A volume-phase holographic spectrograph for the Magellan telescopes

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ABSTRACT

We present the design for an optical spectrograph for the 6.5-meter Magellan II Telescope. The spectrograph covers the full visible spectrum in a single exposure at very high efficiency through a dual-channel design and the use of volume phase holographic (VPH) gratings in lieu of traditional surface gratings. A pair of symmetric fold mirrors about the grating keep the spectrograph in Littrow configuration, eliminating the need for an articulated camera. Efficient VPH prescriptions have been developed for all resolution modes up to R=11,000. The resulting design is, mechanically and optically, relatively simple, compact, and inexpensive.

Keywords: Spectrograph; astronomy; volume-phase holographic gratings

1. DESIGN GOALS

Between the 1960's and the 1990's, vast increases in detector efficiency, from photographic plates and photon counters to CCDs, produced tremendous gains in our understanding of the Universe, even as optical telescope apertures remained the same. Detection efficiencies of over 80% and negligible read noise are now typical for large CCD mosaic cameras, so that visible imaging has achieved maximum efficiency. Spectroscopy remains further from optimum, however, due to low efficiency dispersers, complex optics, and more stringent CCD requirements. The technology now exists, however, to build a spectrograph that detects the full spectrum of visible light from a source with an efficiency of >50% past the focal plane. This would represent a substantial improvement over existing spectrographs, which would amplify the astronomical capabilities of all existing and future optical telescopes.

We present here a design for the **Magellan II High Efficiency Spectrograph** (*M2HES*), which meets this goal through several techniques. First, we have designed the instrument as a double spectrograph, which allows us to optimize the optics, coatings, gratings, and detectors for red (0.50-1µm) and blue (0.31-0.55µm) wavelengths, respectively, offering an efficiency increase factor between 1 to 2.5 (depending upon wavelength) over a single-beam spectrograph. The blue side optics and detectors have high efficiency to the limit of atmospheric transmission. The capability to capture the full 0.3-1.0 µm spectrum in a single R=1000 exposure will be nearly unique among 8-m-class telescopes (the future MODS spectrograph[1] for LBT is double). Second, the spectrograph will make use of CCDs on order from the Hawaii/Lincoln Labs consortium, which are specialized to the blue and red sides, and offer an unsurpassed combination of efficiency and low read noise.

Finally, we propose to use volume-phase holographic (VPH) dispersers instead of traditional reflection gratings or grisms. VPH gratings have been demonstrated to be feasible and cost-effective for astronomical applications, and offer diffractive efficiencies equal to or greater than *perfect* surface gratings. For many projects, multiplex VPH gratings offer the potential for even greater speed gains. The M2HES will be the first spectrograph designed to use VPH gratings on an 8-meter-class telescope. VPH gratings work best in transmission, so previous proposals for VPH spectrographs are either low-resolution grism designs, or require mechanically complex articulated cameras. In our design the VPH gratings are incorporated with little additional complexity. The overall design of the spectrograph is conservative and robust, with spherical optics, a straightforward passive mechanical design, and use of component designs from other Magellan instrumentation.

The Magellan Project is a collaborative effort† to construct two 6.5-meter telescopes in the Chilean Andes. Magellan I has now achieved first light, regularly produces images with FWHM <0.5" in the visible, and is scheduled for science observations in early 2001. Magellan II completion is expected in mid-2002. The *IMACS* spectrograph[2], currently being constructed for the first telescope, is a reflection-grating spectrograph with an exceptionally wide field of view (FOV) of 25' for imaging or multislit spectroscopy. To complement *IMACS*, it has been decided to emphasize efficiency over FOV in the design of a visible spectrograph for the second Magellan telescope. In this *Proceedings* contribution, we will give a relatively brief overview of the optical and mechanical design, followed by a more detailed discussion of the unique features for incorporation of VPH gratings, and finally a short description of the design and expected performance of the gratings themselves.

2. DESIGN OVERVIEW

2.1. Optical design

Both the red and blue arms of the high-efficiency spectrograph incorporate cameras with a focal length of 500 mm, and a collimated beam diameter of 150 mm. The final scale is 105 microns/arcsec, or 0.143 arcsec/pixel. The FOV of a 4096 x 4096 array is 9.75 x 9.75 arcmin. The optical materials in the blue arm consist only of fused silica and calcium fluoride, to assure the highest possible transmission in the UV. The red arm contains two calcium fluoride elements optically coupled to other optical glasses. There are no aspheric surfaces in either optical system. The collimators and cameras incorporate a small amount of vignetting (not more than 10% at the corner of the field) in order to achieve significant savings in the size, weight and cost of the optical elements as well as to improve the final image quality.

The specific secondary mirror configuration for the Magellan telescopes (f/11 Gregorian) was chosen in order to optimize the performance of a particular family of designs for wide-field collimators. This arrangement has been retained for M2HES, resulting in very high image quality in the collimated beam. The combined primary and secondary mirrors of the telescope produce theoretically perfect images on axis, but the off-axis images exhibit coma which grows to a total diameter of 0.5 arcsec at a field radius of 3 arcmin. A 2-element field corrector (which can incorporate atmospheric-dispersion-compensating prisms within the same 2 elements) produces images of only a few hundredths of an arcsec across the full FOV (it will be necessary to remove the field corrector when the spectrograph is used at wavelengths below 330 nm).

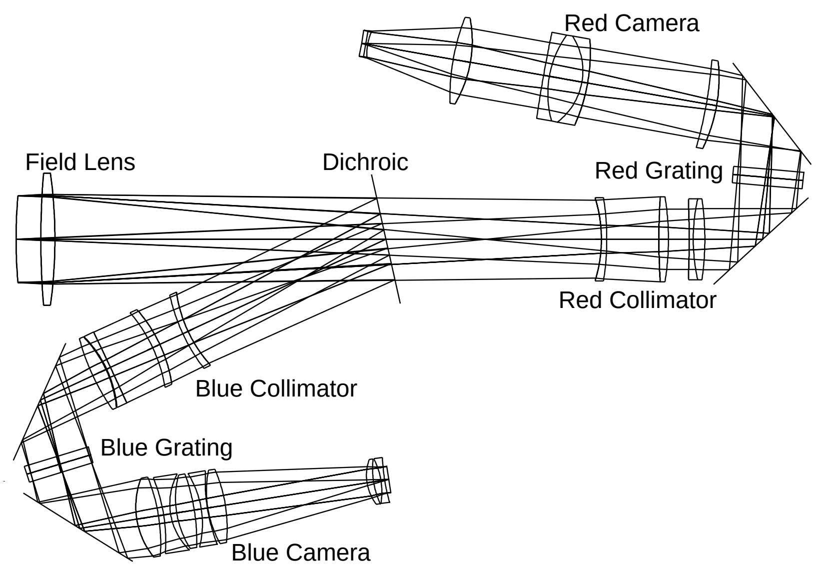

Figure 1: Optical Layout. The fold mirrors are shown in position for direct imaging.

Figure 1 is an optical layout of the spectrograph. The field lens is located 60 mm beyond the focal plane to minimize the impact of defects. Immediately following the field lens, a dichroic mirror directs the red (transmitted) and blue (reflected) light into two separate optical paths. A pair of flat mirrors tunes the VPH gratings while maintaining Littrow condition, as described below. It will be possible to use gratings with resolution up to R = 11,000 for a 1 arcsec slit.

The camera optics for the blue side have been adapted from the design of the UVES spectrograph[3] at the VLT. Three positive CaF_2 lenses and 2 negative fused silica lenses in a +/-/+/-/+ arrangement provide a large amount of positive power with good

† The members of the Magellan Consortium are: the Carnegie Institution (OCIW); the Harvard-Smithsonian Center for Astrophysics (CfA); the University of Michigan (UM); Massachusetts Institute of Technology (MIT); and the University of Arizona Steward Observatory (UA).

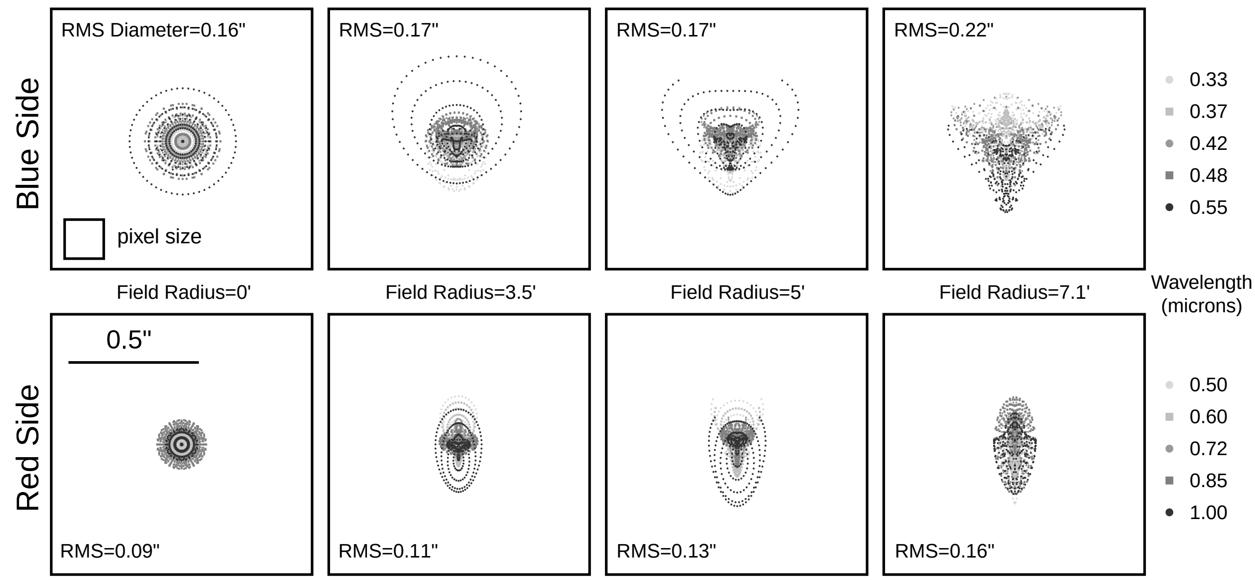

Figure 2: Spot Diagram. Presence of the field corrector is assumed.

color and field correction. Spot diagrams for the complete optical system are shown at the top of Figure 2. Since the wavelength coverage of the blue side is significantly less than one octave, it will be possible to provide anti-reflection coatings of particularly high efficiency, compensating for the larger number of glass-air surfaces.
The camera optics for the red side are based on the design of the red camera from the *MIKE* echelle spectrograph[4]. The images for the complete optical system are shown at the bottom of Figure 2. The average image diameter is 0.13 arcsec.

2.2. Mechanical design

To limit instrumental flexure to no more than about 1 pixel, the mechanical structure must maintain the relative positions of the slit mask assembly, optical elements and CCDs to within 10 microns under a change in gravity loading of 1*g* about the Nasmyth axis, and maintain the angle of the butterfly fold mirrors (described below) to within 2 arcsec. Specific observing strategies (TDI and charge-shuffling) will provide the extremely stable flat-field performance which is required to observe objects which are especially faint compared to sky background.

A preliminary design study has been carried out at Paragon Engineering. The mechanical structure of the instrument consists of a series of plate elements precisely machined from cast aluminum tooling plate and bolted together. The optics are arranged in a plane which defines a relatively flat structure, with perpendicular reinforcing gussets at the attachment to the Nasmyth instrument rotator. The top plates can be removed to provide access to the collimator and camera optics, which are mounted on flexured optical benches to provide focus adjustment. Accessible grating wheels accommodate 4 different gratings at any one time, as well as a clear position for direct imaging. The CCD dewars and the slit-mask cassette mount on external surfaces for easy access. Two views of the mechanical layout are shown in Figure 3.

The total weight of the instrument is 2500 lb., and the size of the flat structure is 8 by 6 ft. It is not feasible to support the instrument to the required precision as a cantilevered load from the Nasmyth instrument rotator. Instead, a small bearing is mounted at the far end of the instrument, through which an astatic support force can be applied in order to support the instrument from both ends. An additional set of astatic levers, mounted near the instrument rotator, provide support at the center of the instrument. Astatic support is the same principle of flotation which is used to support the primary mirrors for large telescopes (to much higher precision), and has been successfully applied to a number of previous instruments[5].

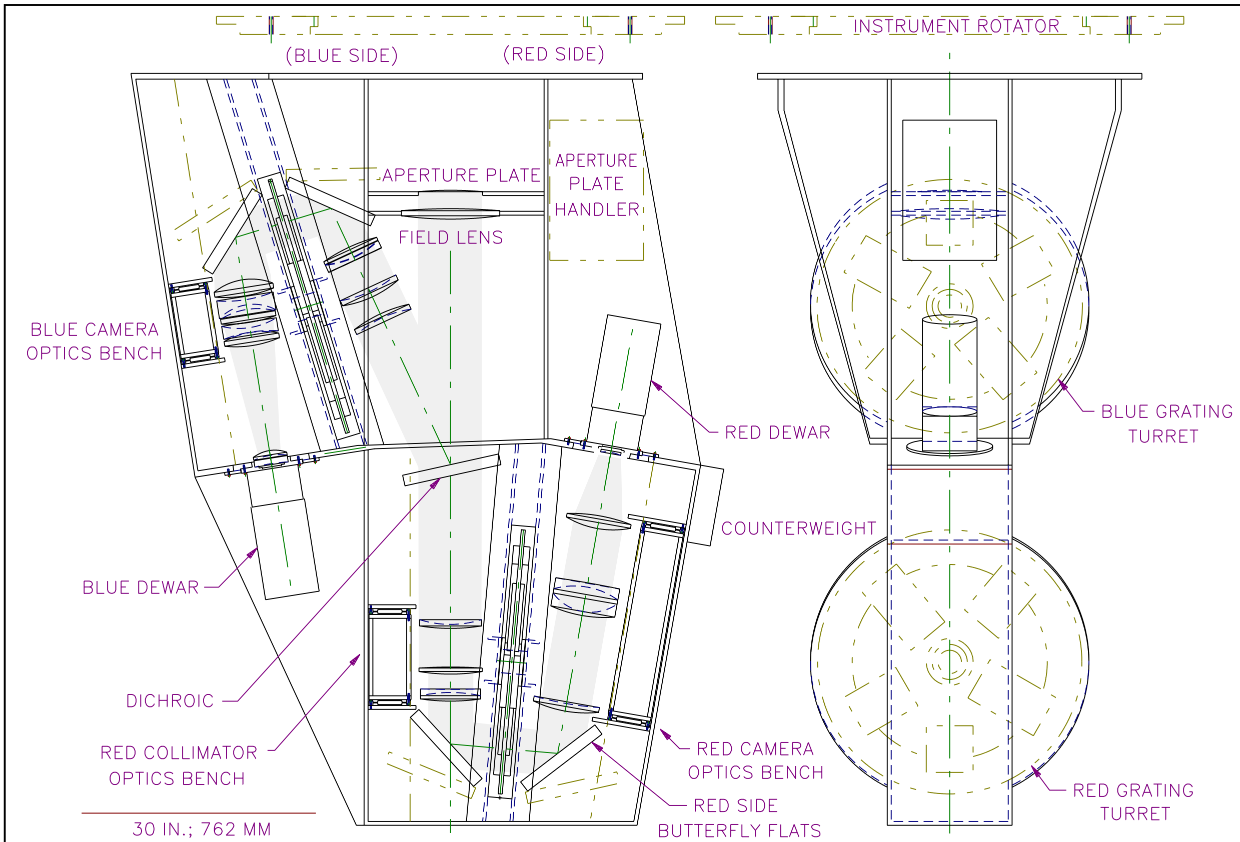

Figure 3: Mechanical Layout. Top (left) and side (right) views of the instrument structure.

A finite element analysis of the preliminary design, which includes realistic local deflections for individual optics mounts, indicates that the design goals are achievable with this structure. A similar structure is being used to construct the *MIKE* spectrograph.

2.3. Detectors

Each side of the spectrograph will have its own mosaic of 2 2kx4k CCDs, with 15 micron pixels. This will produce 0.15 arcsecond pixels for a FOV roughly 10' square. Detectors are being fabricated at MIT Lincoln Labs under a consortium led by G. Luppino of U. Hawaii. Two of the CCDs are optimized for outstanding red performance, the other two for blue and UV performance. Control electronics and software will be straightforward as the system requirements are well within the parameter range of existing cameras.

3. INCORPORATION OF VPH GRATINGS

The virtues of VPH gratings for astronomical spectrographs have been elaborated elsewhere;[6] the primary motivation for designing the Magellan spectrograph around VPH gratings is the very high diffractive efficiency that is possible, particularly at resolving powers of 5000 and above, where surface gratings must often operate in second order. A major drawback to use of VPH gratings in large spectrographs has been that they operate best in transmission, and in this configuration, tuning the spectrograph causes the diffracted beam to rotate. In previous designs[7] the rotating beam is captured by placing the entire camera assembly on an articulated stage, which is a major engineering challenge. For this reason, implementations of VPH gratings has been limited primarily to grism spectrographs, which can more easily be retrofit with VPH grisms.

We have eliminated the need for an articulated camera by introducing a simple arrangement of two symmetric fold mirrors about the grating, as illustrated in Figure 4. This "butterfly mirror" has the following virtues:

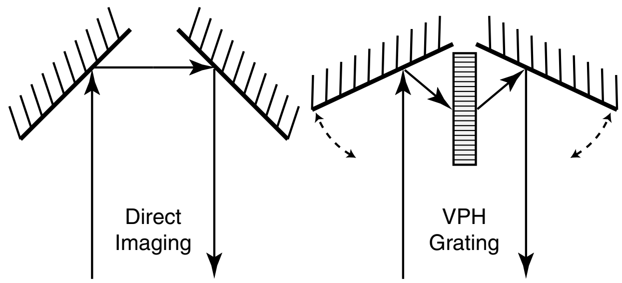

Figure 4: "Butterfly Mirror" Mount for VPH Gratings. A symmetric rotation of the two fold mirrors takes the incoming and outgoing beams from a direct imaging configuration (left) to a high-dispersion mode though a VPH grating (right). Smaller mirror motions tune the spectrograph wavelength. With grating fringes perpendicular to the surface, as shown, the butterfly mirror guarantees that the spectrograph is in Littrow and at the peak of the blaze function.

• The camera beam is maintained at a fixed angle to the collimator beam. This angle may be chosen to optimize the packaging of the instrument.
• If the VPH gratings are fabricated with fringes normal to the surface, then the symmetry of the configuration guarantees that the observations are always in Littrow, with no anamorphic magnification. We know of no situation that would favor the use of non-normal fringes in the VPH gratings.
• The central wavelength on the detector is always at the peak of the blaze function.
• No grating tilt is required, greatly reducing the mechanical complexity of the grating select mechanism, which can be a simple wheel or slide.
• Direct imaging mode is easily implemented, as are surface transmission gratings if desired.
• The symmetric arrangement of the mirrors means that they may be driven by a single motor if an appropriate synchronous-rotation mechanism can be devised.

There are some disadvantages to use of the butterfly mirror rather than an articulated camera:

• One advantage of transmission gratings over reflection is that the pupil, if located on the grating, can be very close to the last (first) optical element of the collimator (camera). The presence of the butterfly folds places the grating farther from the optical elements, negating this gain.
• The optical path length will vary as the butterfly mirror is tuned. Since the beam is collimated at this point, there is no defocus, but it does mean that the pupil cannot be located on the grating in all configurations.
• The butterfly mirror adds two reflections to the optical path. Since these are relatively small flats, however, it is feasible to use sophisticated pro-reflection coatings if desired, so that the total reflection losses are well below those typically encountered with a single reflection grating. In our double spectrograph, the mirror coatings can be separately optimized for red and blue sides.
• The flexure tolerances for the butterfly mirror are very tight, as for any reflecting elements. Note, however, that "common-mode" flexure of the two mirrors is, to first order, cancelled out in the dispersion direction.
• There must be some maximum incidence angle on the gratings (and hence a maximum resolution) beyond which the folded beam collides with the camera/collimator elements.

On balance, the use of the butterfly mirror greatly simplifies the mechanical design and results in a structure that is compact and lightweight for a facility-class 8-meter instrument. The drawbacks of the butterfly mirror have not resulted in significant degradation of the optical performance. We have developed preliminary designs for the butterfly mirror mechanism—both synchronous and asynchronous—that should meet the flexure specifications. The current design will produce angles of incidence up to 45 degrees from normal on the grating, which suffices to produce resolving powers up to R=11,000 through a 1 arcsecond slit. The optical spots and pixel sizes are small enough to permit full exploitation of the narrower slits that would like be used in the 0.6 arcsecond seeing more typical of the initial Magellan operations. The resolving power at high efficiency will therefore be well in excess of that available on other non-echelle astronomical spectrographs.

The M2HES design requires elliptical VPH gratings with minor axes of 150 mm; for high-resolution gratings, the major axis of the footprint can be as high as 270 mm. At this writing there are no facilities regularly producing astronomical-quality VPH gratings of this size, but as reported elsewhere in these *Proceedings*, such facilities are under development at Centre Spatiale de Liege, and there are other vendors capable of producing VPH gratings of the requisite size. We therefore expect to be able to fully exploit the benefits of VPH gratings: high efficiency; mechanical robustness; high line frequencies and efficiency to 300 nm (using silica substrates); low costs for custom configurations; and possible use of multiplex gratings.

4. VPH PRESCRIPTIONS AND PERFORMANCE

VPH astronomical gratings have already demonstrated[6] the exceptionally high diffractive efficiencies (well above 90%) that are predicted by the approximate theory of Kogelnik.[8] Such nearly perfect performance should be attainable over modest bandwidths for the gratings we require at resolving powers of several thousand. The predicted diffractive efficiencies for our grating prescriptions drop to 70–80% at the highest resolutions (R=10,000) because at higher incidence angles one cannot simultaneously obtain high efficiency in both polarizations.

An important feature of the spectrograph will be its ability to record the entire 300–1000 nm spectral range simultaneously. VPH gratings have more difficulty at this lowest resolution, because the Bragg condition must be weakened to pass a broad bandwidth, and therefore the most challenging grating to design is the one which provides simultaneous coverage of the 500–1000 nm range on the red side of the spectrograph. In Kogelnik theory, a broad passband requires a very thin grating with very high index modulation; but the Kogelnik theory breaks down for thin gratings, and we must therefore perform rigorous coupled-wave analysis (RCWA) to design our low-resolution grating. We have to this end implemented the methods of Moharam and Gaylord[9] as a set of C programs (available from the first author upon request). An exploration of the parameter space yields the surprising result that in fact a very thick grating (30 microns) with relatively low index modulation ($\delta n/n=0.01$) has good performance over the full octave. Figure 5 plots the diffractive efficiency, calculated with RCWA, of this grating, at several points in the field of view of the spectrograph. Also plotted are the theoretical diffractive efficiencies (using GSolver[10]) of favorably blazed surface gratings operating in reflection and in transmission at the same line frequency (250 lpm). We see that the VPH grating meets our goal of matching the performance of ideal surface gratings at the lowest resolution. The VPH grating has lower peak efficiency than the blazed Al reflection grating, but the efficiency varies less over the bandpass. Our spectrograph design will accommodate either the VPH grating or the surface transmission grating; as the performance are similar, the choice will rest upon economic factors. We expect the VPH grating to be less expensive, as there is no ruling of sufficient size available for the surface grating.

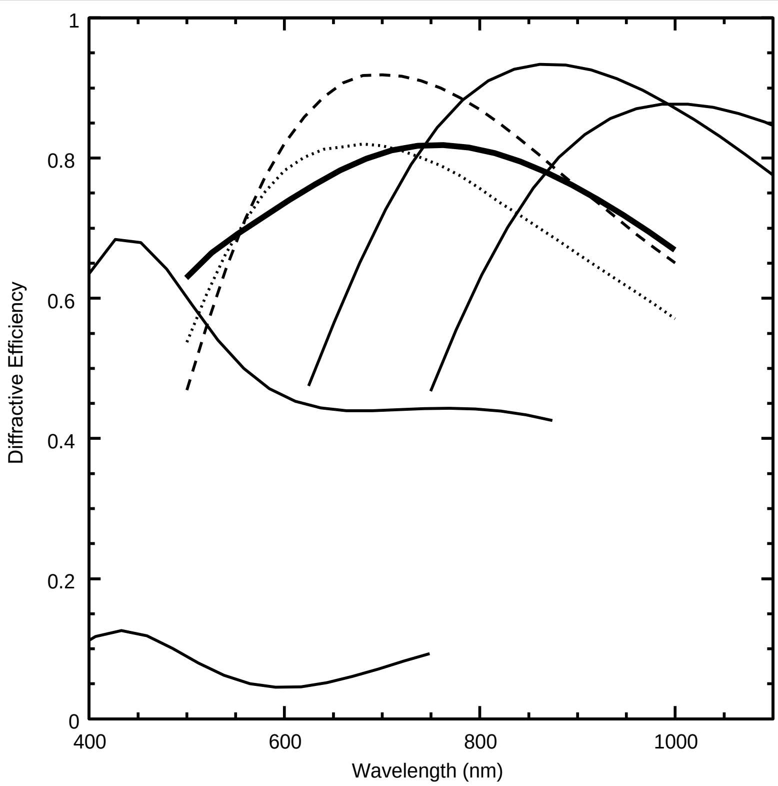

Figure 5: Diffractive efficiency calculated with RCWA for our low-resolution VPH grating is plotted vs wavelength as the solid lines. The heavy line is for an object in the center of the field, with the canonical 0.5-1.0 micron spectral coverage. The outer solid lines show the coverage and efficiency at points halfway and all the way to the edge of the 10' FOV. The performance varies in a very non-intuitive fashion. The dotted line is the central efficiency calculated for an ideally blazed surface grating used in transmission, and the dashed line is for an ideal Aluminum surface reflection grating. Performance averaged over the full octave is very similar for all 3 gratings.

Realistic performance estimates for all the system components (optical surfaces, VPH gratings, and CCD detectors) have been combined to give a total quantum efficiency for the spectrograph. We find that the spectrograph efficiency (from the slit to detected electrons) in the low-resolution, full-spectrum mode should indeed be above 50% from about 330 nm to 900 nm, dropping outside this range due to detector QE. It is likely that future high-resistivity CCDs[11]will be available to keep the system QE high to

1000 nm.

The total system efficiency will drop below 50% for much of this range due to losses in the atmosphere and the 3 telescope mirrors. Nonetheless the M2HES will outstrip most existing or planned spectrographs on 8—10 meter telescopes in its speed at capturing a full-coverage spectrum.

The system efficiency will be even better at R=5000 than in the lowest-resolution mode. This will make the M2HES exceptionally powerful for astronomical investigations, such as galaxy dynamics, that require moderate-resolution spectroscopy of faint targets.

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