APOLLO's APO Interface: Critical Design Review

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1 Scope of Document

This document is a follow-on to the document on the preliminary design, dated 28 Feb., 2003. The earlier document was prepared for the March 10–12 preliminary design review (PDR) meeting at Apache Point. At the end of this meeting, it was agreed that we would hold a critical design review (CDR) meeting at APO in early May to address a few specific issues in greater detail. These issues break out into four categories:

- mounting of the laser on the mirror cell
- design of the cabinet enclosure and of the umbilical from the cabinet to the laser enclosure
- chiller installation and plumbing considerations
- design of the intermediate level enclosure.

The scope of this document is limited to these four items. As such, this does not represent a CDR on the broadest level—only that which is sufficient to allow forward progress at present.

An up-front apology is in order with respect to mixed units. Many of the units in this document are metric, but there are also plenty of of cubic feet per minute, gallons per minute, inches, etc. Hopefully it is helpful and not distracting to have "comfortable" units interspersed.

2 Outcome of the PDR, and Charge to the CDR

At the PDR meeting, we established the location of the laser on the telescope, and received approval for our proposed distribution of equipment on the telescope back port, in a cabinet behind the corner port, and in an intermediate level enclosure below the back port. An ambitious timeline was laid out that would get the laser on the telescope by the time of summer shutdown. Given this aim, we decided to defer certain aspects of the design until later, focusing for now on the requirements to get the laser mounted on the telescope and ready to be "installed" by a representative of the laser company. The PDR consensus regarding each of the four themes outlined above is discussed here, along with the charge to the CDR pertaining to each of these.

2.1 Laser Location on Mirror Cell

One of the first tasks associated with the PDR was finalizing the intended location of the laser bench. The default position was on the large back-port surface (see Figure 1), though there were significant concerns about weight, moment of inertia, thermal influence, cable/hose routing, etc. We spent some time exploring alternate locations, like the crawl space, on top of the Nasmyth-1 fork tine, and as a Nasmyth-2 roll-up instrument. We were greatly assisted by the plywood box that had been built prior to the meeting

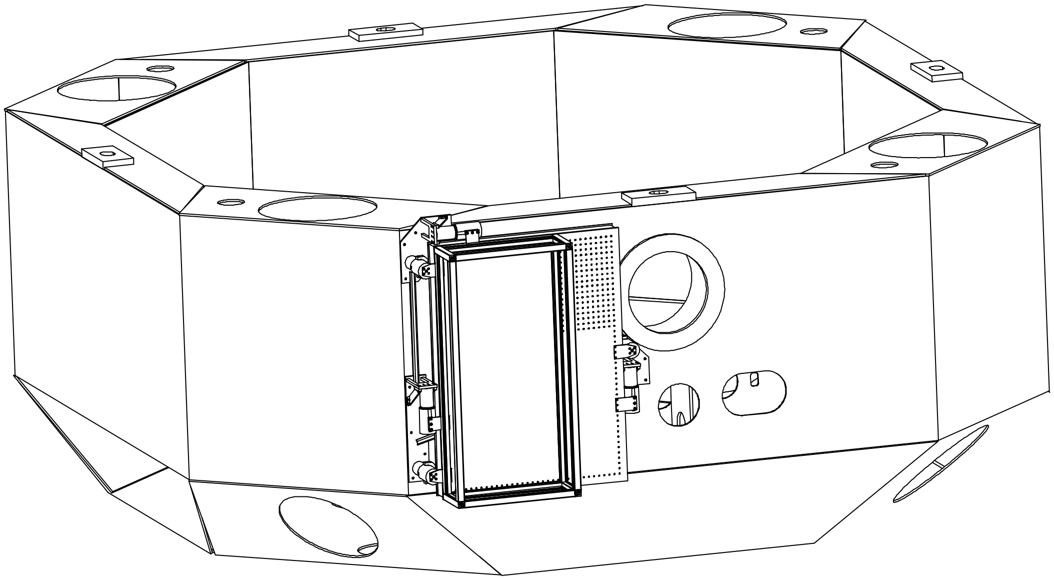

Figure 1: Positioning of the laser bench on the primary mirror cell.

representing the minimum size of the laser bench as enclosed by the requisite thickness of insulation. We could assess the issues associated with a box of this size located at the default position, and became aware of the serious difficulties we would encounter if we tried to put the package anywhere else. In the end, we all agreed that the intended position was the best.

As for weight and moment issues, these were found not to be significant problems. Already in place on the back-port surface is 325 pounds of counterweight (plus four 7.5 lb mounting lugs) for a total counterbalance weight of 355 lbs. If we add a roughly 600 lb load to this location, we are in essence adding only 250 lbs that require counterbalance, or 500 lbs total to the telescope structure. Compared to the 34,000 lb moving mass of the telescope, this represents an addition of only 1.5%.

The more serious issue is the modification to the moment of inertia of the telescope. We got a handle on the moment of inertia of the telescope by three different methods:

1. Jon Davis simulated the maximum acceleration of the telescope by pulling on the top of the secondary structure with a spring scale, delivering 515 ft-lbs of torque to the structure.

2. We calculated the torque capabilities of the motor drive system (512 ft-lbs @ 1.33 A), and related this to the maximum possible angular acceleration of 1.7 deg per s^2.

3. A simplified numerical integration of the primary mirror cell and secondary structure. These three techniques produced moments of inertia ranging from 23,000 kg m^2 to 34,000 kg m^2.

Adopting 25,000 kg m^2, we find that adding 250 lbs to each side of the telescope at 8 ft from centerline adds 1,350 kg m^2, or about 5% to the total. This leads us to conclude that the drive train should be able to handle this load, at worst requiring maintenance 5% more often.

The six-flexure mounting scheme for attaching the laser bench to the telescope was discussed at the PDR, but it was clear that a more detailed design was required before final approval could be granted by the observatory. Specifically, we were asked to provide the following information/analysis for the CDR:

- load test of the flexures; failure modes, protections
- engineering drawings of the components to be manufactured
- counterweight requirements/locations
- fully developed installation procedure
- assessment of azimuth balance

We have made the mechanical mounting of the laser on the mirror cell our highest priority for the CDR, feeling that this is the most "critical" aspect of the installation.

2.2 Cabinet Enclosure and Umbilical

A consequence of the decision to mount the laser on the primary mirror cell (PMC)—while trying to minimize weight on the PMC—is the necessity of locating a permanent cabinet on the observing floor near the position of the laser. A number of short cable requirements mandates this action. Originally intended to sit directly behind the laser (a few feet back from the outermost wall of the laser insulation when pointed at zenith), we found that this position presented significant interference with observatory operations. An alternate location to the left of the laser enclosure was agreed upon. We were "pre-approved" for a cabinet measuring 30 inches on a side, with no restriction on height (e.g., 6 ft). The cardboard boxes used for a placeholder were unfortunately much smaller than this, so we didn't gain a full appreciation for the impact that a cabinet of this size would present. However, tape marks on the floor delineated the approximate footprint of a 30×30 cabinet, and no problems were anticipated.

The cabinet location *does* limit the size of an instrument located at the corner port of the PMC. Specifically, the instrument cannot extend too far back from the mounting flange. This is an issue for any cabinet height exceeding about 3.5 feet. It was generally agreed that:

1. there are no instruments currently slated for this spot;
2. the other corner port is available for any large instrument requiring a corner spot; and
3. the available space still permits a reasonably-sized ($\approx$ 30-inch cube) instrument to occupy this location.

We were asked to present a concrete design of the cabinet enclosure and umbilical for the CDR, including the floor interface to the intermediate level enclosure. This has taken second priority in our preparation to the CDR, behind the laser mounting.

2.3 Chiller Installation, Plumbing, and Thermal Control

A significant concern for all of us is the possibility of fluid leakage, especially around the mirror cell. APOLLO makes use of two Neslab chillers in the intermediate level enclosure, one of which forms a closed loop with the laser cooling group (within the same enclosure) and the other sending coolant (50/50 ethylene-glycol/water) to the heat exchangers in the laser bench enclosure on the PMC. The laser cooling group routes de-ionized water to the laser rods on the laser bench.

Our proposed umbilical routing allows us to use rigid conduit for all fluids on the PMC. The only flexible conduits required go between the cabinet and the PMC, and within the intermediate-level enclosure.

As requested for the CDR, we will cover the chiller/plumbing/thermal-control issues at some level of depth. But given the relative ease of handling these issues, we have spent less time detailing this aspect of the design.

2.4 Intermediate Level Enclosure

The intermediate level enclosure (ILE) houses the majority of the laser electronics, as well as the two chillers. The enclosure is located directly under the laser and cabinet, on a platform high in the intermediate level. Hatches in the wall to the observing level (crawl-space) allow access to this enclosure. Open airflow is supported between this enclosure and the adjoining cabinet, so that both are kept at the same temperature.

As the most straightforward of the design elements represented in this CDR, the ILE is the least developed of the CDR items. Thermal and structural requirements are far less stringent for the ILE, and we feel that we can work these issues out in due time. Nonetheless, this document takes a stab at the design, exposing the details yet to be resolved.

3 Mechanical Mounting of the Laser on the Telescope

The laser will mount on the back plate of the PMC, next to the bent-Cassegrain focus referred to as the back-port. The installation will be semi-permanent, with the expectation that the laser's presence will not interfere with normal observatory operations.

3.1 Six-Flexure Design Scheme

Because the laser is maintained at a temperature that differs from the telescope and its surroundings, we require a minimally-constrained (kinematic) mounting scheme that will accommodate the expected range of temperatures. Over the ~ 1 m length of the optical bench, 30°C of temperature differential will produce differential expansion at the level of 0.5 mm. We have designed a six-flexure support system that exactly constrains the six degrees of freedom that a rigid body possesses. The flexures are arranged in a 3-2-1 configuration. Three parallel flexures act as table legs for the optical bench, setting the bench parallel to the surface of the back plate. Two parallel flexures set the vertical position of the laser bench (vertical when the telescope is pointed to zenith) and prevent rotation about the axis normal to the telescope back-plate. A final flexure perpendicular to the other five prevents left-right translation of the table with respect to the telescope.

3.1.1 The Flexures

The 8-inch-long flexures, pictured in Figure 2, are made of 303 stainless steel, having pairs of webs six inches apart that are 0.15×1.0 inches in cross section. Quarter-inch flanges separate the various webs, and a beam with a ~ 0.15 in^2 cross-section separates the two ends. Under a weight of 250 lbs (a typical load), the flexures stretch in their long dimension by 0.0004 inches, or 9 μm. In the transverse direction, though, one pound of side force results in 0.005 inches (0.127 mm) of parallel displacement of the two ends (measured value), corresponding to about 2,000 psi of stress on the outer wall of the web. The maximum deflection anticipated for any given flexure is 0.5 mm, or 0.02 in, corresponding to a skin stress of 8,000 psi. With a yield strength of roughly 35,000 psi, we expect to stay well within the elastic regime of the material.

Because of the stainless steel construction and the small cross-sectional area, each flexure is a decent thermal insulator. Specifically, the flexures pass less than 0.01 W per °C differential, so that the three legs between the laser bench and the PMC will at worst transmit 0.75 W.

All six flexures share the same physical properties, though one version is manufactured with square cross sections, and one is round. The square one is expected to be very slightly stronger, and will be used for the two legs that take all the weight when the telescope is pointed at zenith. Aside from this subtlety, all flexures are interchangeable.

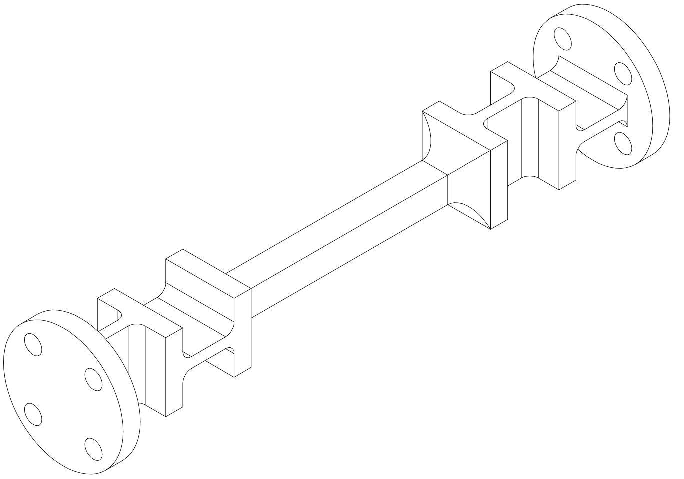

Figure 2: Flexure geometry (square cross-section).

3.1.2 Flexure Arrangement

Figure 3 shows the arrangement of the flexures around the bench. The positions are consolidated so that three mounting fixtures are mounted on the telescope—all three in structurally rigid locations. The legs are arranged with two on the left side, where the laser weight is important, and one on the right. The two vertical flexures are located at the same level along the left and right sides, and displaced to the lower side for compatibility with the back port mounting flange. The final flexure is locate along the top surface so it can easily share the mounting plate of the top-left leg.

3.1.3 Flexure Attachment

The flexures all have 1/4-20 threaded inserts on a 4-hole bolt-circle on the end-flanges. Each flexure is mounted within a pair of concentric, nested cups that prevent flexure motion greater than 0.05 inches in any sideways direction. Should any number of the flexures fail mechanically, the cups are strong enough to hold the laser in place—even in the event of a catastrophic simultaneous dynamic failure of all the flexures. The outer cup in each case attaches to the laser bench, and the inner cup is rigidly mounted to the telescope. Three outer cups are made of G-10, and three of aluminum, having outer diameters of 3 inches and inner diameters of 2.5 inches. The inner back wall of each cup is carefully made to be perpendicular to the cup axis, and a radius transition into the wall minimizes stress concentrations in the event that the cups take up the load. The inner cups are made either of G-10 or aluminum. G-10 is used wherever thermal and/or electrical isolation are needed. In this case, the G-10 cups are associated with the three flexure-legs. The G-10 inner cups attach directly to the steel mounting plates that bolt to the telescope. The aluminum inner cups attach to G-10 braces that extend down to these same steel plates. Figure 4 shows how the mounting scheme would appear from the side, and Figure 5 shows a side view with hidden lines revealing the flexures within the cups.

The half-inch steel plates to which the flexures attach (either directly or via rigid braces) are held in relation to each other via 3/4×1-inch box-beams welded to the plates in a triangular configuration. These members bear no load, but establish the dimensional relationships between the three plates so that the plates may be unambiguously located on the telescope in a way that does not impose artificial stress in the flexures. The two plates on the left side attach along the strong seam at the corner of the mirror cell. The plate on the right attaches adjacent to a rib in the PMC weldment.

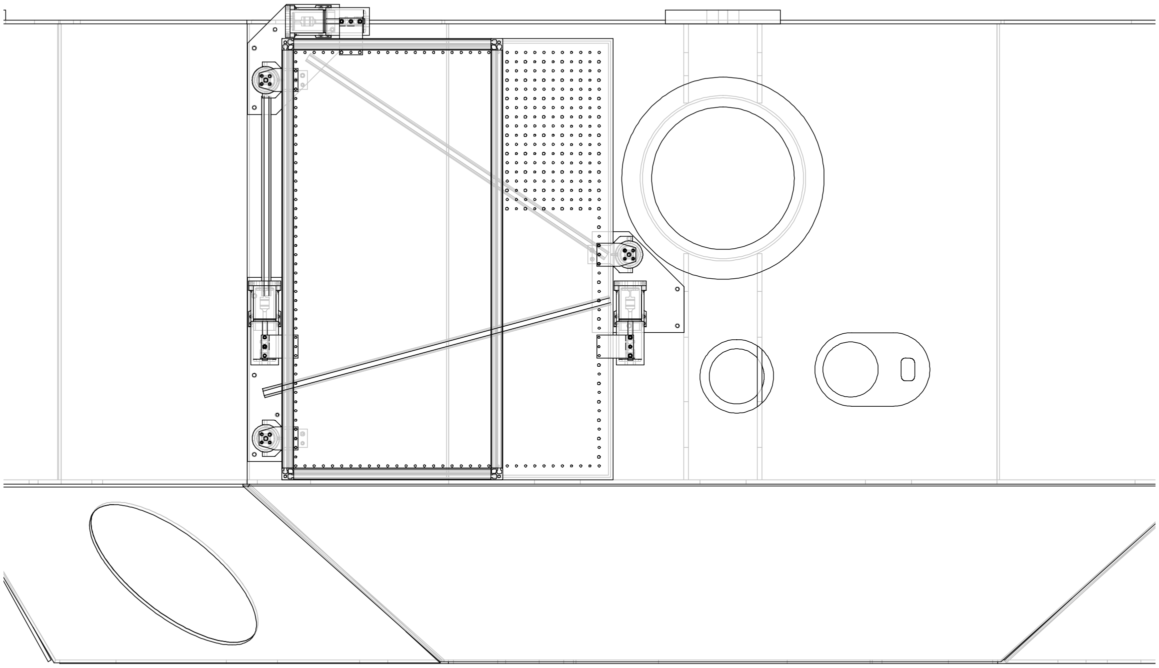

Figure 3: Plan view of laser bench on back port, showing intended flexure mounting locations.

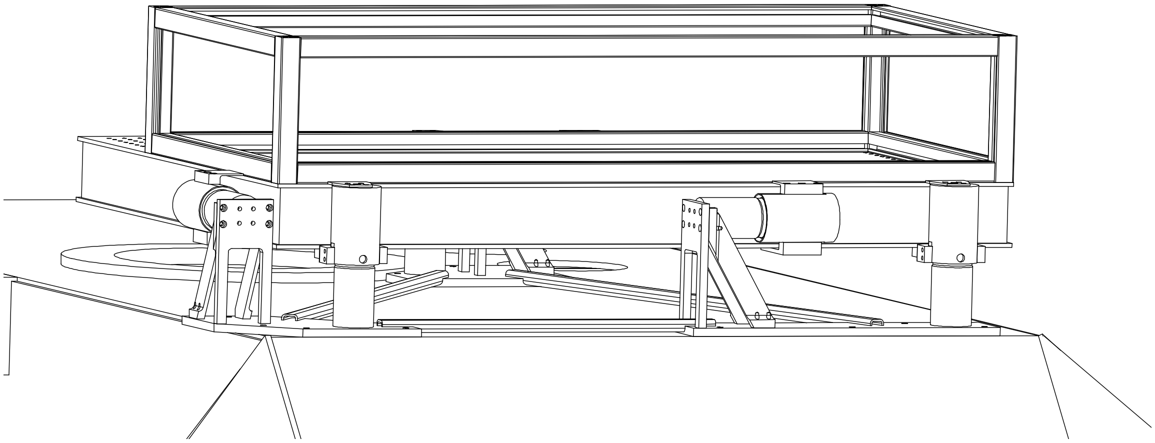

Figure 4: Appearance of the flexure mounting scheme. The vertical flexure “legs” are housed in G-10 cups, and the horizontal flexures are situated in aluminum cups.

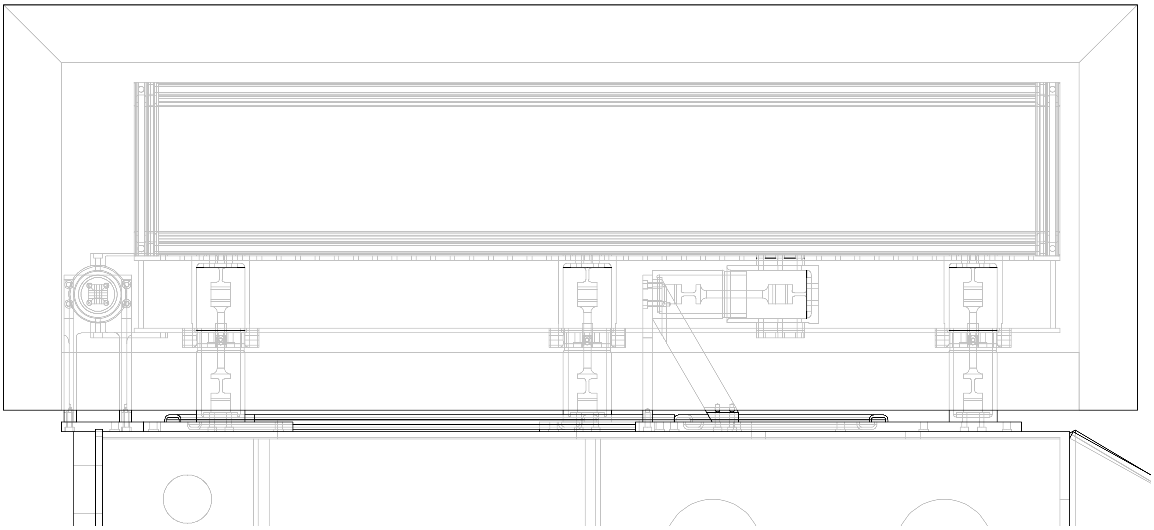

Figure 5: View of the mounting scheme from the side, showing the flexures within the cups and the nesting nature of the cups. The 3-inch insulating box has also been placed around the laser to show its clearances, etc.

The three flexure legs attach to the steel plates via four 1/4-20 socket-head-cap screws counterbored into the bottom of each plate. The G-10 cup is a captive member between the plate and the flexure. The three G-10 angle braces likewise attach via six such screws through the bottom of each plate. The aluminum inner cups then are held captive between the angle brace and the flexure. Heat conduction for the G-10 cups and G-10 angle braces will be negligible, amounting to about 0.1 W apiece for a ΔT of 25°C. We will want to stuff the G-10 cups with fluffy batting to eliminate an air-transport path that could raise this number significantly.

The outer cups for the three legs attach to the optical bench primarily through thick (0.75–1-inch) aluminum forks mounted to the bottom of the bench. The top end is held against motion in the plane of the bench by a 0.125-inch G-10 plate. This plate is G-10 for electrical isolation purposes. The flexure itself will be at telescope ground, but there is no electrical connection between the flexure and the optical bench.

The outer cups for the brace-mounted flexures need holding-strength primarily along the flexure long-axis, and can be held by relatively thin plates attached to the top and bottom of the bench. The bottom plate is 0.25 in thick, and the top plate is 0.125 in thick. Electrical isolation is completely handled by the G-10 brace to the mounting plate, so no special provisions are needed here to ensure isolation.

The mounting scheme protects the optical bench against de-lamination in that the legs support the bottom of the bench, and are loaded only in compression, and the two flexures that support the laser bench in the vertical orientation hold both the top and bottom surfaces of the table. Most of the time the telescope is stowed pointing toward the horizon, and during this time, the laser is supported primarily by the three flexure legs and the bench is resting on its bottom surface.

3.2 Failure Analysis and Safety

3.2.1 Flexures

It is perhaps disconcerting to mount this expensive (and heavy) laser via members that can only take ten pounds of side force. But a sound design and correct installation lead to a perfectly rigid configuration that simply cannot impose side-loads on the flexures. The only thing capable of doing this is thermal expansion of the steel framework relative to the optical bench. In this case, the maximum motion of 0.5 mm will be shared by the various flexures so that each one only experiences a worst-case deflection of 0.25 mm, or 0.01 inches. This corresponds to a mere two pounds of equivalent side-load, and less than 5,000 psi of shear stress on any of the members (for a safety margin of 7). In the nominal loading arrangement, the static axial loads on the flexures will never exceed about 250 lbs, for a tensile/compressive stress of about 1,500 psi, corresponding to a safety margin of 20. These numbers, incidentally, use the *yield* strength for stainless steel of 35,000 psi at which point permanent plastic deformation is seen. The *ultimate* strength of the material is almost *three times higher*, so the safety margin for breakage is that much higher. In any case, the flexure mounting should be able to handle dynamic loads of over 10 g's.

The retainer cups allow a sideways motion of 0.050 inches (and less for angular motions). This amount of motion corresponds to a radius of curvature of 90 in for the 0.75-inch long flexure rib. This induces a strain on the surface of 8.3×10^{-4}, for a stress of 23,000 psi. This is getting close to the yield strength of 35,000 psi, but 1) it is *shy* of the limit, 2) the other flexures cannot allow this motion to happen, and 3) the parallel (purely sideways with no angular) displacement is a worst-case scenario. If indeed another flexure fails, the angular constraints are compromised, and the cups will touch before a displacement this large is reached.

We will perform load tests on one of the flexures, up to the breaking point. We expect this to verify the calculated values based on material properties and geometry, but we will know the limits for sure after the test.

3.2.2 Retainer Cups

A simple calculation of the tube thickness needed to carry 500 lbs of weight cantilevered 5 inches away from support (assuming 2-inch tube diameter) yields 0.041 inches thick (for an allowed stress of 10,000 psi). Our cups are 0.25 inches thick. In each telescope orientation (zenith and horizon), three cups are available to support the $\sim$ 325 lbs of the laser bench plus optics. So in a static sense, our cups will experience a stress on the outer wall of $\sigma_{\max} = (R + t)Wl/(2\pi R^3 t) = 500$ psi—well below the yield strengths of G-10 and 6061-T6 aluminum (at 30 and 40 ksi, respectively). The previous formula used a tube radius $R = 1.0$ in, a thickness of $t = 0.25$ in, a weight of $W = 125$ lbs, and force application at $l = 5$ in from the back wall of the tube. A trickier issue is the manner in which the wall stress is transferred to the back wall of the cup. A radius on the inner interface eases this transition, but in any case the shear stress for our geometry is about 1,250 psi—well below yield. For these calculations, we used a 125 lb load at 5 inches for a moment of 625 in-lbs. A 2 in diameter tube then sees a force of 312 lbs on the upper wall, and this is transmitted into the 0.25 in thick back wall over, say, a one-inch horizontal strip for a cross-sectional area of 0.25 in^2, and a shear stress of 1,250 psi.

Therefore the cup system is more than adequate for supporting the static load of the laser weight. But what about dynamic support? After all, in the event that the flexures suddenly failed, there would be kinetic issues. A falling bench must be stopped. In this case, the tube/cup acts like a spring. There will be an oscillation in which the cup (spring) moves past the static deflection point, reaching some maximum displacement before turning around again. The material stresses will be greatest at the point of maximum deflection.

A fall of height Δy lasts a time given by $\Delta y = gt^2/2$, or $t = \sqrt{2\Delta y/g}$. During this time, the bench picks up a velocity, $v = gt = \sqrt{2g\Delta y}$. If the oscillation is characterized by a sinusoid ($y = A\sin\omega t$) with amplitude A and angular frequency $\omega = \sqrt{k/m}$ (mass m and spring constant $k = W/y_{\text{static}}$), then the velocity is the derivative of displacement, or $v = A\omega\cos\omega t$. Associating the velocity on impact as the maximum velocity (at $t = 0$), we have $v = \sqrt{2g\Delta y} = A\omega = A\sqrt{k/m}$. So $A = \sqrt{2gm\Delta y/k}$. The maximum force on the spring is the spring constant, k, times the maximum displacement, A. Then $F_{\max} = kA = \sqrt{2gmk\Delta y} = \sqrt{2Wk\Delta y} = W\sqrt{2\Delta y/y_{\text{static}}}$. Here, we have recognized that $W = mg$, and that $k = W/y_{\text{static}}$, where y_{static} is the static displacement of the spring under load W. Because the load is split among at least three flexure-cups, the weight can be taken as the load per cup.

The square-root factor $\sqrt{2\Delta y/y_{\rm static}}$ can be viewed as a margin of safety, since it represents the maximum dynamic force one would experience relative to the static force, W. If the flexures simply evaporated (certainly a worst-case) and the bench fell the entire 0.050 inches until the cups hit, the safety factor is about 10 for aluminum, and about 15 for G-10. The 500 psi in the tube walls becomes 5,000 psi in aluminum, and 7,500 psi in G-10 (G-10 is stiffer). The 1,250 psi at the top of the back wall of the cup becomes 12,500 psi in aluminum and 19,000 psi in G-10. These numbers approach the yield limits, but 1) do not exceed them, and 2) assume a catastrophic worst-case free-fall. Because thicker tubes are stiffer, and therefore promote a higher $F_{\rm max}$, one might be tempted to use a thinner wall. We shied away from walls thinner than 1/4-inch mostly based on intuition. The choice appears to be sufficient with regard to safety, but it is not clear that a slightly thinner wall wouldn't actually be better.

3.3 T/R Motor Location

The plan laid out in the PDR had the transmit/receive (T/R) mirror motor situated outside the insulated enclosure. This was done both to remove a heat source from within the enclosure, and to allow the enclosure to be smaller—not having to accommodate the motor. It turns out that the external location of the motor would require an uncomfortably long shaft, and would place the motor above the level of the mirror cell. While it is possible to mount the motor underneath the step-shield (Section 3.4), we have explored an internal arrangement as well.

The critical design change would be not a direct drive of the T/R mirror, but a pulley and timing belt drive system. This allows the motor to move much closer to the optical bench, and has nice properties with regard to tolerance of shaft misalignment (not to mention removing the need to pass the shaft into a sealed box.

The first question is: will it fit? Figure 6 shows the optical layout on the APOLLO bench. The T/R mirror can be seen at right center situated within a pillow-block. The motor can be moved up nearly to the pillow block, sticking out only ~ 2.5 inches beyond the table—within the insulation. Figure 7 shows the three-dimensional arrangement of the optical elements, and that the motor is sufficiently high enough to avoid interference with other optical elements.

The main drawback of placing the motor inside the laser bench enclosure is that it generates 50 W of heat when running. Since this only runs when APOLLO is using the telescope, we did not care that this heat was released into the dome. Inside the enclosure, we need to make sure we can remove the heat, and that the proximity of the source to our optical train does not perturb the beam or nearby optics.

In terms of heat removal, we estimate a total heat load inside the enclosure of ~ 250 W when everything is running. The Noren heat exchangers remove 25 W per 1°C temperature differential between coolant and internal air temperature at the relevant flow rate. Running two exchangers at $\Delta T = 5^\circ$C should be sufficient to carry away this heat. The addition of a 50 W source does not stress the cooling system unduly.

The thermal distortion of the wavefront is a potential problem. If little air cells of size r have temperature fluctuations ΔT, the refractive index modulation is $\Delta n \approx \Delta T \times 10^{-6}$. If a pathlength l is exposed to this turbulent mix, there will be roughly $N = l/r$ cells along the line of site, some warm, some cold. On the average, all points in the beam would experience the same refractive influence, but there will be fluctuations at the level of $\sqrt{N}$ times the refractive delay of one cell—which is roughly $r\Delta n$. So the total wavefront error would be roughly $\Delta\lambda \approx \Delta T\sqrt{rl} \times 10^{-6}$. Incidentally, applying this relation to the atmosphere with $\Delta T = 0.1^\circ$C, $r = r_0 = 0.1$ m, and $l = 7$ km gives 2.6 μm of wavefront error (5 wavelengths of visible light), which is about right to account for seeing. Applied to our situation, choosing $r = 1$ mm (small-scale turbulence), $l = 0.2$ m pathlength, and $\Delta T = 35^\circ$C (motor skin temperature) gives 0.5 μm wavefront error, or about one wavelength. Because the ΔT estimate was extreme, and because this value is still smaller than

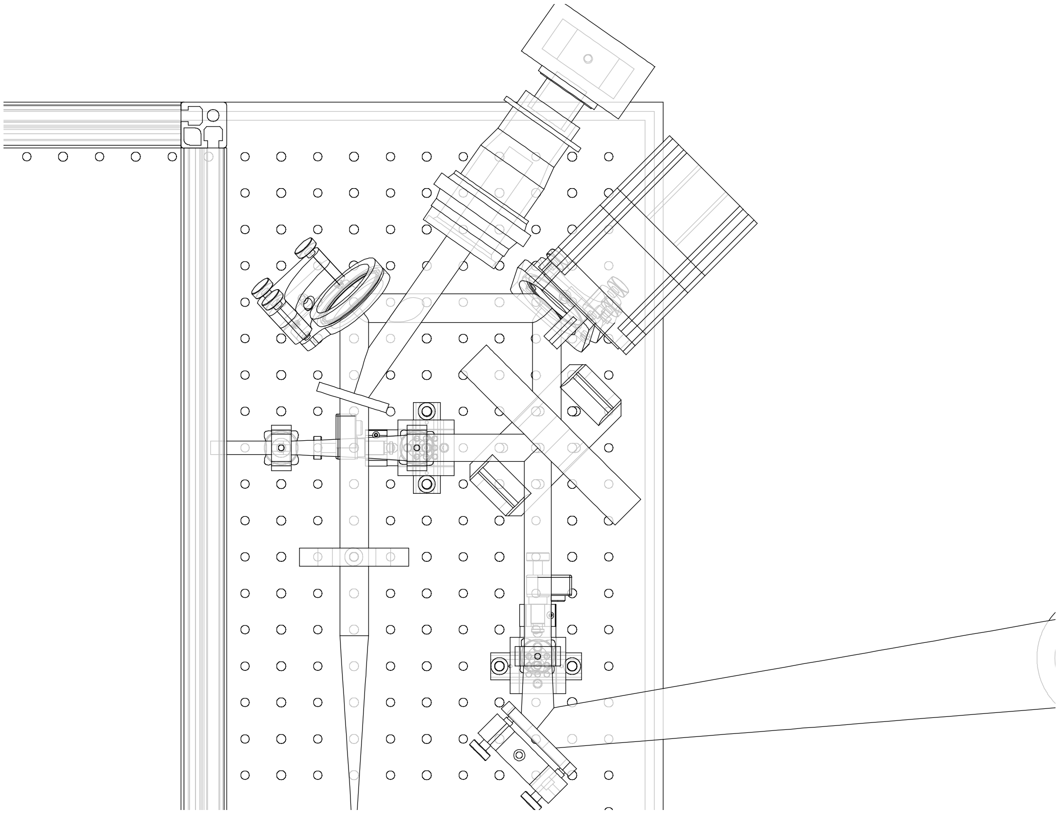

Figure 6: Layout of the receiver optical train from above. The motor is situated near the pillow-block supporting the T/R mirror. Not clear in this view is that the motor centerline is 5–6 inches off the table. A belt would run between the two shafts (mirror shaft not shown here).

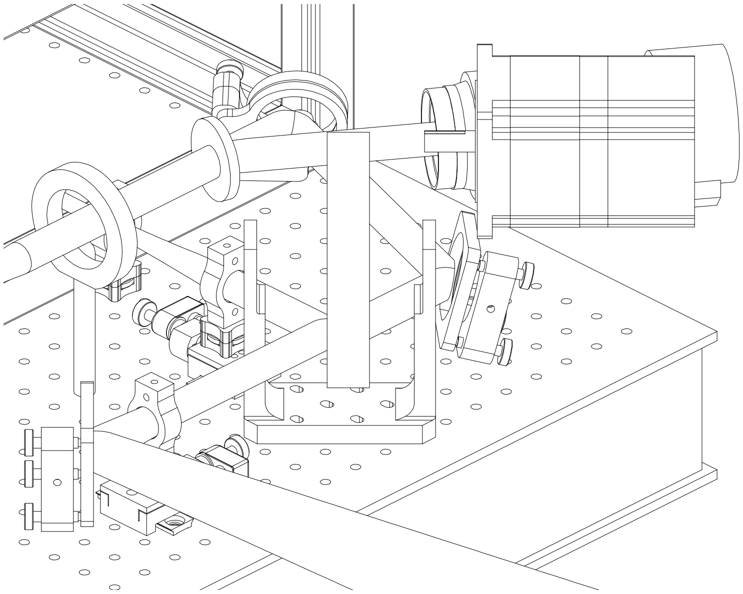

Figure 7: Oblique view along the plane of the T/R mirror (center). The motor sits high enough to be out of the way of other optical elements.

the (typically) ~ 10 wavelengths of atmospheric distortion across the telescope aperture, we will assume that the motor's contribution is not important.

Nonetheless, we will be careful in the way we route the airflow in the laser bench enclosure to try and carry the heat from the motor away from critical optical elements. The bottom line is it looks like we can incorporate the motor into the enclosure, but we will reserve a spot under the step-shield in case we need to locate it there instead.

3.4 Step-Shield Design

We will place a combination step-over and spray-shield onto the PMC over the top of the laser bench enclosure. The primary purpose is to make it easy to maneuver around the telescope truss by providing a platform strong enough to stand on. The step will be approximately eight inches above the PMC rim—the size of a standard step. The shield will step up again to accommodate the CAMAC crate within the laser bench enclosure. There should be at least 15 inches of clearance between this step and the truss, so getting around it should not be cumbersome. The second step in fact provides a hand-hold for stabilization. You might even want these all the way around the PMC! The structure that holds the step-shield attaches directly to the PMC in strong places, and additionally provides the support for the CAMAC crate and GPS clock within the laser bench enclosure (through insulation-penetrating G-10 members).

By putting walls on the step-shield, we can also protect the PMC against the possibility of spraying coolant lines being able to reach the primary mirror. The insulation already does this, but the step-shield provides an extra level of protection in case an accident happens when the insulation is partly removed (e.g., during maintenance).

3.5 Weight and Balance

The weight of the laser bench is said to be 230 lbs. But this does not include the laser enclosure and componentry. The total laser weight is therefore probably around 300 lbs. We will place about 25 lbs of optics onto the laser bench, so that the flexure mounts will support roughly 325 lbs. But this is not all that the PMC sees. The flexures within their cups weigh about 3 lbs each, the angle braces weigh 1 lb each, the half-inch steel plates weigh about 12 lbs each, and the box-beam sums to about 9 lbs. So the structural mounting apparatus weighs around 65 lbs. The electronics add about 60 lbs, the heat exchangers at 9 lbs each total 18 lbs, the insulation amounts to 40 lbs, the T/R motor is 10 lbs, and the step-shield will weigh in at maybe 75 lbs. This makes a total of 600 lbs, but uncertainties in the guesses could modify this total by 50 lbs in either direction.

Given the 355 lbs of counterweight currently on the back-plate of the PMC, we will be adding 245 ± 50 lbs to the back port, thus requiring about the same weight on the opposite side of the PMC for balance. This amounts to 5 ± 1 stacked steel plates at 50 lbs each. As discussed before, the relative modification to the total moving mass of the telescope and the moment of inertia are not substantial.

3.6 Installation Procedure

We plan to mount the laser onto the telescope with the telescope pointed near the horizon. The insulation that sits between the laser bench and the telescope is held captive by the mounting fixture, and extends over the entire fixture, making it difficult to grab the fixture from the sides. Instead, we have designed the outer cups on the three flexure legs to accommodate 3/8-16 thread eye-hooks so that we can hoist the laser table in a horizontal orientation onto the PMC. We are therefore holding the laser table at points designed to be strong enough to carry its weight. Installation will require no more than two people on the PMC—one sitting more-or-less at the position of the back port, and one accessing the area from the top of the Nasmyth-2 fork tine (we need to verify that this will work). Because we don't anticipate having to remove the laser for normal observatory operations, we do not see this installation procedure to be an inconvenience.

3.6.1 Telescope Preparation

The following list of tasks is to be carried out in preparation for mounting the laser on the PMC.

1. Take mount weldment (three plates and triangle beam) and use as a jig to place mounting holes into the PMC.
2. Tap mounting holes in PMC.
3. Install the step-shield onto the PMC.
4. Install the approximate amount of counterweight onto the front of the PMC.
5. Orient the telescope at a low elevation and lock in place.
6. Set up access ladders or platforms.

3.6.2 Laser Bench Preparation

This list details the installation of the flexure mount onto the laser bench in such a way as to ensure that the flexures are unstressed in their final (isothermal) configuration.

1. Hoist laser bench onto elevated supports allowing access to the underside, and not interfering with the flexure mount positions.

2. Remove laser enclosure shroud and machine clearance slots in the base extrusions for the four mounting plates that mount on the laser side.
3. Use a custom jig to locate mounting holes on the bottom of the laser bench relative to the hole pattern in the top plate of the bench.
4. Install the three forks onto the G-10 outer cups.
5. Mount the G-10 top-braces to the bench-top at the locations of the three flexure legs.
6. Mount the six flexures (temporarily) into their inner cups. Fill volume with insulation/batting.
7. Attach forks and G-10 outer cups to the bottom of the laser bench, three places.
8. Using 0.050-inch shim material, center each inner cup in the outer cup, and bolt the top of the flexure to the top of the outer cup and top-brace.
9. The legs are almost done. Leave shims in for now.
10. Put the top and bottom braces on the optical bench, with the aluminum outer cups in place.
11. Insert the inner-cup/flexure combination into the outer cups using centering shims, as before.
12. Attach the G-10 angle braces to the cups and flexures.
13. Reinstall the shield onto the laser bench.
14. Attach eye-bolts to three flexure-leg cups and hoist laser in horizontal orientation.
15. Place lower insulation sheet onto flexure-leg cups and angle braces. Temporarily secure.
16. Remove bolts from bottoms of flexure-leg cups, relying on shims and insulation to hold them in place.
17. Bring up triangular mounting fixture and attach three flexure-legs first.
18. Assemble end-braces onto mounting plates.
19. Remove shims, measure displacements between the cups for future reference.
20. Secure the insulation to triangle box-beam frame.
21. Re-insert shims for protection during installation.
22. Set laser down in preparation for hoisting into the dome.

3.6.3 Installation onto Telescope

Once the laser bench has been prepared, the three mounting plates can be installed onto the telescope. The procedure will go roughly as follows.

1. Hoist laser into dome, set on top of PMC, with two people guiding from either side.
2. Captive screws in mounting plates will have rounded ends sticking out about 1/8 inch. These will guide the mounting plates into the pre-drilled/tapped holes in the PMC.
3. Once aligned and down, the 12 3/8-16 bolts can be tightened using an open-ended crescent wrench.

4. The laser will be firmly attached to the PMC at this point, and the telescope can be moved.
5. Not all of the 12 bolts need to be tightened when the telescope is pointed toward the horizon. If some are hard to access in this orientation, they can be accessed with the telescope at zenith.
6. Install the rest of the insulating box onto the base piece.

4 Cabinet and Umbilical Design

4.1 Cabinet

4.1.1 Cabinet Contents

The existence of the cabinet is required to provide an environment for equipment that has to be relatively close to the laser and be kept warmer than ambient conditions, but that does not need to be physically on the PMC or maintained at tight temperature tolerances. Included in the cabinet are:

- Two rack-mount capacitor bank units associated with the laser
- `houston`, the control computer for APOLLO, along with monitor, keyboard, trackball-mouse
- STV CCD controller with LCD display
- Picomotor optics actuator with hand-paddle controller
- Laser remote control box
- Power supplies
- DATAQ DI-720 data acquisition unit
- Ortec 4111A fiber receiver for GPS signal to clock

The units are arranged in such a way as to facilitate user access. Many of the devices have interactive modes, so that a user can sit at the cabinet "station" and run the APOLLO apparatus. This will be especially important and relevant in the early days of operation, before the apparatus is streamlined enough for remote operation.

The interior of the cabinet will have the same set-point temperature as the laser bench and ILE. In fact, the air within the cabinet is contiguous with the ILE air. This set-point will be roughly 50°F during cold months, and 75°F during warm months.

4.1.2 Construction

The cabinet structure will be made out of 80/20 aluminum T-slotted extrusion, specifically the 1515 variety (measuring 1.5 inches square). This "erector set" approach allows a customized configuration that is easy to build and incredibly strong/robust (not to mention free thanks to Alan Diercks). The general configuration is shown in Figure 8. A bay at top right holds the two capacitor bank units. They are each oriented such that the top panel of each can be accessed and removed so that maintenance can be performed without removal from the cabinet (a procedure complicated by the captive cables going into the umbilical). The height of the cables emerging from the back of the capacitor units dictates the height of the cabinet. The optimal height of the umbilical as it emerges from the cabinet is about 55 inches off the floor. This puts the tops of the 19-inch capacitor units at 64.5 inches off the floor. The 1.5 inch extrusion then puts the cabinet structure's top at 66 inches off the floor. The cabinet needs to be 29 inches deep, and we have chosen a square design of

29×29 inches. The STV CCD controller and Picomotor controller will be situated high in the cabinet, to the left of the capacitor banks (mounting scheme TBD). The laser remote controller is to be located just below the capacitor banks. A slide-out tray accommodates the computer monitor, keyboard, and trackball-mouse. Below this, on the floor level, sits the control computer, the power supplies, the DATAQ unit, etc.

The cabinet structure attaches to the observatory floor via eight angle braces and lag screws into the plywood below the aluminum floor covering. Hoses and cables will be routed in the back-left corner of the cabinet up to the umbilical exits high on the back wall.

On the outside of this structure, we will mount 1-inch thick panels of reinforced rigid-foam insulation with an R-value of ~ 7. We anticipate mounting directly into the T-slots of the frame using plastic retainers such as those used for automotive paneling/interiors. This way, the insulation can be pulled off any number of times with no tools, granting access to any part of the cabinet interior. Each side will probably have three panels for access to top, middle, and bottom portions of each side. Bevel joints and maybe latches on the aluminum exteriors of the insulation will eliminate air gaps that would otherwise compromise the thermal isolation to the outside.

Surrounding the insulation will be a sheet-metal plenum shield for ducting air around the outside of the insulation. This is necessary to pull away the bulk of the roughly 100 W emitted by the cabinet insulation on the very coldest nights. A layer of foam (such as foam-core posterboard material) adhered to this sheet metal reduces the heat loss to the dome. Based on the assumption of quarter-inch foam and 3/4-inch air gap, the total cabinet structure has a footprint of 33 × 33 inches on the observatory floor.

The plenum shield surrounding the cabinet can be built onto angle (steel or aluminum) on each of the four corners, attached to the floor. The sheet metal skin could attach by spring-loaded screw latches much like those that secure airplane cowlings. Also arranged in panels, certain portions can be removed to perform specific tasks on the cabinet interior. Another option for the underlying structure is more 80/20 extrusion. The panels would in this case slide into the slots of the material. A smaller 1-inch variety could be used for this. This approach gains attractiveness for a slight increase in footprint, and perhaps less convenient panel removal (must slide out all panels to access bottom).

4.1.3 Floor Cutout

Rather than cut out the entire footprint of the cabinet to create an opening to the intermediate level, we now feel that it would be sufficient to make a series of holes specifically for the various conduits and air ventilation channels. The airflow in the plenum could be carried through several slots cut into the floor—roughly one inch wide by 10 inches long, and maybe two on each of the four sides (see Figure 9). A roughly 4-inch hole within the cabinet footprint would connect to a “drinking straw” conduit that extends to the top of the cabinet and draws the hot air out of the cabinet and into the ILE below the floor. This air is re-supplied via a series of other holes in the floor that are used to route cables and hoses from the ILE. Many of the cable-bearing holes would be located in the back-left corner of the cabinet, where most of the cable/hose routing is accommodated. This scheme leaves most of the floor intact, and obviates the need to cleverly mount the cabinet from the edges of the hole. The job does not require extreme precision, and could be accomplished with a hole saw and saws-all.

4.1.4 Thermal Calculations

A versatile set of thermal calculations has been carried out to investigate the construction parameters for the cabinet enclosure. The goal is to answer questions like:

- How thick does the insulation have to be?
- Does a foam lining on the plenum shield help much?

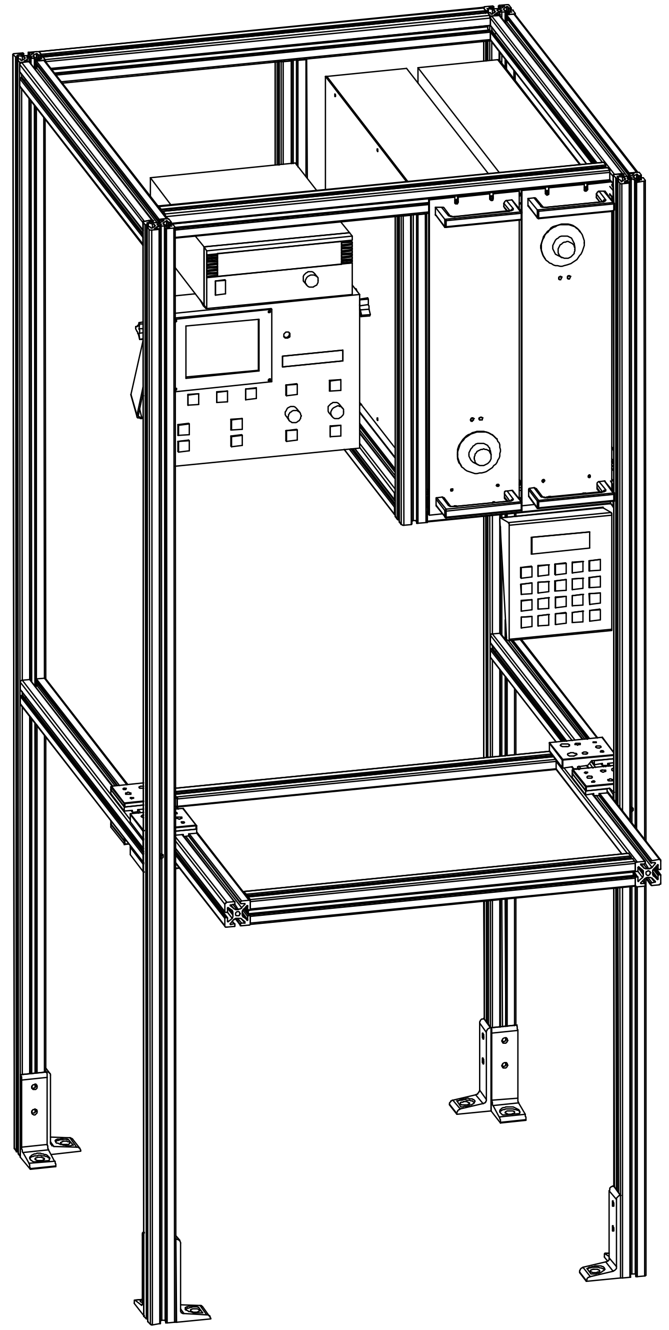

Figure 8: Appearance of the partially-filled cabinet. Capacitor banks are at upper right, the picomotor controller and CCD controller are at upper left, the laser remote box is below the capacitors, and the sliding shelf will accommodate the computer monitor, keyboard, and mouse. The computer and other items will sit below the shelf. Hoses and cables will be routed in the back-left corner. The frame is constructed from 80/20 T-slotted extrusion.

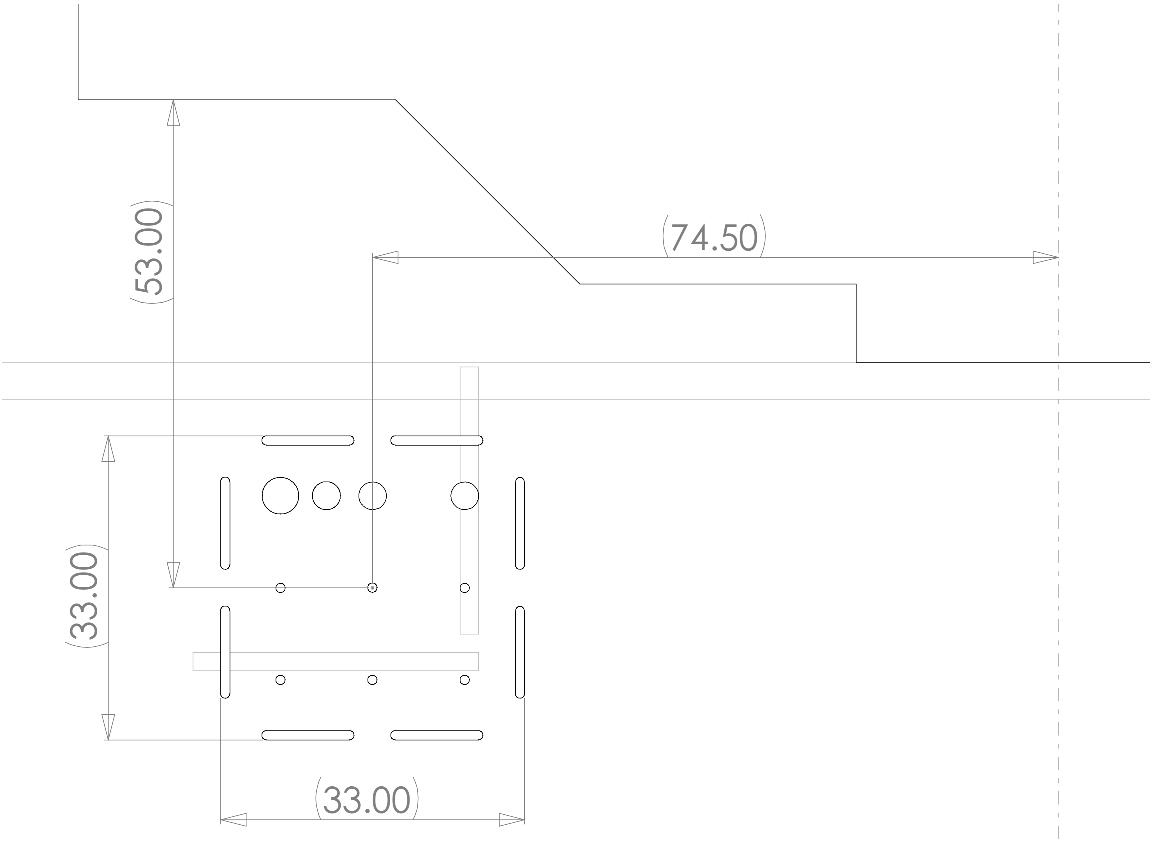

Figure 9: Floor cutout pattern for cabinet, showing also the existing cutout pattern. The location of the crawl-space/ILE wall is shown, as is the position of the tape marks laid down during the PDR visit. The slot holes carry heated air from the plenum into the intermediate level. The largest hole is for cabinet exhaust, and the small holes are inlets. The other holes are for routing hoses and cables from the ILE.

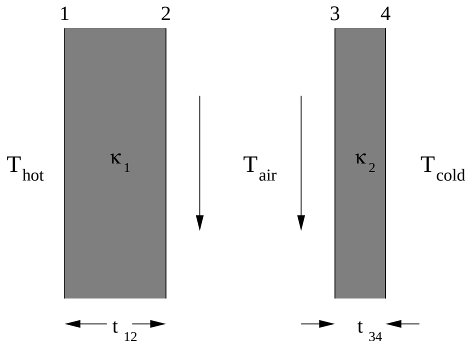

Figure 10: Geometry for the cabinet thermal calculations. Each surface, numbered 1–4, has an associated temperature and emissivity.

Table 1: Cabinet Thermal Scenarios

Departure from Nominal	T_2 (°C)	T_{air} (°C)	T_3 (°C)	T_4 (°C)	Q_2 (W)	Q_4 (W)
Nominal Condition	−11.36	−13.97	−13.99	−14.44	99.2	12.5
$t_{12} = 0.5$ in	−8.90	−13.54	−13.49	−14.16	175.6	18.7
$t_{34} \to 0$ (no foam lining)	−11.40	−14.00	−14.18	−14.18	99.4	18.2
$\epsilon_2 = \epsilon_3 = \epsilon_4 = 0.2$	−11.24	−13.96	−14.08	−14.49	98.7	11.3
$\epsilon_4 = 0.8$	−11.37	−13.98	−14.07	−14.59	99.3	14.7
$\epsilon_2 = \epsilon_3 = \epsilon_4 = 0.8$	−11.84	−14.00	−13.73	−14.48	101.5	20.0
flow rate doubled	−12.54	−14.21	−14.24	−14.58	104.73	9.4
flow rate halved	−9.72	−13.59	−13.60	−14.22	91.6	17.3
$\Delta T_{\mathrm{admit}} = 1$°C	−10.96	−13.50	−13.65	−14.25	97.4	16.7

- What kind of airflow do we need?
- How shiny do we have to make the various surfaces?
- What is the price of letting in pre-heated air from the umbilical housing?

The parameters that can be explored are depicted in Figure 10, and correspond to such things as material thicknesses and thermal conductivities, airflow rates, emissivities (infrared shininess) of surfaces, temperatures of inside, outside, and airflow layer, and plenum geometry. The nominal design has $t_{12} = 1$ in, $t_{34} = 0.25$ in, $\kappa_1 = 0.02$ W K^{-1} m^{-1} (characteristic of Thermax sheathing) $\kappa_2 = 0.03$ W K^{-1} m^{-1}, airflow of 0.08 m^3 s^{-1} (170 cfm), emissivities of $\epsilon_2 = 0.2$, $\epsilon_3 = 0.8$, and $\epsilon_4 = 0.2$, $T_{\mathrm{hot}} = 10$°C, $T_{\mathrm{cold}} = -15$°C, and admitted air that is $\Delta T_{\mathrm{admit}} = 0.5$°C above the (cold) ambient air—having been heated by the hot hoses (treated in Section 4.2.3). Various scenarios are treated in Table 1 with regard to this nominal case.

The most interesting information in Table 1 from the observatory perspective is the last column: the heat released through the cabinet into the dome. The nominal design releases 12.5 Watts into the dome when the dome temperature reaches −15 °C, or 5 °F. Note that the airflow around the insulation carries away about 90% of the cabinet heat, so that this is a critical design feature. Looking at the conditions that move the emitted heat into the 20 W regime, we see that several conditions are important. Surface #2 should be shiny. The foam lining on the plenum wall is important. One-inch insulation around the cabinet interior is necessary. We wouldn't want a flow rate less than the nominal value. It's not terribly important that surface #3 or the outside surface be shiny.

4.1.5 Air Ducting

The thermal calculations highlight the importance of the airflow around the cabinet. We want this air (which exits at $2(T_{\mathrm{air}} - T_{\mathrm{cold}}) - \Delta T_{\mathrm{admit}}$ above ambient) to go straight to the intermediate level. The air will be drawn by fans in the intermediate level through the slot-holes cut into the floor. A typical 3–4-inch fan pulls about 30 cfm, so two fans per side will work well to both provide adequate airflow and distribute this flow evenly over the surfaces (one larger fan per surface would be less likely to promote uniform flow).

The air drawn around the cabinet will be admitted from both the ambient dome air (at T_{cold}) at the top of the cabinet and the conduit carrying the "hot-loop" hoses to the laser heads. This conduit itself lets ambient air in at its entry point near the laser bench enclosure. Because this air is carrying away heat let off by the hoses, it arrives at the cabinet at a slightly elevated temperature (by about 1°C—see Section 4.2.3). The mixture of this pre-heated air with ambient air leads to the $\Delta T_{\mathrm{admit}}$ used in the calculations above. If, for instance, half of the cabinet flow comes from the hose conduit and half from the surrounding air, then $\Delta T_{\mathrm{admit}} = \Delta T_{\mathrm{hose}}/2$. The only challenge here is getting these air inputs to mix properly. For this reason, we will probably want the hot-loop hoses to enter/exit the cabinet on its top surface. We can arrange to have the appropriate number of inlet holes to achieve the desired fraction of the flow from the hose conduit versus the surrounding air.

There will also be air flow inside the cabinet, as previously mentioned. This is to keep the inside of the cabinet at the same temperature as the ILE, and to discourage hot air from collecting at the top of the cabinet—which would otherwise be a natural "chimney" for the ILE. A tube extending through the floor into the ILE with a fan at the lower end would draw air from the top of the cabinet into the ILE, and well-mixed air in the ILE would replace this air through various holes in the floor.

4.2 Umbilical Design

The umbilical is really four separate groupings, arranged into two pathways. The four groups are:

- electrical cables to the laser head
- hoses to the laser head
- electrical cables to the detector and timing electronics
- hoses to the laser bench heat exchangers.

The upper two will enter the laser bench enclosure on the bottom face (bottom when the telescope is pointing toward the zenith), and the lower two will enter the left side of the laser enclosure. The separate routing is both for purposes of allowing the shortest runs, and for keeping the noisy laser cables well-separated from the timing cables.

4.2.1 Routing Options and Applied Torque

We spent a fair amount of time during the PDR visit exploring options for routing the umbilical hoses/cables, and evaluating load requirements. As for tolerable loads, we got at this from four different methods.

- When the scope is balanced with half (4) of the mirror covers down, the motors need service about 25% more often. Each cover is 60 lbs, and the center of mass changes by 2 ft between stowed and deployed positions, for a total torque differential of 480 ft-lbs.
- Once the scope was driven at horizon with all mirror covers closed, which burned out the drive train immediately. This corresponds to 960 ft-lbs.

- Wind load exerts a torque on the telescope. A stiff wind of 10 m/s (22 m.p.h.) can exert about 20 lbs on the telescope at 17 ft, giving 400 ft-lbs.
- Typical drive acceleration is 0.2 deg/s^2, resulting in 60 ft-lbs of torque.

The bottom line is that 1,000 ft-lbs is hopelessly bad, 500 ft-lbs is bad, a few hundred ft-lbs is probably something we could live with, and < 100 ft-lbs is ideal. To some extent, a static umbilical load can be counterbalanced for most observing orientations of the telescope, so that we could place separate static and dynamic limits on the torque imposed. Roughly speaking we could probably accept a static limit twice that of the dynamic variability, assuming that the static part is largely balanced out. If we take 200 ft-lbs as the static component and 100 ft-lbs as the dynamic variability, then an umbilical tugging at 8 feet is limited to 24 lbs static and 12 lbs dynamic. Given that our roughly 15 ft umbilical will weight approximately 100 lbs, this is very hard to accomplish, requiring an active support mechanism to take the load off of the telescope.

On the PDR visit, Larry, Jon and I explored an alternative routing for our umbilical that not only reduces the length of "hanging" umbilical, but moves its moment arm substantially closer to the axis of rotation. Simple analysis suggests that the imposed torque will never be greater than about 120 ft-lbs, and most of this will be static. This routing utilizes the ground-facing tube of the corner port, blocking its usage for other instruments. But given that this is the least desirable of the three corner-port instrument locations, plus the fact that another such port exists on the other side leads us to conclude that this is no huge sacrifice. In addition to the reduced torque and simplified umbilical design, this routing has the advantage that much of the fluid routing can be accommodated by rigid tubing. All of the fluid conduits on the PMC can be fixed and rigid, the only flexible portion spanning from the cabinet to the bottom of the PMC.

4.2.2 Umbilical Weight

The weight of the umbilical can be estimated based on the known cable and hose requirements. The laser head cables are ∼0.4 lbs/ft, 3/4-inch O.D. hoses full of water are about 0.2 lbs/ft, typical 25-conductor signal cable is about 0.06 lbs/ft, and RG-58 cable is 0.03 lbs/ft. Given that we have 2, 4, 15, and 5 of these in the umbilical, respectively, means the minimum umbilical weight is about 2.6 lbs/ft. If we use a couple of supporting flexible cable-tray conduits (typically 0.7 lbs/ft), the total weight including the hose insulation/conduits may be as high as 5 lbs/ft.

Revisiting the torque question, if we take 4 ft as the maximum cable length hanging from the telescope (the side of the umbilical not supported by the cabinet), and use its attachment point 5 ft from the telescope axis, we get 100 ft-lbs of torque. This is equivalent to about 14 lbs of counterweight on the outside of the PMC. In reality, the maximum force (hanging cable weight) is placed on the telescope when it is pointing near the horizon, when the moment arm is reduced (to about 3.5 feet), for a net torque of 70 ft-lbs. When the moment arm is maximum (near zenith), the cable load on the telescope is more like 2–3 feet, for a net torque of 75 ft-lbs. So a ten-pound counterweight may almost entirely get rid of the umbilical torque.

4.2.3 Thermal Calculations

The copper conductors in the umbilical will readily transport heat from the cabinet and laser bench enclosure interiors into the dome. The relatively small cross-sectional area of the conductors saves us, but the load may be in the tens of Watts on the coldest of nights. As yet we have done no detailed calculations on the cable contribution. But we *have* looked closely at the heat given off by the "hot-loop" hoses. At 30°C (85°F) when the laser is powered, these could present a very serious thermal leakage into the dome if not protected—upward of 90 W per hose if not insulated, and 50 W per hose when the fluid has cooled down to the 10°C set-point of the laser and intermediate level enclosures (these calculations are for an ambient temperature of −15°C). So it is this pair of hoses to which most of our attention has been devoted. The "cold-loop" hoses

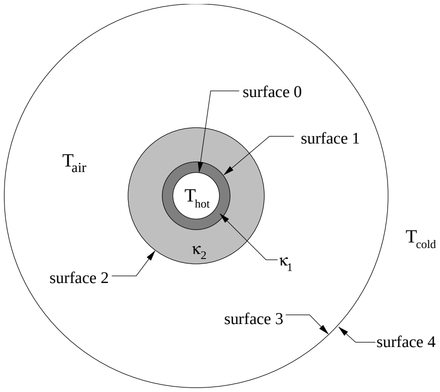

Figure 11: Geometry for the hose thermal calculations. Each of the surfaces, numbered 0–4, has an associated radius, temperature, and emissivity.

Table 2: Hose Conduit Thermal Scenarios

Departure from Nominal	T_1 (°C)	T_2 (°C)	T_3 (°C)	T_{air} (°C)	Q_2 (W)	Q_4 (W)	$\Delta T_{\text{exhaust}}$ (°C)
Nominal Condition	25.83	-7.75	-14.42	-14.20	38.7	6.3	1.59
$r_2 \rightarrow r_1$ (no foam)	22.39	21.74	-13.94	-13.54	70.7	11.5	2.91
$r_2 = 0.75$ in	25.05	-3.18	-14.31	-14.05	46.0	7.5	1.90
ϵ_2 OR $\epsilon_3 = 0.8$	25.80	-8.03	-14.36	-14.21	39.0	7.0	1.57
$\epsilon_3 = \epsilon_4 = 0.8$	25.80	-8.07	-14.50	-14.25	39.1	8.7	1.49
$\epsilon_2 = \epsilon_3 = \epsilon_4 = 0.8$	25.66	-9.31	-14.30	-14.31	40.3	12.3	1.38
flow rate doubled	25.54	-10.45	-14.62	-14.54	41.5	4.1	0.92
flow rate halved	26.24	-4.10	-14.19	-13.71	35.0	8.8	2.57
$T_{\text{hot}} = 10$°C	7.68	-10.97	-14.68	-14.56	21.5	3.5	0.88

containing the ethylene-glycol solution are of less concern, since 1) they will never be warmer than the 10°C set-point, and 2) they will be allowed to relax to ambient when the laser is not running (98% of the time).

The geometry for performing the thermal calculations is shown in Figure 11. While only one hose is implied by the (calculable) circular symmetry, in practice both hoses will likely be bundled together. All the same, the calculations give us insight into what elements are important in designing an effective thermal solution. In these calculations, the nominal state is assumed to be: $T_{\text{hot}} = 30$°C, $T_{\text{cold}} = -15$°C, $r_0 = 0.25$ in, $r_1 = 0.375$ in, $r_2 = 1$ in, $r_3 = 3$ in, $\epsilon_2 = \epsilon_3 = \epsilon_4 = 0.2$, $\kappa_1 = 0.1$, $\kappa_2 = 0.03$, and the flow rate is 0.02 $\text{m}^3\ \text{s}^{-1}$, or 42 cfm (one-quarter of the nominal cabinet flow rate). The exposed length of conduit is assumed to be 6 m, or about 20 ft. In truth we may get away with 75% of this, so the heat fluxes indicated below would be reduced by this amount. Table 2 explores the results of varying these parameters.

From Table 2 we learn that we can knock the 90 W figure for an uninsulated length of hose down to numbers less than 10 W (Q_4 column). Arranging two hoses into the same insulated bundle will yield slightly higher numbers, but only by perhaps 50% (not double). Scanning the table for heat flows that are roughly double the nominal value, we see that it is important to use foam insulation, and that at least surface 2 or 3 should be shiny. Note that the last column in the table indicates the rise in the temperature of the air flowing through the conduit. This mixes with other air being drawn around the cabinet, and influences the ΔT_{admit} parameter used in the thermal analysis of the cabinet. Because the nominal flow rate in the hose conduit is one quarter of the nominal cabinet flow rate, $\Delta T_{\text{admit}} = \Delta T_{\text{exhaust}}/4$. In general, this meshes well with the previous assumption for the cabinet that $\Delta T_{\text{admit}} \approx 0.5$°C.

One might ask what the effect of Q_2 is on the temperature of the fluid in the hoses. After all, heat is leaking out. At the nominal (low-end) fluid flow rate of 1 gpm, a 50 W heat flux translates to a temperature drop of 0.8°C. This is not enough to cause concern.

When the hot-loop runs cool (the majority of the time when the laser is not powered), the T_{hot} temperature settles to the ILE set-point (this is where the reservoir sits). At this temperature, the nominally insulated hose system emits less than 5 W into the dome on the coldest nights. If we apply this nominal design, or something close to it, we remove a significant source of heat from the dome environment.

4.2.4 Umbilical Structural Design

At present, the design for the umbilical goes as follows.

- The electrical cables to the laser all travel together, and emerge from the cabinet directly behind the position of the capacitor banks, roughly 55 inches off the floor, pointing straight at the telescope. At the minimum, we will put a strain relief at this exit point, holding the cables perpendicular to the cabinet at the exit point. At most, we will enclose the entire bundle in a flexible track system that limits the radius of curvature of the cables. Because of the location of the cabinet relative to the intended attachment point on the PMC, we can expect the cable motion to be entirely confined to a plane, simplifying the requirements of the flexible cable-tray conduit.

- The electrical cables to the detector, timing electronics, etc. will take a similar path to that of the laser cables, but displaced as much as possible to reduce cable crosstalk. Each bundle will likely be enclosed in braided shielding. The timing cables come in three varieties: digital signal cables, AC power cables, and DC power cables. We need to separate the DC cables from the other two (and shield them) to keep them from picking up spikes and 60 Hz signals from the other cables. Strain relief and conduit will be handled in the same way as the laser cables.

- The cold-loop hoses to the Noren chillers are at present intended to run uninsulated. These may be routed through the same flexible cable tray that is used for the timing cables, in an effort to prevent the line from kinking. Once on the PMC, rigid tubing will carry the fluid to the heat exchangers in the laser bench enclosure.

- The hot-loop hoses need to be carefully insulated as indicated in the previous section. We imagine using shiny metallic heater tubing roughly six inches in diameter to accommodate the hoses. The hoses will be bundled side-by-side and wrapped in foam insulation. We probably need not bother making this arrangement shiny, but if we decide to do so, we will probably use aluminized mylar to do the job. The hoses will penetrate the cabinet and laser enclosure insulation through close-fit holes sealed against airflow, but the heater tube conduit will terminate at the cabinet plenum, and just outside the laser enclosure where air is drawn into the tube. Because of the need to mix the emerging heated air with ambient air for flow around the cabinet, the hot-loop hoses will be routed into the top surface of the cabinet. We need to work out a method for suspending the hoses within the conduit, but we have several ideas for this.

5 Chiller Installation and Plumbing

5.1 Chillers

We have quotes for the two Neslab Merlin-series chillers. We will be getting chillers with all the bells and whistles: low-level/low-flow detection, serial communications package, air filters, and the low temperature option on the cold-loop chiller. The idea is to permit unattended operation and remote activation. The chillers also have an option that allows us to tune the delivered pressure, so that we don't promote excessive over-spray of the ethylene-glycol solution in the vicinity of the PMC.

The chillers should be plug-and-play for the most part. We can get them into the ILE via the crawl-space hatches. We will install a couple of fans around the chillers to force proper circulation of air past and around them.

5.2 Plumbing

Figure 12 shows the general plumbing scheme. The M-75 chiller forms a closed loop with the CG-604 "cooling group" unit in the laser electronics rack. These units sit side-by side in the ILE, so the plumbing is as simple as a couple of hoses. We *do* need to make sure we provide a bypass valve, because the CG-604 will sometimes block the coolant input, and we need to ensure that the M-75 doesn't "dead-head."

The M-33 unit controls the cold-loop consisting of a 50/50 ethylene-glycol/water solution. We will use hoses or rigid tubing to go from the ILE to the top of the cabinet, where we connect through the wall to the umbilical hoses. Once on the PMC, we switch to rigid tubing up to the Noren heat exchangers in the laser bench enclosure. We will include an auxiliary pump on a bypass loop so that we can continue to circulate coolant even when the M-33 is off. This will allow us to keep the laser bench from warming up when the system is off. We have not yet selected a pump or bypass scheme for this purpose, but do not consider this to be a significant challenge.

The CG-604 manages the thermal state of the laser rods. During operation, it brings the temperature of the de-ionized water up to 85°F and stabilizes on this value for operation. The plumbing will consist of either hoses or rigid tubing to the top of the cabinet, where the lines emerge through the cabinet roof and connect to the flexible umbilical hoses that are suspended inside the insulating conduit. As with the other coolant lines to the telescope, we can transition to rigid tubing once on the PMC, though still within the insulating duct. Because water has a tendency to freeze if it gets too cold, we need to maintain circulation when the laser is off. Otherwise the bit of fluid in the umbilical would be subject to freezing. The flow doesn't have to be that high. The calculations of Table 2 show that when the coolant is at the ILE/laser bench set-point of 10°C, the heat loss rate is about 20 W. At a flow rate of 1 gpm, this translates to a temperature loss of 0.3°C during one pass of the umbilical. Because the CG-604 reservoir is 6 liters, and the umbilical contains 1.5 liters total, we could probably tolerate a few degrees loss per pass (should do a real calculation here), so that we can probably get away with liter-per-minute flow rates.

The CG-604 is open to "pumping through" with an auxiliary pump in series. In fact, a space exists in the CG-604 unit itself where we could locate the auxiliary pump on separate power. We would power the auxiliary pump whenever the temperature could get below freezing and the laser is not on. We may be able to get away with operation when the laser *is* on, provided the pump does not significantly impede the higher flow rate (a few gpm) of the CG-604.

6 Intermediate Level Enclosure

The intermediate level enclosure should be relatively simple. The bulk of the effort is done (building the platform, routing power). We need to construct an insulating box using 2-inch sheathing, but it doesn't have to be structurally robust. We will situate the laser electronics rack and the two chillers in the ILE, along with several fans and a space heater. The trickiest aspect of the ILE is the actuated walls to provide variable-sized gaps for regulation of temperature when running. This may be as simple as freely-swinging walls that are forced open depending on how many fans we turn on. Or we may have actuated rods that control the size of the openings.

The interconnects to the cabinet can be as simple as little ducts connecting the two. We anticipate a 6–8 inch gap between the roof of the ILE and the bottom of the observing level floor. We don't worry too much

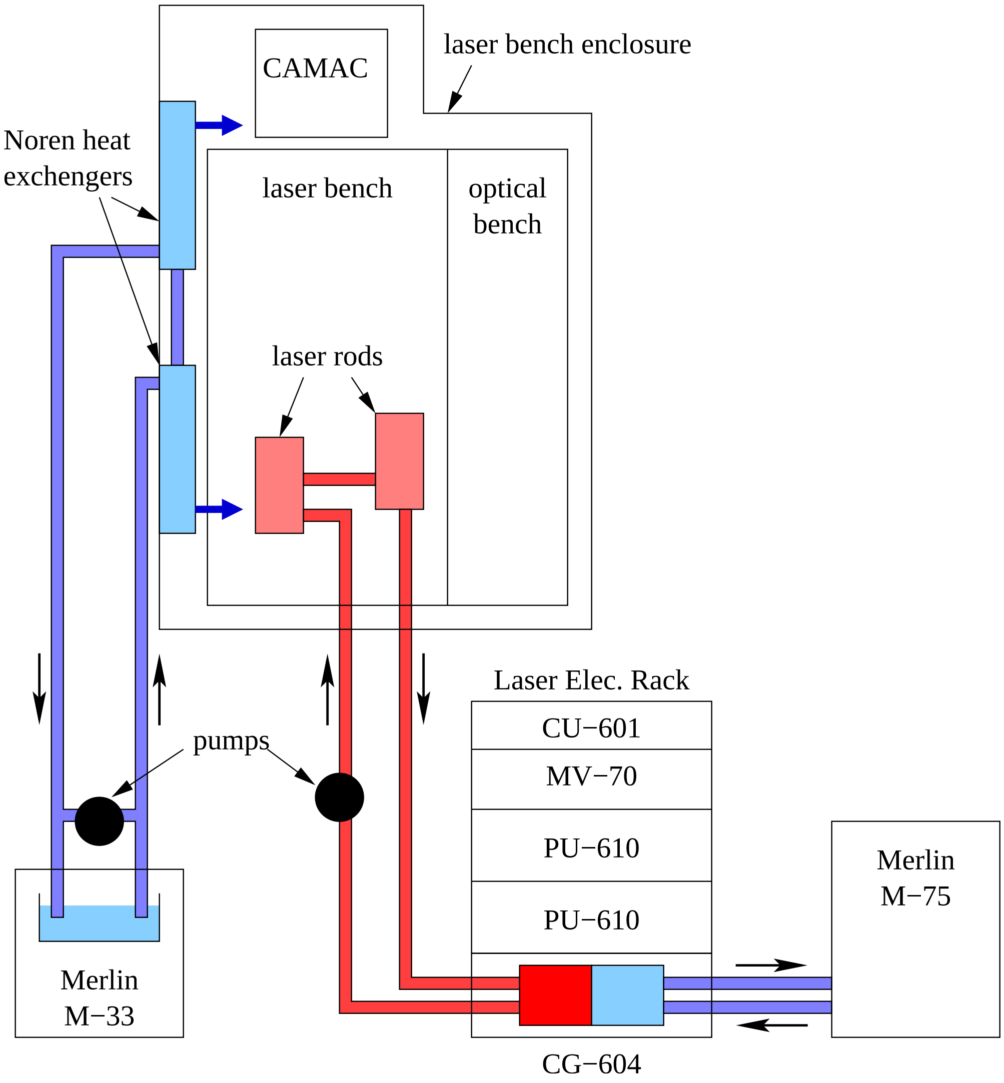

Figure 12: Plumbing schematic, consisting of three loops. The hot-loop circulates de-ionized water to the laser heads. The cold-loop circulates coolant to the heat exchangers in the laser bench enclosure. The third loop takes heat away from the laser heat exchanger. The auxiliary pumps serve to circulate the fluids when the chillers are powered off.

about heat loss through the interconnecting ducts, because 1) their area is small, and 2) the intermediate level is not a temperature-critical area.

The slotted holes in the observing level floor that allow the airflow around the cabinet to pass into the intermediate level will be outfitted with ducts in the space between the ILE roof and the observing floor above. These ducts will funnel the air from the slots into small fans that exhaust into the intermediate level air. Two 3-inch fans for each of the four sides is about right. For this reason, we don't want the cabinet to be located too far forward, or the wall between the crawl-space and the ILE will preclude the installation of these ducts for the telescope-facing wall of the cabinet.

7 Rough Schedule of Events

The UW physics machine shop already has drawings of the laser mounting fixture components, and has initiated the material order. Subject to the approval of the CDR, we will authorize them to begin fabrication of parts. We expect to be in a position to ship parts to APO by early June. The cabinet frame will likewise be ready by that time. In mid June, we will plan to install the laser on the telescope, build the cabinet, and run the plumbing and umbilical. The installation will be partial at this point. We need not yet worry about thermal protection, as this is the warm part of the year, and we won't be fully operating in any case until the fall. At that time, we will complete the outfitting of the apparatus and thermal protections. We can delay building the ILE until this time. Fall will be a period of active integration, with Murphy (and others) spending substantial amounts of time at the observatory.