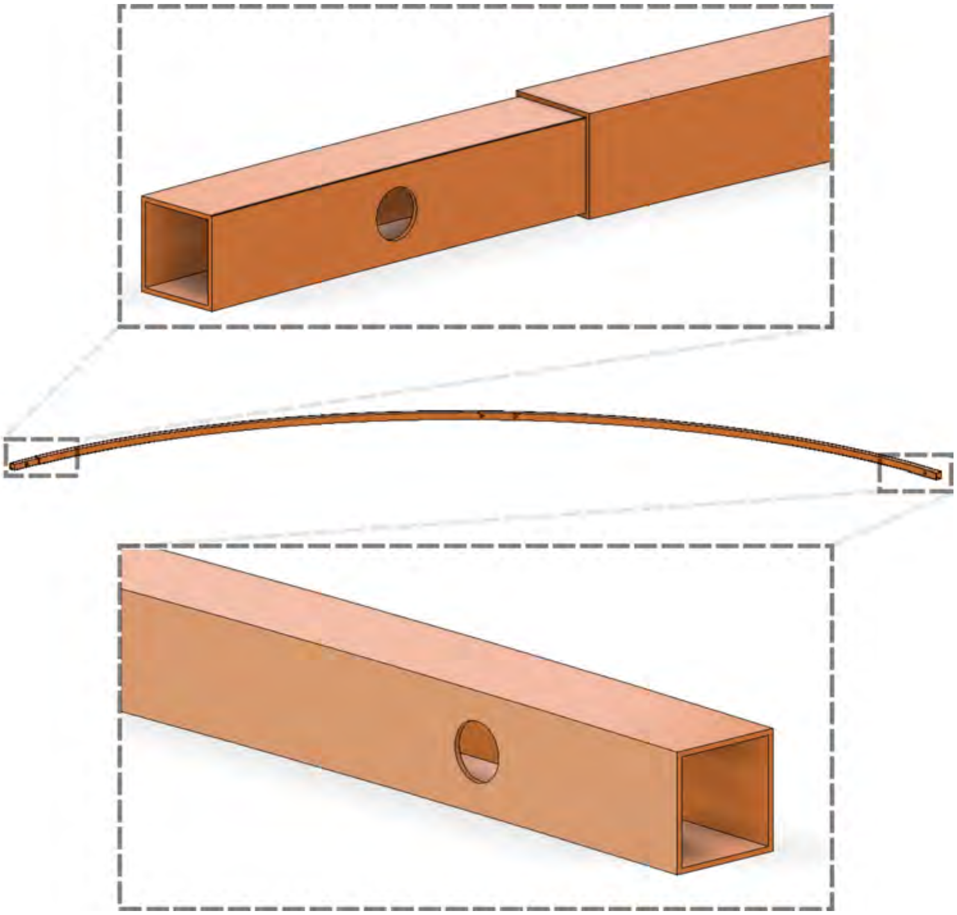

Figure 8. The ends of a subring.

Figure 9. The bolt holes in the middle of our subring.

2.2.2 Ring Nuts and Bolts 4x

The subrings are joined to form the complete ring through four pairs of nuts and 1.5" bolts.

2.3 Poles 4x

When in operation, the dome is held aloft by four 20 m poles, holding the dome with a high tensile steel wire. Each pole has a winch with a lever attached to it (see Figure 10) which houses the wrapped wire.

The wire ends on a clip hook on one end. The wire passes through a pulley on top of the pole before connecting with baseplate of a carpel, as shown in Figure 11.

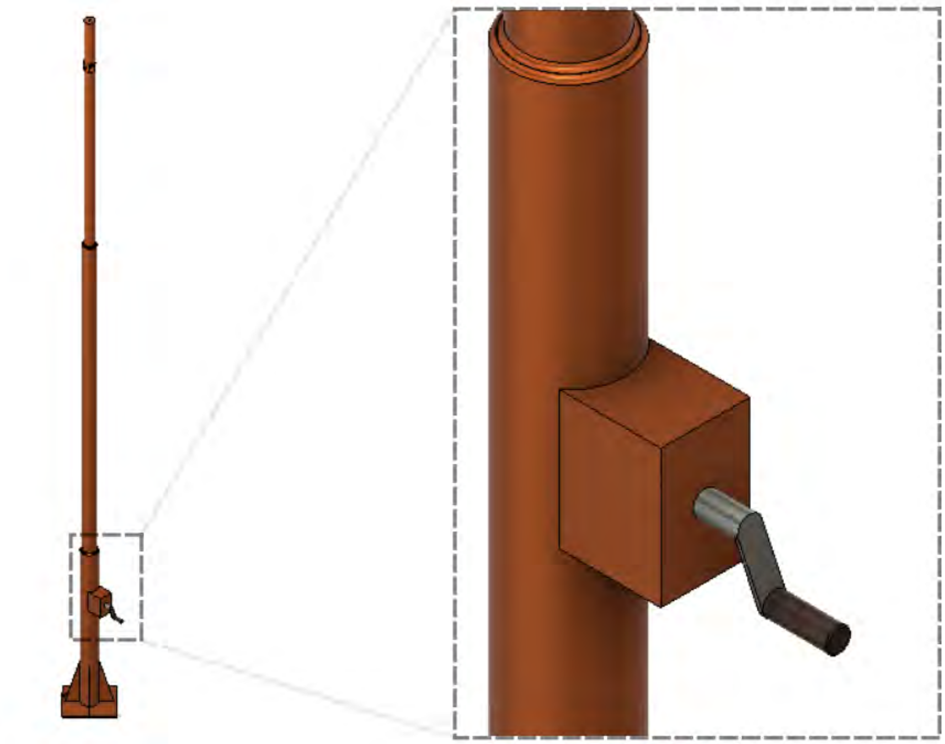

Figure 10. The pole and the wire winch and lever shown. (Note that the high tensile steel wire is not visible).

2.4 Top Supports

The top supports consist of four iron pipes which hold the poles together by their tops, thus providing crucial structural integrity. The positions of the top supports are shown in Figure 12.

2.4.1 Upper Supports 2x

The upper supports are iron pipes which extend from one pole to the other. They have a pill slot where they are bolted to the pole tops, as well as a square slot where orthagonal lower supports pass through and are bolted together. Figure 13 shows an upper support and its distinguishing features.

2.4.2 Lower Supports 2x

Like upper supports, the lower supports extend from one pole to another while being orthogonal to the upper supports. Unlike the upper supports, however, these slot into and are bolted to the upper supports rather then the poles themselves. Figure 31 shows the lower support.

Figure 11. The steel wire loops through the pole's pulley and attaches to a carpel's baseplate.

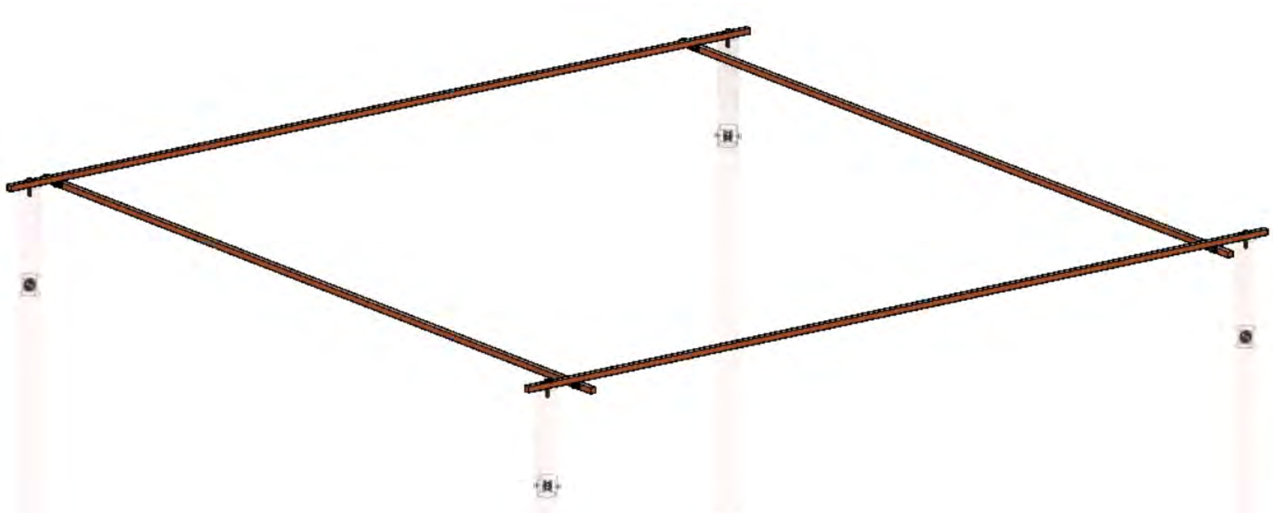

Figure 12. The top supports securing the (translucent) poles.

2.4.3 Top Support Nuts and Bolts 4x

The lower supports are joined with the upper supports through four pairs of nuts and 1.75" bolts.

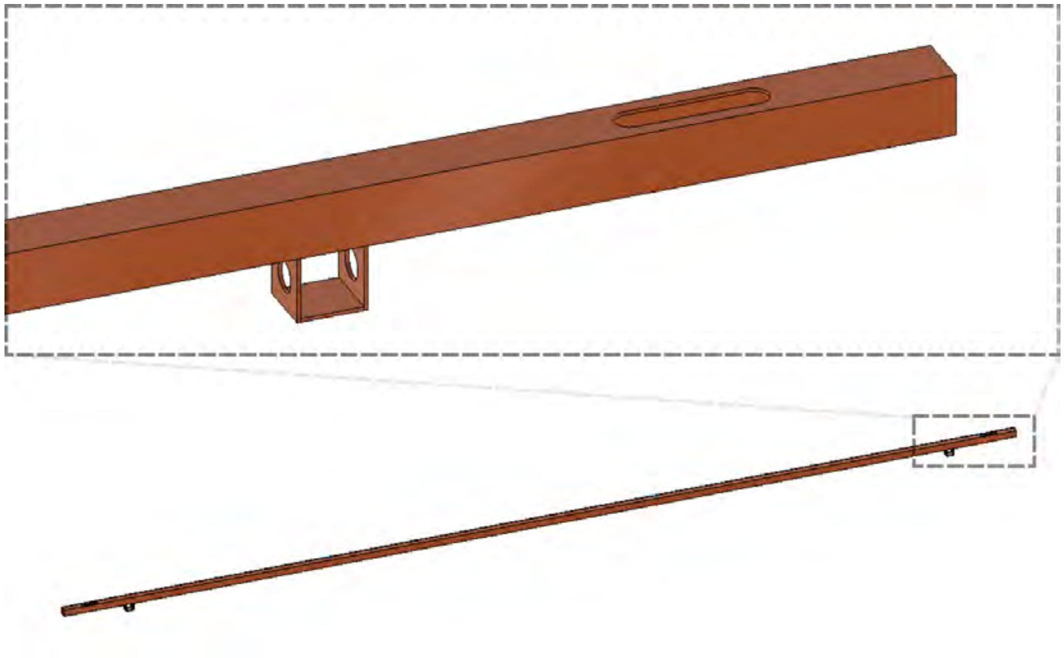

Figure 13. An upper support with its pill slot (on the right) and square slot (on the left).

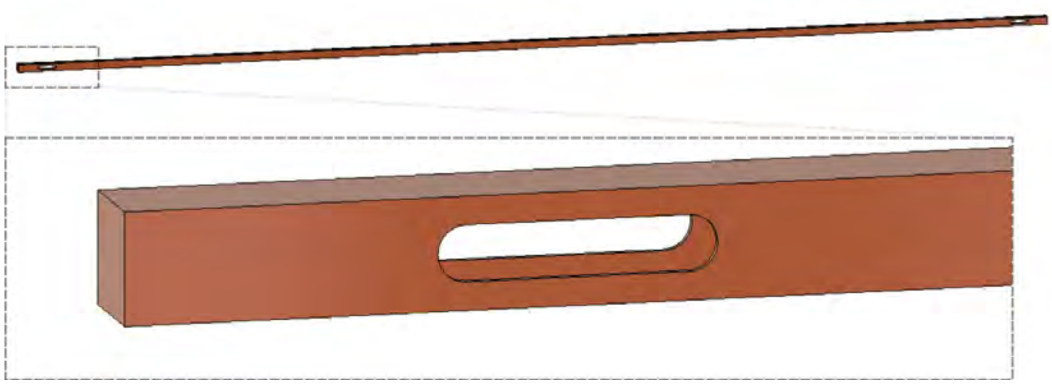

Figure 14. The lower supports have pill slots on either end to be bolted onto the upper supports.

2.5 Mirror System 1x

The mirror system plays a vital role in image projection. It consists of the mirror (15) and the mirror holder. The holder attaches to the inner surface of the projection carpel, near its base. The holder consists of two parts made out of steel plates. One of these is flat and has holes to be attached to the carpel. The other part is a harness to which the mirror is attached permanently. Figure 16 shows the complete mirror system.

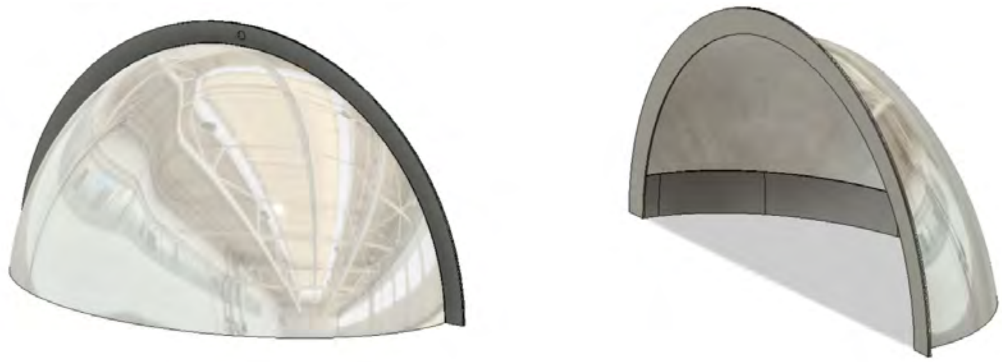

Figure 15. The quarter-spherical mirror that helps make fulldome projection possible.

Figure 16. The mirror system consists of a T-shaped steel plate and a curved mirror holder joined together with hinges. The mirror is riveted to the holder, so the mirror system comes as a singular component.

2.6 Projection System

The projection system consists of several parts which position the projector at a consistent point from the mirror. Figure 17 shows the projection system attached to the projection carpel.

2.6.1 Outer Holder 1x

The outer holder attaches to the outer surface of the projection carpel and extends iron pipes toward the inside from under the dome. Figure 18 shows what this piece looks like.

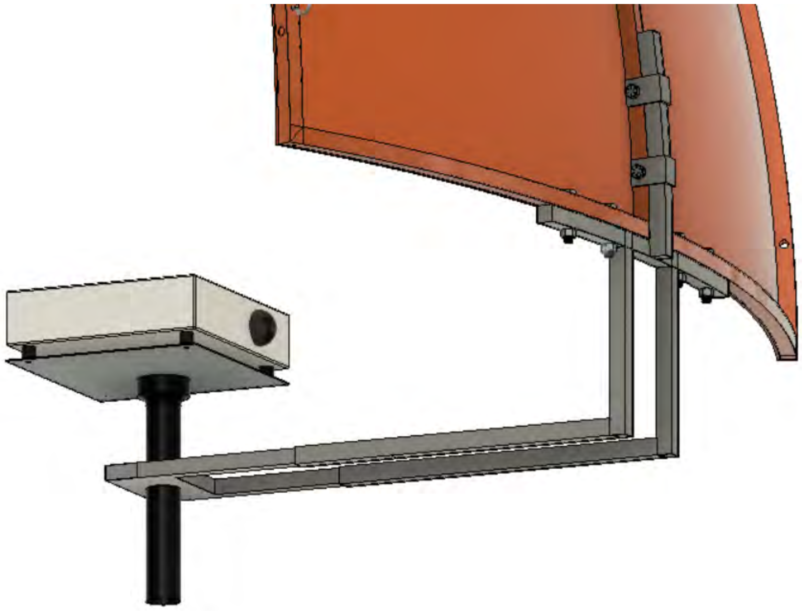

Figure 17. The projection system in full, attached to the projection carpel.

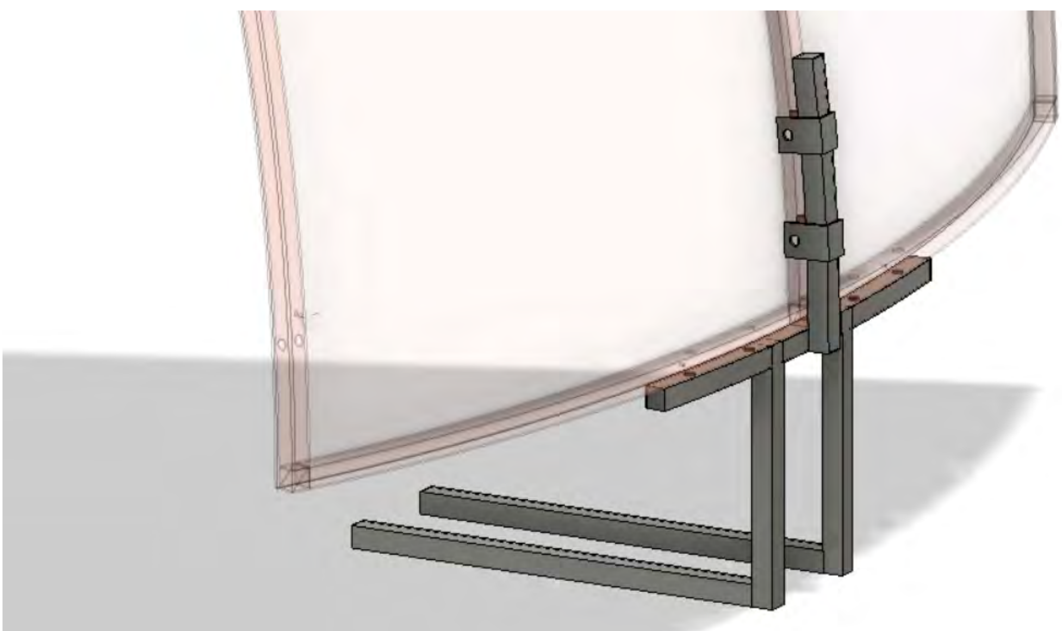

Figure 18. The outer holder and its position with respect to the (translucent) projection carpel.

2.6.2 Platform 1x

The platform attaches to the outer holder through the outer holder's pipes. The platform has two smaller iron pipes which slide into the outer holder's larger pipes. This enables us to make adjustments to the projector's horizontal distance from the mirror. The platform comes with fasteners with which we can lock down the desired horizontal distance. The other end of the platform has a circular hole which, in turn, holds the projector plate. The horizontal pipe of the plate (Section 2.6.3) can pass through the platform's circular hole. Figure 43 shows how this component looks like.

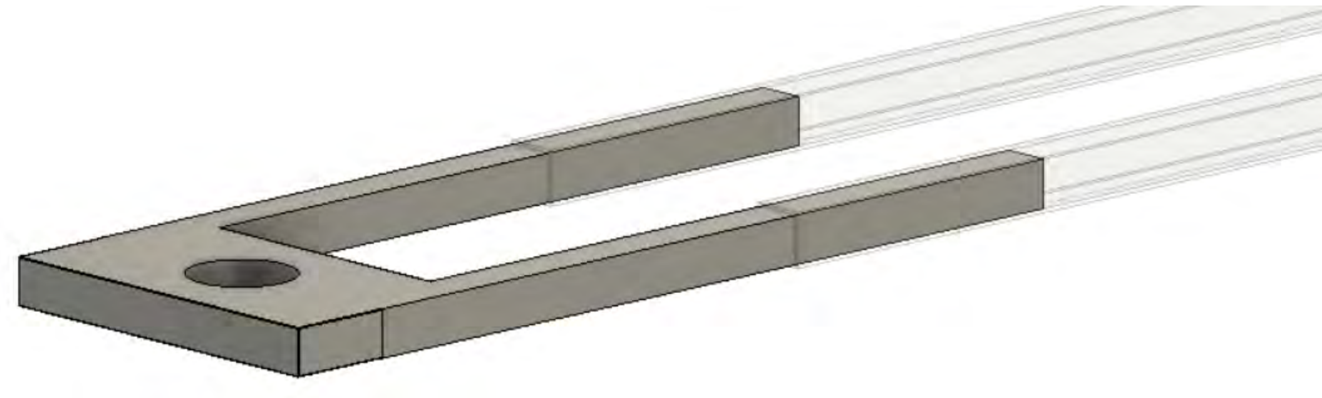

Figure 19. The platform slides into the (translucent) outer holder.

2.6.3 Projector Plate 1x

The projector plate consists of a circular iron pipe attached orthogonally to an acrylic platform. The projector sits atop this platform. The circular pipe vertically passes through the circular hole in the platform, and its fastener helps us to lock the desired vertical distance from the mirror. Figure 20 shows this plate attached to the platform.

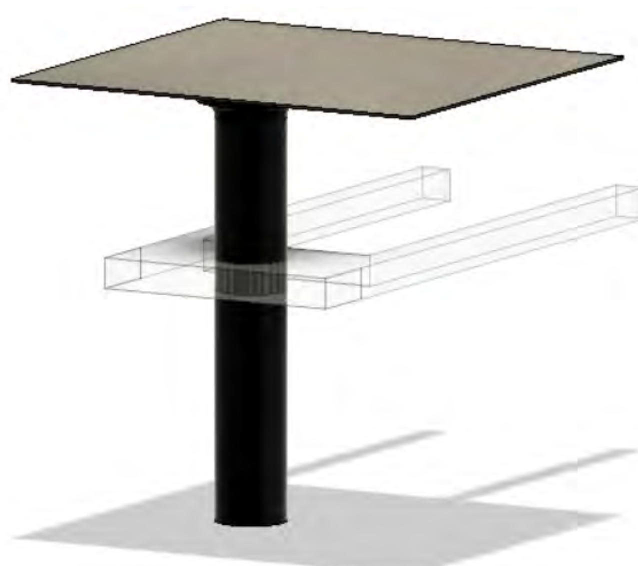

Figure 20. The plate's pipe slides into the (translucent) platform.

2.6.4 Projector 1x

The projector is a simple linear projector. In our case, this is an Epson EB-L200F (specifications in Table 1). The projector sits atop the projector platform at a position defined by marks on the plate, and is secured with a band around the projector and plate. Figure 21 shows what a projector might look like atop the plate.

Projection System	Epson 3LCD, 3-chip technology
Zoom	1 - 1.62 (Optical Zoom)
Throw Ratio	1.33 (Zoom: Wide), 2.16 (Zoom: Tele)
Offset	10 : 1
Brightness	2,500,000 : 1
Reported Contrast Ratio	10 : 1
Resolution	1080p
Aspect Ratio	16 : 9

Table 1. Hardware specifications for the Epson EB-L200F.

Figure 21. A simplified visual of a projector on top of the (translucent) plate.

2.7 Miscellaneous

This subsection will cover nuts and bolts which join the different sub-assemblies of the *Khalai Kachwa* together, as well as some other components needed for assembly.

2.7.1 Projection Carpel-Mirror System Screws 3x

The mirror system is screwed onto the internal surface of the projection carpel with three 1.5" wide head screws. These screw through the fibre projection surface and into the iron support pipes on the carpel's outer side.

2.7.2 Projection Carpel-Outer Holder Nuts and Bolts 6x

Six pairs of nuts and bolts attach the projection system's outer holder to the projection carpel. Four of these have 2.75" bolts while the other two have 2" bolts.

2.7.3 Subring-Pole Nuts and Bolts 8x

Each subring is attached to a pole through two pairs of nuts and 1.75" bolts. With four subrings and poles, this means a total of eight pairs of nuts and bolts 1.75".

2.7.4 Upper Support-Pole Bolts 4x

Each upper support is attached to two poles on either end. This is done through two large 2.5" bolts. With two upper supports, this means four bolts in total.

2.7.5 Tarpal

Of course, we will notice that raising the dome produces a great source of external light as the sides raise up. To combat this, the *Khalai Kachwa* ships with a cotton black-out cloth which goes around the perimeter of the dome. The *tarpal* is a 6×47 ft cotton black-out cloth with hole punches at regular intervals on both long ends. These hooks are present to hang the *tarpal* around the dome through hooks on the outer surface.

The *tarpal* helps us retain the flexibility in dome positioning provided by the pulley system. The fabric also means that the tarpal is extremely portable.

2.7.6 Air Conditioning Unit

When deployed outside, especially in the summer months, the sealed *Khalai Kachwa* can quickly become quite hot during a show. For viewers' comfort, it is highly encouraged to install an air conditioning unit within the dome. We opt for a vertical chiller to minimise the AC's footprint.

2.7.7 Carpet

There are several seating options when organising a show. While bean-bags or small benches are an option, floor seating can be an advantageous option. This can accomodate a lot more people, especially young viewers.

2.7.8 Sound System

The *Khalai Kachwa* comes with a 5.1 channel surround sound system, which includes 5 full-range speakers and one sub-woofer.

2.7.9 Sound Card

A regular laptop usually does not have the requisite 6 channel output required to drive a 5.1 channel surround sound system. In this case, it must utilise an appropriate sound card which can then be connected to the laptop via USB. The card contains 3 3.5 mm audio jacks, which can then connect to the 5.1 channel sound system driver (on the backside of the sub-woofer in our case).

Figure 22. A 5.1 channel sound card with 3 $\times$ 3.5 mm audio output jacks.

2.7.10 MacOS Computer

Finally, the warping software used for Sphemir projection (Section 5.1) requires MacOS, and thus necessitates a computer running MacOS.

3 Assembly

This section will cover the recommended procedures for assembling the *Khalai Kachwa*'s individual components.

3.1 Ring

Click here for a video walk-through of the ring assembly.

Begin the assembly process with the *Khalai Kachwa*'s base ring (Section 2.2). Slot the smaller ends of the subrings (Section 2.2.1) into the larger ends of the adjacent subrings to form a complete ring. See Figure 23.

Secure adjacent subrings with the ring nuts and bolts (Section 2.2.2). See Figure 24.

You should now have a complete iron ring for the dome to sit upon, as in Figure 25.

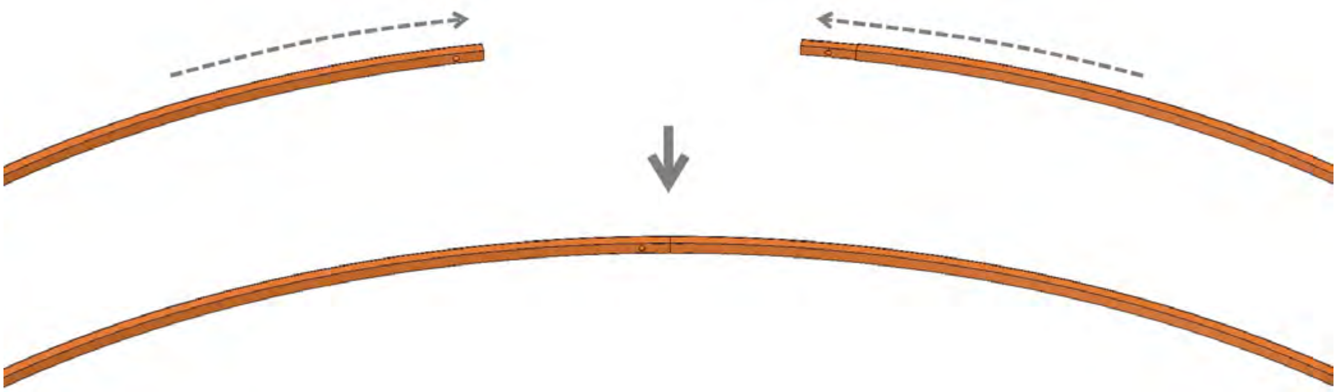

Figure 23. Slot adjacent subrings into each other.

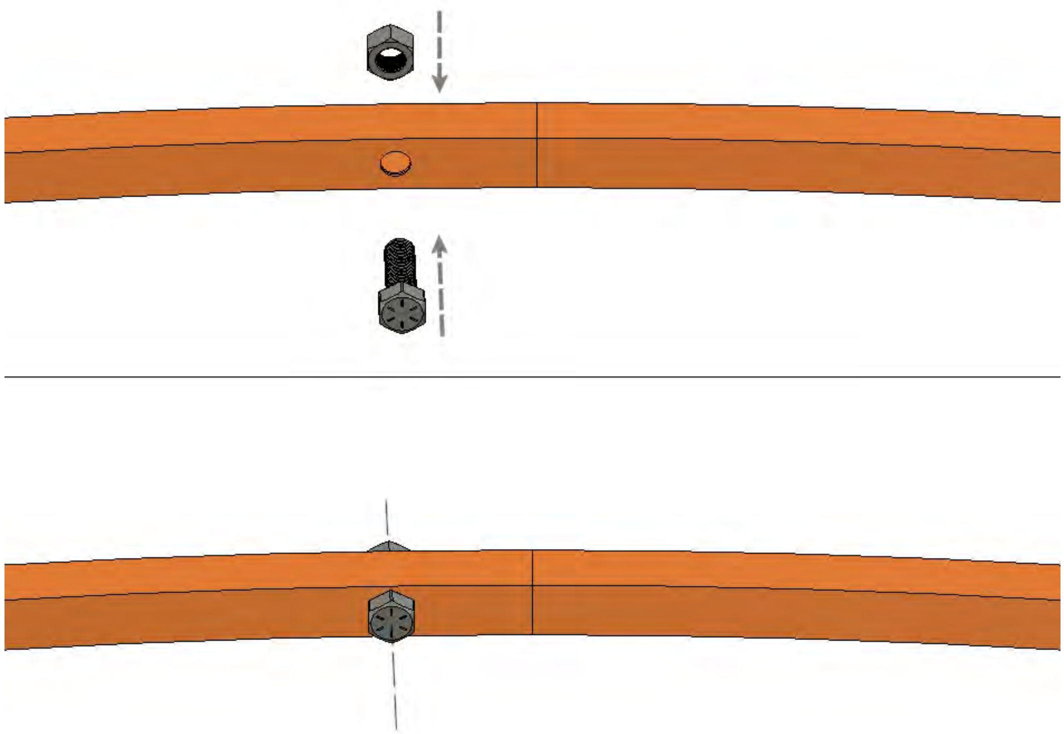

Figure 24. Bolt the adjacent subrings together.

3.2 Poles

Click here for a video walk-through of the pole assembly.

Once the ring is assembled, we can proceed to attach poles to it. Note, however, that while the poles can independently stand on their base, they should be considered **unsteady** until top supports are attached. As such, they should be supported by hand while they are being bolted to the ring, and any lateral force/weight

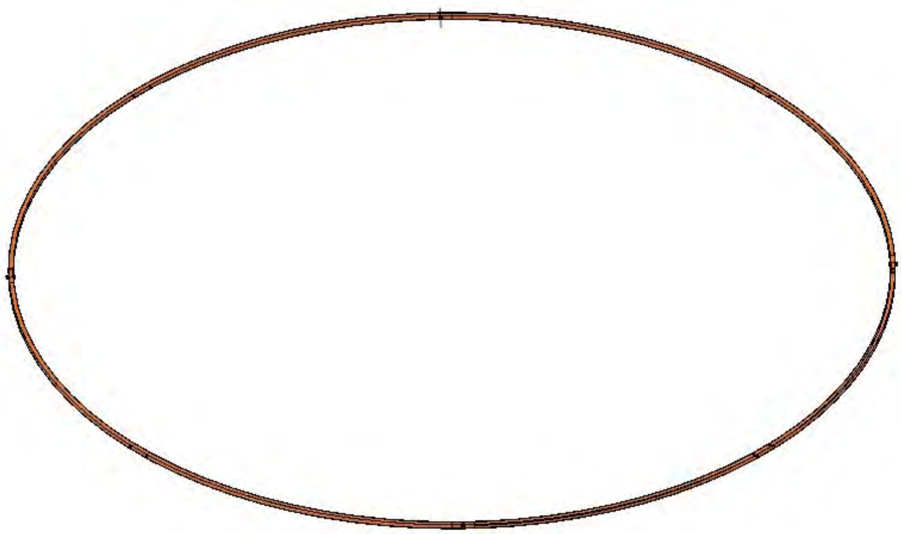

Figure 25. The four subrings combine to form the complete ring.

should be avoided.

We recommend **at least three individuals** for pole assembly. Carry the pole and stand it near the holes in the middle of the subring. Make adjustments until the joining plate at the pole's base is on the inside of the ring, with the majority of the base on the outside. Additionally, the holes on the joining plate should align with the holes in the centre of the subring. This is shown in Figure 26.

Figure 26. How the pole should be positioned with respect to the ring.

Once positioned, the pole should be secured to the ring with the provided nuts and bolts as in Figure 27.

The remaining three poles can be attached similarly, attached symmetrically onto the ring (Figure 28).

3.3 Top Supports

Click here for a video walk-through of the top supports.

Once the poles have been attached, the top supports should soon follow. The two upper supports (Section 2.4.1) should be attached first. We recommend at least two people to attach one upper support at the same

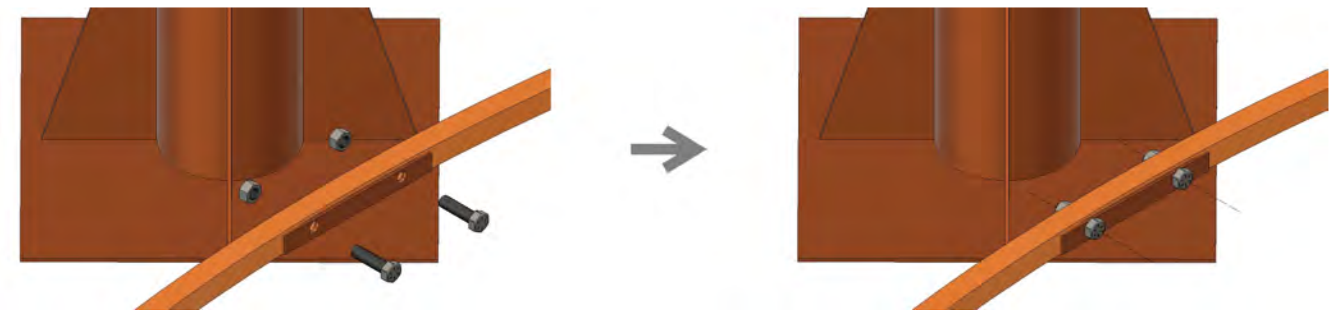

Figure 27. Secure the pole to the ring with the nuts and bolts.

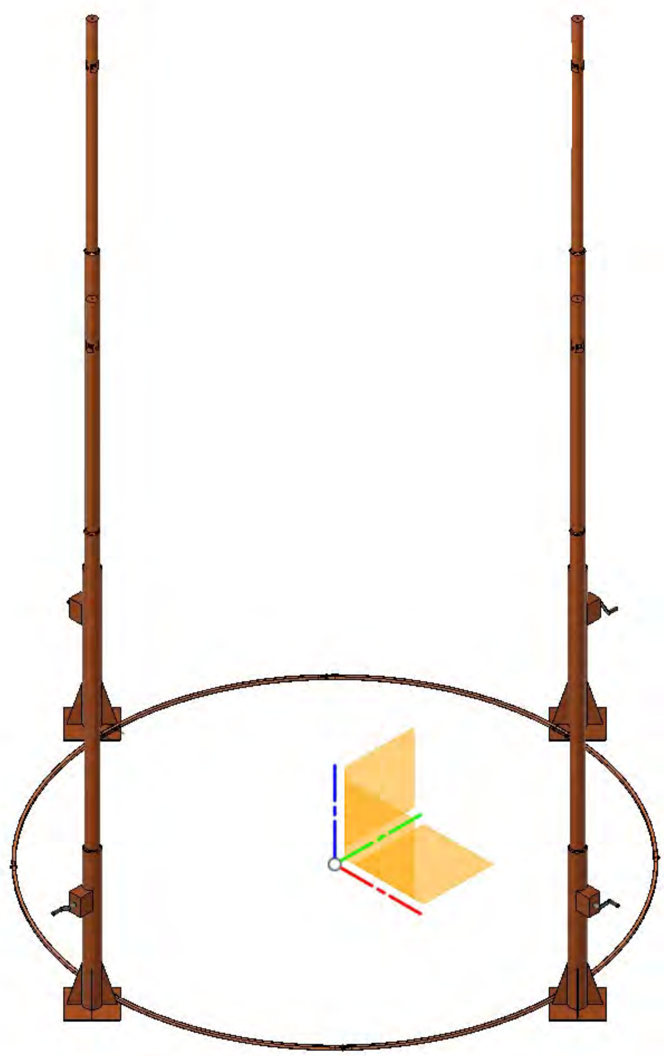

Figure 28. All four poles attahced.

time. With two appropriately tall step-ladders, carry the support together and place it atop the poles. Make sure that the pill slots on the upper supports align with the bolt hole at the top of the pole, and that the square slots are towards the ground. This is shown in Figure 29.

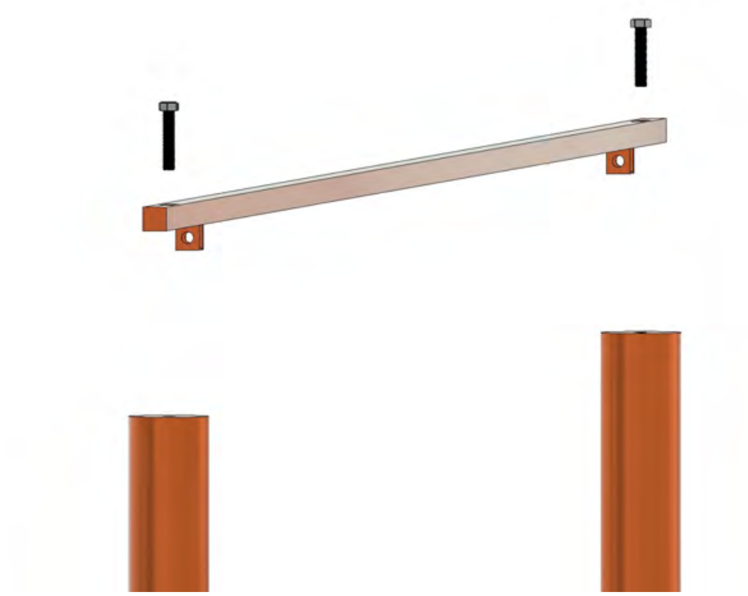

Figure 29. Align the upper support slots with the bolt holes at the pole's tops, making sure that the square slots face downwards.

Once aligned, secure the upper supports ends to the poles with the provided large bolts (Section 2.7.4), as shown in Figure 30.

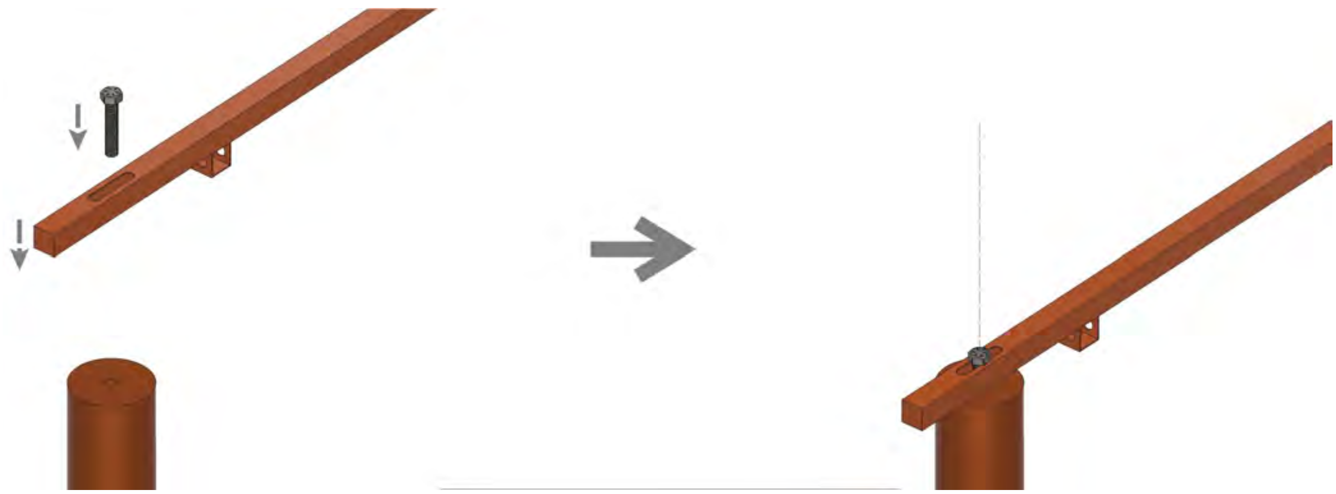

Figure 30. Secure the upper support with the pole via the bolt.

Secure the second upper support to the other two poles in a similar manner.

The upper supports should be followed by the lower supports. Once again, we recommend two people holding either end of the support while carrying it up between the poles, orthagonally to the upper supports.

Slide one end of the lower support through the square slot on the upper support. Pass through enough of a length so that the other end can be passed through as well. Make adjustments (you might need to hammer the lower support's ends) until the lower support's pill slots align with the holes on the square slots.

Figure 31. Slide the lower support into the slot on the upper support.

Attach the second lower support to the other two upper support ends to complete the top support assemblies. You should end up with a stable structure that looks like Figure 32.

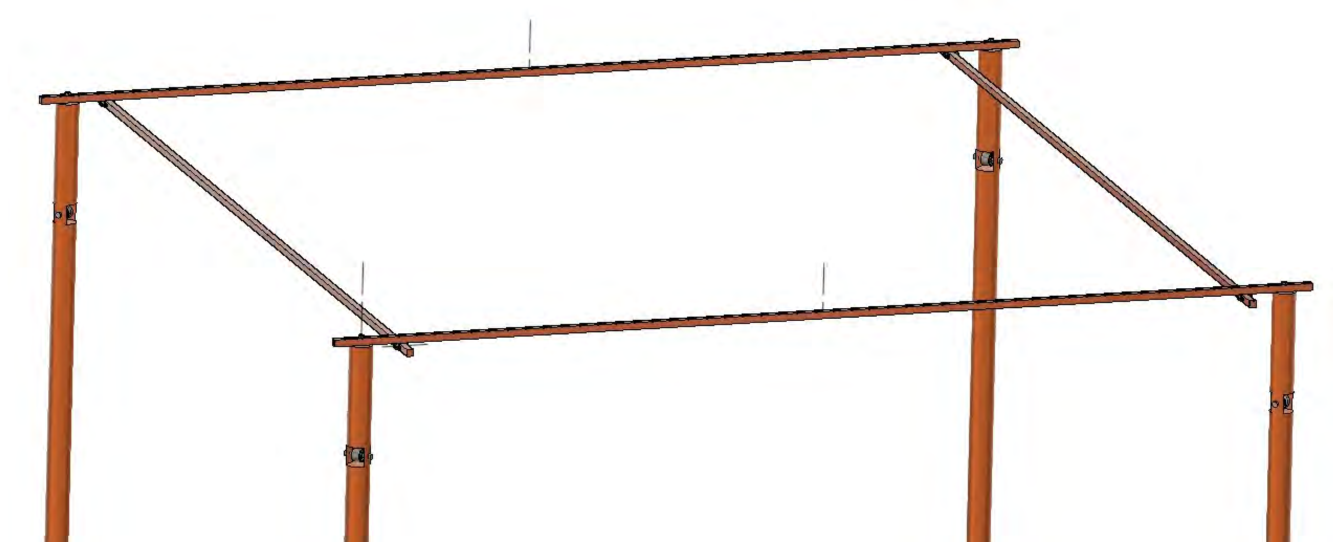

Figure 32. The top supports assembled.

3.4 Dome

Click here for a video walk-through of the dome assembly.

We should discuss carpel positions before assembling the dome. While certain carpels are identical, it is recommended to attach them in a prescribed order to ensure correct mechanical fitting. To ensure this, each carpel has a certain number of rivets on either side of the outer support. This is shown in Figure 33.

Begin dome assembly with the primary carpel (Section 2.1.3). We recommend at least three people to assemble the dome together. The dome will need to be propped up and supported at various points throughout the assembly. Since the primary carpel has a baseplate, carry and place the carpel on the ring in front of a pole, with its inner surface facing the centre of the circle. This is shown in Figure 34.

Once placed, we will position carpels on either side, making sure that the sides' rivet numbers correspond.

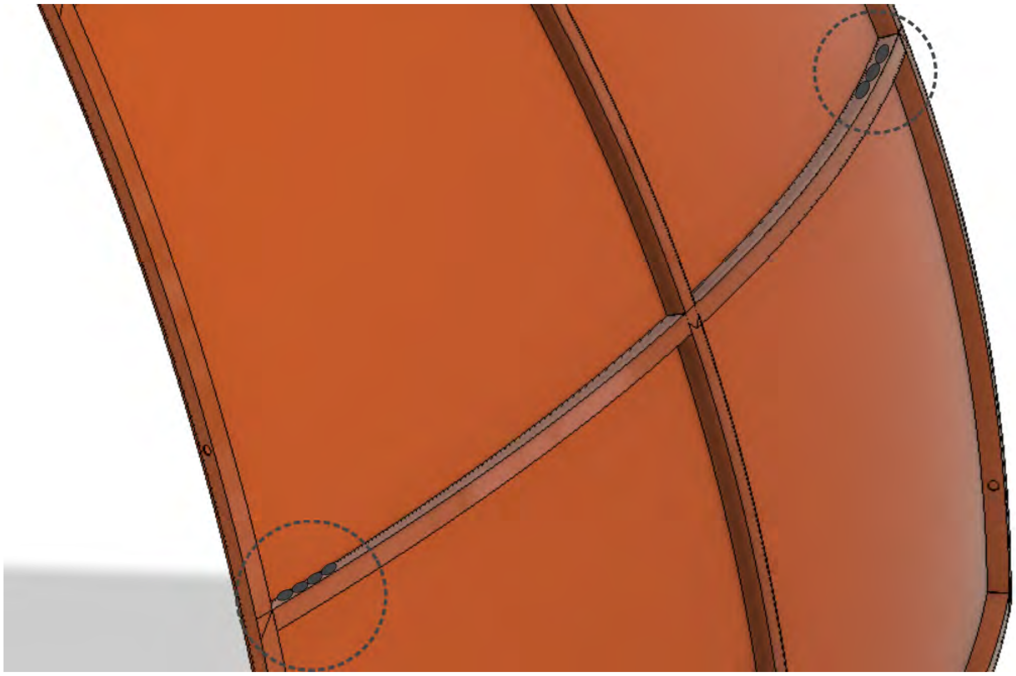

Figure 33. Every carpel has rivets at the position shown. The depicted carpel, for instance, has three and four rivets on either side. Thus we will attach adjacent carpels which have a corresponding rivet number.

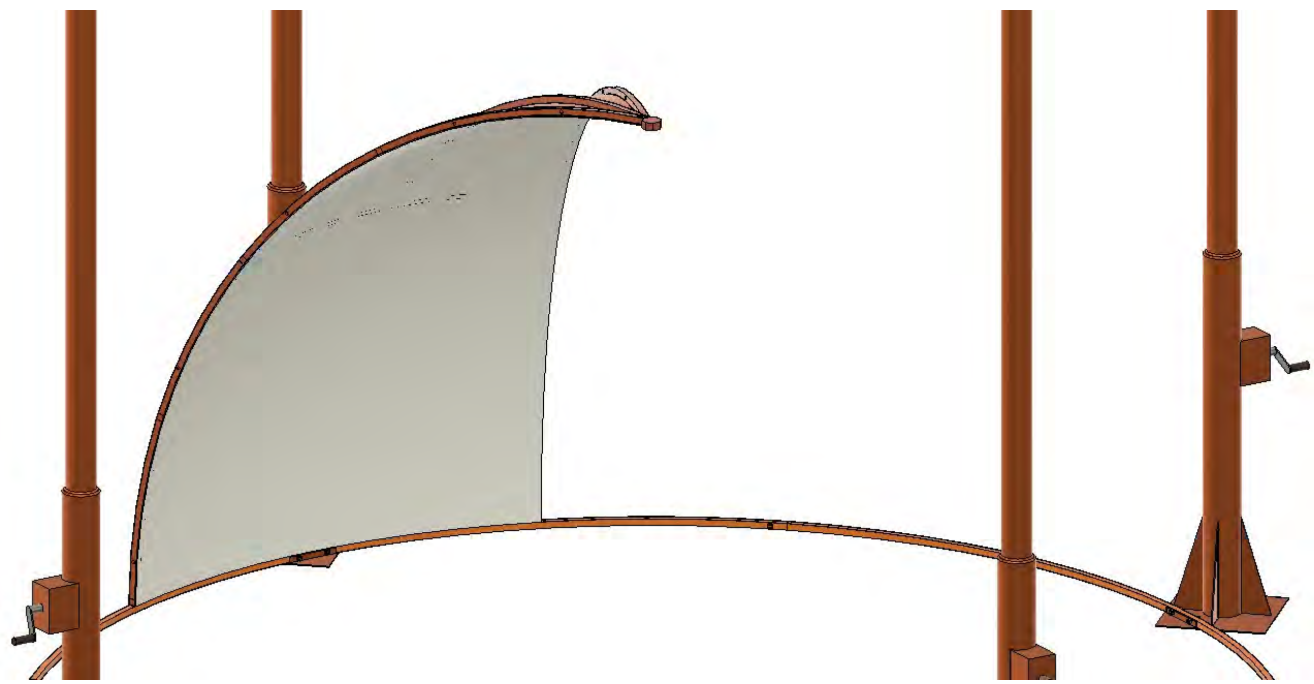

Figure 34. Position the primary carpel first.

While we place and attach the other carpels, it is necessary to support the carpels so they don't tip over. The carpels will need to supported until we secure a total of three carpels, at which point the sub-dome can stand independently.

Each carpel side features five bolt holes, which should be aligned as shown in Figure 35

Figure 35. Align adjacent carpels' five bolt holes.

Secure the adjacent carpels with the carpel nuts and bolts (Section 2.1.4). It is recommended to not completely tighten all five nuts and bolts before all nuts and bolts have been seated.

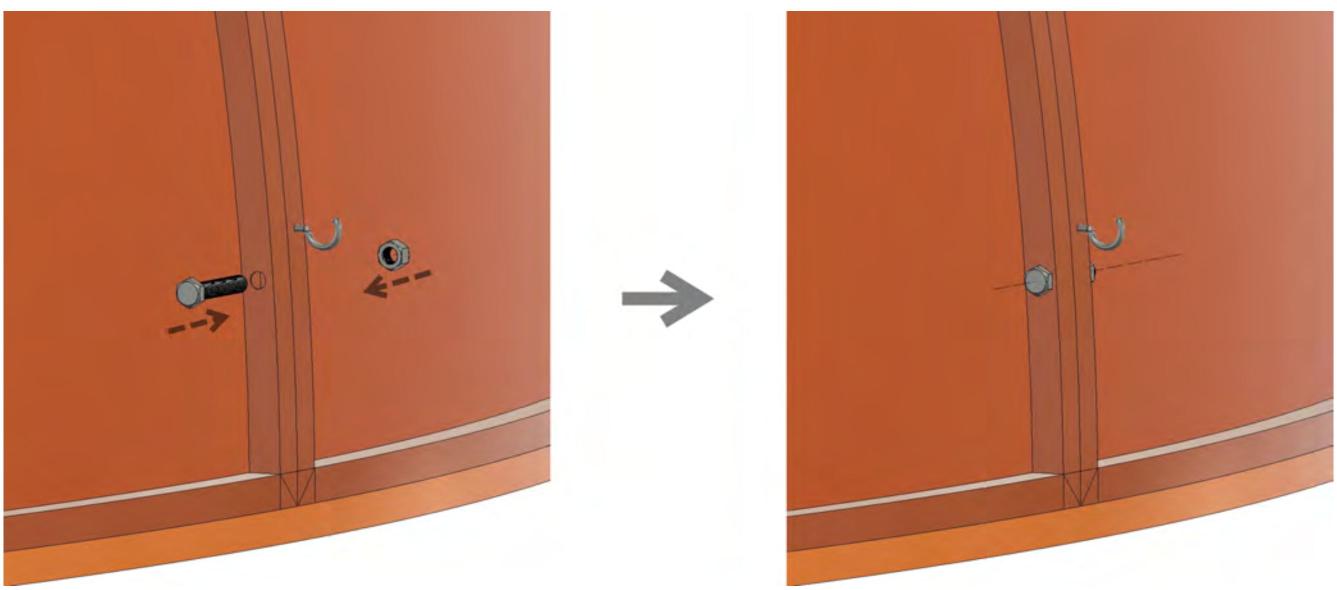

Figure 36. Secure two adjacent carpels with the provided nuts and bolts.

Once all carpels are attached, dome assembly is complete!

At this point we should consider additional internal sealing. The rubber strips between the carpels should block most external light from entering the dome. However, additional steps can further improve light blocking. How long the planetarium might be deployed for, and how long after assembly the first show might be are important considerations in deciding additional steps. For instance, if assembly times are constrained, it might be more feasible to cover the carpel seams with painters tape or white duct tape, and simply screwing in the top plate at the point where the tips of all carpels meet.

If more assembly time is available, filling in the seams with white plaster of paris can be an effective way of blocking all light and producing a seamless internal surface. The plaster of paris requires around four hours to completely dry, however.

3.5 Attach Dome to Poles

Once the dome is assembled, we can clip the hooks on the high tensile steel wires onto the baseplate, as shown in Figure 37.

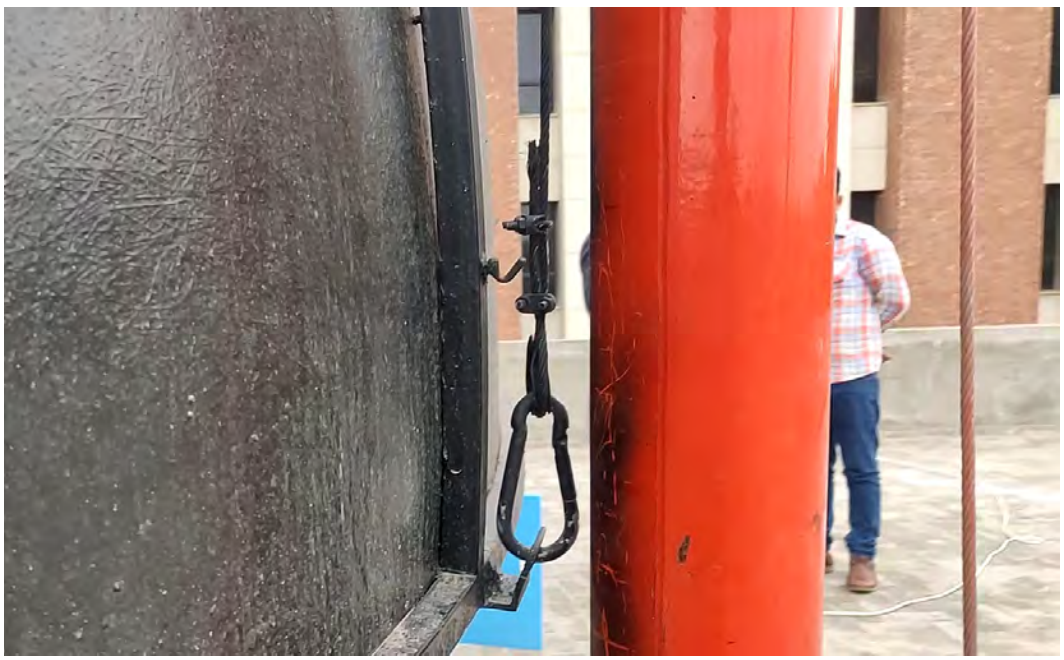

Figure 37. Attach the poles' high-tensile steel wire to the carpels by the baseplate.

3.6 Mirror System

Click here for a video walk-through of the mirror system and its installation.

It is now time to attach the mirror system. Align the mirror system's plate to the screw holes on the projection carpel, as shown in Figure 38.

Secure the mirror system to the projection with the provided screws (Section 2.7.1) as shown in Figure 39.

Figure 38. Align holes in the mirror system's plate to holes in the projection carpel's inner surface.

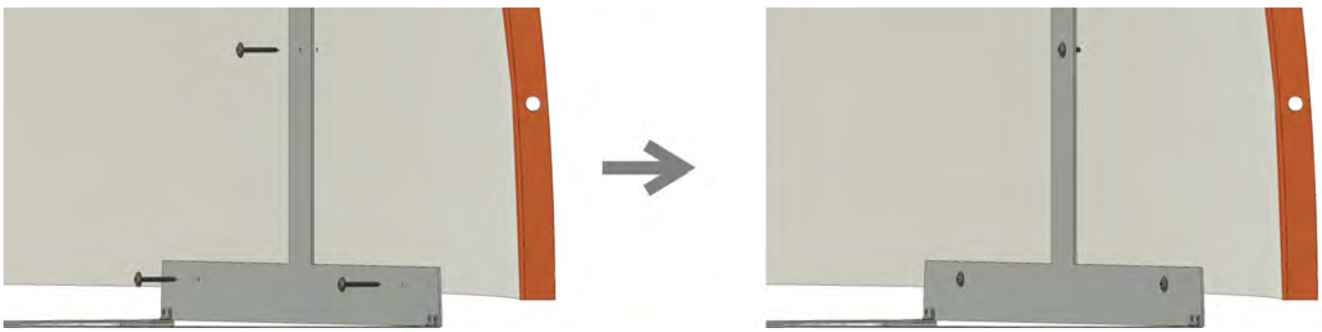

Figure 39. Secure the mirror system with the provided screws.

3.7 Projection System

Click here for a video walk-through of the projection and its assembly.

We can now attach the projection system to the projection carpel. Begin by aligning the outer holder (Section 2.6.1) with the holes on the projection carpel (Figure 40).

Figure 40. Align the holes on the outer holder with the holes on the projection carpel's supports.

Once positioned, secure the outer holder with the provided nuts and bolts (Section 2.7.2), taking care to use the two shorter bolts on the top. This is shown in Figure 41.

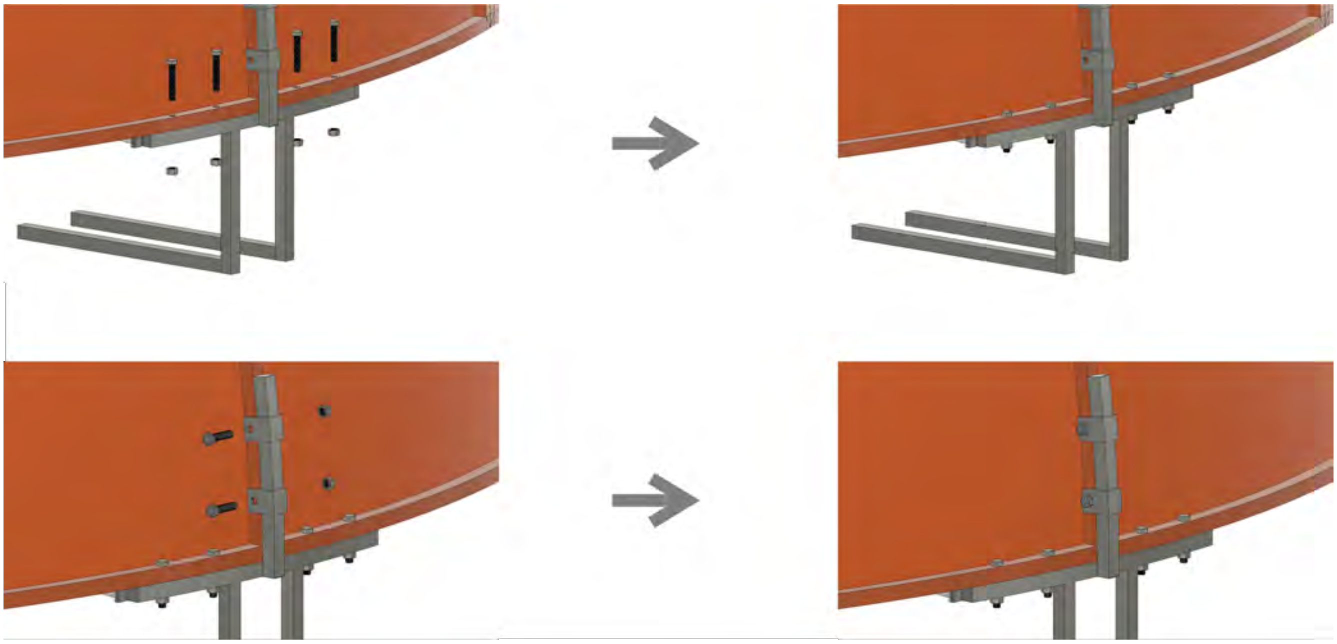

Figure 41. Align the holes on the outer holder with the holes on the projection carpel's supports.

Following the outer holder. Slide the platform (Section 2.6.2) into the rails of the outer holder as shown in Figure 43. Secure with the provided fasteners.

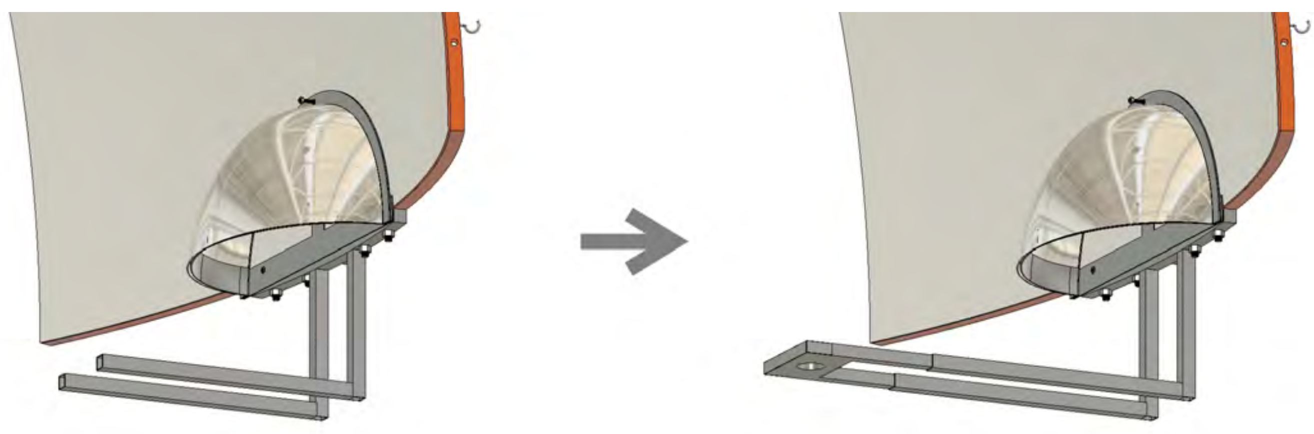

Figure 42. Slot the platform into the outer holder and secure with fasteners.

Following the platform, slide the projector plate's pipe (Section 2.6.3) into the platform's circular hole, as shown in Figure 20.

We can finally place the projector on the plate and secure it. Figure 44.

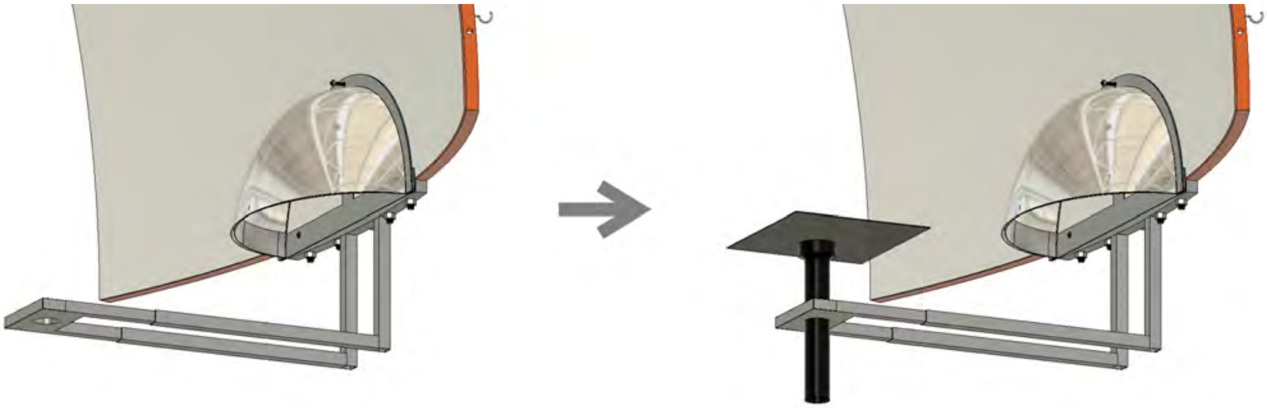

Figure 43. Slide the plate's pipe into the platform and secure with the provided fastener.

Figure 44. Place the projector atop the plate and secure.

3.8 Positioning

The high tensile steel wires allow us to position the dome in a variety of ways. The dome can be lifted from the bottom upto around 10 ft vertically. Besides vertical movement, the dome can also be tilted to a certain degree by wrapping different poles to different degrees. This is, in fact, recommended. Figure 45 shows how the dome might be tilted

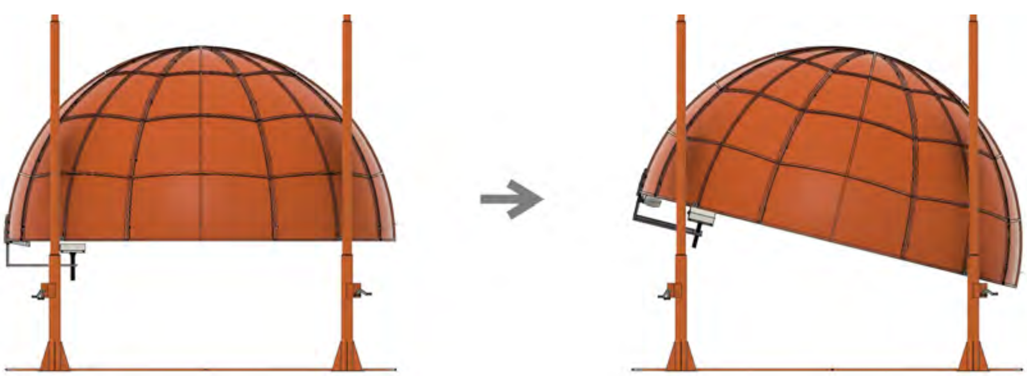

Figure 45. It is recommended to raise the two sides surrounding the projection system to produce a tilt.

This tilt has several advantages. Firstly, it is better for viewers to face a direction in which the dome is tilted down, making it an easier neck position. Secondly, distracting features like the projection system, projection computer, sub-woofer, air conditioning unit, and projectionist can be positioned out of sight, behind the viewers. This is further discussed in Section 3.9.

3.9 Miscellaneous Additions

It is recommended to install creature comforts like a carpet, an air conditioning unit, seats, theatre lights, etc. as well as projection elements like the projection computer, the sound system, projectionist's chair, laptop stand, etc.

3.9.1 Carpet

A carpet can prove to be a great addition in case you plan your shows with floor seating, and makes the *Khalai Kachwa* more welcoming in general. It is recommended to place the carpet prior to any other internal components placed on the floor. Figure 46 shows carpet placement during the *Eminabad Science Mela* in March 2023.

Figure 46. The KSS team installing a carpet before a *Khalai Kachwa* show.

3.9.2 Sound System

The *Khalai Kachwa* comes with a 5.1 surround sound system, for which the speaker positions are shown in Figure 47. The main speakers are placed around the viewers, and the sub-woofer can be placed right underneath the projection system. This puts it out of the viewers' sights and saves space.

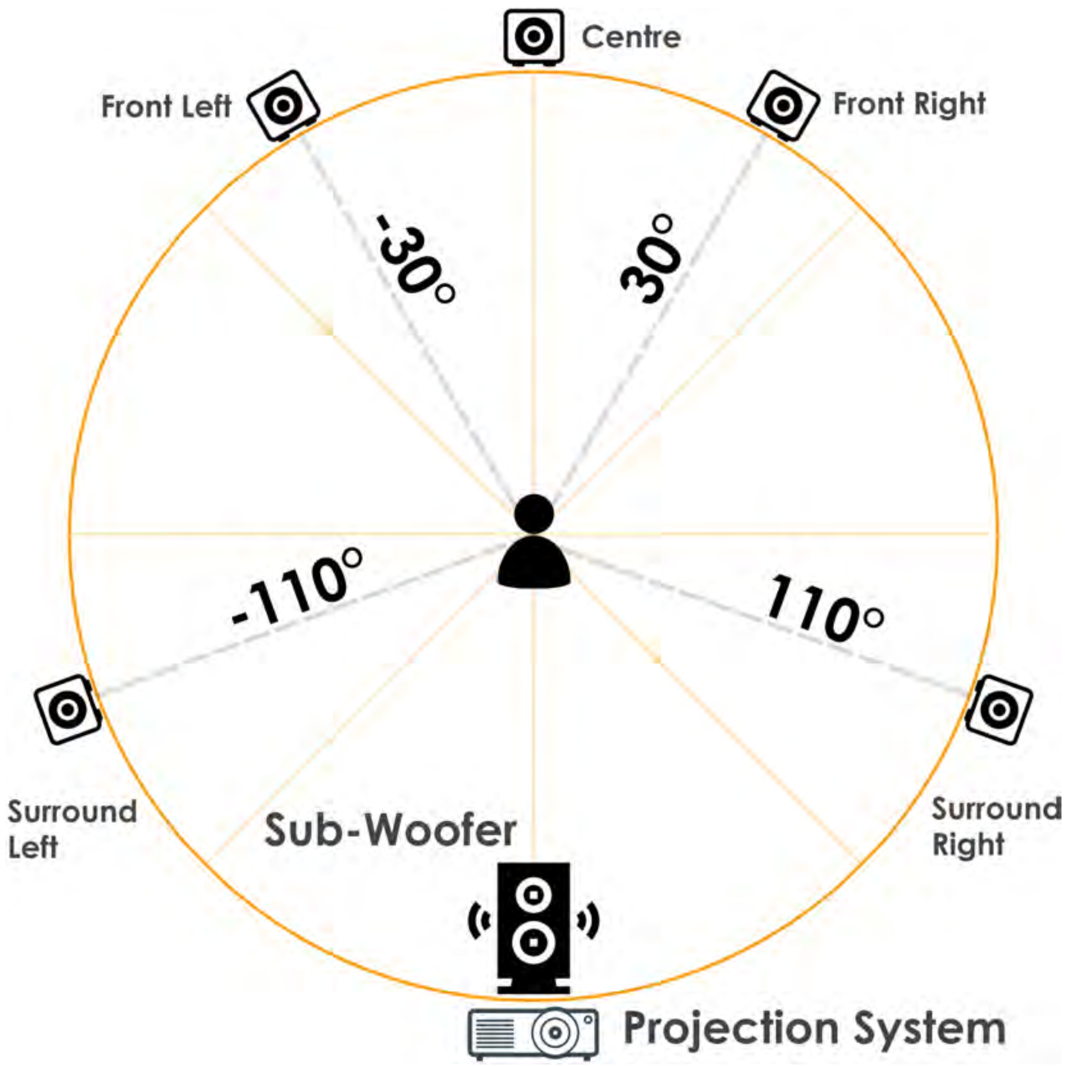

Figure 47. Recommended sound system positions.

3.9.3 Air Conditioning Unit

As a large item, AC unit can be challenging to place. Positioning it in the raised section on the dome, right next to the projection system (Figure 48) can keep it out the projection—and the viewers'—way.

3.10 The *Tarpal*

Once the dome is positioned, we can quickly attach the *tarpal* (Section 2.7.5 onto it. We must first decide where we want the 'door' for our planetarium to be. In case of our recommended orientation in Figure 49, We recommend an opening right beside the projection system. This is because the part of the dome near the projection system is raised higher, making it easier for viewers to enter and exit.

Begin hanging the *tarpal* by simply beginning hanging on the hook nearest to the desired opening point (Figure 50). Continue hanging around the dome until the entire perimeter is covered. Tuck the excess

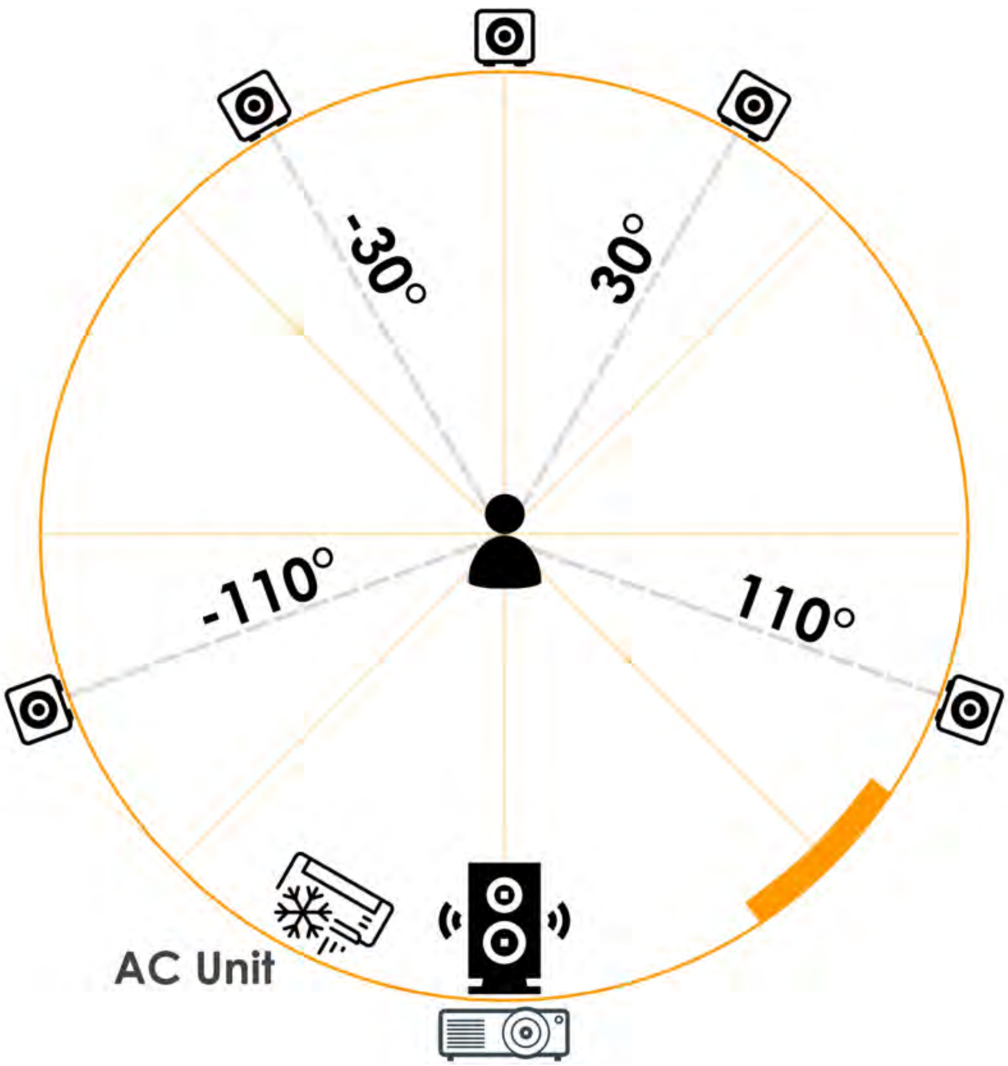

Figure 48. Recommended AC unit position.

cloth at the bottom inwards under the carpet for excellent light proofing.

4 Software and Media

4.1 Media

The *Khalai Kachwa*, being a portable planetarium made to accommodate Pakistani viewers of all ages, necessitates accessible, informative, and entertaining shows. To facilitate this, the Khwarizmi Science Society has formed a great collection of planetarium shows diverse topics. The subject matter for these shows range from the search for Dark Matter to the biological processes which make sight possible. Each movie typically lasts about 30 minutes in its entirely, but we also maintain portions in the 5–10 minute range for shorter shows.

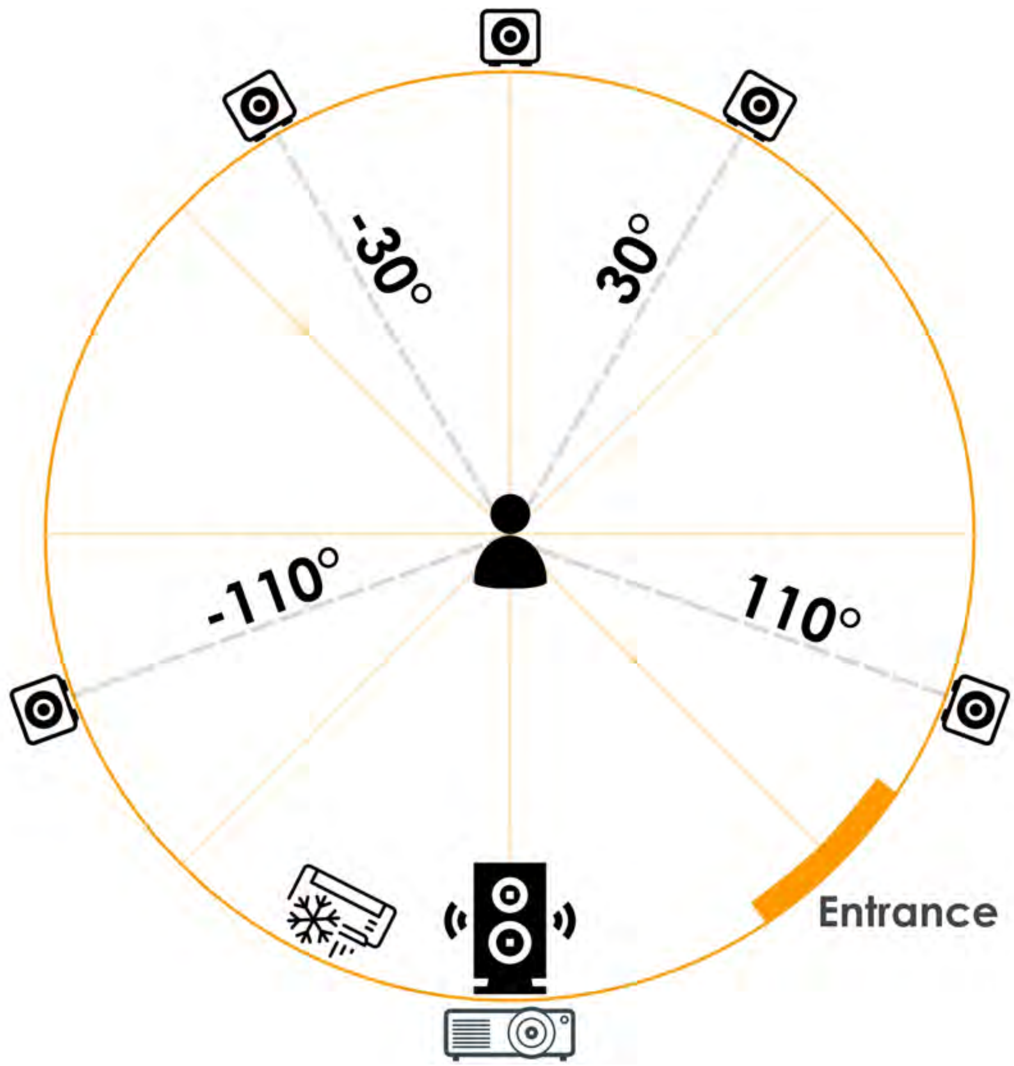

Figure 49. The recommended position for the entrance.

In addition to a diverse collection, we have produced Urdu dubbings for our shows, which make them accessible to viewers from all backgrounds. Figure 51 depicts some of these shows available presently. We also continue to produce more dubs and expand our media library.

4.2 Software Warping

The *Khalai Kachwa*'s projection system necessitates warping fulldome shows, as these are usually only available in the fisheye format (Figure 52). These fisheye movies can be warped into the Sphemir format, which our mirror can reflect and project onto the surface normally. Sphemir is discussed in detail in Section 5.1 and in Bourke (2005). These fisheye formatted shows usually cannot be pre-warped as small variations factors such as projector placement and angles can dramatically alter the particular warp settings needed to properly project. Hence, it is recommended to change these settings after each individual projector and mirror placement.

Figure 50. Hang the *tarpal* on the hooks outside.

Figure 51. Just some of the shows in our library presently.

Users can change warp settings using a software called **meshmapper**. Meshmapper can be run through the MacOS terminal, and it provides a calibration image which is projected onto the dome's internal surface. This is shown in Figure 53. Meshmapper presents the user to input several geometrical details, including mirror size and placement, projector throw ratio and placement, and the size of the dome. The software also allows the user to make adjustments to the mirror's geometry, which is reflected in real-time by the calibration image on the surface. This allows the user to make fine corrections until the desired projection

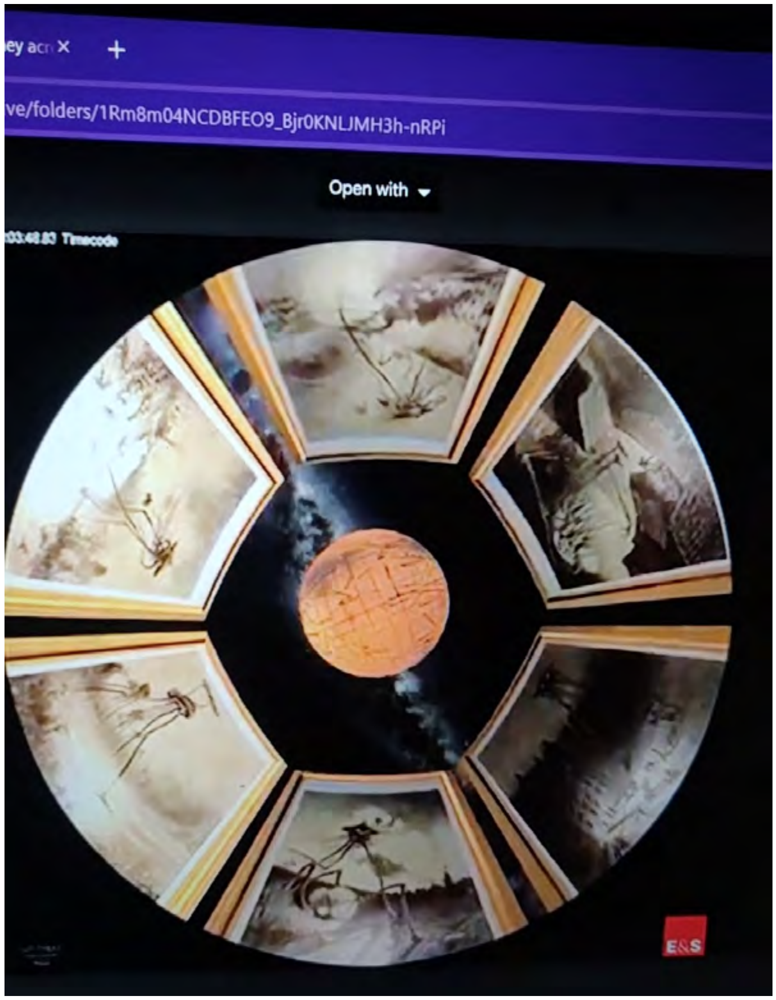

Figure 52. The fisheye movie format cannot be directly used with the Sphemir projection system.

is achieved. The result is a geometry file which can be saved. Documentation on the usage of meshmapper can be found at http://paulbourke.net/dome/meshmapper/.

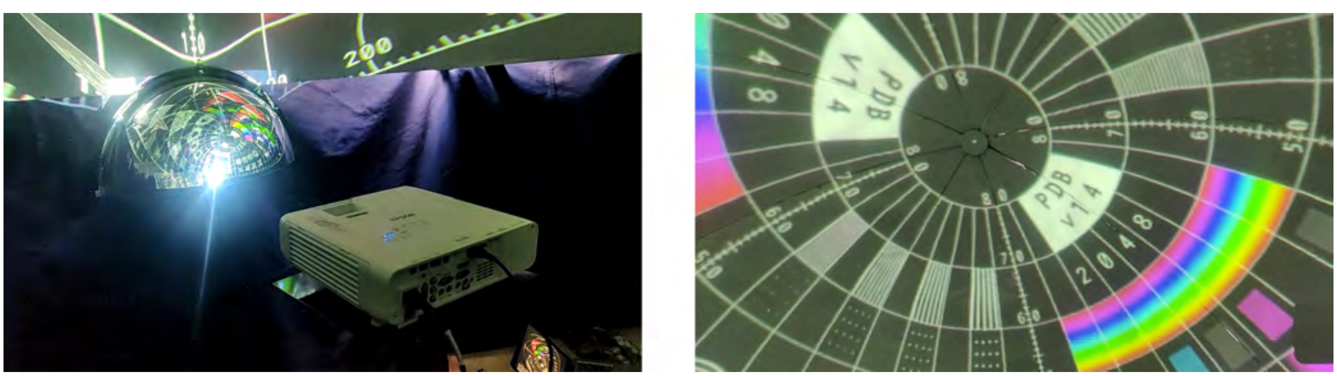

Figure 53. *Right*: What meshmapper's calibration image looks like on the mirror. *Left*: Adjust warp settings in meshmapper until the calibration image is projected appropriately on the dome surface.

Following meshmapper setup, the saved geometry file can be exported to **Fisheye Movie Player**. The user can then play movies with Fisheye Movie Player. Fisheye Movie Player acts much like a regular media player, and uses the geometry file produced by meshmapper to warp movies on the fly (Figure 54).

Figure 54. Fisheye Movie Player can warp fisheye movies on the fly following meshmapper setup.

It should be noted that these projection software are presently available for MacOS only.

5 Discussion

5.1 Mirrordome or Sphemir Projection

Fulldome refers to an environment where the viewer is surrounded by media projected upon a broadly hemispherical surface. Planetariums are perhaps the most well-known theatre of fulldome media, traditionally offering astronomy centred training, education, and entertainment. Fulldome media has become a focus of a myriad different applications in recent years, though. Art, games, and other immersive media have found success in the fulldome format, and domes of different scales have been finding their niche in different applications. Large-scale planetariums utilise purpose-built star projection systems or complex combinations of multiple linear projectors. The cost of these projection systems make large scale planetarium implementations forbiddingly expensive. Smaller domes can, however, still benefit from more affordable projection techniques.

Paul Bourke's Sphemir projection technique is one such affordable technique. The particulars are well documented in Bourke (2005). The basic idea is to use a linear projector to project a warped image onto a spherical mirror. The mirror, in turn, transposes the warped image onto the spherical surface of the dome. This enables us to skirt expensive fisheye projectors or star projectors. Paul Bourke maintains an

FAQ page on his website (http://paulbourke.net/) detailing various recommendations for the Sphemir method.

5.2 Spherical Mirror

The Sphemir system relies upon a linear projector casting an image on a spherical mirror. Projection within a hemispherical dome can be achieved with a quarter spherical mirror. Some of the most common and economical options are mirrors used in road safety and surveillance. These mirrors are often made of acrylic or steel, and are available in a variety of sizes. Contacting in your local market specialising in security and safety equipment seems to be the most probable way.

In Pakistan, most road safety equipment including these mirrors is imported from various Chinese manufacturers. Our search in the Lahore area failed to reveal a reliable source for spherical mirrors, following which we purchased them through an importer.

The use of road safety and surveillance mirrors is supposed to reduce costs in implementing such a system. However, in the absence of an existing local supply in Pakistan, the price to procure such mirrors quickly increases owing to customs and high freight costs per piece in relatively small orders. We are presently investigating other viable spherical mirrors and alternative projection methods which might reduce costs. In the meantime, importing seems to be the most viable way to obtain these mirrors.

Road safety/surveillance mirrors are available in a variety of sizes and spherical portions. One can purchase hemispherical, quarter-sphere, and even eight-sphere mirrors. Available diameters are often in the range of 20–80 cm. Most implementations of the Sphemir system utilise a quarter-sphere with a 30 cm diameter, however. A quarter mirror allows us to project inside a hemispherical dome while being easy to position and install. Additionally, along with being ubiquitous, the 30 cm diameter strikes a great balance between being a large enough target for a linear projector and occupying a small footprint inside the dome.

The use of 30 cm quarter-sphere mirror for fulldome projection is widespread enough that various first-surface mirror manufacturers offer an engineering grade, 30 cm quarter sphere mirror if requested. These mirrors are free of any structural distortions, which can be a problem in road-safety/surveillance mirrors. Since these are also first-surface mirrors, they offer unparalleled sharpness due to an absence of partial dual reflection and good quality coatings keep brightness loss to a minimum. Since first-surface mirrors maximise sharpness and minimise brightness loss, our Sphemir system can also incorporate a flat first-surface mirror in addition to the spherical mirror to reduce the Sphemir footprint even more. This is done by reflecting the image from the projector with the flat mirror before redirecting to the spherical mirror, and thus reducing the linear space required between the projector and mirror. Such a setup has been employed by the University of Washington's mobile planetarium (Rosenfield, Gaily, Fraser, and Wisniewski, 2014), and examples are shown in Figure 55.

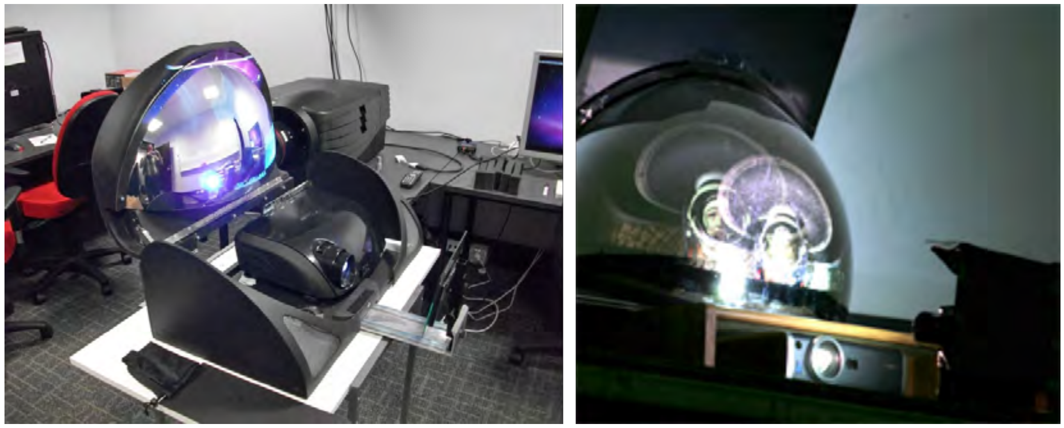

Figure 55. Examples of sphemir systems incorporating a flat mirror to reduce their footprint. *Left*: E-Planetarium's 'Newtonian' projection solution. *Right*: Mueller planetarium's projection solution.

First-surface mirrors do come with their disadvantages though. Engineering grade first-surface mirrors can be extremely expensive, even without factoring in customs, taxes, and freight costs. The recent currency depreciation and restrictions on imports at the time of writing make expensive imports far more costly. Additionally, first-surface mirrors are far more fragile and their reflective coatings are extremely prone to damage, with no option of repair. Special procedures and equipment must be implemented and procured for repeated deployments, storage, and any cleaning.

With these factors present, we procured a 30 cm quarter-sphere road-safety mirror through a local importer. As expected, this mirror is not perfectly spherical and instead is an asymmetric ellipsoid. Modifications in our warping mush must be made to account for these irregularities. 2D dimensions for our mirror are shown in Figure 56.

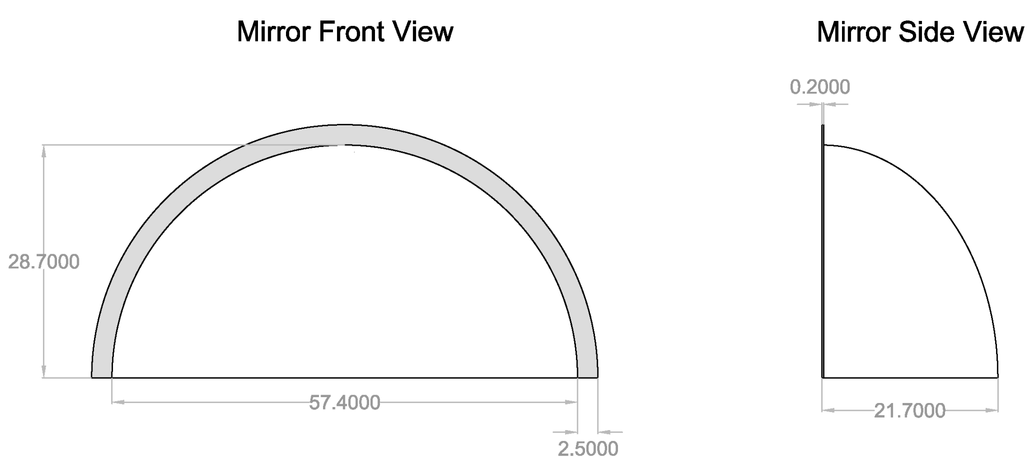

Figure 56. Dimensions of our quarter-sphere mirror. Units in cm.

5.3 Projector

Assuming a spherical mirror with a 60 cm diameter, a suitable linear projector should be able to produce an image 40–50 cm wide in focus. This property will likely need verification, as most end users do not require such a small image and thus projector documentation generally tend not to carry this information. Verification before purchase is highly recommended. Bourke estimates that about 50% of commercial projectors will fulfil this requirement, and the FAQ page also contains a list of projectors that are confirmed to be working.

Bourke also recommends a resolution of 4K (or 1080p at the very least), and an aspect ratio closest to $16 : 9$. This aspect ratio helps us use more of the spherical mirror's surface area.

The projector should maintain an ANSI contrast ratio of more than $2000 : 1$. Care must taken while checking this metric as manufacturers often factor in the projector's dynamic iris to inflate this number.

As a rule of thumb, LCD projectors have a much lower contrast ratio as compared with DLP projectors. Additionally, LCD projectors can also display a more obvious 'screen-door' effect, which is where the grid separating pixels in a digital display is projected as well.

The projector's brightness is a relatively minor factor towards fulldome projection. Although the projector covers a much larger surface area and the reflection from the mirror diminishes some brightness, a pitch-black dome ensures our eyes can adjust to environment quite well.

5.3.1 Epson EB-L200F

For our purposes, we chose the **Epson EB-L200F** 3LCD 1080p projector. This choice was motivated by the L200F's ability to focus at the appropriate distance and its sharp picture quality, along with hardware availability. The L200F displays a sharp image owing to its laser projection. However, it does display a screen-door effect on particularly bright images. In addition, the 1080p resolution appears 'blown-out' inside our 4.5 m diameter dome. A higher resolution would aid with both these limitations.

5.3.2 Analysing your projector

Being intimately familiar with your chosen projector's image output is crucial in developing a precise mirror setup which functions reliably per use. Usually, this level of detail cannot be obtained from the projector's hardware manual alone, and some measurements need to be performed manually.

The L200F has a standard build and throw ratio, and thus is a good representation for a projector one might use in a Sphemir system. This section explains how we analysed the image from the L200F to determine optimal geometry with respect to our mirror.

To begin, there are some features in the L200F which should be turned off. The L200F has automatic vertical keystone correction. This means that placed at a vertical angle, the projector will attempt to modify the image assuming a perfectly vertical projection screen. This correction necessitates that some part of the projection area is unused, causing a significant loss of pixels. Additionally, our image warping software does not account for vertical keystone correction when the projector is placed at an angle, causing complications while fine-tuning corrections. Thus, we turn off vertical keystone correction by navigating to **Installation** > **Geometry Correction** > **H/V-Keystone** > **Auto V-Keystone** and selecting 'off'.

Next, we ensure the correct aspect ratio for the projector. We check that our computer is using the L200F as a separate display, and that its image is set to its native resolution of 1080p.

We carefully note the L200F's dimensions to ensure the final projector placement. While the L200F has a unique external design, we simply note cuboid dimensions for our purposes. These are shown in Figure 57.

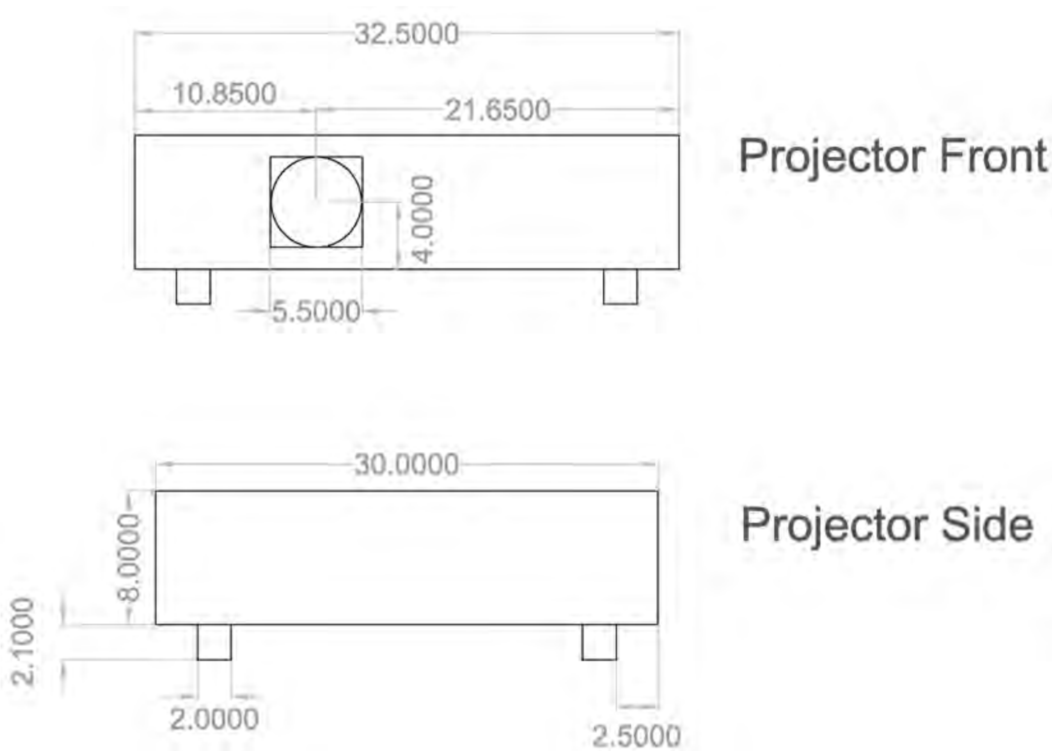

Figure 57. Simplified dimensions for the L200F. Units in cm.

We place our projector directly perpendicular to a wall by ensuring that either edge around the lens is 49.53 cm away from the wall. After this, we note the position and dimensions of the image. The resulting projection is shown in Figure 58.

At this point, we confirmed the image's aspect ratio to be 16 : 9 by dividing the image width by the image height. One of our tests showed a slightly lower aspect ratio, prompting us to modify aspect ratio settings in the projector menu. Thus, checking your image's aspect ratio might be well worth your time.

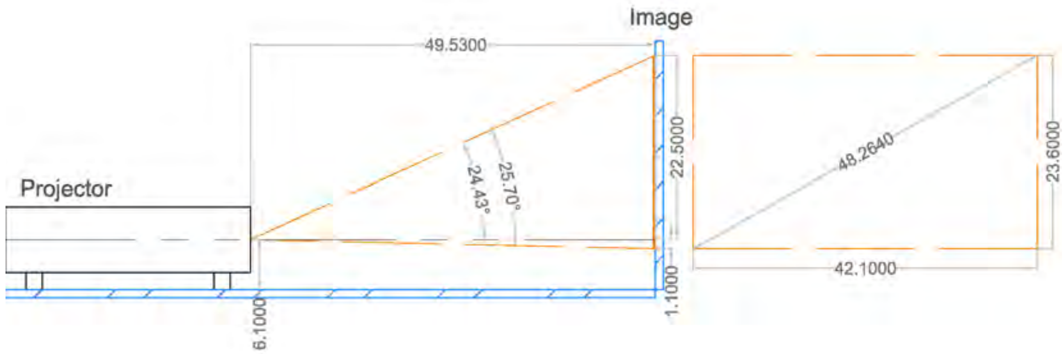

Figure 58. A projected image from the L200F. Units in cm.

Note that the image in Figure 58 was projected at the L200F's minimum throw ratio (producing the largest image at the smallest distance). This is because we'd like to minimise the Sphemir system's footprint in the dome. The L200F's throw ratio (the ratio of the projector-screen distance and the image width) is quoted to be in the range of 1.3–2.10. However, we found that the widest setting on our L200F corresponds to a throw ratio of about 1.17.

We also noted the L200F's vertical offset. How manufacturers define offset can differ[1], but we can define our offset as the ratio of image height above the centre-line and image height below the centre-line. Here, the centre-line is defined to be a line from the centre of the lens to the image, while being perpendicular to the projection screen. The Epson Europe website notes the L200F's offset is noted to be 10 : 1[2]. However, our measurements showed an offset ratio of 20.45 : 1.

We also note that the L200F seems to have a 0% horizontal offset, as the image width on either size of the centre-line is equal. This is shown in Figure 59.

6 Conclusion

The Khwarizmi Science Society strives to create a scientific culture in Pakistan by engaging with the public, fostering scientific curiosity, and encouraging critical thinking. KSS aims to inspire the younger generation to pursue careers in science and contribute to the advancement of knowledge and innovation. KSS's goal is to make science education more engaging, interactive, and accessible to every Pakistani.

The *Khalai Kachwa* is yet another tool to further these goals. Owing to its portability, local production, and accessible projection system, the *Khalai Kachwa* can bring an unparalleled, immersive media environment to every child, as it should be.

[1] https://www.projectorcentral.com/Understanding-Lens-Offset-and-Lens-Shift.htm
[2] https://www.epson.eu/en_EU/products/projectors/eb-l200f/p/30525

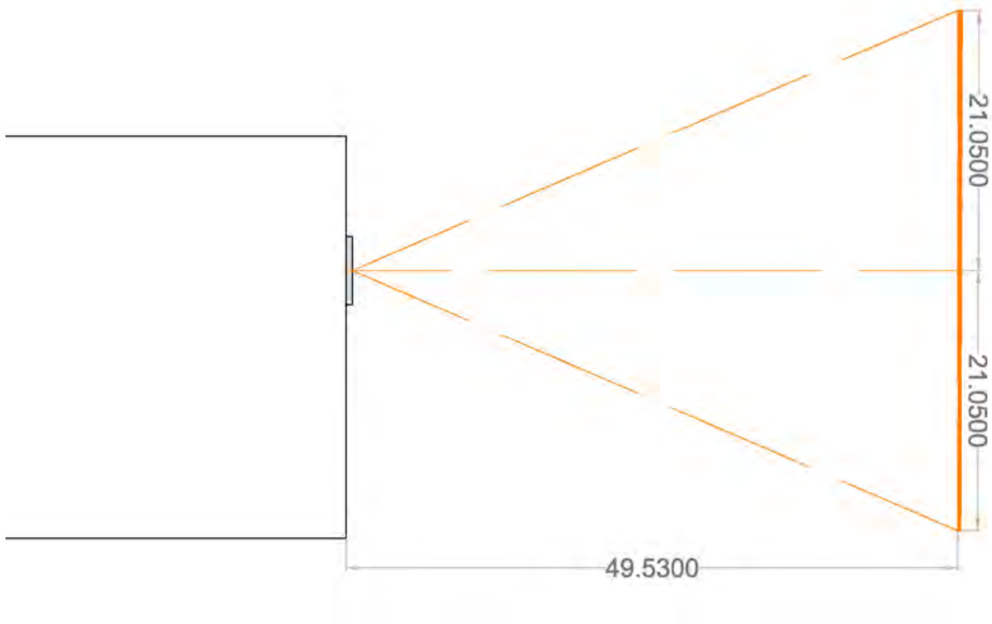

Figure 59. Top view of the L200F and its image. Units in cm.

Figure 60. The KSS team after a *mela*, with the *Khalai Kachwa*'s dome providing with some shelter from the rain!

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