NIRSPEC

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NIRSPEC Optics Design Note 4.00
Calibration Unit

Introduction

Calibration 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)

A calibration unit that will be attached to the front of NIRSPEC will be used for internal optical calibration and is the focus of the design note.

Requirements

The calibration unit must provide for the following types of calibration: flat fielding, absolute wavelength calibration, relative 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 and it must have some way to feed the beam into NIRSPEC while remaining out of the way during observations.

Flat Fielding

Flat fielding requires a source that is relatively flat across each window and is uniform in intensity spatially. An integrating sphere will be used to provide light that is uniform and Lambertian (the intensity is independent of direction). The light enters an input port and bounces around off of a highly reflective surface. By the time the light reaches the exit port of the integrating sphere it has lost all memory of direction and polarization. Labsphere offers many choices in integrating spheres. A 4" diameter general purpose sphere with Infragold coating is suitable (Labsphere p. 93). The integrating sphere will be illuminated with a quartz tungsten halogen lamp. These are offered by Oriel (Vol. II, p. 40).

Wavelength Calibration

Absolute calibration is needed for each order. Many lines per order are required to calibrate any non-linearity in wavelength. A reasonable number is ten lines per order. Noble gas discharge lamps are one source of absolute calibration. They produce narrow lines at well defined wavelengths. Standard lamps are Ne, Ar, Kr, and Xe. They come in a pencil style which is convenient for this kind of application (Oriel Vol II, p. 30). However, these lamps in combination do not give enough lines per echelle order. The free spectral range of the echelle grating is given by

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

where λ is the central wavelength and m_e is the echelle order. For 2.2 µm the FSR = 0.0.04 µm for $m_e = 55$. This is right for an echelle with approximately 15 lines per mm. The above lamps only provide 34 bright lines from 2.0 to 2.4 µm, therefore on average there will only be 3 lines per order. The noble gas discharge lamps are useful for absolute wavelength calibration but in addition relative wavelength calibration is required.

Illuminating a Fabry-Perot etalon with light from a tungsten lamp is an ideal way to produce 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 of the Fabry-Perot.

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

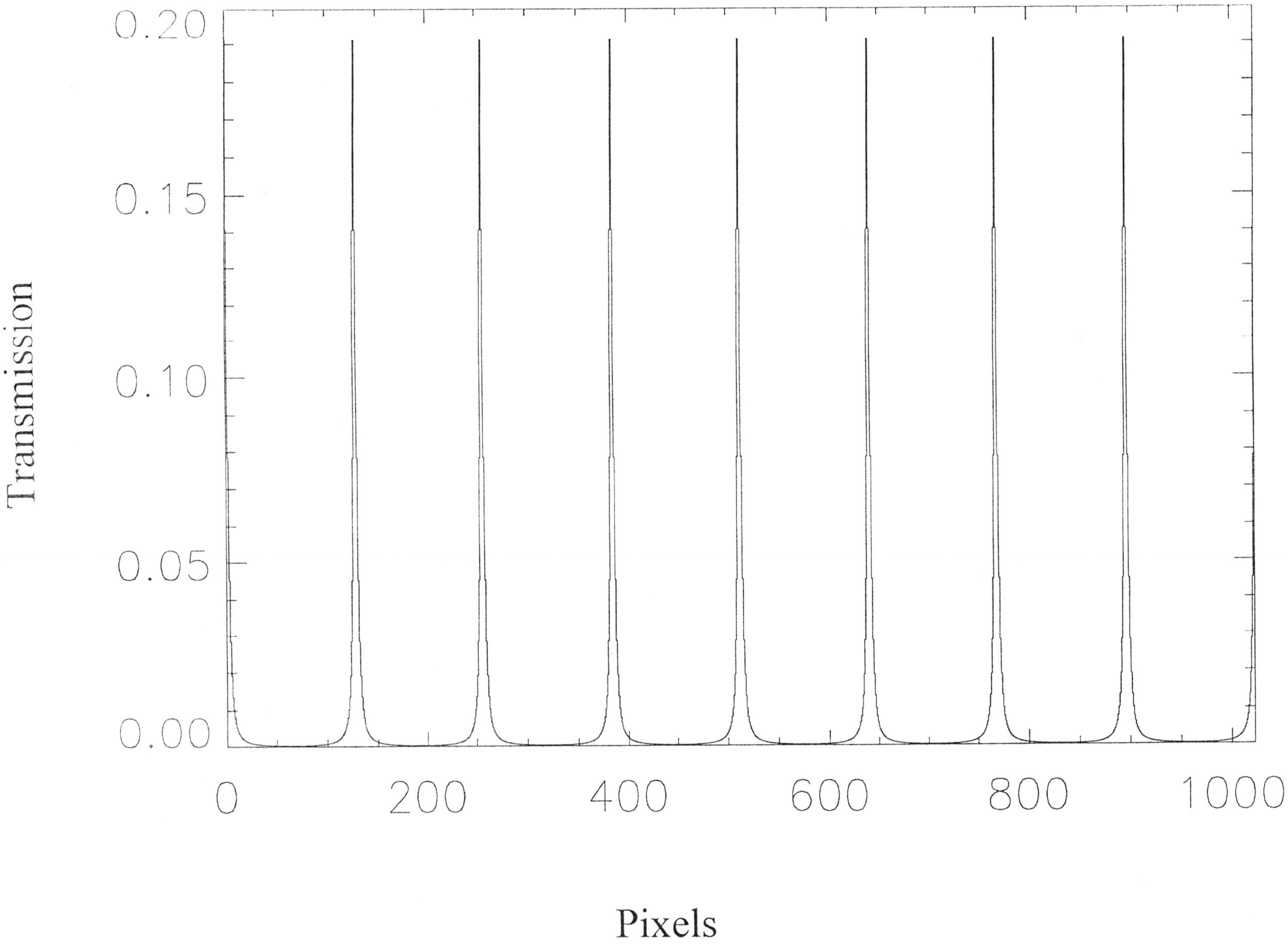
Here d is the separation of the plates. The fringes are evenly spaced in wavenumber but not in wavelength. The fringe pattern on the detector is shown in Figure 1.

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

$$FSR_{FP} = \frac{FSR_e}{10}$$

Etalon Fringes

Finesse = 30, d = 0.5 mm



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. For $\lambda = 2.2$ μm and $m_e = 55$, $d = 0.6$ mm. Melles Griot (p. 13-47)have air spaced etalons with $d = 0.5$ mm and $d = 1.0$ mm. They will need to be contacted to determine the cost of specifying a different spacing.

Scanning Fabry-Perot etalons 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 some system that could measure the separation of the plates very accurately in order to know the exact fringe separation. With a fixed etalon the separation d can be measure once and then the only change in d would be due to temperature variations. A UV-visible light blocker should be used to reduce heating of the etalon in either case. A temperature sensor could be placed near the etalon to calculate the true spacing of the etalon plates.

The spectral resolution of the Fabry-Perot is required to be high enough so that it doesn't degrade the width of the lines. 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 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, $N > 55$.

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 $R > 94.5$ %. Melles Griot offers several coatings for the infrared (p. 5-47) including bare gold which has a reflectivity of > 98% across 1 -5 μm. Protected gold has the same performance, is more durable, and is only slightly more expensive.

Slit Location

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 slit location 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 the pinhole 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.

Dispersion Direction

The dispersion direction will generally be along the rows of the detector. 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 same setup as for determining the slit location (tungsten lamp + integrating sphere + pinhole) can be used. The spectrum of the pinhole will be quite narrow and will define the angle between the rows and the dispersion axis.

Slit Tilt

The images of the slit are tilted and this tilt varies across each order, increasing at 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, one will be able to measure the variation in slit tilt across each order.

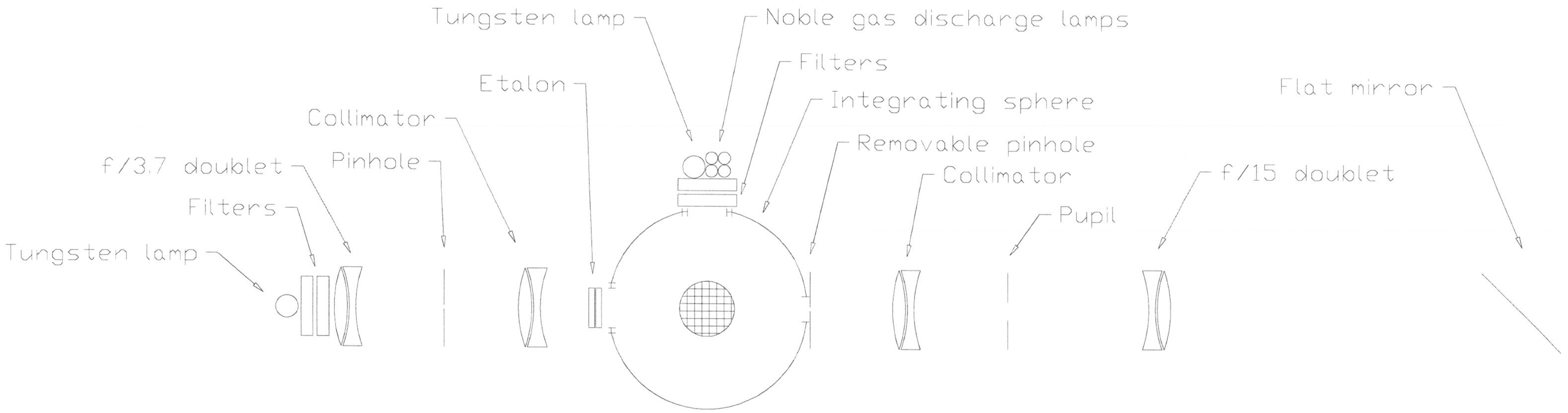
Basic Layout

Figure 2 shows a sketch of the basic layout of the calibration optics. The central feature is an integrating sphere with two input ports and one exit port. One input is for light from a tungsten lamp and etalon. Filters (such as a UV-vis blocker or neutral density filter) could be placed in front of the lamp. The beam must be highly collimated before reaching the etalon. This could be accomplished by 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 would be 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. Again, filters may be placed in front of the lamps. A second tungsten lamps 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 and the integraing 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. If a neutral density filter is required for low resolution mode, it could be placed at this location on a slide with the pinhole.

Calibration Unit



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 (flip or slide) 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 necessary. Depending on the location of the calibration unit there may be an additional flat mirror used to direct the beam into NIRSPEC.

Optical Design

At the time of this draft a detailed analysis of the optical design has not been done. However there can be a discussion of the basic reuirements of the design.

Requirements

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, and any distortions must be similar to those produced by the telescope.

As discussed above, the filament of the tungsten lamp will be imaged onto a pinhole which is at the focus of a collimating lens. The angular size of the pinhole is limited to $\delta\beta$ which is the angular diameter of an axial hole that accepts all the light in the full width at half maximum of the central order.

$$\delta\beta = \left(\frac{8}{R_{FP}}\right)^{1/2}$$

A larger pinhole will degrade the spectral resolution of the Fabry-Perot.

To maximize the light from the lamp the focal ratio of the first lens, F_1, must be as small as possible. The fraction of light collected is $\pi/4F_1^2$. 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 $F_1/3.7$. The minimum light loss due to the fractional solid angle intercepted by F_1 is

$$\frac{d_{IS}^2}{8Rr_f^2}$$

This is 5×10^{-4} for the above example.

Operation

Optical calibration must be done each time the optical setup is changed. Ideally the mechanisms will be very repeatable so that all optical calibration measurements can be made before astronomical observations are made. This will allow full use of the pipeline data reduction system.

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

slit width
slit height
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. The slit location and slit tilt must be measured each combination of grating angles.

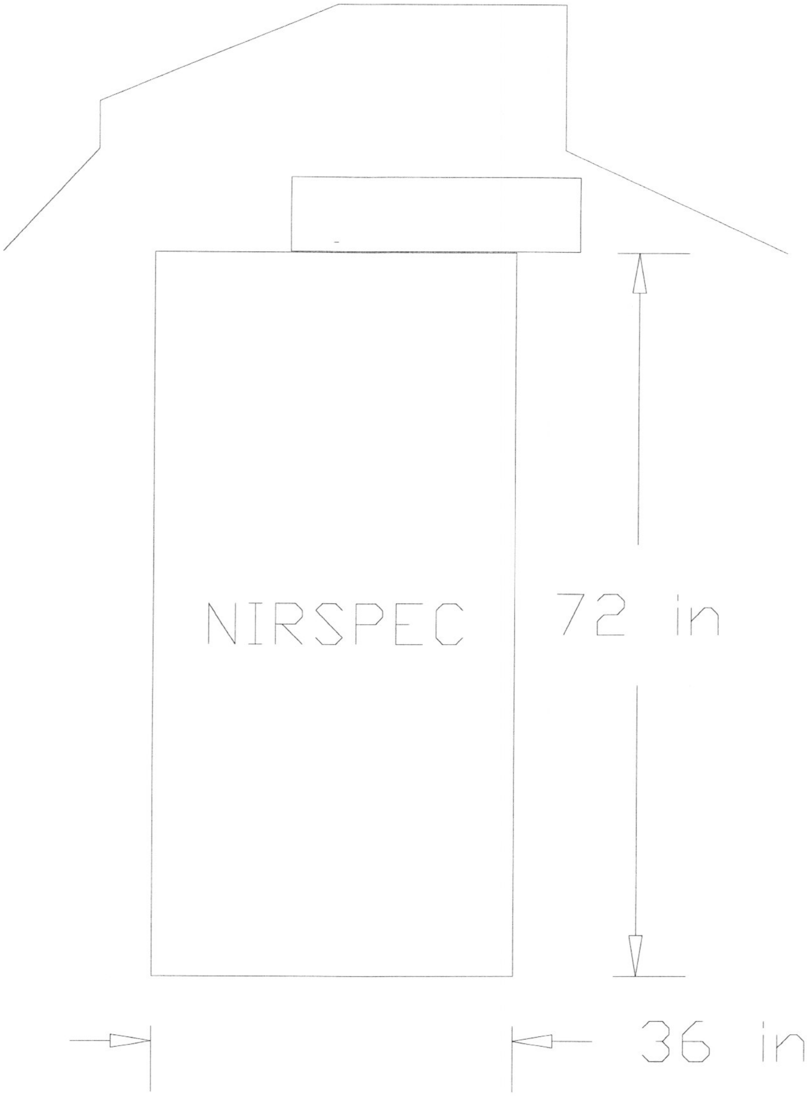
The time that it takes for calibration measurements must be reasonable. This can be estimated from the number of photons produced by the lamps that will be used. A 100 W tungsten lamp produces about 2×10^8 photons s^{-1} per resolution element (slit width). Therefore with an etalon in series with four lenses and an integrating sphere with 10% efficiency, we can expect about 3.5×10^4 photons s^{-1} per resolution element. This should provide adequate signal to noise for calibration with reasonable integration times.

This calculation must also be done for the discharge lamps that will be used. Also, consideration of the low resolution mode is needed.

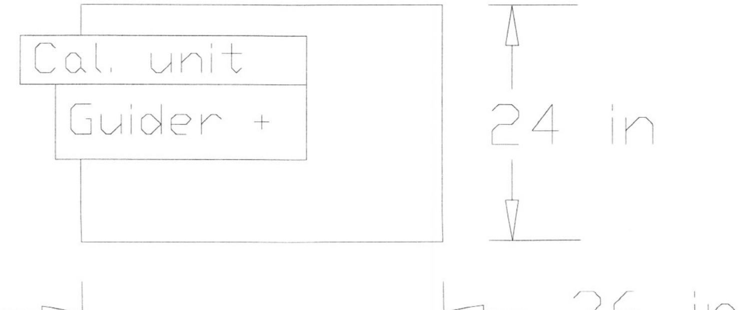
Also not considered yet is the relay system that must tell the calibration unit what to do (e.g. turn on the lamps).

Space Constraints

NIRSPEC on Nasmyth platform



Looking down NIRSPEC optical axis



The calibration unit will be located in front of NIRSPEC so that it can feed its beam into the spectrometer. The telescope, adaptive optics (AO) bench, and guider camera all place constraints on the possible location of the calibration unit. The top section of Figure 3 shows the composite boundary determined from the telescope and AO bench. The box in front of NIRSPEC represents one possible location of the calibration unit. It was determined by drawing a box around the basic layout of the unit. Since a detailed optical design has not yet been done, all of the dimensions used to draw this box are approximate. However the figure shows that the space available is probably adequate.

The current design of the guider camera includes some space between the first mirror and the outside wall of NIRSPEC. This seems to be a good location for a moveable flat that will send the calibration beam into the spectrometer. The calibration unit itself could be almost anywhere. The bottom section of Figure 3 shows it just above the guider unit oriented horizontally. In this depiction the general optical path would be from left to right. At the right end of the unit there would be a flat that sends the beam down to the movable flat.

No effort has yet been made to consider the location of or space required by housings or power supplies.

Cost

The following is a preliminary table of approximate costs.

ITEM	COMMENTS	COMPANY	Pg.	COST (EA)	CATALOG #	#.	COST
integrating sphere	4 “ gold coated	Labsphere	93	$2285	IS-040-IG	1	$2285
etalon	d = 0.5 mm gold coated	Melles Griot	13-47	3450	03 ETA 007/045	1	3450
arc lamps	Ar, Kr, Ne, Xe	Oriel	v. II, 30	217	6030 to 6033	4	868
power supply	for arc lamps	Oriel	v. II, 30	151	6043 & 6045	2	302
tungsten lamp (QTH)	100 W inc. socket	Oriel	v. II, 40	94	6333	2	188
power supply	for QTH lamps	Oriel	v. II, 60	835	68735	2	1670
pinhole	estimated diameters	Oriel	v. III, 9-4	100	15475	2	200
UV-vis blocker	RG 850	Ealing	331	50	26-9589	2	100
neutral density filter	only good to 2 μm	Ealing	334	60	26-5975	2	120
flat mirror	Al(SiO) to 10 μm	Oriel	v. III, 5-6	40	45581	2	80