NIRSPEC

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NIRSPEC Optics Design Note 4.03
Calibration Unit

1.0 Introduction

Calibration of the instrument is necessary in the lab as well as at the telescope. In the lab, spectra from calibration sources are a useful way to test data reduction procedures. Calibration sources also provide a way to test image quality, resolution, interorder stray light, and wavelength stability.

For observations there are three categories of calibration that are required. These are:

Internal Optical Calibration
Detector Calibration (e.g. dark current)
Astronomical Calibration (e.g. flux calibration)

Characterization of the detector at the telescope is done by taking bias and dark current frames. Astronomical calibration such as flux calibration is done by taking spectra of standard stars. A calibration unit that will be attached to the front of NIRSPEC will be used for internal optical calibration.

The calibration unit must provide for the following types of calibration: flat fielding, absolute wavelength calibration, slit location, slit tilt, and dispersion direction. The beam that it feeds to NIRSPEC must mimic the beam from the telescope as much as possible. The calibration unit must fit in the space available in front of NIRSPEC which is to be shared with the guiding system and it must have some way to feed the beam into NIRSPEC while remaining out of the way during observations.

2.0 Internal Optical Calibration

2.1 Flat fielding

Flat fielding of astronomical data is necessary to account for pixel-to-pixel variations in quantum efficiency. For a good flat field the light source should have the same optical path as the telescope. The source should be uniform both spatially and spectrally so that the flat field is uniform in both directions on the array. The accuracy of the flat field is important since it can determine the final signal-to-noise of the observations. This is because both the object frame and the sky frame must be flat fielded and the flat field affects how well the image can be sky subtracted.

A quartz tungsten halogen lamp will be used to provide a source that is approximately flat spectrally. An integrating sphere will be used to provide a source that is Lambertian (the intensity is independent of direction). The light enters an input port on the sphere and bounces numerous times off of a highly reflective and diffuse surface. By the time the light reaches the exit port of the integrating sphere it has lost all memory of direction and polarization. The integrating sphere will be discussed in more detail in Section 4.0.

A goal should be determined for how uniform the beam should be for flat fielding. CGS IV has a measured uniformity of 99.5%. This is a reasonable goal that we should strive to obtain. The spatial uniformity is given by the ratio of edge to axial illuminance at the object

$$\frac{E_e}{E_o} = \frac{\pi B \sin^2 u \cos^4 \varphi}{\pi B \sin^2 u} = \cos^4 \varphi$$

where B is the radiance, u is the half angle of the source at the slit, and ϕ is the half angle of the slit at the source (see Figure 1). The uniformity for radiation from a Lambertian surface is limited by this $\cos^4\phi$ factor.

Numerical aperture is related to F/# and marginal ray angle by

$$NA = n \sin\theta = \frac{1}{2F/\#}$$

φ is half of the marginal ray angle so the uniformity can be written in terms of the object space numerical aperture in air

$$U = \cos^4\left(\frac{\sin^{-1} NA}{2}\right)$$

We will calculate this for the final system in section 6.2.2.

The calibration unit setup required for flat fielding is a tungsten lamp plus the integrating sphere.

2.2 Wavelength calibration

2.2.1 Absolute

Absolute wavelength calibration is necessary for accurate subtraction of atmospheric lines. There must be lines in each order to have continuous calibration across the observed window. Many lines per order are required to calibrate any non-linearity in wavelength. A reasonable number is at least ten lines per order for determination of an accurate wavelength map on the array. Noble gas discharge lamps are one excellent source of absolute calibration. They produce narrow lines at well defined wavelengths. Standard lamps are Ne, Ar, Kr, and Xe.

However, these lamps in combination do not give the necessary number of lines per echelle order. The free spectral range of the echelle grating is given by

$$FSR_e = \frac{\lambda}{m_e}$$

where λ is the central wavelength and m_e is the echelle order. For 2.2 μm the FSR = 0.063 μm for $m_e = 35$. This is the right order for an echelle with 23.2 lines per mm and a cross disperser with 75 lines per mm. The above lamps in combination only provide 34 bright lines from 2.0 to 2.4 μm, therefore on average there will only be 5 lines per order. Adding other standard commercially available lamps (e.g. Fe) does not appreciably increase the average number of lines per order. The noble gas discharge lamps are useful for absolute wavelength calibration but in addition relative wavelength calibration is required to obtain the necessary number of lines. These lamps do not provide many lines past 2.5 μm. In the longer wavelength region the night sky emission lines will have to be used for calibration.

The calibration unit setup will be the arc lamps plus the integrating sphere. The CDR committee recommended having a set of spare arc lamps to be used in the event that the arc lamps burn out.

2.2.2 Relative

Illuminating a Fabry-Perot etalon with light from a tungsten lamp is an ideal way to produce narrow lines of known separation for relative wavelength calibration. If the etalon is illuminated by collimated light with an angle of incidence equal to zero, then fringes are produced that are separated by the free spectral range (FSR) of the Fabry-Perot.

$$FSR_{FP} = \frac{\lambda^2}{2d}$$

Here d is the separation of the plates. Of course the incidence angle will not be zero in practice and the consequence of the non-zero angle will be discussed in Section 6.1.1. The fringes are evenly spaced in wavenumber but not in wavelength. An etalon can be selected that has a spacing that will give the appropriate FSR for the required number of lines per order. The etalon and requirements on it are discussed in more detail in Section 5.0.

The setup used will be a tungsten lamp plus etalon plus integrating sphere.

2.3 Slit location

The gratings are scanned in angle to select the wavelength range that falls on the array. As the angle of the cross-disperser is adjusted the orders move up and down the array. Because of this, it is necessary to determine the location of the slit images in the spatial direction for each grating setting. This can be done by creating an artificial star by placing a pinhole at the exit port of the integrating sphere. If the pinhole is at the optical axis then it will produce a narrow spectrum at the center of the slit. Taking this kind of spectrum determines the slit location for a given setting of gratings.

The setup will be tungsten lamp plus integrating sphere plus pinhole.

2.4 Dispersion direction

The dispersion direction will nominally be along the rows of the detector (if the array is rotated). However, it will not be exactly parallel to the rows and the angle between the dispersion axis and the detector rows must be known for accurate data reduction. The spectrum of a pinhole will be quite narrow and will define the dispersion axis. Thus the angle it makes with the rows of the detector can be determined.

The same setup as for determining the slit location (tungsten lamp + integrating sphere + pinhole) can be used.

2.5 Slit tilt

The images of the slit are tilted because the echelle is used in quasi-Littrow mode and this tilt varies across each order, increasing towards the edges. This tilt can be measured from the tilt of the fringes created by the etalon and tungsten lamp. Since we require about ten lines per order for relative wavelength calibration, there will be enough lines per order to measure the variation in slit tilt across each order.

The calibration unit setup will be the same as for relative wavelength calibration (tungsten lamp + etalon + integrating sphere).

3.0 Basic Layout

Figure 2 is a block diagram of the calibration unit showing the required components and their relation to each other. One input to the integrating sphere is for light from a tungsten lamp and etalon. A UV-vis blocking filter should be placed in front of the lamp to prevent heating of the etalon. The beam must be highly collimated before reaching the etalon. This will be accomplished by first imaging the filament of the lamp onto a pinhole. If the pinhole is placed at the focus of a collimating lens the beam will be highly collimated. The next element is the etalon, followed by the integrating sphere. This setup allows calibration of relative wavelength and slit tilt.

Another tungsten lamp and the array of noble gas discharge lamps will be placed at the other input port of the integrating sphere. A second tungsten lamp is required to produce a flat field since the first one is in front of the etalon and therefore fringes are produced. The spectral line lamps plus the integrating sphere is the setup used for absolute wavelength calibration. To calibrate dispersion direction and slit location there should be a pinhole at the exit port of the integrating sphere. This pinhole needs to be removable because it is not desired for flat fielding, wavelength calibration, or slit tilt.

Some optics after the exit port of the integrating sphere are required to produce an *F*/15 beam similar to that from the telescope. There must also be a way to feed this beam into NIRSPEC. There will be a movable flat mirror that will either block the beam from the telescope and send the calibration beam into NIRSPEC or be stowed behind the first guide mirror. By locating the calibration unit in such a way that the guider is not required to move out of the way, guiding can be done while calibrating if desired. Depending on the location of the calibration unit there may be an additional flat mirror used to direct the beam into NIRSPEC.

Figure 3 is a summary of the calibration unit modes and what they are used for.

4.0 Integrating Sphere

I attended a seminar given by Labsphere on integrating spheres and their uses. It was quite helpful and we were able to handle samples of the various materials and coatings. We will be using the integrating sphere to provide a uniform source, therefore a material or coating should be used that is as Lambertian as possible. This means that the intensity of the reflected light goes as $cos\theta$ regardless of the angle of incidence. The material must also be highly reflective over the wavelength range of interest to have adequate throughput. Labsphere offers two materials that seem appropriate. One of these is a proprietary material called Spectralon. It is very Lambertian (Figure 3) and has a very high reflectivity (> 95%) from 1.0 - 2.5 μm (Figure 4). The reflectivity of the Spectralon material from 2.5 - 5.0 μm is shown in Figure 5. The reflectivity drops to almost 0.8 near 2.9 μm. This relatively small decrease in reflectivity dramatically lowers the throughput as will be seen in Section 7.0. Since NIRSPEC will operate from 1.0 - 5.0 μm it would be better to use a material that has a high reflectivity across a broader wavelength range. Another material offered for the infrared is Infragold. The intensity profile is shown in Figure 6 and the reflectivity in Figure 7. Values range from 0.951 at 1.0 μm to 0.965 at 5.0 μm. Infragold is the material that was used to coat the sphere for CGS IV. Even though it is more specular, they achieved uniformity of 99.5%. It has been decided that we will also use Infragold.

Another factor to consider is that a larger sphere will have better angular performance. This must be balanced against the fact that a smaller sphere will have a higher throughput. One must also try to minimize the area of the openings in the sphere. A good rule of thumb is that the area of the ports should be < 5% of the total surface area of the sphere. Off the shelf spheres will meet this requirement and will be cheaper to obtain than custom ones. We will use a standard 4″ diameter integrating sphere coated with Infragold. These spheres come with three 1″ input ports and one 0.5″ output port. Since we only need two input ports we will plug one of the openings with the port plugs that are provided. The throughput of the sphere will be discussed in Section 7.0.

5.0 Etalon

The spacing of the etalon can be set so that there are ten Fabry-Perot fringes per echelle order.

$$FSR_{FP} = \frac{FSR_e}{10} = \frac{\lambda^2}{2d} = \frac{\lambda}{10m_e}$$

$$d = 5\lambda m_e$$

Even though the separation of the fringes in wavelength is not constant, the number of Fabry-Perot fringes per echelle order is constant for the same grating. If NIRSPEC uses more than one echelle grating, using a fixed space etalon means the number of lines per order will not be constant. In that case the spacing will need to be optimized for one wavelength. It appears that there will be only one echelle grating. For $\lambda = 2.2$ µm and $m_e = 35$, $d = 0.4$ mm. A larger spacing will give more lines per order. Melles Griot have air spaced etalons with $d = 0.5$ mm giving 13 lines per order which will be plenty for relative wavelength calibration.

Scanning Fabry-Perot etalons (allowing the spacing to be adjusted in the case of more than one echelle) are also a possibility but they are more costly and would cause the system to be much more complicated. To calibrate effectively with a scanning Fabry-Perot, there would need to be a feedback loop that could measure the separation of the plates very accurately in order to know the exact fringe separation. Therefore if there is more than one echelle it seems better to optimize for one wavelength.

With a fixed etalon the separation d can be measured once and then the only change in d would be due to temperature variations. A UV-visible light blocking filter should be used to reduce heating of the etalon. A temperature sensor should be placed near the etalon to monitor temperature stability.

The spectral resolution of the Fabry-Perot is required to be at least as high as the echelle so as not to degrade the width of the lines. Narrow lines are needed to accurately centroid on them for relative wavelength calibration. This places a constraint on the finesse of the etalon. The resolution of the Fabry-Perot is given by

$$R_{FP} = \frac{2Nnd}{\lambda} > R_e$$

where N is its finesse. The finesse is determined by the reflectance finesse and the wavefront defect finesse. For $R_e = 25{,}000$, $\lambda = 2.2$ µm, and $d = 0.5$ mm, we require $N > 55$.

The finesse of Melles Griot etalons is dominated by the reflectance finesse which is given by

$$N_R = \frac{\pi R^{1/2}}{(1-R)}$$

where R is the reflectivity of the plates. The required finesse implies we need a coating with $R > 94.5\ \%$.

A summary of the specifications for the etalon is given in etalon.doc and was sent to vendors.

6.0 Optical Design

There are two optical designs required, one to create a collimated beam for the etalon (hereafter, Section 1) and one after the integrating sphere to simulate the Keck telescope for NIRSPEC (hereafter, Section 2). The optical design must satisfy at least three requirements: it must create a highly collimated beam to illuminate the etalon, produce an *F/*15 beam to simulate Keck, and fill the pupil at the Lyot stop in NIRSPEC the same way the telescope does.

6.1 Section 1

6.1.1 Purpose and Requirements

One of the jobs of the first section of optics is to get as much light from the lamp as possible into the integrating sphere. To maximize the light from the lamp the focal ratio of the first lens, F_1, must be as small as possible. On the other hand if the focal ratio is too small the image of the filament will over fill the pinhole and light will be lost. If d_{IS} is the diameter of the input port of the integrating sphere and r_f is the radius of the filament, then the condition that the image of the filament just fills the pinhole is

$$F_1 = \frac{2r_f}{d_{IS}}\left(\frac{R_e}{8}\right)^{1/2}$$

Using typical values ($r_f = 2$ mm, $d_{IS} = 20$ mm, $R_e = 25{,}000$), the fastest system that loses no light at the pinhole is $F_1/9.8$. This assumes a size of the pinhole that is consistent with the resolution of the echelle grating.

The other and perhaps more important purpose of the first section of optics is to create a parallel beam of light that will pass through the etalon before entering the integrating sphere. Ideally all rays should have an angle of incidence equal to zero. This would give the maximum resolution of the Fabry-Perot. In practice however this is not possible and we require that the resolution of the Fabry-Perot be at least as good as that of the echelle grating. This places a constraint on the parallelness of the rays incident on the etalon.

$$R_{FP} = \frac{\lambda}{\Delta\lambda} = \frac{2}{\theta^2}$$

The limiting angle is then

$$\theta = \left(\frac{2}{R_{FP}}\right)^{1/2} = \left(\frac{2}{R_e}\right)^{1/2}$$

A larger angle will degrade the spectral resolution of the Fabry-Perot. The requirement is then that all rays should make an angle with the optical axis no larger than 8.94 mrad. This is a goal for all rays from all field points for the entire wavelength range which may be quite difficult to achieve.

6.1.2 Zemax design

Figure 8 shows the layout of the first section of optics. The design consists of two doublets. The first pair of lenses images the filament onto a pinhole while the second pair creates the highly parallel beam. Imaging the filament onto the pinhole concentrates the light into a small spot which is then much easier to collimate and obtain the correct angles. The lenses are made of BaF_2 and LiF. Table 1 gives the optical prescription for Section 1 after test plate fitting to the ISP (International Scientific Products) test plate list. Radius refers to the radius of curvature of the surface while the diameter of the element is specified by the aperture. The useful aperture refers to the diameter where no vignetting occurs while the total aperture includes room for mounting of the element.

In order to image the filament on the pinhole, a large demagnification is required. This forces the first element to be farther away from the filament increasing the *F/#* of the input beam. As seen in the previous section we would like the *F/#* to be as small as possible to minimize light loss but it must be large to accommodate the demagnification. The actual design has *F*/20, two times larger than the optimal *F*/9.8. This means that the light loss is increased by a factor of four. This can be partly compensated for by placing a reflective assembly behind the lamp. It will produce an image of the filament at the location of the filament, thereby increasing the light that can be collected.

Table 1. Optical prescription for Section 1.

Element	Surface	Radius (mm)	Material	Thickness (mm)	Distance (mm)	Useful Aperture (mm)	Total Aperture (mm)
Filament	-	-	-	-	199.4	4.2 x 2.3	-
Lens 1	1	32.66	LiF	2.6	-	20.177	26
	2	13.92	-	-	2.09	19.780	26
Lens 2	1	16.943	BaF_2	11.913	-	21.545	27.5
	2	-28.2	-	-	43.813	21.375	27.5
Pinhole	-	-	-	-	43.926	1.271	-
Lens 3	1	31.05	BaF_2	9.530	-	21.548	28
	2	-19.31	-	-	2.736	21.820	28
Lens 4	1	-15.922	LiF	2.794	-	20.258	27
	2	-66.83	-	-	32	20.660	27
Etalon	1	Infinity	Air spaced	0.5	32.5	19.953	20
	2	Infinity	-	-	15	19.868	20
Mirror (X_{rot}=45°)	-	Infinity	glass	-	30	28.731	35
Sphere	-	-	-	-	-	20.674	25.4

6.2 Section 2

6.2.1 Purpose and Requirements

The second section of optics has several purposes: it must take light from the integrating sphere output port and get it down the slit in a manner that simulates the telescope, it needs to be able to image a pinhole for field points in the slit, and it must provide for flat fielding (including the entire field of view (FOV) of the SCAM).

The calibration unit when attached to NIRSPEC must form a good pupil at the Lyot stop. How well it can do this is a measure of how closely the working *F/#* (14.9583480) and chief ray angle (with respect to the optical axis = -0.000836152) of Keck have been simulated. One way to measure this performance is to look at the blur of field points at the pupil. For a perfect pupil all field points should coincide. The spread of the field points can be measured as a percent of the pupil diameter. For the front end of NIRSPEC fed by Keck this value is 1.9% and is the same for all wavelengths (since both NIRSPEC and Keck are all reflective). The goal for the calibration unit is to produce a blur at the Lyot stop that is less than or equal to the blur produced by Keck. The goal for imaging is to have > 80% ensquared energy in half of a resolution element (the slit width) at the slit focal plane. This is only required for field points in the slit where the pinhole will need to be imaged for determining the slit location and dispersion direction. The longest slit length is 30″. There must be a uniform beam provided for the entire FOV of the SCAM which is 46″ by 46″. The wavelength coverage for field points in the slit should be from 1.0 to 5.0 μm. However, performance at short wavelengths should not be sacrificed for the longer wavelength region. Outside of the slit the desired wavelength range is 1.0 - 2.5 μm since the SCAM's sensitivity cuts off at 2.5 μm. The slit will be rotated 90° between the standard (high resolution) mode and the low resolution mode.

6.2.2 Zemax design

The layout of the second section of optics is shown in Figure 9. The design consists of two triplets. An earlier design consisted of two doublets with one lens having an aspheric surface. Since aspheric surfaces are hard to make on fluoride materials they increase the cost of the lens and increase the risk in the manufacturing of such a lens. Therefore it was decided to eliminate the aspheric surface. It was then necessary to make the second doublet a triplet in order to get good performance. The first doublet was also changed to a triplet since the symmetry induced helps to reduce aberrations and increase performance. The first triplet creates a pupil, where the stop of the system is located. This also provides a convenient place to put a central obscuration in order to mimic the primary of the Keck telescope. The second triplet produces an *F*/15 beam with the correct FOV for the SCAM. This design was obtained by using the wavelength and field weights given in Table 2. It was decided that performance in the corners of the SCAM array are not crucial. Removing the weight on this area greatly improved the performance of the system. It was necessary to experiment with weights for the wavelengths to obtain a design with good wavelength coverage. The centers of the astronomical wavebands were specifically weighted to assure performance there as well as at the ends of the expected coverage. It was not possible to design a system that worked well all the way out to 5.0 µm. The optical prescription is given in Table 3.

Table 2. Wavelength and Field Weights (Section 2).

		Weight
Wavelength:	1.0 µm	1.25
	1.25 µm	1.5
	1.65 µm	1.5
	2.2 µm	1.5
	2.5 µm	1.5
	3.0 µm	1.0
	3.5 µm	1.0
Field Point:	Center	1.7
	SCAM Edge	1.0
	SCAM Corner	0.0

Figure 10 shows the spots at the focal plane of the calibration unit. The size of the box is half a resolution element and spots are shown for the central field point, one end of the slit, and for one edge of the SCAM's FOV. A diagram explaining the field point numbers is shown in Figure 11. The calibration unit is rotationally symmetric so the center, one edge of the slit, and one edge of the SCAM FOV are adequate to characterize the performance. Points along the Y-axis were used so that Zemax knows to exploit the symmetry of the system. The wavelengths shown are 1.0, 1.25, 1.65, 2.2, 2.5, 3.0 µm. For the central fieldpoint the spots are almost entirely inside the box. Spot diagrams are a geometric representation and do not include diffraction.

Figure 12 shows the diffraction ensquared energy as a function of wavelength. The goal of 80% is met from 1.0 - 3.3 µm for the center field point. For the edge of the slit and SCAM FOV the goal is met from 1.0 - 3.4 µm. It would be better if the performance cut off at 2.5 µm outside of the slit but this could not be achieved without sacrificing the wavelength coverage for the field points inside the slit.

Table 3. Optical prescription for Section 2.

Element	Surface	Radius (mm)	Material	Thickness (mm)	Distance (mm)	Useful Aperture (mm)	Total Aperture (mm)
Sphere	-	-	-	-	43.959	12.700	-
Lens 1	1	154.17	BaF_2	19.191	-	15.804	22.5
	2	-130.02	-	-	6.5137	16.356	22.5
Lens 2	1	-3300.0	CaF_2	11.570	-	16.292	22.5
	2	216.27	-	-	1.6012	16.280	22.5

Lens 3	1	123.75	BaF_2	18.410	-	16.337	22.5
	2	-68.68	-	-	25.422	16.029	22.5
Central Obscuration	-	-	-	-	-	1.959	-
Stop	-	-	-	-	140.04	12.871	-
Lens 4	1	-193.2	BaF_2	18.622	-	34.924	43
	2	-27.42	-	-	2.357	37.106	43
Lens 5	1	-25.35	CaF_2	20.0	-	35.703	45.5
	2	-31.48	-	-	7.0	39.371	45.5
Lens 6	1	-31.9	BaF_2	20.0	-	38.901	50
	2	-60.53	-	-	27	43.595	50
Mirror ($X_{rot}=45^\circ$)	-	Infinity	glass	-	155	53.718	56
Mirror ($Y_{rot}=90^\circ$) ($Z_{rot}=45^\circ$)	-	Infinity	glass	-	43	44.672	47
Focal Plane	-	-	-	-	-	33.363	-

Figure 13 shows spots at the slit once the design has been attached to the front end of NIRSPEC. The wavelengths are the same as in Figure 10. Since the front end of NIRSPEC is not rotationally symmetric more field points are required to adequately characterize the performance. The field points used are shown in Figure 11. Figure 14 is the same as Figure 12 but now it is at the slit focal plane and plots are shown for four image rotator positions. The diffraction limit is shown for reference. The performance is similar to that at the calibration unit focus although it changes somewhat with rotator position. As expected the field points in the corners of the SCAM FOV have poor performance since they were given zero weight. Several intermediate field points for a few wavelengths were also checked to make sure that nothing unexpected happened across the field.

Figure 15 shows full field spot diagram at 2.2 µm at the Lyot stop of NIRSPEC when the calibration unit is attached to the front end. The blur at this wavelength is 2.4%. Figure 16 shows a similar plot at the same wavelength for Keck plus NIRSPEC. Figure 17 shows the blur caused by the calibration unit as a function of wavelength. The blur of the calibration unit is comparable to that of Keck plus NIRSPEC from 1.0 - 2.2 µm after which it starts to increase considerably. Figure 18 shows wavelengths from 1.0 to 2.5 µm on the same plot. The size of the pupil actually changes with wavelength causing the ray bundles to have a spread in radius. A plot of the percent difference in diameter from that of Keck plus NIRSPEC is shown in Figure 19. The difference is $< 0.5\%$ out to 2.8 µm. The spatial uniformity of the calibration system for CGS IV is 99.5%. Calculation of this quantity for the NIRSPEC calibration unit gives $U = 99.63\%$ ($NA = 0.0858$).

A bid package for both sections of the optical design was sent to Janos Technology and to ISP (International Scientific Products). We have decided to place the order with ISP since the service we received from them was much better and the price was approximately one third of

The calibration unit will be located in front of NIRSPEC so that it can feed its beam into the spectrometer. The telescope bearing, AO bench, and guider camera all place constraints on the location of the calibration unit. There is also limited space for power supplies.

Figure 21(need updated figure) shows the proposed layout of the calibration unit and guider optics. The light from the telescope goes into the page and hits the first guider mirror which has a hole in it (on the right hand side in the figure). For observations light travels from the telescope, through the hole in the guide mirror, and into NIRSPEC. During calibrations the turning mirror blocks the light from the telescope and sends light from the lamps into the instrument. A mask will need to be placed around the slide mirror to insure that no light from the telescope gets into the instrument during calibrations. Figure 22(need updated figure) is an angled view that shows the area behind the guider mirror.

The calibration system itself is located above the guide system. One QTH lamp will located on the right, almost directly above the first guide mirror. Light travels right to left, through the etalon and into the integrating sphere by way of a flat mirror. The other QTH lamp and the noble gas discharge lamps will be to the left of the integrating sphere (they aren't shown in the drawing). After the integrating sphere the light path is from left to right. A folding flat sends the beam down toward the optical axis of the NIRSPEC instrument and a turning flat sends the light through the window. The turning flat will slide down behind the guide mirror when it is not needed. The focal plane is quite close to the wall of the vacuum enclosure and if the optical axis of section 2 is in the same plane there is not enough room for the integrating sphere. It will bump into the dewar. Therefore it will not be coplanar with the focal plane and the two flats will not be at 45°.

Figure 23 shows the front wall of the NIRSPEC vacuum chamber with a box representing the calibration/guider enclosure. The optical axis of the instrument is shown for reference. NIRSPEC will usually look directly into the telescope from the right Nasmyth platform which it will share with DEIMOS. The calibration unit is also constrained by the AO bench since NIRSPEC can also be used with AO when it becomes available. Figure 24 shows the boundary of the AO bench. There is a one inch gap between the edge of the AO bench and the calibration unit box. Some of this space will probably be take up by the planned enclosure for the AO bench and insulation. The telescope bearing also places a constraint on the size and shape of the calibration/guider unit enclosure (Figure).

There are four power supplies required for the noble gas discharge lamps and one for the QTH lamps. The QTH power supply is 6.5″ x 5.12″ x 3.44″. The dimensions for the arc lamp power supplies from Oriel are 6.5″ x 3.75″ x 2.5″. All of the power supplies for the calibration unit will be housed in the electronics cabinet for NIRSPEC that will be located underneath the instrument.

9.0 Mechanical Design

[show figure of overall mechanical design and discuss]

9.1 Mounting

9.1.1 Components (etalon,sphere,lamps,fans)

Mounting of the components in the calibration unit will be to an external optical plate that will also be used by the guide system. The lenses will be mounted using spring fingers as shown in Figure 27. This is the standard lens mount used in the lab and has been successful in the past. The fingers keep the lenses centered on the axis as changes in temperature cause the mount to expand or contract. Because they are springy, the fingers hold the lens without crushing it. This concept is essential for lenses used in cryogenic temperatures but will also benefit the calibration unit since the temperature difference between the lab and the mountain will be quite large (20°C). These mounts lend themselves to a tube shaped housing that also supports the baffles. The small glass mirrors will be held in kinematic mounts that constrain the degrees of freedom that the mirror can have. Peelable shims will be used in alignment of the mirror. The mirror mount concept is shown in Figure 28.

9.1.2 Plate and Enclosure

Mounting of the external optical plate itself is an important issue. Ideally the mount would be constructed in such a way that the calibration/guider unit could be in place (and operable) even if the NIRSPEC vacuum enclosure is removed (e.g. for alignment in the lab). Therefore the optical plate should be mounted to the NIRSPEC bottom cover plate so that it is independent of the vacuum chamber. The external optical plate should always go back to the same place so that once the components mounted to the plate are aligned, they stay that way even though the unit is taken on and off many times. Triangular supports will be bolted to the outside edge of the bottom cover plate, one on each side, and will also be pinned so that they go back to the same place. The NIRSPEC cover plate will need to have clearance holes to accept the pins and screw holes for mounting of the brackets while the brackets will need to have clearance holes for mounting to the cover plate. The brackets should be stood off from the cover plate so that they keep clear of the flange on the NIRSPEC dewar. Along the long side of the triangle there will be an angle bracket where the external optical plate will bolt onto. This bracket will have pins that guide the plate back to the same position each time it is taken on and off as well as clearance holes for bolting on the plate. A gasket will provide the seal between the plate and the NIRSPEC dewar wall. The triangle brackets will have to be thick (1/2″) and extend back far enough and up high enough so that the plate doesn't tip forward. An estimate should be made of the weights of the components, external optical plate, and the enclosure. The triangle brackets could have a hole cut out of the center to make them lighter and would then look something like a draftsman's angle. The unit enclosure will have a flange around the edge for mounting to the external optical plate. It will be bolted on as well as positioned by pins located on the optical plate. Another gasket or open cell foam will provide the seal to the plate.

9.2 Baffling

9.3 Mechanisms

At least two mechanisms are required in the calibration unit. One is a pinhole that can be move into the beam at the exit port of the integrating sphere. Since only two positions are required (pinhole or no pinhole) it lends itself to being a slide mechanism. The position of the pinhole with respect to the optical axis of the system will need to be very repeatable in order to calibrate the slit location on the array. More thought must be given to the repeatability requirement. Figure 29 shows the slide mechanism that is being considered.

The other mechanism required is a mirror that moves into the beam for calibration but is out of the way for observations. As mentioned above, the best place for it seems to be on a slide behind the first guider mirror. The mirror will be mounted on two rails on which it will slide up and down. Again a stepper motor system such as is already in use in the lab would be suitable. The requirements on repeatability will also be high for this mechanism since the system must simulate the telescope as closely as possible.

9.4 Optical Plate

The optical plate will be 1/2″ thick aluminum. It must have holes in it to accomodate the flat guider mirror, the elliptical reflectors for the lamps, and the turning mirror slide mechanism. There will be foam or gasket material around these holes to provide the seal to the dewar wall. It will have pins in the four corners that are 3/8″ to 1/2″ diameter for positioning of the enclosure. The pins must be long enough so that the enclosure completely clears all of the optics before it is clear of the pins. There will be a screw hole pattern around the edge of the plate where the flange on the enclosure will bolt to. It must also have holes in the rear to accept positioning pins from the triangle mounting brackets as well as screw holes for mounting to the bracket. There should be 1/8″ gasket on the back of the plate at the location of the edge of the dewar wall as well as around the edges of the holes cut in the plate. This space must be accounted for in the design and thickness of the plate to make sure that the calibration unit and guider are in the correct position with respect to the telescope focal plane.

9.5 Enclosure

The enclosure will not be a simple rectangular box so that it will stay clear of the telescope bearing. One of the corners will be cut as shown in the figure. The box should be thick enough so it is sturdy enough to mount the fans and provide protection to the components but it should also not be too heavy for ease of handling. It will be made of 1/16″ aluminum and will probably be black anodized to match the dewar. It can be constructed by using angle brackets that bolt the pieces together or by tack welding the joints. The wall inside the box separating the two sections will also be put together one of these two ways. There will be a flange around the outside of the box with clearance holes for bolting the enclosure to the external optical plate. There may be a square groove with gasket material for sealing to the plate, similar to an o-ring. Tubes will be mounted to the inside top and bottom corners of the box to accept pins on the optical plate. The tubes should be long enough to prevent the box from tipping as it is maneuvered into place. The inside of the box will have a layer of insulation to prevent heat loss through the walls. One side of the box will have two filtered fans that draw in ambient air while the other side will have a hose to duct the heat to the back of the instrument.

Some items requiring electrical connections will be mounted to the inside of the enclosure. These are the fans, temperature sensors, solenoid, and a limit switch for the aperture cover. These will simply connect to connectors on the outside of the box for cables from the electronics cabinet to plug into. Other components requiring electrical connections will be mounted directly to the external optical plate. These are the motors and switches for the slide mechanisms and the lamps (QTH #1, QTH #2, arcs, and spare arcs). These must be able to operate both when the calibration/guider unit enclosure is mounted as well as when it is not in place. The wires and connectors must not get in the way when the enclosure is being mounted or taken off. One way to do this is to have a piece cut out of the enclosure that slides over the edges of a panel mounted to the optical plate at right angles to it containing the connectors for items mounted to the plate. The cutout will need to have foam around it to make a seal, either on the enclosure or on the panel. A separate piece of metal, again with foam to make a seal, could then be bolted on to close off the gap created by the cutout. The enclosure may also have grooves on the inside to guide the bundles of wires from a component to the appropriate connector or they could just be taped to the wall.

As mentioned earlier, there will be a wall inside the enclosure that separates the "warm" section from the "cool" section. This wall will not go straight across the box but will have some convoluted shape. It will start between the two filtered fans on the side of the box near the arc lamps and go across towards the integrating sphere. There will be a piece cut out for the light from the QTH lamp. The wall will bend upwards for a small distance and then continue across the box and will have another cutout to clear the top of the integrating sphere. It will continue straight across but may come down some at the other end of the box to provide more room for the hose that will carry the warm air away. If all of the electrical connectors for items mounted to the plate are in one location (the panel mounted to the plate), the wall may need to have holes in it for the wires to feed through. At these holes there should be some insulation or something else to plug the hole around the wires to prevent airflow between the sections through these holes.

10.0 Operation

10.1 When to calibrate

Optical calibration must be done each time the optical setup is changed. If the internal mechanisms meet their repeatability goals all optical calibration measurements can be made before astronomical observations, for example during the day. This will allow full use of the pipeline data reduction system.

The flat field must be measured for each combination of the following:

slit width
slit height
image rotator position
blocking filter
echelle angle
cross disperser angle

Absolute wavelength calibration can be done during the day with the noble gas discharge lamps and/or at night using airglow emission lines or atmospheric absorption lines and must be done for each astronomical window that will be observed. Relative wavelength calibration must also be done for each wavelength region. The slit location and slit tilt must be measured for each combination of grating angles.

10.2 Integration times

The time necessary to perform the required calibrations must be reasonable. Therefore we should calculate the integration times for the various calibration unit modes.

$$L = A\sigma T^4 = \pi I A \qquad \Rightarrow \qquad I = \frac{L}{\pi A}$$

The flux (in cgs units) is

$$F = I(A\Omega) = \frac{L}{\pi A_l}(A\Omega) \text{ ergs/sec}$$

where L is the luminosity of the lamp, A_l is the area of the integrating sphere output port, and $(A\Omega)$ is a constant for the system. This can be converted to flux per pixel since the resolution is 25,000 and there are two pixels per resolution element (slit width).

$$F = \frac{L}{\pi A_l}(A\Omega)\frac{1}{50{,}000} \text{ ergs/sec/pixel}$$

Using the energy of a photon to convert to photons/sec/pixel

$$F = \frac{L}{\pi A_l}(A\Omega)\left(2\times 10^{-5}\right)\frac{\lambda}{hc} \text{ photons/sec/pixel}$$

We can calculate $(A\Omega)$ since we know the size of a pixel at the focal plane and the F/# at the focal plane.

$$(A\Omega) = x^2\pi\frac{1}{(2\cdot F/\#)^2} = (0.01455\text{cm})^2\pi\frac{1}{4(15)^2}$$

The diameter of the integrating sphere output port is 12.7 mm giving

$$F = \left(1.87\times 10^4\right)L\lambda \text{ photons/sec/pixel}$$

Full well for the pixels is $2\text{x}10^5$ electrons, so the integration time to full well is

$$t(\text{sec}) = \frac{1.0697\times10^{-2}}{\lambda(\mu\text{m})L(\text{W})\tau}$$

τ is the throughput for the mode being considered (including the quantum efficiency of the detector). t turns out to be on the order of 20 sec for most modes. The time for absolute wavelength calibration is only 4 sec. The integration times for the various modes are given in Table 5 and all seem reasonable. The times given are to reach full well while in practice integration times will be shorter to avoid any nonlinear region of the array.

Table 5. Integration times.

Mode	Elements	L (W)	λ (μm)	τ	t (sec)
flat fielding	reflector, QTH lamp, sphere, Section 2, NIRSPEC	100	2.2	$2.3\text{x}10^{-6}$	21.1
relative wavelength, slit tilt	reflector, QTH lamp, pinhole, etalon, Section 1, sphere, Section 2, NIRSPEC	100	2.2	$1.76\text{x}10^{-6}$	27.6
absolute wavelength	reflector, arc lamps, sphere, Section 2, NIRSPEC	8.6	2.2	$2.3\text{x}10^{-6}$	4
slit location, dispersion direction	reflector, QTH lamp, sphere, pinhole, Section 2, NIRSPEC	100	2.2	$2.2\text{x}10^{-6}$	21.9

11.0 Thermal Issues

Since the total heat output from NIRSPEC is limited to 50 W, the heat output into the environment from the calibration unit must be minimal (and certainly cannot be 100 W from the QTH lamp). There are two primary sources of heat in the calibration unit. The power supplies, required to run the QTH lamps and arc lamps, produce heat, the one for the QTH lamp produces 50 W while the ones for the arc lamps produce about 10 mW each. The power supplies will be housed in the electronics enclosure that will be located underneath NIRSPEC. The cooling system for the cabinet is a glycol/water based unit. The cabinet will also be insulated to minimize heat loss into the environment and will be temperature monitored (see the appropriate electronics design note). The 100 W QTH lamps are not very efficient. Approximately 80 - 90 W is heat. The arc lamps combined produce about 4.3 W of heat.

We must look at what we require the system to do and what we have available. Following is a list describing different aspects of the system:

(1) Heat load from one QTH lamp is 95 W.

(2) We have 30/70 ethylene glycol and water mixture (EGW) available at 1 gpm.

(3) Temperature of the EGW is about 0°C.

what Janos quoted. We requested anti-reflection coatings for 1.0 - 4.0 μm. ISP sent us plots of the calculated relectivity for their coating on LiF, BaF_2, and CaF_2 (Figure 20).

7.0 Throughput

The throughput of the system depends on which mode the calibration unit is being used in. One mode (for relative wavelength calibration and slit tilt) includes Section 1, the integrating sphere, Section 2, and NIRSPEC. The other two modes include the sphere, Section 2, and NIRSPEC. Therefore we should determine the throughputs of the etalon, the integrating sphere, and the two sections of optics.

The throughput of the integrating sphere is given by (Labsphere catalog)

$$\tau = f_e M$$

where f_e is the fractional surface area of the sphere taken up by the detector and M is a multiplication factor given by

$$M = \frac{\rho}{1-\rho\left(1-f_j\right)}$$

where ρ is the integrating sphere wall reflectance and f_j is the fractional surface area of all the ports. The 4″ general purpose integrating sphere from Labsphere has three 1.0″ diameter input ports (we'll only use two) and a 0.5″ output port. The reflectivity of Infragold at 2.2 μm is 0.963. These values give a throughput of 5.3%.

The Section 1 optics consist of two doublets (8 lens surfaces) and one mirror in addition to the etalon. The lenses will be anti-reflection coated as discussed above. We will assume a transmission of 98% for each surface. For the gold coated mirrors we will estimate a reflectance of 98%. There will also be lightloss at the pinhole ($\ell\ell_p$). The fractional lightloss will just be the area of the pinhole divided by the area of the image of the filament at the pinhole.

$$\ell\ell_p = \frac{\pi\left(\frac{\theta F_2 d_{IS}}{4}\right)^2}{\pi\left(\frac{r_f F_2}{F_1}\right)^2}$$

which reduces to

$$\ell\ell_p = \left(\frac{\theta d_{IS} F_1}{4 r_f}\right)^2$$

Here θ is as in Section 6.1.1, F_1 is the object space *F/#*, F_2 is the *F/#* after the first doublet, d_{IS} is the clear aperture of the integrating sphere input port, and r_f is the radius of the filament. For our case this gives a throughput at the pinhole of 96.6%. Thus Section 1, including the etalon and pinhole, has a throughput of 76.5%.

Section 2 uses two triplets to create the *F*/15 beam as well as two mirrors to send the beam into NIRSPEC. The path then has 12 lens surfaces and two mirrors. Assuming the same transmission values for the lenses and mirrors as above, Section 2 has a throughput of 75.4%.

There will also be light loss because not all of the light will be collected from the lamps. For an example let's look at the QTH lamp for Section 1. The minimum light loss due to the fractional solid angle intercepted by F_1 is

$$\ell\ell_{\Omega} = \frac{\dfrac{\pi}{4F_1^2}}{4\pi} = \frac{1}{16F_1^2}$$

This is 1.6 x 10^{-4} for the above example. A reflective assembly behind the lamp can help with a factor of two.

It is estimated that the efficiency of NIRSPEC (including detector quantum efficiency) will be 30% in the high resolution mode (from the CDR document). With the above calculations we can compute the throughput for each mode of the calibration unit (Table 4).

Table 4. Throughput of Calibration Unit by mode.

Mode	Elements	Throughput (hi-res mode)
flat fielding	reflector, QTH lamp, sphere, Section 2, NIRSPEC	$2.3\text{x}10^{-6}$
relative wavelength, slit tilt	reflector, QTH lamp, pinhole, etalon, Section 1, sphere, Section 2, NIRSPEC	$1.76\text{x}10^{-6}$
absolute wavelength	reflector, arc lamps, sphere, Section 2, NIRSPEC	$2.3\text{x}10^{-6}$
slit location, dispersion direction	reflector, QTH lamp, sphere, pinhole, Section 2, NIRSPEC	$2.2\text{x}10^{-6}$

8.0 Space Constraints

(4) The system cannot be closed loop because we require openings for the light path of the optical system..

(5) The size of the enclosure is approximately Height=20.5 in, Width=46.5 in, Depth=10.5 in

(6) Space available for mounting is about 9 in square.

(7) We plan some type of insulation for the enclosure.

(8) The system must work both in the lab and at the telescope, although it is only at the telescope that we are worried about the heat released into the environment.

(9) The lab is essentially at sea level and the typical ambient air temperature is 20°C.

(10) The telescope is at 14,000 ft and the typical ambient air temperature will be 0°C.

The Figure shows the initial design concept for the cooling system that was shown at CDR. The part of the enclosure with the QTH lamps (the 'warm' section) will be separated from the rest of the unit (the 'cool' section) by a wall. Ambient air will be drawn into the warm section by a fan and will flow past the QTH lamp on the left. Another fan near the other QTH lamp will keep air circulating near it. The warm air will be drawn into the radiator and cooled by the glycol mixture that is also used by the electronics cabinets so that the air released into the environment will be close to or cooler than ambient. The wall that separates the warm section from the cool section will need to have two holes in it for light paths. To prevent the warm air from leaking back into the cool section through these holes there will be air forced from the cool section into the warm section. This will be done by placing another fan in the cool section that draws in ambient air. The air will leave this section through the holes in the separator wall and through the main opening of the enclosure. The fans in the cooling system will be mounted in such a way as to vibrationally isolate them from the rest of the calibration unit/guider system.

As of CDR detailed calculations had not been done for the system described above. We need to look at whether this is a feasible idea. We can do some calculations to determine what kind of heat exchanger we will need. They are characterized by performance capability

$$PC = \frac{Q}{ITD}$$

Here Q is the heat load on the coolant (BTU/hr), ITD is the initial temperature difference between the warmed air and the coolant (°F) and PC is in BTU/(hr °F). Q can be determined from the heat transfer equation giving

$$PC = \frac{\dot{m}_{EGW} \, C_{p,EGW} \left(T_{warm} - T_{air,out} \right)}{T_{warm} - T_{EGW}}$$

where $\dot{m}_{EGW}$ is the mass flow rate (lb/hr) of the coolant, C_p is the specific heat of the fluid (BTU/(lb °F)), T_{warm} is the temperature of the warmed air, $T_{air,out}$ is the temperature of the air released into the environment, and T_{EGW} is the temperature of the ethylene glycol/water mixture. $\dot{m}$ for water and air is given by

$$\dot{m}_{wat} = 8.04\,\dot{v}(\text{gpm})\rho\left(\frac{\text{lb}}{\text{ft}^3}\right)$$

$$\dot{m}_{air} = 60\,\dot{v}(\text{cfm})\rho\left(\frac{\text{lb}}{\text{ft}^3}\right)$$

where v& is the flow rate (in gallons per minute and cubic feet per minute) and ρ is the density of the fluid. The remaining variable is the temperature of the warm air. This can be calculated using the heat transfer equation as the air flows past the lamps.

$$T_{warm} = \frac{Q_{lamp}}{\dot{m}_{air}\,C_{P,air}} + T_{amb}$$

Putting everything together we have finally

$$PC = \frac{8.04\,\dot{v}_{EGW}\,\rho_{EGW}C_{P,EGW}\left[\dfrac{Q_{lamp}}{60\,\dot{v}_{air}\,\rho_{air}C_{P,air}} + T_{amb} - T_{air,out}\right]}{\left[\dfrac{Q_{lamp}}{60\,\dot{v}_{air}\,\rho_{air}C_{P,air}} + T_{amb} - T_{EGW}\right]}$$

with $\dot{v}_{EGW} = 1$ gpm
$\rho_{EGW} = 65.6$ lb/ft^3 (40/60 mixture)
$C_{P,EGW} = 0.84$ BTU/(lb °F) (40/60 mixture)
$Q_{lamp} = 95$ W $= 324.14$ BTU/hr
$\rho_{air} = 0.04838$ lb/ft^3 (at Mauna Kea)
$C_{P,air} = 0.24$ BTU/(lb °F) (at room temperature)
$T_{amb} = 32$ °F
$T_{EGW} = 32$ °F

and the free parameters are

$\dot{v}_{air}$ (flow rate of the air due to the fans)

$T_{air,out}$ (temperature of the air released into the environment)

Lytron has been contacted about our cooling needs. They think that a heat exchanger is the wrong way to go because the air is not warmed very much by the lamps. In their minds a heat exchanger is overkill and the cooling could simply be done by a fan. The temperature is raised from ambient by

$$\Delta T(^\circ\mathrm{F}) = \frac{Q_{lamp}}{60\,\dot{v}_{air}\,\rho_{air} C_{P,air}} = \frac{465.269}{\dot{v}_{air}(\mathrm{cfm})}$$

Peter Wisinovich was contacted to see if he had a problem with this. At NIRSPEC project meeting #21 it was decided to use fans to cool the lamps and to duct the warm air to the back of the instrument. The hose that is used should be insulated to prevent it from being a heat source.

12.0 Dust and Foreign Objects

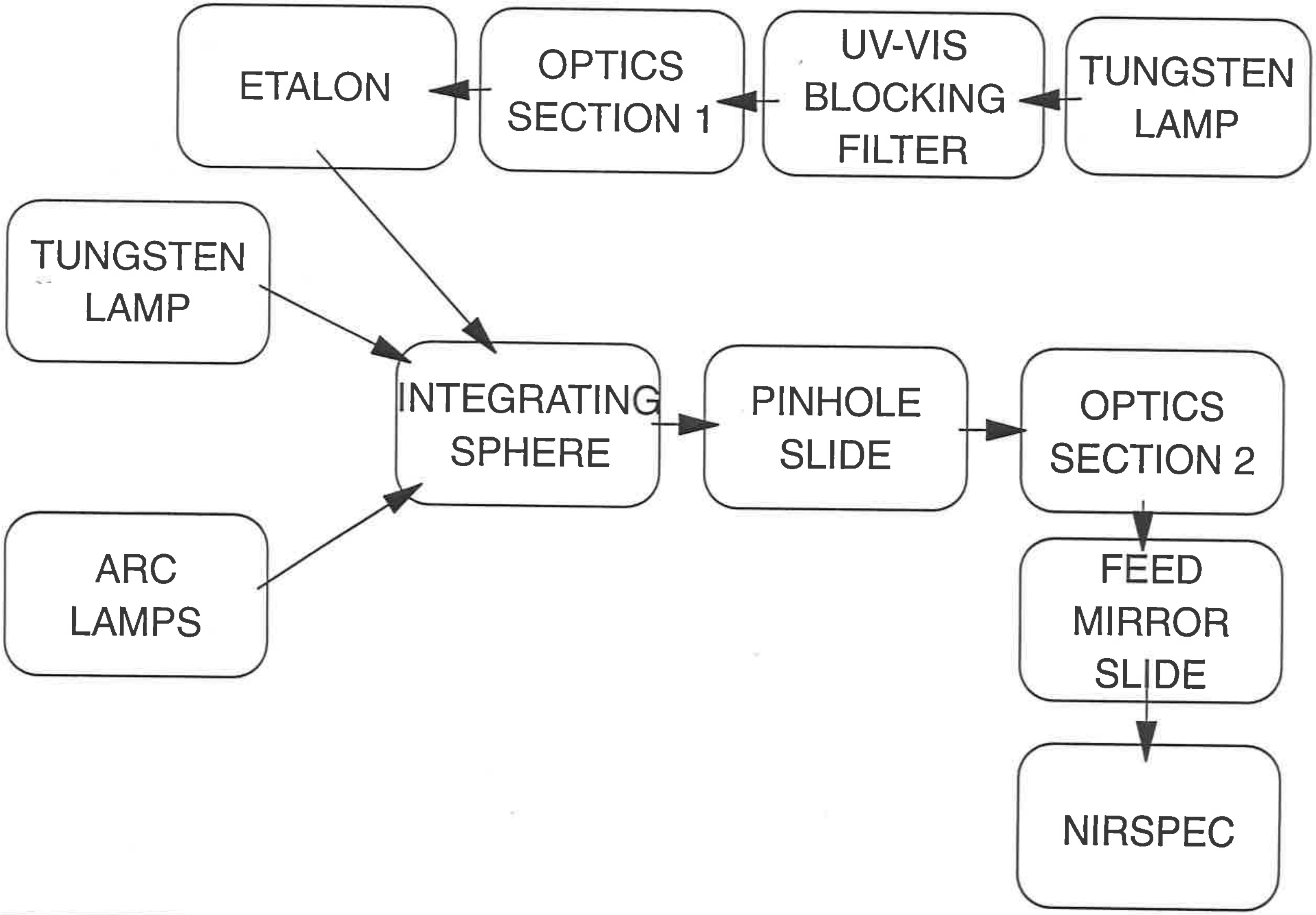
Mauna Kea is a dusty environment requiring that care be taken to keep optical elements clean and free of dust. Required maintenance by the staff at the telescope should be kept to a minimum. The enclosure surrounding the calibration unit and guider mirror system will be the major source of protection. The only opening will be the hole that allows the light from the telescope to enter the system. The cooling system causes a flow of air out of the unit through this opening. This is beneficial in that it will keep dust from drifting into the enclosure through the opening. The fans that draw air into the enclosure will be equipped with filters to remove dust from the air before it comes in contact with any optical surfaces. In addition, lenses will be mounted in lens tubes offering another layer of protection.

As recommended by the CDR committee, the opening to the enclosure should have a cover that prevents objects from entering the box when it is being moved, aligned, etc. Two important requirements for the cover are that it should be accessible when the instrument is in place and one should be able to tell from the control room whether it is open or closed. One convenient way to do this is to have it mechanized and controlled by the NIRSPEC software. A disk slightly larger than the opening with a tab on it could be pulled and pushed by a solenoid pivoting about a point on the tab so as to move across the aperture out of the way (Figure). A magnetically latching solenoid does not require power to hold its position so a pulse could be sent to either open or close the cover.

Calibration Unit: Modes

- Flat field: QTH + sphere
- Absolute wavelength: arc lamps + sphere
- Relative wavelength: QTH + etalon + sphere
- Slit location: QTH + sphere + pinhole
- Dispersion direction: QTH + sphere + pinhole
- Slit Tilt: QTH + etalon + sphere

Calibration Unit Block Diagram



TUNGSTEN LAMP

UV-VIS BLOCKING FILTER

OPTICS SECTION 1

ETALON

TUNGSTEN LAMP

ARC LAMPS

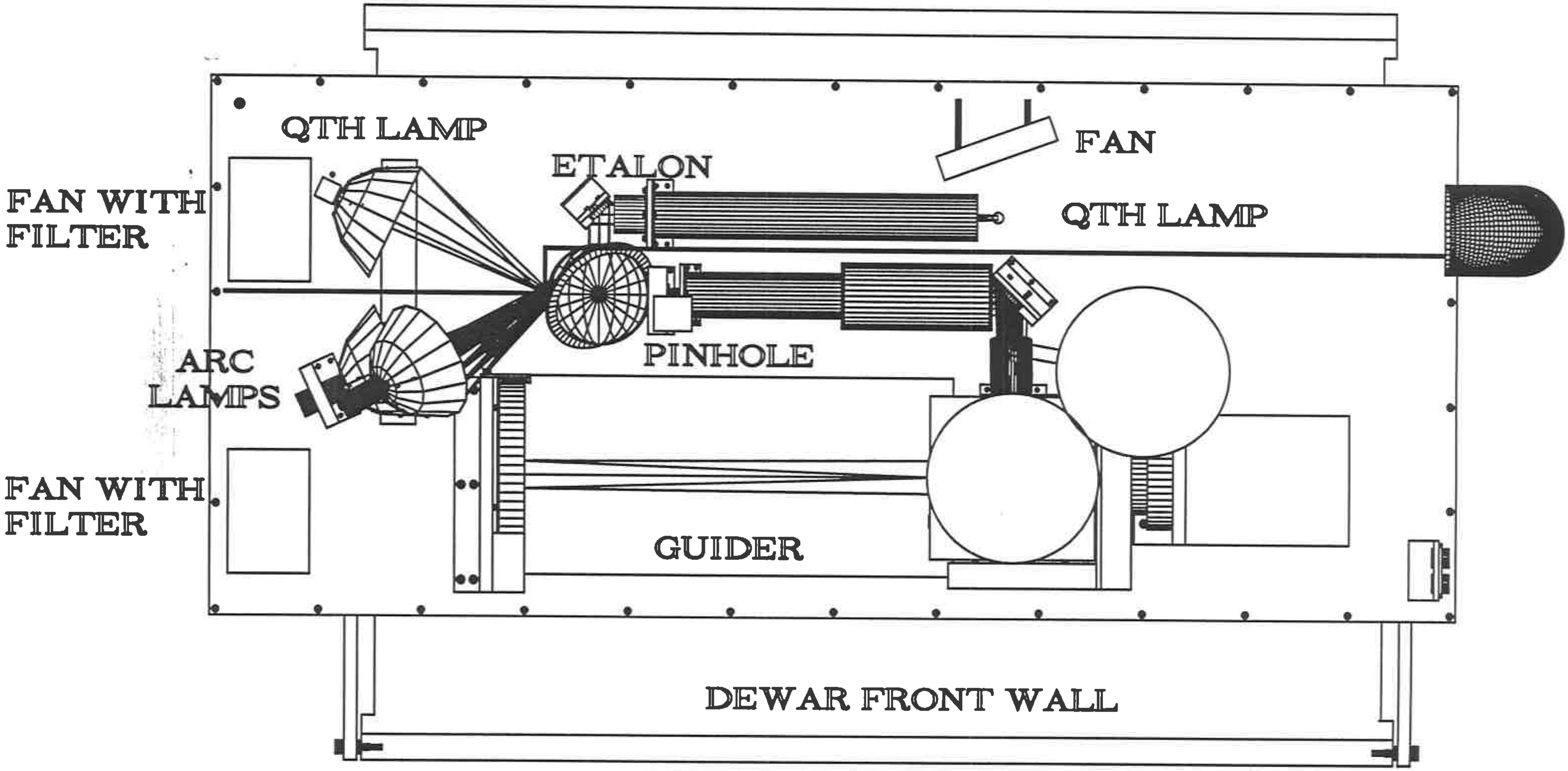
INTEGRATING SPHERE

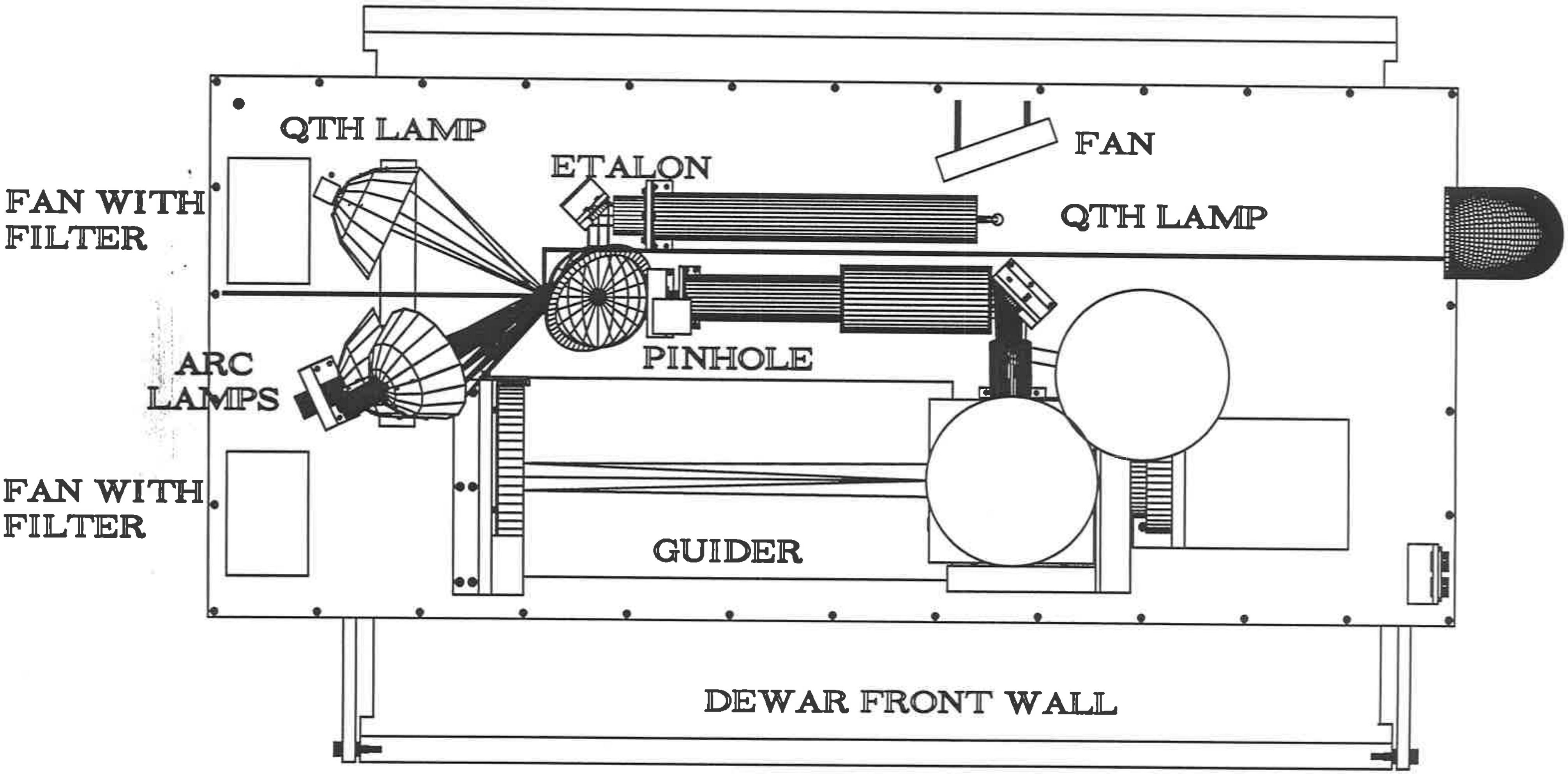
PINHOLE SLIDE

OPTICS SECTION 2

FEED MIRROR SLIDE

NIRSPEC


QTH LAMP
ETALON
FAN
QTH LAMP
FAN WITH FILTER
ARC LAMPS
PINHOLE
FAN WITH FILTER
GUIDER
DEWAR FRONT WALL


QTH LAMP
ETALON
FAN
QTH LAMP
FAN WITH FILTER
ARC LAMPS
PINHOLE
FAN WITH FILTER
GUIDER
DEWAR FRONT WALL

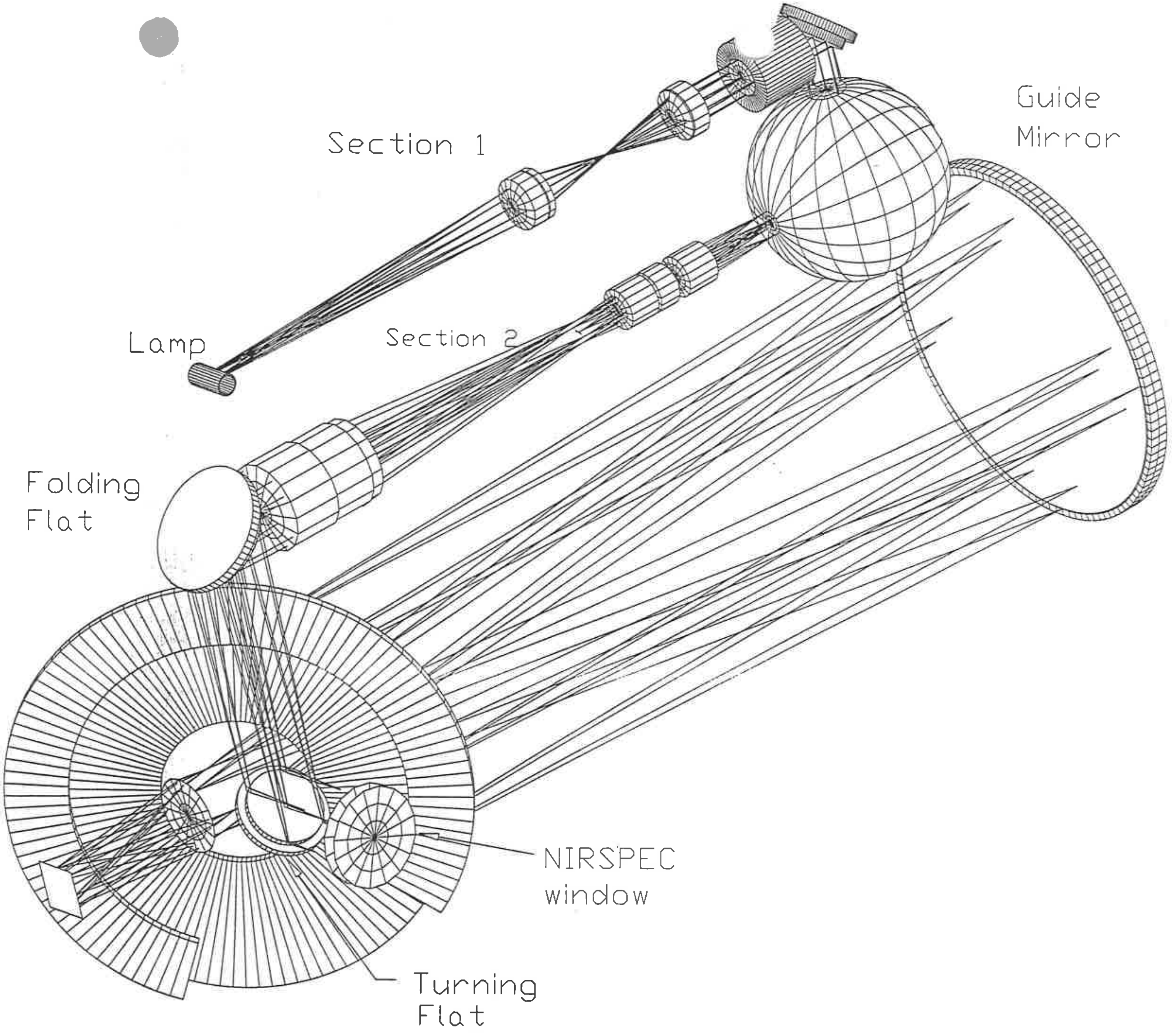


Figure 24. Proposed layout of the calibration unit with relation to the guider system and NIRSPEC. (angled view from back)

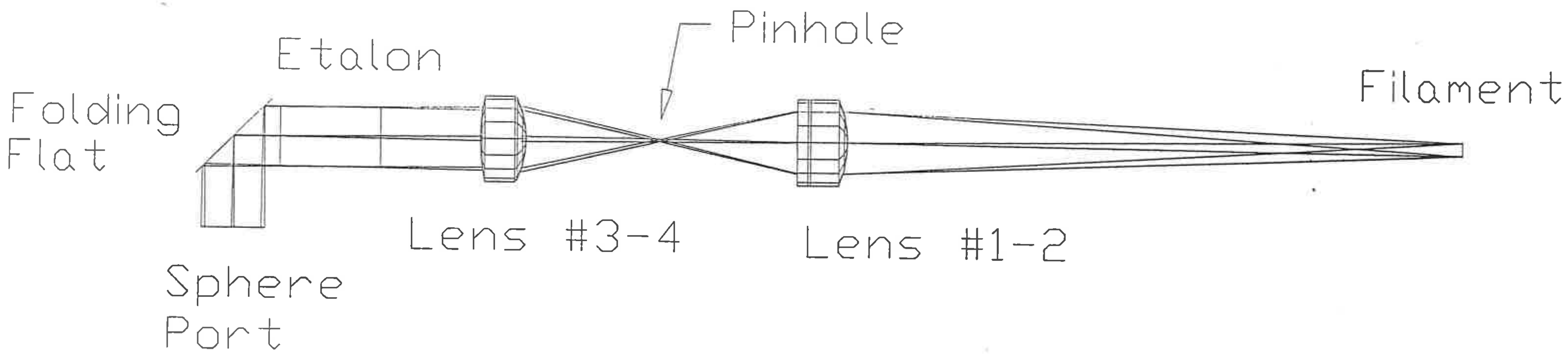


Figure 11. Optical path of Section 1. Rays travel primarily from right to left.