Volume Phase Holographic (VPH) Grisms for Optical and Infrared Spectrographs*

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ABSTRACT

Highly efficient Volume phase holographic (VPH) gratings do not lend themselves to use in existing spectrographs except for grism spectrographs where VPH grisms can be designed that disperse but do not deviate the light. We discuss our program to outfit existing spectrographs (the Imaging grism instrument (IGI) on the McDonald Observatory Smith Reflector, and the Hobby-Eberly Telescope Marcario Low Resolution Spectrograph (LRS)) with efficient VPH grisms. We present test data on sample gratings from Ralcon Development Lab, and compare them to theoretical predictions. We have created a simple test bench for efficiency measurements of VPH gratings, which we describe. Finally we present first results from the use of VPH grisms in IGI and the LRS, the latter being the largest grism ever deployed in an astronomical spectrograph. We also look forward to using VPH grisms in the LRS infrared extension, which covers the wavelength range from 0.9 to 1.3 microns.

Keywords: Astronomical instrumentation: Optical and Infrared Spectrographs; Volume Phase Holographic Gratings

1. INTRODUCTION AND MOTIVATION

Volume phase holographic gratings[1,2] have recently come to the attention of the astronomical community, though the technology has been around for a couple of decades and has been used in Raman spectroscopy for a decade (see refs 1,2 and references therein). They offer the potential of significantly higher efficiency and low order dispersion when compared to the surface relief gratings (either ruled or holographic) in standard use in astronomy. Refs 1,2 present the theory of, and test results on, VPH gratings and discuss astronomical applications. VPH gratings disperse light by Bragg diffraction from the periodic modulation of refractive index in a thin layer of processed dichromated gelatin (DCG).

The classical grating equation applies to VPH gratings, but the diffraction must also obey the Bragg condition, leading to maximum efficiency when the incident angle and wavelength match the Bragg condition. Since these quantities are related in a continuum, a given VPH grating will diffract different wavelengths (and orders) as it is tilted with respect to the incident light. If the camera then follows with twice the tilt of the grating, the spectrograph can be tuned to a range of wavelengths and resolutions with the same grating. This feature has been seized upon in the design of several upcoming spectrographs[3], though the design of articulating cameras does present significant mechanical engineering challenges. Here, instead, we consider the simpler problem of retrofitting existing grism spectrographs with VPH grisms, and present successful examples from McDonald Observatory.

2. VOLUME HOLOGRAPHIC GRISMS TO RETROFIT EXISTING SPECTROGRAPHS

While one gives up the tunability of VPH gratings if they are used in fixed-format traditional spectrographs, VPH gratings offer higher resolution and significant advantages in tuning the grating to a particular application, when used as grisms in existing imaging spectrographs. The advantages are particularly important in the red where few suitable physical grating masters exist for transmission gratings. Classical surface relief diffraction transmission gratings have an upper limit to the

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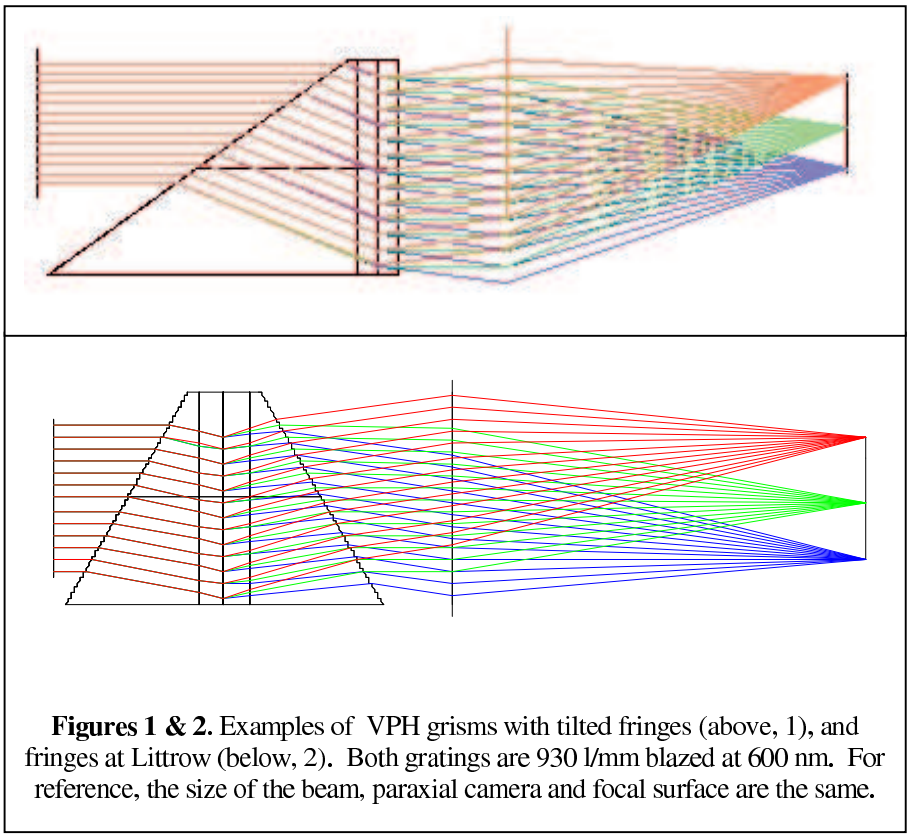
groove density of about 600 l/mm for high efficiency, due to the irregularity of the grooves, which causes scattering of light out of the order. This is a serious limitation for spectrographs on the largest telescopes, where beam size must be increased at a given image quality to gain spectral resolution. The advantages of grisms are of course the ability to create efficient imaging spectrographs (e.g. EFOSC[4], FORS[5], and LRS[6]) that are also good imagers with a simple linear format, where the insertion of the grism into the collimated beam changes the instrument to spectroscopic mode.



Figures 1 & 2. Examples of VPH grisms with tilted fringes (above, 1), and fringes at Littrow (below, 2). Both gratings are 930 l/mm blazed at 600 nm. For reference, the size of the beam, paraxial camera and focal surface are the same.

The first example of the use of a VPH grism in an existing spectrograph that we are aware of is in the LDSS++ instrument for the AAT[7]. In this case, the VPH grating was blazed (by tilting the fringes so they present the Bragg angle to the incident light). This geometry is shown in figure 1a. Other instruments that have VPH grisms are Taurus++ on the AAT[8], FORS-1 on the VLT[9], MARS on the Mayall 4 m at KPNO[10], and our own IGI and LRS spectrographs (as reported here). These spectrographs all use a format where the VPH grating is sandwiched between two prisms that refract the light to be incident at the Bragg angle onto the grating, and then refract the diffracted light back onto the spectrograph axis (figure 2). This Littrow configuration minimizes the camera aperture required, because it avoids the anamorphic magnification evident in the asymmetrical case (figure 1).

2.1 Design of Volume Holographic Grisms

We will not discuss the theory of VPH gratings here, as this has been covered in refs 1,2. We have used a model in MathCAD™ adapted from one created by R. Rallison to design VPH gratings. It is not a fully rigorous coupled-wave analysis, solving only to 2nd order, which is the Kogelnik approximation[11]. It is in any case not possible to control the manufacturing process of VPH gratings to exactly produce the predicted efficiency curves, so our approach is adequate for the grating design.

As shown in figure 1b, the symmetric grism with untilted fringes is simple to design. Here we consider the limits in terms of dispersion and glass choices for the prisms. Figure 1 shows a typical application for a low dispersion grism that does not present significant design challenges. For VPH gratings used in spectrographs with articulated cameras (for example), Bragg

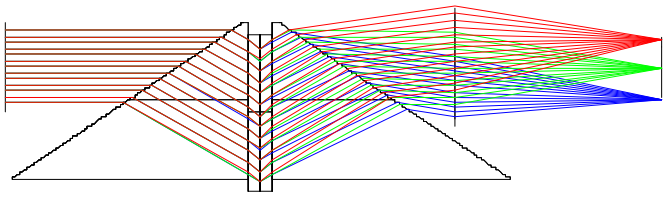


Figure 3. VPH grism with dispersion close to the maximum possible. The glass is SFL57 and the grating has 3000 l/mm and a Bragg angle of 27 deg. The grism is designed for a central wavelength of 600 nm. Note the shifts of prisms and grating.

angles of 45 degrees and fringe frequencies of 6000 fringes per mm are quite feasible[1,2]. If we try to design a symmetric grism around such a VPH grating, we are forced to use high index glasses and extreme prism angles that approach total internal reflection. Figure 3 shows the toy design of a VPH grism consisting of a grating with 3000 l/mm sandwiched between SFL57 prisms with internal angles of 56 degrees. When high index is required, we use SFL57 due to its high index (n = 1.85) and relatively low weight (density = 3.55 g/cm^3). SFL57 is a rather soft glass that is not as easy to figure compared to BK7, and it has the drawback that it tends to stain when exposed to air. However, we have found that the amber surface stain can be removed with isopropyl alcohol from uncoated surfaces, and coated surfaces do not stain.

As demonstrated in fig. 2, the grism needs to be larger due to the refractive magnification of the beam size, and needs to be offset in the direction of the refraction to prevent vignetting. Vignetting is a problem for tight clear apertures, even for quite low dispersion grisms (e.g. 700 l/mm, as implemented in HET LRS, below). The grism in figure 2 would be manufactured with prisms cut to minimize weight and space requirements, but practical constraints of space envelopes probably limit the resolving power in an existing spectrograph. Note that the grism in fig. 2 has a diameter and length about 2x and 4x the pupil diameter, respectively, which gives a sense for the space required.

2.2 Tests of VPH gratings manufactured by Ralcon Development Labs

Our development thrust has been towards manufacturing large (170 mm diameter) VPH gratings for use in the HET LRS, which has a 142 mm diameter pupil. The only vendor currently able to produce gratings of this size is Ralcon Development,[12] and we have worked with R. Rallison to design and manufacture gratings to our requirements. The first phase of development was to procure small test gratings with properties spanning the range of interest and to test their efficiencies against predictions. While the MathCAD program allows optimization of fringe density and other parameters, in practice one aims to produce a grating in the Kogelnik regime and specifies the Bragg angle, fringe frequency, wavelength of peak efficiency, and expected bandpass. During manufacture, it is possible to play bandpass off against peak efficiency, to some extent, but the gratings delivered are each unique and have efficiency curves that tend to depart somewhat from predictions. Typically, we have found that the bandpasses have been wider than expected at the expense of a small loss in peak efficiency. We have also found very good second order performance when we have looked at it, which is contrary to the expectation in the Kogelnik regime, where the aim is for the majority of the light to be diffracted into the first order.

We created a simple test-bench from scavenged parts (e.g. an old bulky monochrometer once owned by the U.S. Air Force), and created a detector system with Si and Ge photodiodes coupled to a model 34401A multimeter from Agilant. The multimeter has an integrating mode to increase signal-to-noise ratio, and in the future will be connected via RS-232 to a computer for automatic measurements with existing software. Currently, we are operating the test setup manually. The light source is a quartz halogen bulb powered by an Agilant E3634A power supply in constant current mode, resulting in extremely stable power output after a few minutes warm-up, required to get the Tungsten-Halogen cycle in equilibrium. A monochromatic collimated beam stopped down to 25 mm diameter is created with a doublet and passes through the test grating, which is located at the center of rotation of an arm that mounts a second doublet, a Fabry lens, and the detector. The optical system is designed to image the pupil onto the detector to make the setup as stable as possible.

Measurements are made in a differential manner. With the detector arm aligned with the optical axis and no grating in the beam, a series of measurements are made by stepping through the wavelength range of interest, and interspersing measurements of the "dark" ambient light with the light source shuttered off. It is necessary to make measurements in a darkened room to keep the contrast in count-rate high. Then a series of light-dark pairs are taken with the grating and detector arm tilted so the light is incident and is diffracted at the Bragg angle. The setup is again stepped through the wavelength range. This mimics the use of the grating in a spectrograph, and measures the response for a fixed setup, rather than the "superblaze" (peak efficiency as a function of wavelength[2]). The procedure is laborious, but we have found very repeatable results. We aim to automate the test bench when time allows.

Table 1 presents the properties of the gratings that we have tested. Note that our emphasis has been mainly on intermediate dispersion far red (600 to 1300 nm) gratings, and the range of the monochrometer was set for this, which prevented measurements blueward of 550nm. In particular we have been investigating gratings for the 900 to 1300 nm region for use in the LRS infrared extension[13]. Table 1 gives the basic parameters specified when we ordered the gratings. The thickness of the DCG layer in which the hologram is exposed and the index modulation are suggestions, rather than quantities that are specified strictly.

Table 1. Test gratings from Ralcon Development Inc.

Grating name	**fringe frequency**	**design wavelength**	**Bragg angle**	**DCG thickness**	**Index modulation**	**Notes**
	fringes/mm	nm	degrees	microns		
V930	930	550	10.53	10	0.026	for IGI
R454	454	800	7.45	15	0.026	for IGI
R700	700	800	11.54	12	0.032	for LRS, IGI
Z520	530	985	10.54	12	0.04	for LRS-J
Z590	590	1010	12.75	12	0.043	for LRS-J
J575	575	1200	14.78	12	0.051	for LRS-J

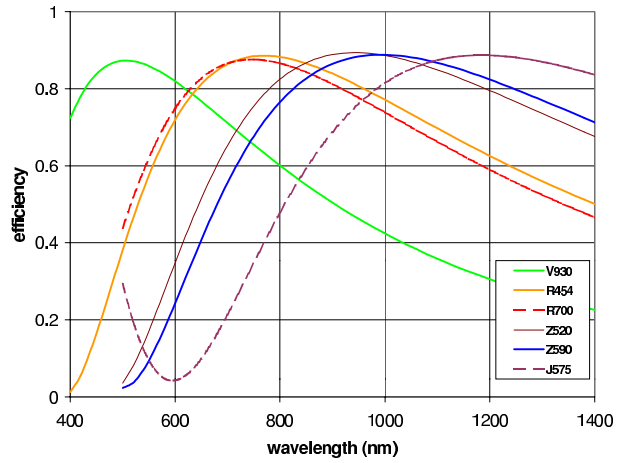


Figure 4. Predicted efficiency curves for a variety of VPH gratings in the visible to near IR wavelength range.

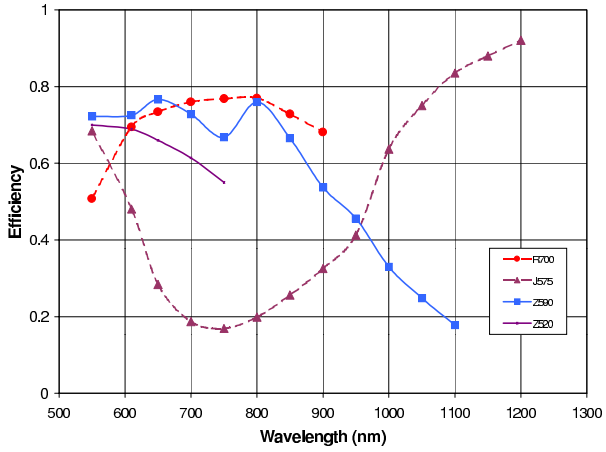


Figure 5. Measured efficiency curves for a selection of the gratings presented in fig. 4.

Predicted efficiency curves for first order are shown in figure 4. Measurements were made of test gratings to compare actual performance with predictions. Figure 5 shows the measurements for the R700, Z520, Z590, and J575 VPH gratings. The R700 and J575 gratings have performance close to predictions, while the other two have peak efficiencies significantly bluer than the requirements. The Z520 grating was manufactured for the first round of tests. It seems the sample was optimized by testing throughput with a laser at a shorter wavelength than required, so we consulted with R. Rallison and he procured a 1.3 micron wavelength laser for testing the subsequent gratings. The success of the J575 grating showed that these gratings can be manufactured with high efficiency, so we have ordered and just received the full size gratings for LRS-J. These will be tested shortly. We are hopeful that the Z590 grating will perform as well as the J575 in the final implementation. The R700 grating was so successful in the initial tests that we ordered a full-size grating for use in the HET

LRS and this has already entered the commissioning phase on the telescope (see below). The V930 test grating has been installed in the IGI instrument (below).

3. SCIENCE APPLICATIONS AT MCDONALD OBSERVATORY AND THE HET

3.1 The Hobby-Eberly Telescope Marcario Low Resolution Spectrograph (LRS)

The design of LRS initially had three replicated grisms. Grism G1 (300 l/mm) covers 420 to 1100 nm at low resolution, while grism G2 (600 l/mm) covers 430 to 720 nm at intermediate resolution. Both of these grisms are from Spectronic Instruments Richardson Grating Lab masters. The third grism was intended to cover 600 to 900 nm at intermediate resolution, complementing G2, and was intended to use the Hyperfine Inc. master ruled for the SDSS spectrographs. However, the performance of grating R700 was so good that we elected to use a volume holographic red grism instead, designated G3, and Ralcon delivered 170 mm diameter gratings for this purpose.

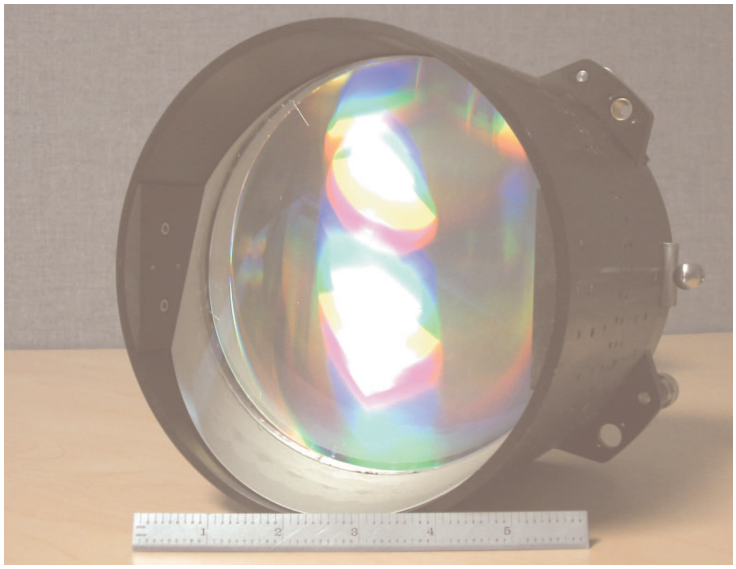


Figure 6. HET LRS Volume holographic Grism 3 mounted in its cell. The scale in front is 6 inches long. The grism is 170 mm diameter, which is the largest so far deployed in an astronomical spectrograph.

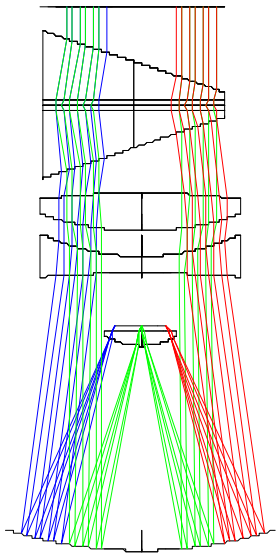


Figure 7. Grism R700 shown with the HET LRS f/1.4 camera. Note the 7 mm shift of the grism to the left, which prevents vignetting.

LRS presents particular design issues for VPH grisms. Because of very tight space constraints, the clear apertures of the optics in LRS are 95% of the physical diameters of the elements. This means that if we simply replace the regular grisms with VPH grisms, there will be vignetting of the beam unless the VPH grisms are translated as described in section 2. In LRS, the shift is 7 mm, and is achieved with manually set adjustable stops added to the main LRS framework.

G3 has now been installed in LRS for initial commissioning tests. The wavelength coverage is 630 to 900 nm at R~2000 in first order. This grating (figure 6,7) has 700 fringes per mm and is used at a Bragg angle of 11.5 degrees. This angle of incidence (and diffraction) is achieved by sandwiching the grating between two identical 18.8 degree prisms of SFL57 with magnesium fluoride-AR coated outer faces. The grating is sandwiched between 10 mm cover plates of Starphire glass, and has 170 mm diameter, cut from a larger grating so the hologram goes all the way to the edge of the grating. This was necessary to avoid vignetting since the tight space constraints in the LRS force optic diameters barely larger than the clear apertures. It is necessary to seal the edges of the grating to prevent damage to the hologram due to hydration of the DCG.

First commissioning observations with this grism have confirmed its high throughput and have offered the opportunity to test the full wavelength range of the LRS for the first time. Grism 3 has high efficiency in second order as well, so using the B

filter as a blocker, we were able to check the image quality of the LRS optics close to their lowest wavelength of 360 nm. Without any refocus, we obtained identical point spread functions for wavelengths between 3727 Å and 1 micron observing both calibration lamps through 0.5 arcsec diameter pinholes and the bright Cat's Eye Planetary Nebula (NGC 6543). These observations confirmed the pan-chromatic image size of 0.35 arcsec FWHM for the LRS spectrograph.

3.2 The Infrared Extension of the HET LRS (LRS-J)

An extension of the wavelength coverage of the LRS to 1.3 microns has always been planned, and we are developing a cryogenic f/1 camera to replace the LRS optical camera[1415]. LRS-J will use two VPH grisms to cover the range 900 to 1300 nm in two exposures. The gratings Z590 and J575 are the test gratings for this application. VPH grisms are particularly suited to this application because we need to cover the 0.9 to 1.3 micron wavelength range in two exposures in order to give a high-enough resolving power to achieve good sky subtraction. This requirement is R ~ 2000, which we will achieve with these grisms and the 1.3 arcsec wide slitlets in the LRS multi-object unit[16]. The VPH gratings are individually manufactured without the need to rule masters as with surface relief gratings, so VPH technology has really enabled this instrument to be built. It will be commissioned this spring, and will provide multi-object spectroscopy for the HET into the J band. The VPH grisms are used warm, so the instrument cannot work at longer wavelengths than 1.3 microns as the thermal continuum would dominate the continuum between the OH^- night-sky emission lines, and would hence limit sensitivity. We expect LRS-J to have peak throughput approaching 30% on the sky once the HET mirrors are re-coated[17].

3.3 The Imaging Grism Spectrograph (IGI)

The IGI is a small imaging spectrograph completed in 1991 that has become a work-horse instrument on the McDonald Observatory 2.7 m Smith Reflector and the 2.1 m Struve Reflector. It has not been described in any publications so we give a summary of its properties here and then describe its performance with a new VPH grism. IGI is a simple focal reducer grism spectrograph based on commercial optics (fig. 8), designed to provide much better sensitivity for low-resolution spectroscopy than any other spectrograph at McDonald Observatory. It was completed in about 6 months, for a cost of about $5000 plus about 4 man-months of effort. Table 2 summarizes its properties. The imaging quality of the optics is quite good considering their low cost, but they do show coma in the outer 20% of the field. IGI mounts at the f/9 bent Cassegrain focus of the Smith Reflector, or at the f/11 straight Cassegrain focus of the Struve Reflector.

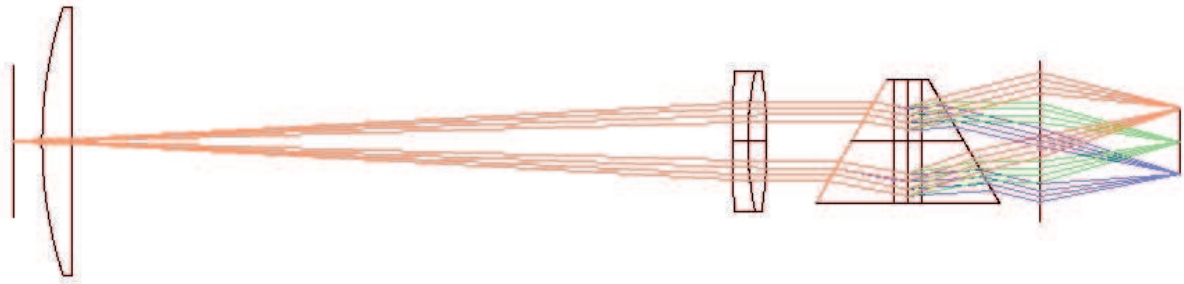


Figure 8. Optical layout of the Imaging Grism Instrument with the 930 l/mm VPH grism. The 50 mm Canon camera lens is indicated by a paraxial lens surface, since the prescription is proprietary. For reference, the singlet field lens is 95 mm diameter.

IGI is designed for visible-red use. Below 450 nm the AR coatings on the camera lens reduce efficiency significantly. Two stages provide some remote control of the instrument. The two-position slit stage at the telescope focal plane is just in front of the field lens, and accommodates a selection of fixed slit inserts or two filters. The slits were manufactured simply by gluing razor blades to the inserts with epoxy. By offsetting some of the slits perpendicular to their lengths (i.e. along the dispersion axis), the wavelength range can be tuned by up to +/-10% of the total range shown in table 2. Typical slit widths are 2 or 2.5 arcsec, giving resolving powers between 500 and 850, depending on the grism (table 2). Multi-object observations are obtained using slitlet masks fabricated of stainless steel (CHECK) by photochemical etching. The masks mount in holders that have registration pins to ensure repeatability, and we adjust the rotation of the instrument on the sky only once in a run. There is no separate stage for filters, but we have not found this a problem for the typical applications of IGI.

The grism is mounted in a two-position stage in the collimated beam between the collimator and camera. Pneumatic cylinders actuate the stages. The instrument can be reconfigured from imager to spectrograph with the insertion of the slit and grism, so it is used as an imager to set up the object on the pixel that corresponds to the slit center. Telescope offsets are made with offset guiding, and software has been developed that allows setup on a new target within 5 minutes. This is also true for multi-object observations, and makes for very efficient observing since typical integrations are 30 minutes to an hour.

Table 2. Properties of the McDonald Observatory Imaging Grism Spectrograph (IGI)

Field lens	301 mm f.l.	Melles Griot LPX309 singlet	Magnesium fluoride AR coating
Collimator lens	260 mm f.l.	Melles Griot LA0238 doublet	Magnesium fluoride AR coating
Collimated beam-size	30 mm	pupil located at the grism	
Camera lenses	Canon 50 mm f/1.4	5:1 reduction	Multi-layer AR coating with approximate coverage from 400 to 950 nm
	Canon 85 mm f/1.8	3:1 reduction	
	Canon 135 mm f/2.8	2:1 reduction	
Grisms	G600	600 l/mm RGL 54-*-660	on 34 ^{o} BK7 prism
	VPH930	930 l/mm VPH grating	sandwiched between two 30^{o} BK7 prisms
Field of view	50x50 mm	7.0 x 7.0 arcmin	Vignetting in corners
Plate scale	1.0 arcsec/pxl		with 50 mm camera lens
	0.62 arcsec/pxl		with 85 mm camera lens
	0.41 arcsec/pxl		with 135 mm camera lens
Dispersion & coverage	G600	430 – 830 nm at 3.9 Å/pxl	with 85 mm camera
	VPH930	430 – 810 nm at 3.7 Å/pxl	with 50 mm camera
Resolving power with 2.0 arcsec wide slit	G600	12 Å	R=500 at 600 nm
	VPH930	7 Å	R=850 at 600 nm

IGI is a very stiff instrument (< 1 pxl flexure over the sky), so calibrations are made against spectral and flat field lamps reflected off the dome, and typically only need to be taken once per run. We have found that a combination of neon and cadmium discharge lamps provide good coverage of the wavelength range without having too great a density of lines, and are bright enough that integrations of 1 minute or less are required. We also usually take an exposure of Argon once a run, but this requires 30 minutes, as the useful blue end is very faint. The quartz halogen flat-field lamp illuminates the dome from the sky side of the telescope's secondary mirror cell.

We have implemented one VPH grism in IGI, called VPH930, as shown in fig. 8. It uses the V930 test grating listed in table 1. Initial results have been very good. The throughput of the instrument is noticeably improved by a factor of 1.5 over grism G600, and peaks around 20% (including telescope and atmosphere). This translates into an instrumental throughput of about 30% at 600 nm, including slit losses. The blue response of the instrument is particularly improved. We have seen the result of this in a program to obtain redshifts of many radio galaxies with redshifts up to z ~ 0.5. An example spectrum is shown in fig. 9, which is a z=0.360 NVSS radio galaxy with R = 18.75, obtained in 2x900s exposures with IGI on the 2.7 m Smith Reflector. The S/N ratio at 650 nm is 15 per resolution element, indicating a limiting magnitude of R ~ 21 in 1 hour at S/N = 3 in the continuum, per resolution element. We have found that for this program, IGI is competitive with the ISIS spectrograph on the 4.2 m WHT, indicating the gains to be had with VPH grism retrofits on existing spectrographs.

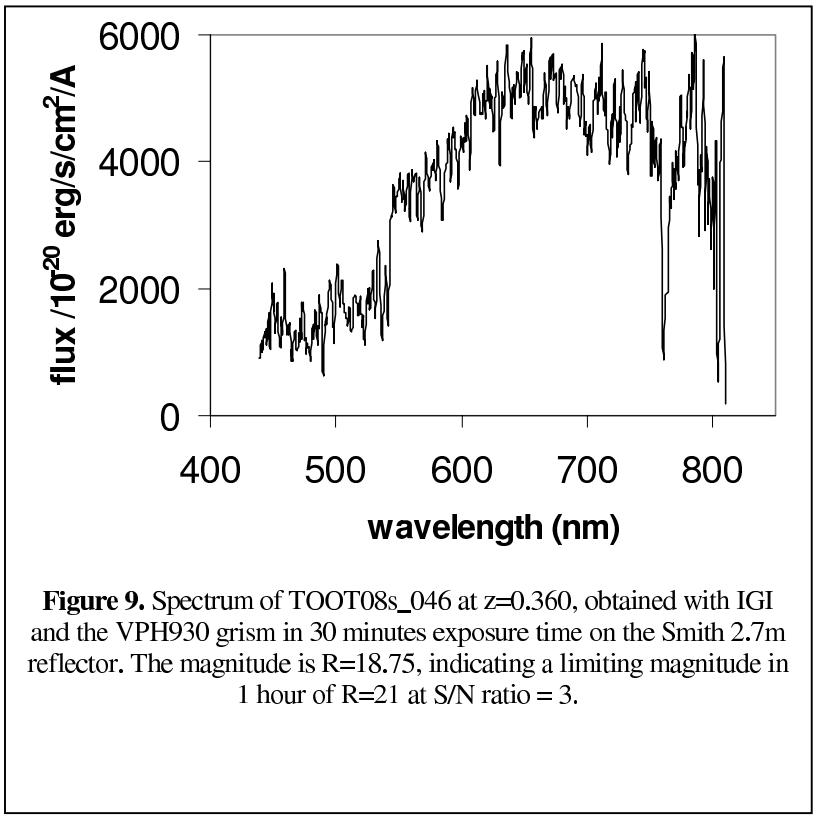


Figure 9. Spectrum of TOOT08s_046 at z=0.360, obtained with IGI and the VPH930 grism in 30 minutes exposure time on the Smith 2.7m reflector. The magnitude is R=18.75, indicating a limiting magnitude in 1 hour of R=21 at S/N ratio = 3.

4. SUMMARY

We have presented an update on our program to install volume phase holographic grisms in existing spectrographs at McDonald Observatory and the Hobby-Eberly Telescope. The 700 l/mm VPH grism in the HET LRS is the largest yet deployed in an astronomical spectrograph. We have undertaken a program to test small VPH gratings. Our test setup is still crude but gives reliable results and can be upgraded to automatic operation when time allows. VPH gratings delivered by Ralcon Development Inc. have proven to have good performance, in many cases approaching the theoretical predictions. We are continuing to procure test gratings to understand which areas of theoretical parameter space result in successful gratings, with an emphasis on the near infrared, up to the red edge of the J band. We expect to deliver efficient VPH grisms into operation with the LRS-J spectrograph on the HET within 6 months.

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