High Bore-Sight Accuracy Collimators

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1. ABSTRACT

A high degree of accuracy is required in the alignment of this off axis Newtonian collimator. The total bore-sight error budget is 5 arcseconds. This includes the unit to unit variations and effects of a standard military environmental range. The bore-sight requirement is driven by subsystem interchangeability in a modular design of the test station which the collimator is incorporated in at the next level of assembly.

This is an Optical Engineer's look at the engineering and testing concerns for a collimator requiring a 5 arcsecond bore-sight to its mechanical mounting datums. The collimator is of the off axis Newtonian type with a fairly fast f/number of 3.75. The primary aim of this paper are the special concerns of aligning a collimator very precisely to a mechanical datum, and doing it quickly. The optical engineering and test aspects of the alignment process will be presented with an emphasis on information applicable to other designs. Metrology methods are all based on the LUPI or Laser Unequal Path Interferometer monitoring the Aspheric Mirror Alignment. The control of the bore-sight to the mechanical datums is reliant on a fixture system designed and built by the author to make volume production as painless as possible. The paper addresses how the fixture design can be used to help the alignment rather than specifics of this exact system design.

Testing FLIR pods (Forward looking Infrared Radar, a night vision device) for bore-sight, MTF and MRTD in the field is the primary design intent of the overall test station. Obviously we are talking about a military application. The aircraft supported is the Navy F/A 18 with a carrier based test station. There are a few design goals derived by other test requirements that add more stringent requirements to this LWIR basic design.

2. INTRODUCTION AND DESIGN BACKGROUND

The collimator design resulted from the requirements of making a field test station for FLIR pods. This is a Navy project for carrier based planes, so the available space was rather limited and the operating conditions are not the best for high precision optics. We all know, of course, that military is just a short hand way of saying terrible operational environment. Basic tests would cover MRTD, MTF, bore-sight, electronics and detector performance. The operator training requirements would greatly benefit from a modular test station design. A typical technician or two could unbolts any module from the test station. Replacement of that module by strictly mechanical means will maintain the optical alignment of the system, all without the benefit of any recalibration or realignment or bore-sight correction. This allows the technician's training time to be dedicated to the Unit Under Test and not Test Station Maintenance. This is a very noble goal in the eyes of the military. Reliability is improved, since you can replace modules. Spares support has vastly fewer operating headaches with the simple mechanical assembly of sub systems like this collimator.

The author was the responsible engineer for the design and fabrication of these collimators as well as program manager.
**Basic Collimator Design Specs:**
- Focal Length: 30.00 inch
- Diameter: 8.00 inch
- Off Axis Distance: 2.50 inch to edge
- Wavefront Quality: \( \lambda/4 @ 633 \text{ nm} \)
- Operating Temp Range: 40° to 105° F
- Bore-Sight **: 5 arcseconds
- Range of focus position from interface plane: 1 500° +/- 005°

**Bore-Sight** defined as a parallelism to alignment pins and mounting system pads. Two axes are specified separately and a square tolerance zone results.

The original specification also dictated the interface and envelope dimensions between the Collimator Subsystem and the rest of the Test Station. The following conceptual drawing of the system shows the basic layout. This is all pretty routine stuff except for the bore-sight. There was not an exact specification of stiffness, resonant frequency or jitter in the operating environment. Most design decisions in these areas came from discussions between the responsible engineers at McDonnell Aircraft Co and Space Optics. The shipping and nonoperating environments are the typical military requirements.

**Space Optics - MDAC / EOTS Collimator**

![Image of collimator design](image)

**Figure 2.0** The basic collimator design for hardware. Isometric view is shown with the covers and related hardware removed for clarity. In use the collimator hangs from a custom optical table's lower mounting surface and has to support a 60 lb focal plane assembly from the focal plane interface. This view shows the collimator resting on its back, so we can see the details inside.

The concept of the two pins, four pads, four bolts interface was dictated by the original specification. There was the usual outcry over the choice of **FOUR** mounting points. After the normal amount of heated discussions of good kinematic mounting practices it was determined that four pads and four bolts were cast in the proverbial stone. This dictates a lot of work in lapping interface surfaces to tight tolerances and generally complicates the whole manufacturing process.
2.1 Bore-sight Specifications

How and why do you get left with only 5 arcseconds in the align budget of a system? When you cascade the optical path through several modules the alignment tolerances start to get rather small. To maintain, let us say, a 1 arcminute alignment of the test station's bore-sight you must look at all the modules and the interfaces between them. For example, if you have 7 modules and 6 interfaces to RSS { root of the sum of the squares } you're down to about 4.6 arcseconds at each point. This is just a straight RSS apportioning of the error budget. Obviously we're talking about a design produced in quantity. The down side of this is that the error budgets must include the unit to unit variations.

Some of the design decisions will be easier to understand with the knowledge that the design was developed with an initial order of 20 units in mind. This greatly influences most fixture choices. Capitalization of fixtures is spread out over decent quantities and the labor savings involved are repeated many times. Final quantities work out to about 55 collimators so far.

3.0 ALIGNMENT STRATEGIES

Starting where this design itself started lets break down the error budget and look at alignment methods that can control the separate tasks of the assembly problem. This allows us to apportion the error budget in the most effective manner. In discussing alignment and test the error budget for bore-sight can be treated as entirely separate from the wavefront errors.

3.1 How is bore-sight defined?

The optical axis of the OAP is the location we want to define as the optical datum. This would be the direction that the collimator would project light along with a perfectly centered target. The mechanical datum was specified by the customer. The output bore-sight was to be parallel to the upper mounting interface and parallel to the center line of the two system alignment pins on the top surface of the collimator. { Please refer to Figure 2.0 for relative positions of features.}
Well, that's fine for a definition but you're not going to be able to easily lay your hands on an optical axis. The physically measurable datum of the optics is the position of the focal point as defined by the interferometer and the line of sight defined by the mirror and this position. That is not exactly the optical axis. Errors in positioning the focal point and residual wavefront error cause this to be slightly out of parallel and displaced from the "real" optical axis. Maybe we should say best fit optical axis to avoid confusion. We are really saying that this is the axis within a certain tolerance, which is acceptable to this design. If we align the mirror to $\lambda/4$ then we know that to that level of accuracy this is the optical axis.

The output line of sight is easy to reference when the LUPI is in place for testing. The LUPI is illuminating exactly this line of sight. It is easy to pick up the reference with other equipment like autocollimators or alignment telescopes. There is also the option of using the LUPI and null flat to serve as a reference.

The focal point is well defined by the interferometer that is used to align the OAP, because the focus location of the diverger objective is a easily measured point. For the f/2 objective that is convenient here, the focus is really $3\mu$ in diameter to the first minima of the airy disk. This is great for optical accuracy, but we need a mechanical device to be located there. Remember that the focal plane equipment is in another subsystem of the test station and is not even being integrated at the same time. A lot more will be said on this in the next two sections.

Figure 3.1 Collimator Layout with null test. The off axis parabolic primary mirror is tested in the classic autocollimation null test. A LUPI is placed at the focus of the collimator for interferometric testing.

### 3.1.1 Testing with a null flat

The autocollimation null test of an OAP is probably familiar to everyone. This is the traditional test for parabolic mirrors. This test is the easiest way to define the optical axis location of the mirror. The null flat is perpendicular to the optical axis of the mirror when the optics are aligned, at least this is true within the accuracy of the alignment. This gives us a method of checking the pointing direction of the collimator optics. Now it is only necessary to relate it to the desired bore-sight as defined by the mechanical datums. That is a lot more involved. The nice part is the same test will check the wavefront quality of the optics at the same time. This is convenient since there is likely to be a reiterative process of correcting the bore-sight and bringing the wavefront back in specification to finish the system alignment.
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Let's look at the problem logically

- What determines the pointing direction of the optics?
  
  Mirror and focus position.

- OK we have the mirror position for this test. What does the focus position depend on?
  
  Most of the hardware.

3.2 Defining the focal point.

In the final system a target is located at the focal point. Parallelism of the focal plane to the target wheel is also a concern. The focal plane location for the focal plane equipment is defined by an angle and focus axis position by four mounting pads. Two bushing receiving nominally 1/4" pins define the x, y location of the focal point in the focal plane.

- How accurate of location is required
  
  A ten thousandth of an inch (0.0001") is 0.68 arcseconds in terms of a 30" focal length.

- How accurately can you control the bushing locations?

- How much time and money does this process consume?

- How do you accurately reference the bushing locations to set the focal point location?

The first two can be answered in a lot of different ways

1. Bushing locations can be established by a jig grinder and bushings pressed into the resulting hole.

2. One bushing location can be fixed by a semi-accurate reamed hole and pressed in place. The second bushing is then adjusted before fixing its location. There are a number of methods to "fix" the bushing. Pinning or epoxy staking are typical.

3. Bushing mountings can be replicated from a fixture.

These methods could all get into the +/-0.0002 or better accuracy range. The methods are listed in decreasing cost order. For hardware cost reasons we wanted to use an assembly of a cast side plate and a stainless steel mounting pad. This meant that the grinding would have to go through two part of dissimilar hardness. Obviously the work would have to be done after the parts were assembled.

Method two is workable but expensive in terms of time. This was done on the alignment of the system alignment pins to somewhat looser tolerances. Either of the first two methods would be more applicable to limited production quantities where the fixture cost are prohibitive.

Replicating, method 3, is the cheaper method when working in volume. Two pins on a fixture define the location of the bushings. Epoxy is then injected around the bushing. A steel filled epoxy is used in this case. The part is removed from the fixture after the epoxy is set. The locations of the bushings are now that of the pins in the jig, with some variation for the fit of the parts. This replication method is often used to make sub-master jigs from a master jig. For instance, you replicate a female bushed part from the pins of a male master jig and then reverse the process and replicate a new pin carrying jig from the female bushed part. This is cheap and fairly easy for the accuracies that need to be held. Figure 3.2 shows the steps in cartoon form that may be easier to follow.
Replication was selected as the best method. Ability to hold the tolerances and cost are the key factors in that decision.

From experience we know that a 0.0001" clearance will be workable if the pins are highly parallel. A layer of oil in the bushing will tend to further center the bushing pin fit, as well as provide an emergency separating agent if the epoxy gets into the bushing. The final design is a 0.2501" +0.0001" -0.0000" ID on the bushing. The pin in the jig is a 0.25000" +0.00000" -0.00004" diameter, a Deltronics X-class gauge pin.

Looking to tolerances on this process, we need to determine if the fixture error is part of the total budget. The customer in this case left fairly loose positional tolerances on the bushing locations, only +/- 0.002". The fixture then becomes the defining dimensions for bushing location. The tolerances in building the fixture do not feed into the bore-sight and wavefront error budget. The construction of the jig is simplified by only having to meet the +/-0.002" instead of the budget tolerances.

Building the master fixture is just an exercise in precision machining, a high cost item that can be spread out over a lot of units. The first and second step in replication are a sub-master fixture with very tight tolerance bushing fits. In all likelihood these can be selected from the production run of bushings. The third and final step are the replication of the bushing locations from the sub master fixture to the actual collimator. The accuracy of the replication process from the master fixture is 50 millionths of an inch {+/- 0.00005"} at each of three steps. The accuracy is roughly half the maximum diameter difference between pins and bushings with a 0.0002" minimum oil layer assumed. This 0.00015" error translates into a one arcsecond bore-sight variation of the collimator from nominal in the worst case. { 0.00015" translational error in the focal plane of a 30 inch focal length OAP}

3.3 Positioning the LUPI at the focus location of the collimator.

Having determined the accuracy of the bushing locations, it is now necessary to locate the interferometer relative to these datums. Another fixture could position a reference at the focal point. At least this is true if you are working in quantity, for one or two units you can certainly measure the position out each time. By locating the bushings with pins again it is possible to set up a fixture that will hang from the focal plane interface and locate the focus. In this fixture we used a small laser drilled pinhole to mark the focus position. It is easy to set the fixture position to customer specified focus position, the tolerances are fairly loose at +/- 0.002" laterally and +/- 0.005" in focus. The intent of this design is to have the focus set to +/- 0.0005" and lateral position to +/-0.001". This was initially set using a video microscope as a positional probe on our Brown & Sharpe Coordinate Measuring Machine.

Once the fixture is built and qualified its position becomes the exact, or I should say "basic", position for all further fixtures and settings for focus. By working from this well defined basic dimension for focus position it is possible to tighten up the focus position control. A master and sub master fixture pair could be setup for this feature.
path of least effort was to use a very accurate coordinate measuring machine to handle calibration and to gauge fixture wear.

3.3.1 Position LUP1 at a pinhole.
The pinhole size is only 2.5μ in diameter. This is about the size of the diffraction limited spot for an f/2 cone. The choice is based on exactly that reason, the aperture of the interferometer objective that was desired was f/2. The normal alignment of a focus spot to a pinhole, the same as any spatial filter, will get light from the interferometer to pass through this extremely small pinhole. The exact positioning can be determined by Foucault knifing on the edges of this hole. The Foucault cutoff effect is a bit messy due to the finite material thickness in the pinhole substrate. The messy cutoff still allows a high accuracy of position. Repeated positioning indicated that the location was determined laterally to better than +/- 0.00005" by the Foucault cutoff. Focus was detected to 0.0002" inch by the same method.

By the way, there is one problem with positioning the interferometer this way. The pinhole is too small to do serious interferometry through. Any aberration in the returning beam will be cutoff by the pinhole. A perfectly aligned system will return some of the image through the pinhole. Remember that the collimator is only Ø3.75, its diffraction spot is 4 times larger in area than the pinhole. Therefore, it is necessary to remove the fixture. A very good focus axis translator on the interferometer will allow just moving the interferometer back a good distance and allow accurate repositioning after the fixture is removed.

3.4 How do we define the mechanical bore-sight direction in the lab?
The bore-sight was defined and specified relative to mechanical datums. What is the best way to measure this? How accurately can this be done?

To find a reference on the mounting surface we would like an extended flat surface in the plane of the system mounting pads. The direct approach is to bolt the unit up to a surface plate. This provides a wide reference surface for the desired plane. The upper surface plate in our setup is 2 x 3 feet and of <0.001" flatness. If you intend to flip a surface plate over and use it at high accuracy, remember that their performance is not guaranteed in that mounting position. You have to properly support the surface plate and make what ever surface figure corrections are necessary. That's pretty easy compared to grinding and polishing an aspheric mirror but it should not be overlooked.

Referencing the alignment pins is not as easy. Ideally we want to pick up the locations to no more than +/- 0.00005" tolerance. This means a bushing with a 0.0001" clearance fit. The pins are hidden by the system when mounting the system, they are in the bottom of that surface plate. If you want to interface to close tolerance bushings under a table top, good luck and have your psychoanalyst call me. The author had no intentions of trying this, so an easier method was needed.

One approach is to reference the side of the pins with a flat surface. If the pins are the same size then the process has a very good centerline pickup. Two "flat surfaces" were epoxied into the bottom of the surface plate. One has a stop built in to position the collimator in the other direction. A side force from a hand screw keeps the pins in contact when bolting the collimator in the fixture. It's really amazing what they will machine into these plates for a few dollars. Figure 3.4 shows the relative location of the System Alignment Pins and the optics. For this to work the two surfaces should be coplanar or the pins an exact separation on all units. Both are done in this design. Coplanarity is good practice to reduce errors and the customer is still using bushing so they need the exact locations. At least the customer has one slotted bushing to allow a +/- 0.005" allowed variation in position and some freedom in installation, being conservative we use +/- 0.002".

Matching the diameters of the system alignment pins is easy. In production quantities it is not expensive to have custom pins ground to your specifications, in this case they are 0.3750" +0.0001" -0.0000" out side diameter. Obviously these pins must be perpendicular to the main mounting surface.
The error budget has a contribution from the system alignment pin interface of \(0.00005^\circ\) over their 22 00 inch separation. This is directly from the maximum miss match of diameters. That is 0.45 arcseconds. If you match the pins by sorting the fat +0.0001 pins from the thin +0 0000 to +0.00005 you can reduce that further. If you are working at too small a volume to custom grind pins, consider that gauge pins are of similar precision, are very well hardened and are low cost.

3.5 Transferring the bore-sight reference.

There has to be an easy way to get the alignment datums down from the upper surface plate. The two axes can be treated separately, that should simplify things.

3.5.1 Vertical bore-sight reference.

The Vertical direction is the easiest so do that first. If a second surface plate is parallel to the small plate it could be used as a reference. If you build the fixture on a surface plate to start with, this is easy. Just get out a very good height gauge and indicator and adjust the two plates into parallel. In this design four large jack screws support the plate near the corners, they are also the adjustment. It a little easier to describe this than do it, but it is not all that bad. Four jack screws can lead to bending of the upper surface plate. Sufficient care will avoid the bending problem.

If the null mirror was perpendicular to the lower surface plate we would be done in this direction. Perpendicular means to within a second at most here. There are a few ways to make that true. Let's consider two possible methods: optical and brute force, if you will.

The optical method is to look at the included angle between the null flat and the surface plate with an interferometer or autocollimator. The image returned will show two diverging planes or images if the angle is not exactly 90°. Adjust the angle till you have it right. This method has been used to check prisms and the like for about a hundred years, it works great. But the surface plate needs to be slightly reflective at least and you may not want to do this too many times.
Figure 3.5.1 Setting the null mirror to nominal position. Level the surface plates to transfer vertical alignment reference from the collimator. It is best to remove the collimator and measure right at the mounting points.

Figure 3.5.1a The collimator in the test fixture. The reference cube is 8 x 8 x 12 inches for a sense of scale and is a subarcsecond three surface cube. The cube defines the final bore-sight direction. The interferometer is setup at focus and that is the actual wavefront of the system under test. Tilt fringes have been added to measure the wavefront. The interferometer can also examine the bore-sight in this configuration.
The brute force method is my personal favorite. We have all seen reference cubes with several perpendicular faces on a small metal or glass cube. Cubes of this sort are often made to one arcsecond accuracy or better. Well just imaging a big one. If the cube was 8 inch across the collimator could be nulled by it and we could see the whole aperture. The cube in the picture below is 8 x 8 x 12 inches and made of fused silica. Now you know the method I chose at the start of the project.

The external surfaces of the reference cube are checked by the same methods described above in the optical methods. This particular cube is good to better than an arcsecond between three faces, Front, Bottom and one side. The side is for the focal plane alignment and is not really part of this paper’s topic. Alignment of the cube to the surface plate is easily checked if the surface plate is slightly reflective, you can see fringes between the cube’s Bottom and the surface plate. We have defined everything’s alignment but the interferometric test in the other axis.

3.5.2 The horizontal bore-sight reference

Horizontally things are not so easy. The "rotation" of the reference cube needs to set, at least it's hard to upset the vertical setting while doing this. The two small flat surfaces in the upper plate are the reference datum in the fixture that needs to be transferred. They are not the easiest thing to work from as they are imbedded in the surface plate by design.

If the two surfaces were on one block and that block polished to a high accuracy it would be a simple matter to sight into that surface with an autocollimator and transfer that angular direction to the reference cube. Well this could be done, and it was considered, but that's not very elegant and it is tough to prevent the upper surface plate from bending if you have milled a slot 24" long down its center. Remember those reference surfaces are a long way apart.

The idea of using a fixture that could reference the mounting surfaces in the same way as the collimator was investigated. A Flip-Fixture with a two sided plano-parallel mirror is used. The flip fixture has to be set first. Figure 3.5.2 shows the Flip Fixture in front of the reference cube as it is being aligned. The idea is to support the two pins parallel to the surface plate and adjust the mirror to be parallel to the cube's face. The parallel and the flip fixture can be rotated or flipped end for end, allowing variations in the accuracy of the parts to be assessed. This process will set the perpendicularly to the limit of the accuracy of the reference cube and the measurement. The Cube is < 1 arcsecond. The measurement can be made in a variety of ways with accuracies down to less than 0.1 arcsecond. Interferometrically with a Fizeau or LUPI gives the best accuracy. An autocollimator measurement will be a little less accurate but possibly easier to perform.

**Figure 3.5.2** Flip-Fixture is used to reference mounting datums for the system alignment pins on the top of the collimator. Illustration shows the fixture being aligned from the reference cube.
Mount the aligned Flip-Fixture in place of the collimator. The location of the reference surfaces for the pins is now picked up with the Flip-Fixture. The Flip-Fixture's mirror can be viewed from the rear of the test setup. The cube appears around the mirror mount. If a large enough aperture is available on an autocollimator it will get returns from both the cube and the Flip-Fixture. That make the measurement very easy. An interferometer, either Fizeau or LUPI, can also be used in this manner. Adjusting the cube is accomplished by rotations of the cube, that motion will not upset the vertical alignment. Accuracies are as seen in the vertical results. One arcsecond on the cube angle and possibilities of better than 0.1 arcsecond measurements. The Flip-Fixture is shown in action with the autocollimator method in Figure 3.5.2a.

![Figure 3.5.2a](image)

Figure 3.5.2a Flip-Fixture is used to reference mounting datums for the system alignment pins on the top of the collimator. An autocollimator is shown in this setup, an interferometer will also work. The reference cube is rotated to align its front surface to the position of the Flip-Fixture.

### 3.6 Allotting error budget to the interferometric alignment.

What is the limit of the interferometric alignment? First we must remember that the interferometric alignment is a two part test, we are checking both the wavefront accuracy and the bore-sight. The bore-sight and wavefront alignments will interact, as you adjust one the other will change.

#### 3.6.1 Sensitivities of alignment.

The relative sensitivities of the wavefront alignment and bore-sight are considerably different. The bore-sight is by far the worse of the two. If we consider a $\lambda/12$ wavefront change as a typical minimum error adjustment increment in aligning to $\lambda/4$, then it is possible to relate that to the bore-sight sensitivity. Let's express everything in terms of distances in the focal plane. The wavefront of the Primary Mirror deteriorates by $\lambda/12$ as shown in the figure by the wavefront isocontour. We are adjusting to 2 arcseconds so that has been plotted on the same distance scale.
Figure 3.6 Wavefront versus bore-sight. Isocontours of $1/6$ wave and $1/12$ wave are shown as distance in focal plane position. Two circles show the distance in the focal plane corresponding to 2 and 5 arcsec bore-sights.

Figure 3.6 shows that we should be able to steer the bore-sight by small amounts without loosing the wavefront. At least there is a "little room" left in the wavefront error budget. Knowing this would be the standard final alignment tradeoff, the mirrors are specified to have a considerably better wavefront than is needed just to insure their alignment { wavefront wise } . The primary mirror or OAP was specified at $\lambda/6$ P-V wavefront. The fold mirror was specified at $\lambda/6$ 5 over the full CA which corresponds to a typical wavefront on $\lambda/13$ over the axial CA of the flat. These two mirrors RSS to 0.184 waves and this is very conservative with off axis optics. *** The range of alignment in the focal plane to maintain a $\lambda/4$ specification is 0.170 $\lambda$ or about $\lambda/6$ and this is the larger isocontour.

*** I'm taking the liberty of RSSing peak to valley wavefront numbers here because I have made some major assumptions on what the wavefronts will look like. This is based on experience with what our opticians produce and the type of mirrors involved. The residual wavefront errors will be small local zones and possibly a turned edge here and there. This is not a strictly additive error. There is also the interesting fact that an OAP will allow you to align almost all of an astigmatic aberration { 3rd order astigmatism } out of the wavefront. Power in the fold flat is mainly astigmatism as it affects the system. Don't knock the logic, it has held up in a lot of production cases!

3.6.2 Setting Bore-sight with a LUPI

In the process of using a LUPI to check bore-sight there is one possible confusion. The analyzer mirror in a LUPI can produce the same tilts as a small lateral misalignment of the focus spot. It is vital to bore-sight alignments that the two effects are distinguishable from one another. The problem is that the diverger objective in the LUPI has a field of view. That will be the only time anyone ever complains about the existence of a FOV. The FOV is what allows the objective to return aberrated images. This problem can apply to fizeau type interferometers and transmission spheres as well.

There is an elegant solution to the problem of identifying the "real" tilt misalignment. A corner cube will return a beam upon itself. A corner cube placed in the parallel light of the collimator output or in the undiverged LUPI test beam will provide a reference to the angular direction that the beam of light is traveling. The limitation on the accuracy is the accuracy of construction of the corner cube. Fortunately, corner cubes are commercially available with better than 1 arcsecond accuracies. With a Fizeau it may be an issue of the accuracy of the internal reference, rather than the lack of an internal reference.
The Space Optics' design of interferometer the LUPI-II, that is shown in Figure 3.5 la, does not include an internal corner cube reference. It is available in a special extension tube for mounting objectives, that allows a small cube to be interposed in the beam. Availability of space in the fixture setup and the stiffness of the interferometer was important in our choice of how to use this reference. A corner cube in front of the primary mirror just fits into the setup better than the addition to the tube. The cube simply rests on a lab space under the collimator assembly.

The view from the interferometer is a hexagonal interferogram of the corner cube return with the edges of null mirror returning the rest of the 8 inch collimated bundle. A five inch corner cube was used in all of the work on this project. The accuracy of the cube is better than 0.25 arcseconds. The accuracy was periodically checked by interferometer.

With the fixturing aligned and the LUPI in place we can get down to the actual measurement. Measuring bore-sight angle is easy with an interferometer. On an eight inch aperture one arcsecond of change in bore-sight is 3 fringes in this double pass test setup. It was easy to steer the primary mirror to correct the bore-sight to the one arcsecond tolerance. One third of that, one fringe over 8 inches, could be done with ease.

3.7 Long term drift in the collimator. A few comments on a lengthy subject.

Long term drift is a materials question in major part. The stability of the mounting hardware is the major concern. The loose focus tolerance allowed the use of some unusual material choices. The "metering" of despace or focus is accomplished by cast iron hardware. This was a low enough CTE for the athermalization to work and has an added benefit. The some Meehanite series of gray nodular cast irons have a long history of use in high stability machine tool structures and metrology instruments. Specifically we are using GC-30 Meehanite. Now Meehanite is not the lightest material in the realm of all things, but it can be cast in thin section. Most of the surface skin of the collimator is only 0.090" to 0.125" thick. The strength and stiffness come from the egg crate ribs of the main strong back parts. Most of the ribbing is on the order of 0.25" thick. If you refer to figure 2.1 it shows most of the rib patterns. This cast to form egg crate design offsets most of the weight gained by the choice of cast iron.

Mirror mounts are of Aluminum 6061-T6 and as such require a heat treatment to stress relieve the parts. The Primary Mirror mount design is shown in the following cross section of the primary mount. Both mounts are adjustable although the methods differ. The primary is adjusted by crossed pairs of fine thread push screws. The secondary which is not used to steer the bore-sight is positioned with lapped shims in one axis and pinned tilt adjustment in the other axis. The details of that mount are not pertinent to this paper. The other big mounting detail in terms of the long term drift is the cell to glass interface. Very conventional potting techniques are used. The potting compound is General Electric's RTV 615, a silicone rubber product. This is not the most common RTV in the optics industry but the design decision was based experience with the material on similar size mirrors, and the ease of handling the material. The potting is also responsible for the athermalization of the cells in the conventional manner.

Beyond the micro creep stability of your materials, long term drift estimates are largely based on experience. The original estimate was a 2 arcsecond drift in 10 years. This drift performance has been born out by the first of the unit to come back for refurbishment, it was still in specification bore-sight wise. The time interval was 24 months.

3.8 The final error budget for 5 arcsecond alignment.

3.8.1 The alignment process error budget.

This error budget addresses the steps in the alignment strategy outline in this paper. The individual accuracies are typical of the results obtainable with the equipment we where using in production. The error budget does not represent the limit of this approach.
The error budget can be handled in a RSS fashion for the most part. There are two terms in the error budget that are always present in the same direction, absolutely no random distribution at all. The angular errors in the reference cube and the corner cube are thus additive if you intend to stay conservative. These two items appear together in the budget and are added together before being RSS'ed.

### Table 3.8.1 The Alignment Process Error Budget

<table>
<thead>
<tr>
<th>Contributing Process or Feature</th>
<th>Horizontal Error in Arcseconds</th>
<th>Vertical Error in arcseconds</th>
</tr>
</thead>
<tbody>
<tr>
<td>System Mounting Pads {repeatability}</td>
<td>0</td>
<td>0.5</td>
</tr>
<tr>
<td>System Alignment Pins</td>
<td>0.5</td>
<td>0</td>
</tr>
<tr>
<td>Focal Plane Mounting Pads</td>
<td>ne</td>
<td>ne</td>
</tr>
<tr>
<td>Focal Plane Bushings</td>
<td>0.45</td>
<td>0.45</td>
</tr>
<tr>
<td>LUPI Focal Point Setting</td>
<td>ne</td>
<td>ne</td>
</tr>
<tr>
<td>Surface Plate Parallelism Adjustment</td>
<td>0</td>
<td>0.92</td>
</tr>
<tr>
<td>Flip Fixture Setting</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>Flip Fixture Adjustment to the cube</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>Reference Cube Accuracy (1.00) &amp; Corner Cube Accuracy in LUPI alignment</td>
<td>(1.00 + 0.25 = 1.25)</td>
<td>(1.00 + 0.25 = 1.25)</td>
</tr>
<tr>
<td>Corner Cube Accuracy in LUPI alignment</td>
<td>0.25</td>
<td>0.25</td>
</tr>
<tr>
<td>Interferometric Alignment</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Total { worst case or straight additive total of error items}</td>
<td>5.2</td>
<td>4.12</td>
</tr>
<tr>
<td>Total RSS { typical }</td>
<td>2.23</td>
<td>1.96</td>
</tr>
</tbody>
</table>

### 3.8.2 System Bore-Sight Error Budget

The alignment budget in section 3.8.1 covers only the actual alignment process. The collimator has to function under a few other constraints. The Thermal drift is the residual from the athermalization of the system. Long Therm Drift is self explanatory in nature, section 3.7 has a few comments on the subject of drift.

### Table 3.8.2 Final System Bore-Sight Error Budget

<table>
<thead>
<tr>
<th>Contributing Process or Feature</th>
<th>Horizontal Error in Arcseconds</th>
<th>Vertical Error in arcseconds</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alignment &amp; Unit to Unit Variation</td>
<td>2.23</td>
<td>1.96</td>
</tr>
<tr>
<td>Thermal Effects</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>Long Term Drift</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Total Bore-Sight Error</td>
<td>4.73</td>
<td>4.46</td>
</tr>
</tbody>
</table>
4.0 OTHER EXPERIMENTAL RESULTS AND CONCLUSIONS

The production program has finished its third build and is awaiting the fourth. About 55 units have been delivered. There have been no outbreaks of insanity with the people building the collimators. So you can build these units for several years and not go crazy.

For anyone who is curious the collimators weigh in at 140 lb. This is 20 lb. over the original design specification but in that design the focal plane equipment did not cantilever off the side of the collimator!

The collimators have been through considerable thermal testing. Wavefront and bore-sight have been checked over the extremes of the operational range of 40° to 105° F with no surprises. The thermal drift values in the error budget shown in this paper where not exceeded.

The learning curve on aligning the collimators is several units but after that point the pay back from fixturing is very good. The average collimator of this type was assembled with about three times the labor of a Space Optics commercial collimator. This is fairly good considering the bore-sight specs and changes in the optical mounting procedures. It's a lot slower to put the primary mirror in this system than to assemble a bezel and mirror to a mounting recess in the commercial equipment.

Four point mounts are still undesirable in a precision instrument! After all these units the lapping process is still time consuming.

5.0 ACKNOWLEDGMENTS

The author would like to thank the other original Space Optics design team members Joe Perry and Chris Bond as well as J. Copple, D. Deathrage, R. Fitzgerald, B. Newbert and T. Sheppard of McDonnell Aircraft Co. There is a large debt of thanks to all the present and a few past members of the Space Optics production and support team that helped make this program a success: D. Boutine, D. Beacock, D. Cooper, A. E. DeCew, R. Desmarais, T. Farmer, J. Fortnam, F. Kingsley, B. Holt, P. Iene, D. Johnson, K. R. Kellet, S. King, J. Kurzwarra, M. L'Antigua, R. Scannell, L. St John, R. Tangua, J. P. Verity, R. Youman and B. K. Zellers.