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Novel kinematic equatorial primary mirror mount

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Background Although there is great interest in mounts for very large telescopes, there are still many new telescopes in the 1 to 3 m range that require carefully engineered mounts to achieve diffraction limited performance. In addition, the very large telescopes have associated large instruments with optics in the 1 to 2 m range that need careful mounting. This paper addresses mounting schemes for optics in this size range.

Because all materials are so relatively flimsy if they are expected to hold their shape to a few nanometers, all but the smallest optics must have mounts that are well conceived. This means the design must be based on the kinematic principle of not over-constraining the optic. Even the modestly large optics of projects like the National Ignition Facility (NIF) can benefit from following kinematic principles. The problem is exacerbated in most telescopes because they operate over such a large temperature range and cost prohibits using structural materials that closely match the coefficients of expansion of most mirror substrate materials.

Given that there is the need to mount moderately large optics and that the mounting must be well designed, there should be an approach to the problem that does not require zero based engineering for every new mount. The approach should also use commercially available components wherever possible and be lightweight. All these aspects of this approach to mount design should be useful in reducing costs. By utilizing a systematic approach to kinematic mount design that is built around readily available components, we show there is a rather universal solution to mounting mid-size mirrors

We outline such a design strategy and illustrate it using the new Indiana University 1 25 m telescope intended for unattended synoptic spectroscopy. The design is applied to both the primary and secondary mirrors, lightweight, gas-fusion bonded sandwich structures made by Hextek Corp.[1]

Overview of mirror mount design: We start the discussion of mount design with the case where the optic is so relatively small that almost any mount configuration will introduce trivial distortion. A successful method is mounting the element off a post centered on the back of the mirror. This design works well in any elevation for mirrors up to about 150 mm in diameter

In the 150 to 750 mm diameter range, a 6 point kinematic mount works well for mirrors of a reasonable aspect ratio. In a classic paper by Nelson, et. al.[2], they show that a 6 point support reduces the rms deflection for a zenith pointing mirror by about 25 times the simple edge support case. Simple edge support is effectively the same support as using a single post in the middle of the back. For typical aspect ratios, if the 6 support points are placed at the optimum radius (about 0 7 of the mirror radius depending on the central hole diameter) of the zenith pointing mirror, the gravity induced deflection will produce less than a $\lambda/4$ of spherical aberration in the reflected visible light wavefront assuming each support point constrains only one degree of freedom

The question then is how to connect the 6 points to the mirror cell such that the mirror is exactly constrained yet the mount is stable. Although there have been many quantitative papers written on this subject starting at least as far back as Lord Rayleigh, surveyors found an empirical solution long before him. If the 6 legs are brought down to a base in 3 pairs with joints at each end of the legs that do not restrict rotation, the support is very stable yet does not introduce moments into the plate to which the 6 points are connected. This scheme is shown in Fig. 1

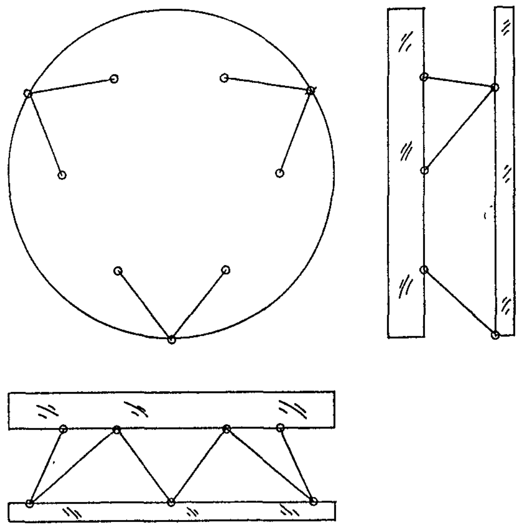

Fig. 1 Stable connection between 2 plates using 3 pairs of legs with ball and socket joints at both ends of the legs.

The hardware solution to joints that do not restrict rotation are rod end joints such as are used in the steering mechanisms of many cars A ball with a hole drilled through it to receive a pin is pressed into a female socket attached to a threaded member that attaches to the leg or strut Such a rod end is shown in Fig 2 With this kinematic support system, the cell base to which the support legs are fastened can expand and contract without changing the forces or moments on the mirror. The only change will be rigid body motion between the mirror and the base plate mostly in the axial direction This will cause defocus and image motion but on a time scale associated with changes in the thermal environment that will affect all other parts of the telescope structure as well.

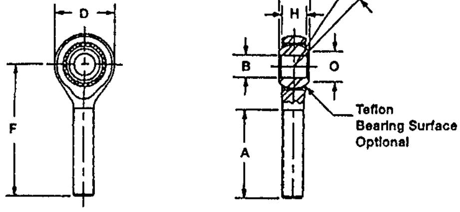

Fig. 2 Commercial rod end joint used in the mount design.

Next is the question of how well does such a support work when the mirror is tipped toward the horizon It is clear that for a zenith facing, circular mirror each of the 6 support points can be arranged so the loads normal to the face of the mirror will be evenly distributed. As the mirror is tipped to the horizon, these loads will be redistributed and will tend to make the mirror astigmatic. Figure 3 shows the change in figure for a mirror tipped 45° from zenith as a function of the support point location. The height units are arbitrary because the actual distortion depends on the mirror stiffness and the moment the mirror makes with respect to the cell base plate to which it is attached.

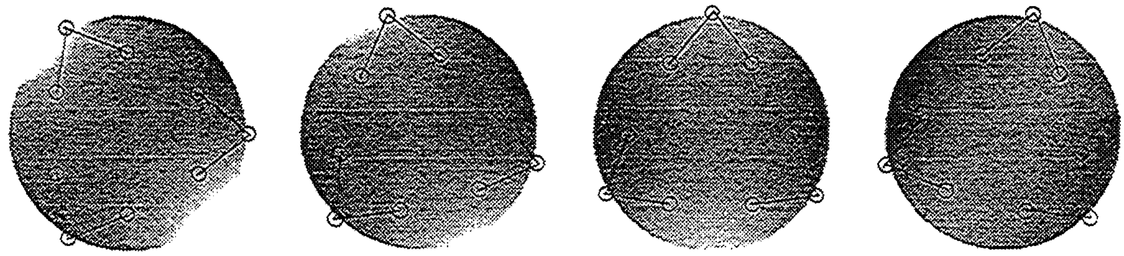

Fig.3 Astigmatic figure of a mirror tipped toward the horizon as a function (every 15 °) of the azimuthal orientation of the 6 support points Light colored areas are high, units are arbitrary

If the support legs are kept short so the legs in combination do not have to resist much of a moment due to the mass of the mirror, the load redistribution is minimized Of course, for larger mirrors in a fixed elevation situation such as in a Nasmyth instrument, the mirror can be figured to the correct shape in the "as mounted" configuration on the 6 point kinematic support In addition, the location of the 6 points of support can be optimized for the particular mirror shape and elevation

Notice that the problem with the 6 point support is that the load begins to hang off of the support legs once the mirror is tipped from zenith producing a moment. To avoid a mirror figure change due to this moment the radial load must be supported through the center of mass of the mirror. This can be done with 6 legs normal to the mirror surface, 3 with rod ends and 3 with springs to take their share of the axial load. Three tangent bars are used to take the radial load. While this points to a general solution to the problem note that the spring rate changes with elevation

Once mirror sizes get larger than roughly 750 mm, the 6 point mount does not provide enough axial support to keep the mirror from sagging in between the supports. The obvious answer is to add more points but now 2 new issues surface With more than 6 points, the mount has to be carefully designed so the support is not over-constrained, that is, so the mount remains kinematic. The other is that since the mirror bends in preferred modes, the additional support points cannot be added arbitrarily but must be added sensibly. Referring again to the Nelson paper, the next logical number of supports is 18. This increases the efficiency of the mount about an order of magnitude and permits us to arrange the support points in 3 groups of 6. Within each group of 6, the support will be kinematic The balance of the paper will focus on this 18 point design but an extension to 36 points is obvious once the 18 point support design is understood.

18 point kinematic mount design· We arrange the supports in 2 rings with 12 points in the outer ring so that each point supports the same area or mass of the mirror. If there were no central hole in the mirror, the ring radii would be 0.408 and 0.817 assuming a unit mirror radius. Now 4 points in the outer ring and the nearest 2 on the inner ring are brought down to a plate in pairs. This gives 3 plates behind the mirror as shown in Fig. 4. Each of these 3 plates is kinematically but rigidly tied to the mirror. These plates are supported by wire ropes through the centers of the load and are tied into a frame directly above the plates. If the frame expands or contracts, the radial load on the plates is a cosine or second order effect.

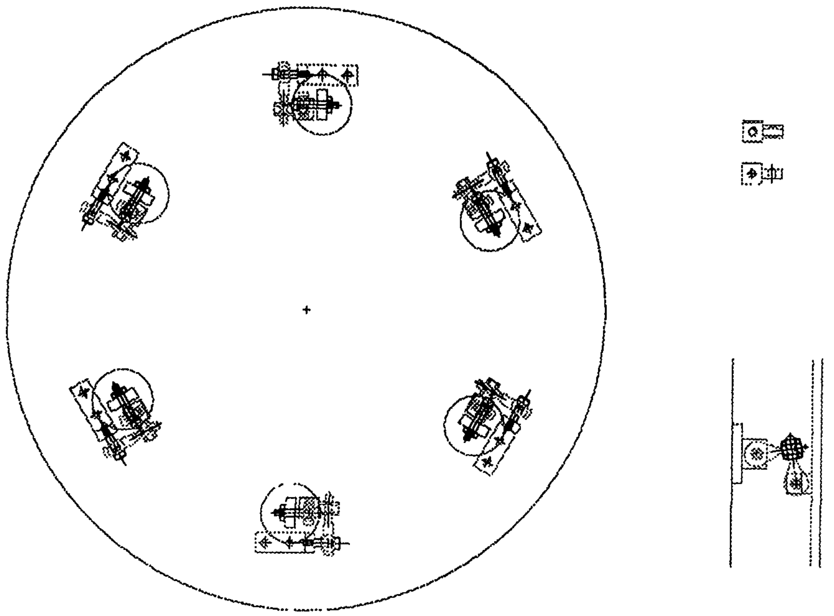

Fig. 4 Plan view of the secondary mirror mount with a side view and detail of the 2 rod ends bolted to the twisted dog-bone shaped link to minimize the distance from mirror to support plate

Of course, this arrangement only constrains 3 degrees of freedom of the mirror. The other 3 constraints are taken up by "tangent bars". We put tangent bars in quotation marks because these bars are usually members that can take compressive loads. In the interests of keeping the mount lightweight and of using commercially available parts, the "tangent bars" are really tangent cables that are pretensioned beyond any possible compressive load. To do this the mirror is surrounded by a 9-sided frame and the cable is tensioned between struts in the frame as shown in Fig. 5. Now the radial or lateral load is transferred through the tangent cables to the cell via the 9-sided and "Y" frames

Since the mirror used in the Indiana telescope is a Hextek fused lightweight sandwich structure, the side walls are not made to support the radial load. In 3 places around the mirror, bars are attached between the faceplates and these transfer the radial load to the tangent cable. The bars have flexures at each end to take up the difference in expansion between the steel bars and the borosilicate mirror.

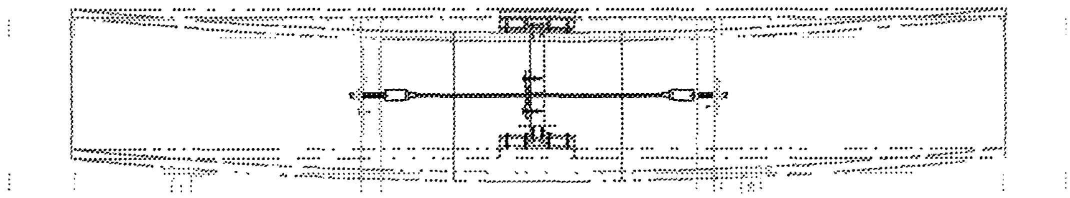

Fig. 5 Side view of mirror with tangent cable tied into the radial support frame and to the mirror via flexure mounted plates between the faceplates.

The whole mirror support structure is tied together with a "Y"-shaped frame. The 3 plates supporting the axial load are hung from the "Y" frame on wire ropes and the 9-sided frame taking the radial load is fastened to the same frame. This entire structure is then bolted into the center section of the telescope that in turn serves as the interface to the yoke and the secondary mirror support structure as shown in Fig. 6

Details of the mount design: While most of the parts of the mount are commercially available hardware or are simple weldments of standard structural steel, there are some specially machined components. The pads to which the rod ends are bolted at the back of the mirror are machined from Invar although the coefficient mismatch is so small that the 0.25 mm RTV bond layer would easily take it up if the pads where mild steel. These pads are just 50 mm diameter disks with a post and clearance hole for a shoulder bolt. We used clearance rather than tapped holes so that when the bolt is tightened, a wrench must be used on the nut. Otherwise the pad would effectively serve as the nut and take an undo moment.

The legs joining the pair of rod ends are hexagonal bar stock with right and left hand tapped threads so the legs act as turnbuckles for final mirror to cell adjustment. Jam nuts are required to keep the legs from loosening. The plates are rather simple structures and have tapped holes for the shoulder bolts attaching the rod ends. The legs must be brought together in pairs at the plate and the projections of the legs must not cross in the same place in space or the 6 legs will be unstable Do not, for example, have the projection along the legs all cross at the projection of the wire rope support. If it were not for wanting the keep the mass low and stiffness of the plates high, it would be a more stable structure if the legs were splayed out like one sees with a surveyor's tripod rather than bringing the legs in toward the wire rope support point.

The wire rope ties from the plate to the "Y" frame are again commercially available wire rope fittings as are the tensioned tangent cables Other pieces of custom hardware are the 3 bars connecting the faceplates that then attach to the tangent cables. These are made of mild steel and the flexures take care of differences in expansion. An adjustable clamp allows one to center the mirror and adjust the axial height before clamping on to the tensioned cables.

Extension to larger diameter mirrors: As mentioned above, by going to 36 points we can support the axial load of a mirror over 2 m in diameter. In this size range, the mirror becomes flexible enough through its diameter that simply using tangent bars may not be sufficient. On the other hand, such a mirror probably would not be used in an equatorial mount so the radial support could be a counterweighted band around the periphery.

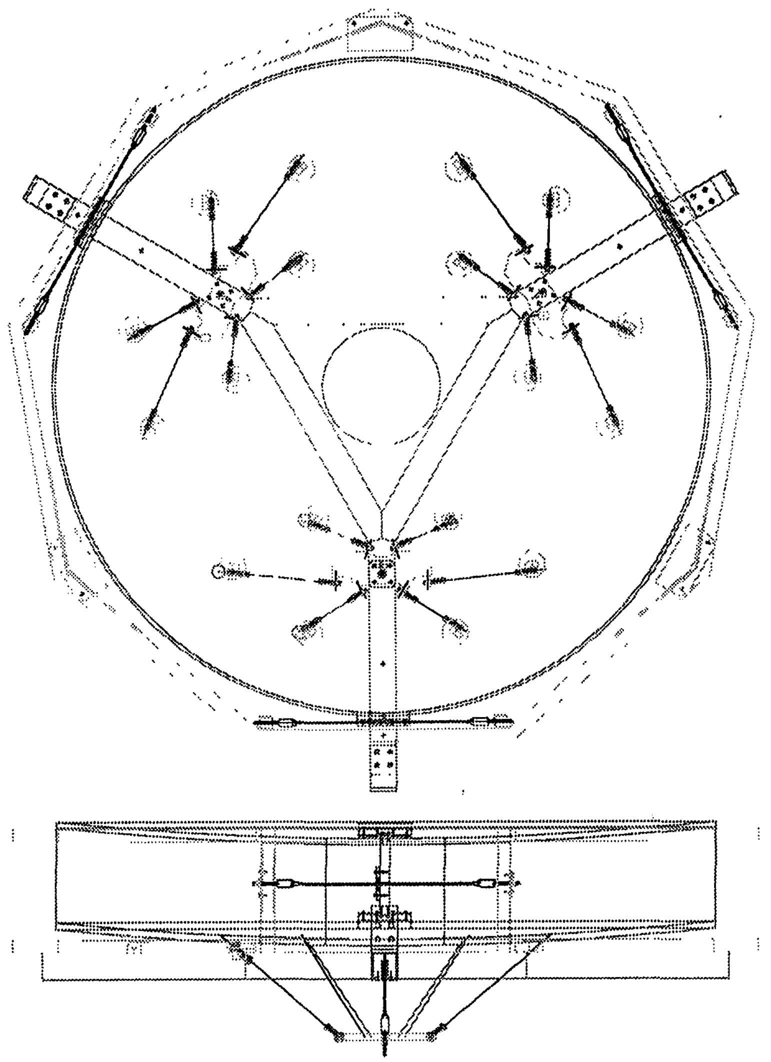

Fig. 6 Plan and side views of entire kinematic mount system showing the "Y" frame with the radial support frame welded on and the plates hanging from it.

In the 36 point support, we use 3 rings of 18, 12 and 6 supports brought down to 6 plates in sets of 6 legs. The plates are still hung by wire ropes but these are now attached to a bar pivoted over the "Y" support arms. This permits the mount to almost as simple as the 18 point support and takes up no more axial space.

Performance: Due to unforeseen delays, we are not as far along with performance testing as we might wish. The mirrors are installed in the telescope and we have obtained star images that are circularly symmetric for all elevations and azimuths within our ability to analyze the images The images are however larger than we expected making a strict analysis of the mount performance difficult at this time. Figure 7 shows the 18 point axial support during installation.

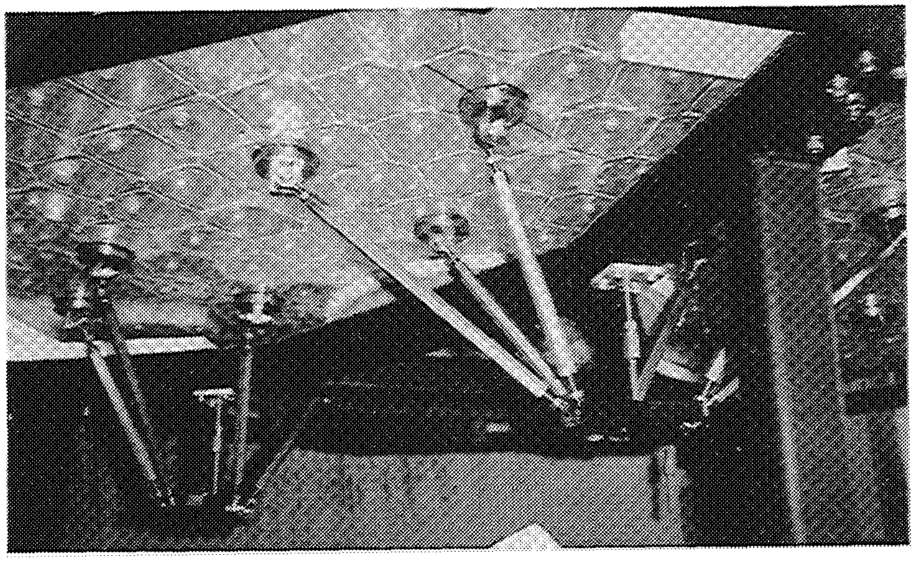

Fig. 7 Photograph of the rear of the 1.25 m primary and the axial support system.

Conclusion: We have presented the design rationale and the design of the kinematic 18 point axial support for the 1.25 m primary for the new Indiana University equatorial telescope. The design incorporates a lightweight tangent cable support for the radial load. We have shown how this rather simple mount made of commercially available hardware can be extended to larger mirrors with a 36 point support system.

[1]Hextek Corp., 1665 E. 18th St., Suite 208, Tucson, AZ 85719.
[2]J. E. Nelson, J. Lubliner and T. S. Mast, "Telescope Mirror Supports. Plate Deflections on Point Supports", TMT Technical Report, Lawrance Berkeley Laboratory, Berkely, CA (1982).