NOAO’s next generation optical spectrograph

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ABSTRACT

The National Optical Astronomy Observatory is developing a new, wide-field, imaging spectrograph for use on its existing 4-meter telescopes. This Next Generation Optical Spectrograph (NGOS) will utilize volume-phase holographic (VPH) grating technology and will have a mosaiced detector array to image the spectra over a field of view that will be something like 10.5 by 42 arc-minutes on the sky. The overall efficiency of the spectrograph should be quite high allowing it to outperform the current RC spectrograph by factors of 10 to 20 and the Hydra multi-fiber instrument by a factor of five to ten per object. The operational range of the instrument will allow observations within the optical and near-IR regions. Spectral resolutions will go from R=1000 to at least R=5000 with 1.4 arc-second slits. The large size of this instrument, with a beam diameter of 200 mm and an overall length of nearly 3 meters, presents a significant challenge in mounting it at the Cassegrain location of the telescope. Design trades and options that allow it to fit are discussed.

Keywords: Spectrograph, volume-phase holographic grating, spectroscopy, multi-object spectroscopy

1. HISTORICAL DEVELOPMENT

The scientific staff at the National Optical Astronomy Observatory (NOAO) first contemplated the concept for a new optical spectrograph to replace the RC spectrograph on the Mayall telescope in the mid-1990’s. The initial thrust was focused on the idea of a very high efficiency spectrograph that would utilize cutting edge technologies. The original concept was to be a dual-beamed, moderate field-of-view instrument in which the blue channel was envisioned to use a modest concave, holographic grating while the red channel would be designed around more classical gratings. This effort eventually led to the investigation of volume-phase holographic gratings[1] as a viable option for the red channel. Eventually it was decided to redefine the spectrograph concept from that of a high-efficiency, modest field instrument to that with an emphasis on field-of-view in order to be more competitive in the era of large 8 and 10 meter telescopes.

Following the recent recommendation of the NOAO user’s committee to develop this instrument in a timely manner, the instrument concept has undergone some descoping in its overall performance objectives. The current development timeline is to define the conceptual design during FY2000 with eventual completion of the instrument targeted for late 2003 or early 2004. In this paper, we address many of the issues currently under study for this project.

2. SCIENCE REQUIREMENTS AND GOALS

The instrument is currently envisioned to have the following characteristics:

- FOV of 20 to 40 arc-minutes with an emphasis on achieving as large a field as possible with minimal impact on efficiency.
- Maximize overall system efficiency with a goal of 45% (including telescope and detector).
- Operable spectral regions from 4250 Å to 1 μm with refocus.
- 1 octave of coverage at R~1000 per 5 pixels from 4350 to 8700 Å.
- Limited spectral coverage at R=5000 with a 1.4 arc-second slit (about 5 pixels).
- Nominal slit width of 1.4 times the median seeing of the 4-meter telescope (currently about 1.0 arc-seconds).
- Spatial sampling of 0.3 arc-seconds per pixel.
- Use of CCD charge shuffling and telescope nodding for enhanced sky subtraction and maximization of target slit density.
- High priority goal of <3 pixel images to allow higher spectral resolving powers (up to 10000) by narrowing the slit.

Additional lower priority goals where possible:

- Near-IR extension with IR detectors covering wavelength region of 1 to 1.7 μm.
- Blue optical extension with CCD detectors covering wavelength region down to 3800 Å and to 3650 Å if possible.
- Dual beam instrument with either blue/red optical or optical/near IR channels.
- Micro-lens IFU capability.
- Iodine absorption cell capability.
- Cross-dispersed Echellette mode.

3. OPTICAL DESIGN

The optical design is based upon volume-phase holographic gratings[1,2]. This decision was made due to the high efficiency of VPH gratings, the ability to make large format VPH gratings, and the fact that the gratings are both transmissive and operate in a Littrow configuration. This allows the camera to be moved up very close to the grating and minimizes the anamorphic magnification resulting in a reduction in the size of and simplification of the camera optics.

The optical design has proven to still be very challenging. The desire for a very wide field of view and the space constraints for mounting the instrument on the telescope have essentially eliminated the ability to use reflective optical systems in either the collimator or the camera. Additionally, the requirement for high efficiency also eliminates the use of Schmidt or other catadioptric cameras due to their large central obstructions. Therefore, the design effort is currently based on all transmissive optics working with a 200 mm diameter pupil. Figure 1 shows one such design under investigation. This particular design is for the R=5000 case with a central wavelength of 6525 Å and spectral coverage from 5964 through 7075 Å.

It is obvious from Figure 1 that the lateral and transverse field angles differ in extent with the lateral field angles only ranging from –5.25 to 5.25 arc-minutes while the transverse field covers a total range of 42 arc-minutes. In an all-transmissive system such as this, there is bound to be residual longitudinal chromatic aberration (probably mostly higher orders). Coupled with this will also be a detectable amount of spherochromatism (change of spherical aberration with color). After passage through the diffracting element, color and field angles become directly related in the direction of the dispersion. The two effects of longitudinal chromatic aberration and spherochromatism will, along the spectrum, either produce a tilted focal surface, a curved focal surface, or could to some extent be self-canceling and give a plane focal surface. In the direction

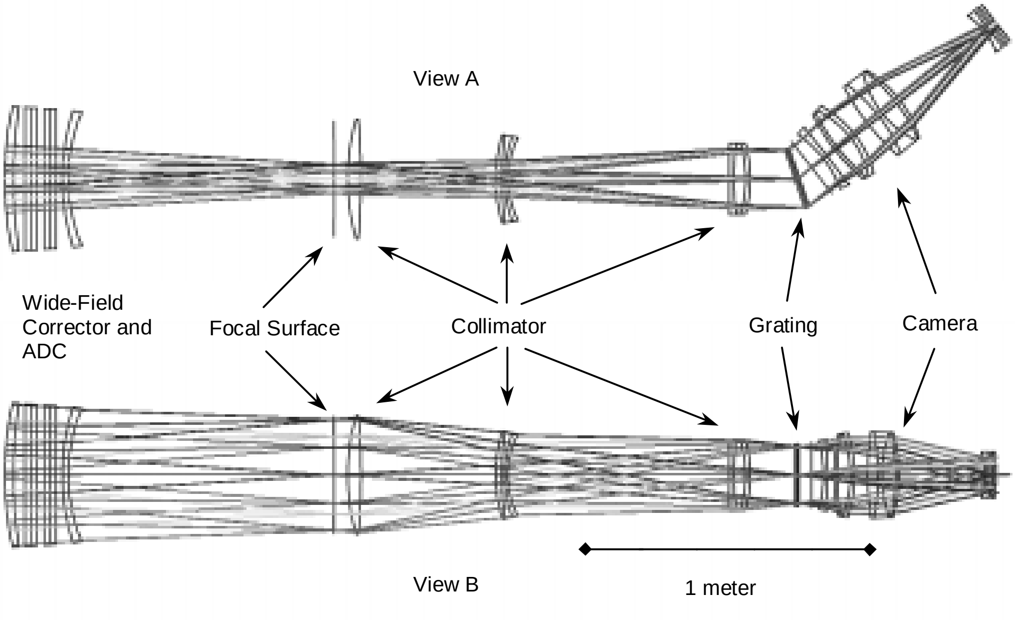

Figure 1 - Optical layout of the concept discussed in the paper. View A looks down along the spatial axis, normal to the spectral dispersion. View B looks at the instrument normal to the spatial direction.

orthogonal to the dispersion the two chromatic effects are not separated by angle. In addition, the normal monochromatic field aberrations enter into the equation. Along this dimension all of these monochromatic and chromatic aberrations could be compensated by defocus. The best fit aberrational balance could be achieved by curving the image plane to match the curvature of the focal surface along this spatial dimension. In NGOS, the field is two-dimensional. The inevitable skew field angles through the grating are, therefore, both along and across the dispersion. The effect of the latter being the greater in this instance. The consequences of this skew passage are to introduce a form of field/color related astigmatism into the final image.

During the course of designing the system displayed in Figure 1, it became evident that the higher order aberrations were getting through the entire system. A number of strategically placed even aspheric surfaces helped in controlling this situation but could not adequately eliminate it. When the behavior of the aberrations described above were accounted for, it was found that the focal surface was cylindrical in form with the curvature perpendicular to the axis of dispersion. The design was optimized to allow the image surface to match the curved focal surface. Significant improvement in the spot sizes was then easily achieved. Sample spot diagrams from this design are displayed in Figure 2 for a variety of diagonal, transverse, and lateral field angles and for spectral coverage of 5964 through 7075 Å. This design certainly meets the resolution requirement for this spectral region over the full 10.5 by 42 arc-minute field. However, it would require that the detector package follow this curve.

Since CCD’s can not be bent to conform to such a surface, the introduction of at least one toroidal aspheric on a glass surface near the focal surface might be a more tenable remedy. Several avenues of solving this problem are currently being investigated including making the CCD’s approximate the cylindrical surface by tilting them along a finite number of tangent planes.

The solution must, of course, be practical in its implementation and must be viable for the wide range of gratings and wavelength regimes required by the scientific objectives. To achieve such a result, optical design optimization must be conducted for numerous configurations representative of those required to carry out the scientific mission of the instrument. Even with today’s fast computers, this mode of operation is exceedingly time consuming. The optical design presented in this paper represents just a small step in the early phases of that process.

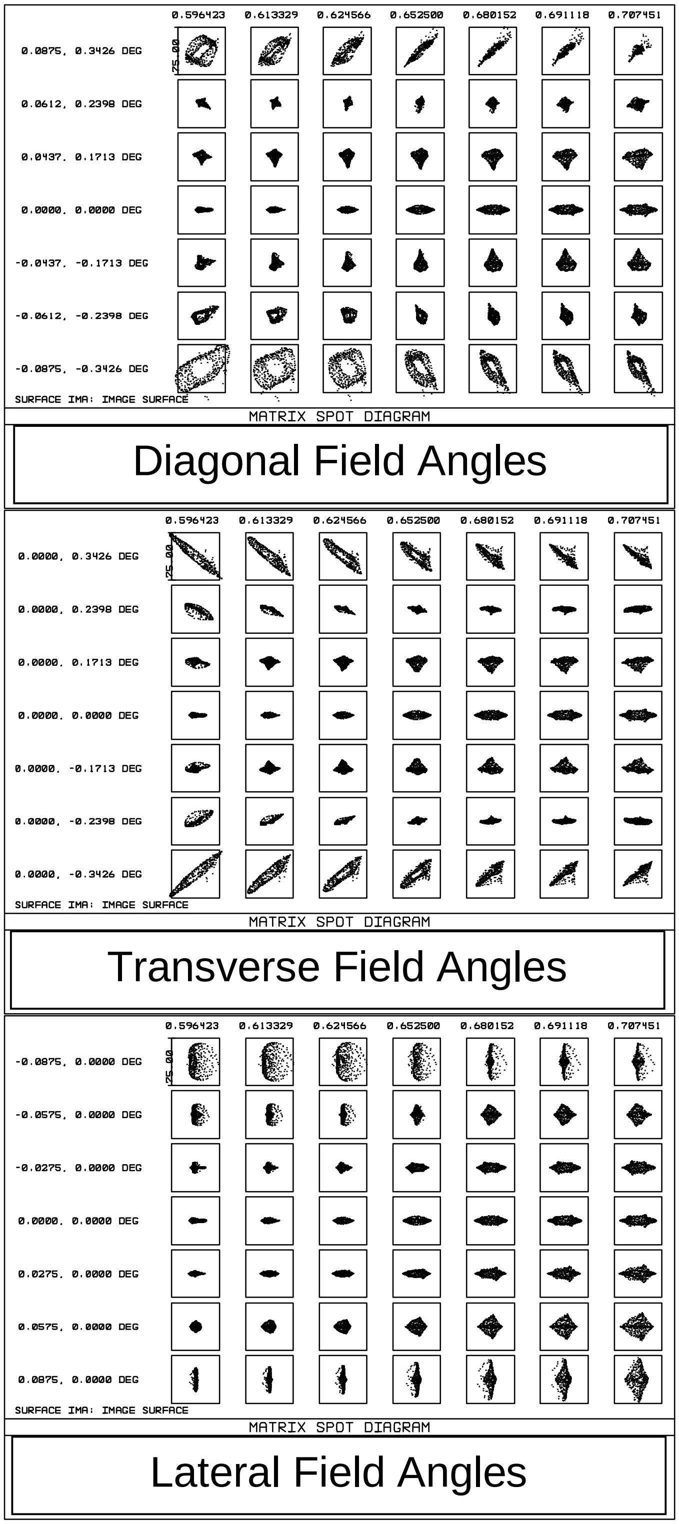

Figure 2 - Spot diagrams for a variety of field angles. The box represents a 5 by 5 pixel area on the detector. Wavelength coverage is from 5964 through 7075 Å at the dispersion required for R=5000 over 5 pixels.

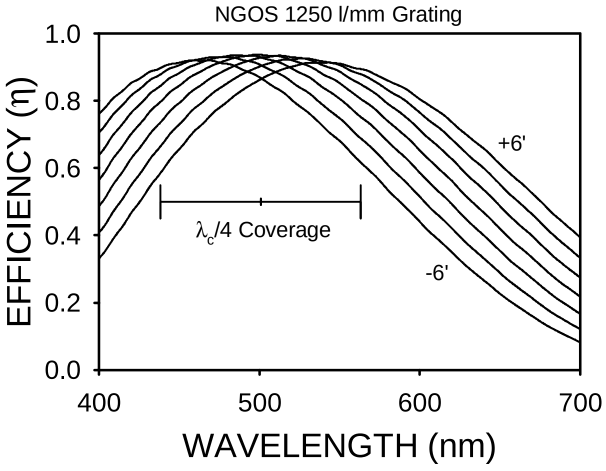

Figure 3 – Efficiency plots for 1250 l/mm VPH grating as a function of lateral field angle. The grating is tilted at 18° for optimal diffraction at 5007 Å.

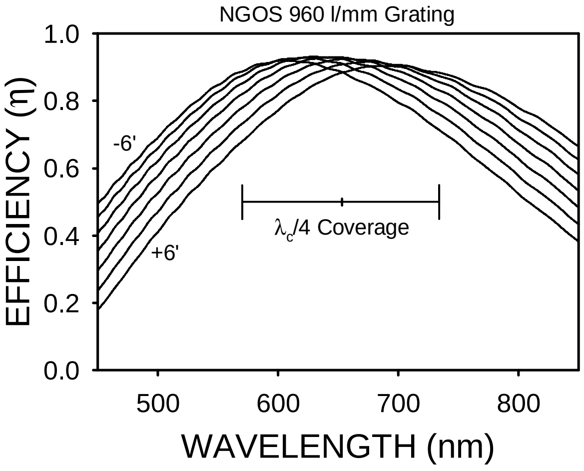

Figure 4 - Efficiency plots for 960 l/mm VPH grating as a function of lateral field angle. The grating is tilted at 18° for optimal diffraction at 6525 Å.

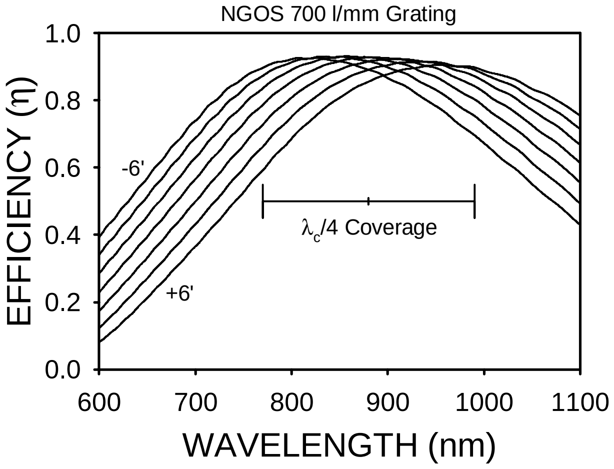

Figure 5 - Efficiency plots for 700 l/mm VPH grating as a function of lateral field angle. The grating is tilted at 18° for optimal diffraction at 8800 Å.

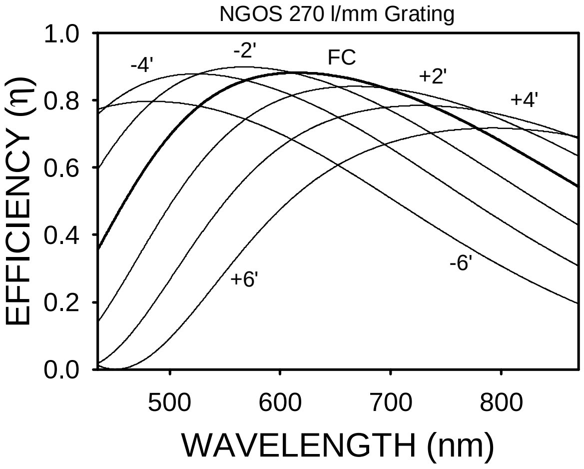

Figure 6 - Efficiency plots for 270 l/mm VPH grating as a function of lateral field angle. The grating is tilted at 5° for optimal diffraction at 6525 Å.

4. GRATINGS

We have selected four gratings for current study with the descoped instrument concept. A 270 l/mm grating that gives a full octave of coverage with a resolving power of about R=1400; a 1250 l/mm grating for R=5000 observations at the blue end of the design spectral band; a 960 l/mm grating for R=5000 observations near the middle of the design spectral band; and a 700 l/mm grating for R=5000 observations at the red end of the design spectral band. All gratings will be volume-phase holographic gratings[2]. Each grating was selected to provide the indicated resolving power for a slit width of 1.4 arc-seconds, which is the width that produces optimal signal to noise in 1 arc-second seeing (the median seeing for the Mayall telescope) on targets fainter than the night sky[3]. This corresponds to about 5 pixels FWHM on the detector. Assuming that the imaging performance of the spectrograph will allow use of a narrower slit, higher resolving powers of up to R=10,000 might be possible when seeing conditions permit.

The high dispersion (R=5000) gratings all show the potential for very high efficiency and acceptable bandwidth versus field angle relationship (see theoretical efficiency curves in Figures 3, 4, and 5). The low dispersion grating (270 l/mm), on the other hand, shows considerable shifting in the efficiency bandwidth as a function of the lateral field angle (Figure 6). This is due to the fact that the "blaze" peak is shifted blueward as the field angle approaches an angle normal to the grating. In such a case, the red light tends to be diffracted into zeroth order rather than first. As the field angle gets larger, the blaze shifts redward and eventually reaches wavelengths that are a factor of two above the desired blue wavelengths. In this situation, the blue wavelengths tend to be diffracted into the second order rather than the first resulting in a loss in efficiency. Alternatively, if the line frequency could be increased so that the field angles wouldn't approach the grating normal, then the bandwidth issue might be somewhat alleviated. We will also explore the possibility of just using a dispersive prism in place of the grating for this low dispersion application. Another possible option is to select a VPH grating design in which the bandwidths are intentionally designed to be narrow and make a grating assembly that contained two complementary VPH gratings in a multiplex configuration[4]. One grating would diffract light from one half of the octave while letting the remainder pass straight through to be diffracted by the second grating. Two spectra would be produced rather than one and the spectra would be separated in the spatial dimension by having the fringe structure of the two gratings slightly tilted with respect to each other. Figure 7 displays how the spectra of a multiplex grating designed to diffract Hα and Hβ at the same diffraction angle look like. A lower dispersion grating pair might do the same for coverage of the full octave at lower dispersion.

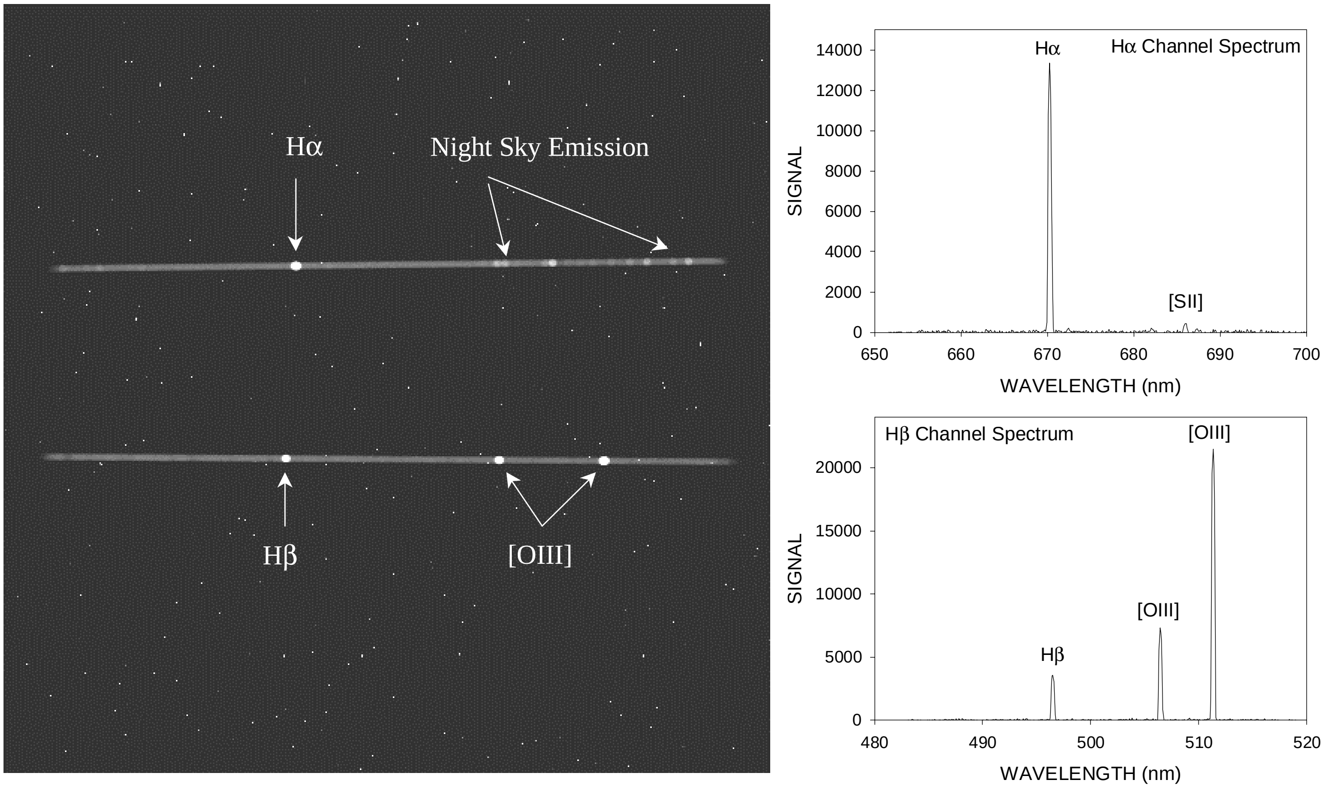

Figure 7 - CCD image of the spectrum of a faint blue galaxy taken with a VPH multiplex grating. The top spectrum is from a 1200 l/mm grating designed to diffract the light around Hα. The bottom spectrum is the Hβ region diffracted by a 1620 l/mm grating. A slight tilt between the fringe planes of the two gratings separates out the spectra as can be noted by the slight tilt of each spectrum. This particular grating assembly has an efficiency of 93% for the Hα channel and about 75% for the Hβ channel.

5. THE FOCAL SURFACE

There are two drivers for making a narrow, but long field of view for the spectrograph. The first is the difficulty in the optical design along the lateral field angles due to the longitudinal chromatic aberration and spherochromatism discussed previously. The second arises from the bandwidth issue of the gratings mentioned above. Although this shape for the field is not completely desirable, it does have some benefits.

For NGOS, the rectangular shape of the field allows significant area in which to place pickoff cameras for slit mask alignment and guiding of the telescope. There will be two regions on either side of the science field, each with field areas on the order of 10 by 30 arc-minutes. In such a field there will be more than enough acquisition, alignment, and guide stars. One could implement imagers that will compute the required linear and rotational offset in the slit mask without requiring a reconfiguration of the spectrograph into an imaging mode for optimal slit mask alignment. These imagers would also be left in place during the course of the observation allowing fine guiding through the slit mask and focus monitoring as well as providing an indicator as to when a new slit mask might need to be inserted to compensate for atmospheric refraction.

A minor benefit of this design may apply to such instruments on very large telescopes (8-meters and larger) in which a wide field of view can be enormous in terms of physical dimensions. In order to best utilize the focal plane with minimal technical risk, it will most likely be necessary to subdivide the focal surface into subsections, each viewed by its own spectrograph. Subdivision may be made somewhat easier with a narrow, but long focal area rather than with square or round areas, especially if more than four subdivisions are needed.

6. BEAM DIAMETER

We opted to work with a 200 mm beam size for NGOS for the following two reasons.

The first is to decrease the line frequency of the gratings for a given resolving power so that the bandwidth issue at high dispersion could be reduced. As pointed out by Robertson et al. in their paper on the ATLAS instrument[5], the resolving power for a fixed slit width scales as either the beam diameter or the dispersion of the grating. For comparable slit widths, NGOS will achieve the same resolution as ATLAS with a grating line frequency of less than 80% than that required for ATLAS due to the 200 mm beam diameter of NGOS compared to the 150 mm beam for ATLAS. This makes a somewhat significant improvement in the bandwidth performance as a function of the lateral field angles for the higher dispersion gratings.

The second reason for such a large beam diameter is for simplification of the optical train by better matching the size of the pupil to that of the image plane. Although we are still poorly matched to the size of the input image, it is unlikely that an instrument with a beam size any larger than 200 mm would fit within the space constraints at the telescope.

The bandwidth problem with our low line density grating may be alleviated somewhat by actually shrinking the beam diameter in order to allow the use of a higher dispersion grating for the low resolution case. This would increase the angle at which the blue light would be diffracted into second order. We have not yet performed any design studies to understand the tradeoffs in this situation. The likely result will be that we will encounter more difficulty in achieving good image performance at the extremes of the long axis of the image surface due to the smaller beam diameter being a poorer match to the physical size of the input image.

7. STRUCTURAL ISSUES AND CONCEPTS

Figure 8 displays a possible configuration for fitting NGOS within the mounting envelope of the Mayall telescope. The close proximity of the equatorial fork assembly and the long optical length of NGOS required that NGOS contain a folding flat within the collimator assembly. This is similar to the folding of the ATLAS instrument being designed at the Anglo-Australian Observatory[5].

While the large aperture of NGOS offers the promise of wide-field spectroscopy, it also introduces the problem of how to configure and mount such a necessarily large and massive instrument without excessively straining the telescope that carries it. Cantilevering it from the back of the primary mirror cell may introduce moments into the cell that alter its ability to provide a stable reference and support for the primary mirror for all orientations. The existing Cassegrain cage, a relic of the “observer-in-the-cage” days, will be removed and an instrument cabinet installed that will carry NGOS in neutral suspension

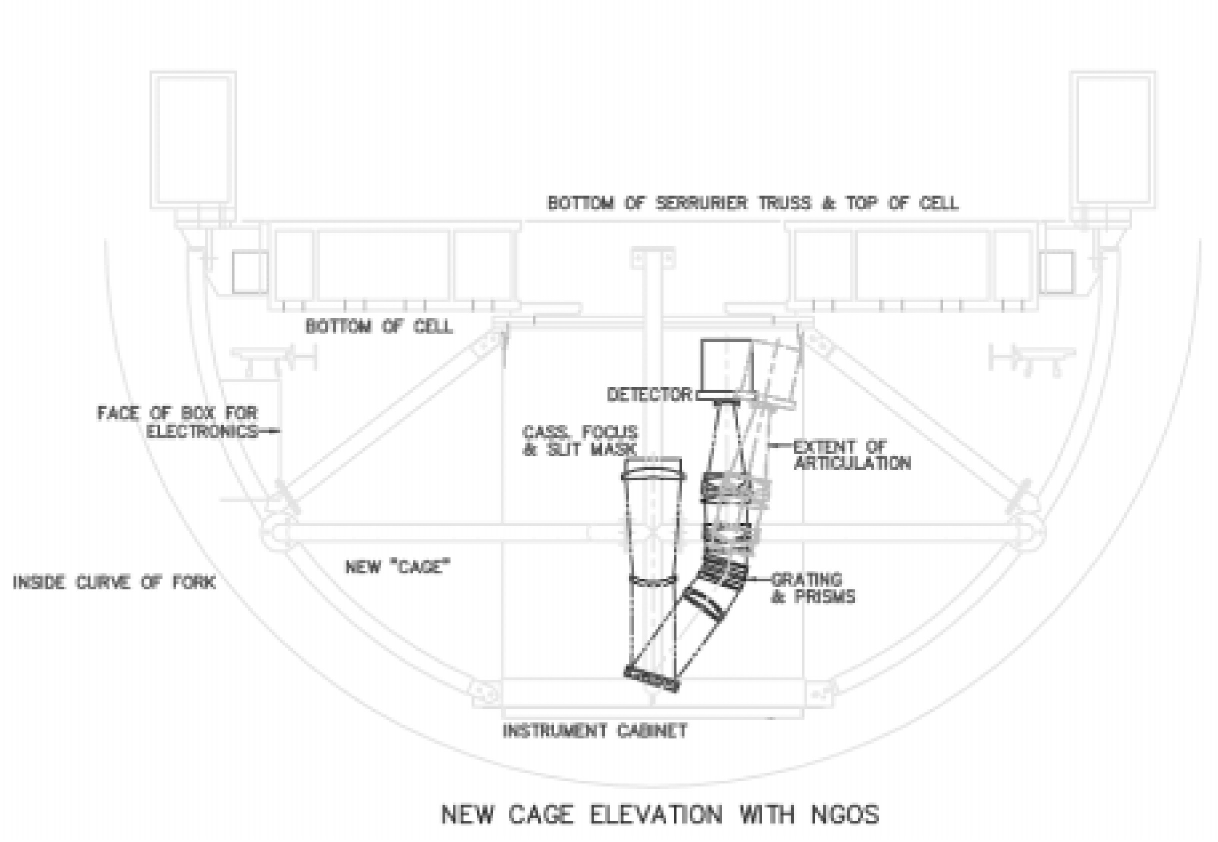

Figure 8 - Schematic view of NGOS mounted at the RC focus of the Mayall telescope. A new cage and instrument cabinet replaces the old “Cass Cage”. A fold mirror in the collimator optical train is required to fit the long instrument without interfering with the telescope equatorial fork. The envisioned extent of camera articulation is also displayed.

inside. The same cabinet will have the capability to support other instruments, large or small, and will allow easy installation through the end furthest from the primary. This “new cage” that will be designed for installation behind the cell of the 4-meter Mayall telescope will carry much of the weight of NGOS directly to the converging points of the members of the Serrurier truss that supports the entire end assembly. Thus, the primary mirror cell’s roll in supporting NGOS will be much diminished and undesirable moments will be eliminated.

The physical size of NGOS is such that deflections from the weights of its own components in its frame could compromise the optical alignment. Compensating components with counterweights has been considered, but as of this writing, achieving neutral suspension with three-dimensional Hindle supports looks like a better answer. The frame that actually retains the components needs only to be strong enough to keep components aligned since the Hindle, whiffle-tree-type supports will actually carry the weights. Thus, the frame is freed of the mass required to maintain alignment through keeping frame deflections very low. The design of the Hindle supports becomes critical, however, and careful attention to where the load is transferred is necessary. Elimination of as much friction in the supports as can be accomplished is paramount, and some of the new methods in primary mirror support technology may be adopted for duty in the support of the NGOS optics.

The deep fold in the instrument allows its design to be compact and makes rotating NGOS within the cabinet for field alignment practical. An earlier configuration concept had such a lengthy extent that fixing its position within the cabinet was considered. Field rotation in that case would have been accomplished by rotating the slit mask, grating, and camera independently with accurate encoders and tapes determining the degrees of rotation. In other words, the instrument would have undergone a twist for rotational alignment rather than bulk rotation. The designers of future large instruments may need to consider similar strategies since instrument length, mass, and support will work against the maintaining of optical alignment whenever such behemoths are rotated.

We are restricting the range of camera articulation in NGOS to that required for the descoped resolution options. The low resolution grating requires a camera to collimator angle of about 10° and the high dispersion gratings require an angle of 36°. We plan to explore the use of immersion and/or deviation prisms to further minimize the range of articulation required to cover the two resolution regimes. One idea is to implement a set of Risley prisms in which the two prisms are rotated to define the amount of redirection required to aim the dispersed light into the camera.

8. CONCLUDING COMMENTS

NGOS and ATLAS build upon the technologies introduced by the DEIMOS and IMACS instruments in the development of modern, wide-field, imaging spectrographs. Such spectrographs will revolutionize wide-field, multi-object spectroscopy by allowing the highly efficient observation of very large samples of faint objects. This generation of instruments will take the studies first enabled by the fiber optic, multi-object instruments (Autofib, Hydra, 2dF, etc.) into the next regime of large number statistical examination. The collection of hundreds of thousands of spectra will become routine and surveys completed on much shorter timescales than are now possible. The implementation of NGOS and ATLAS on 4-meter telescopes brings those telescopes to full maturity in the utilization of their large fields of view for spectroscopic surveys. These newly instrumented 4-meters will provide excellent complementarity to the current generation of relatively narrow-field, large aperture telescopes. The development of these challenging instruments will also serve as a technological stepping stone for the spectroscopic instruments that might be required for wide-field, large aperture telescopes of the future[6,7].

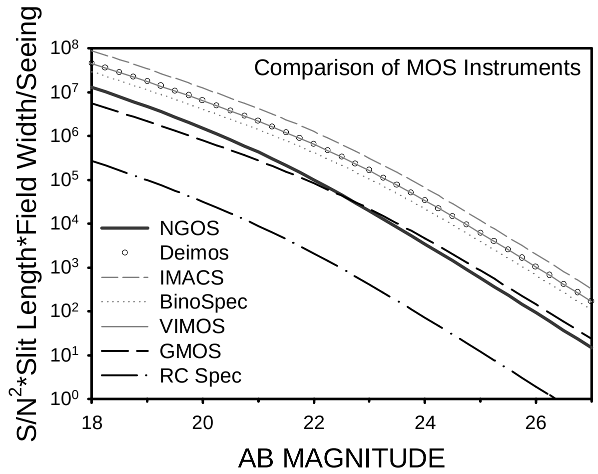

Figure 9 - Comparison in data collection rate for NGOS and other instruments on a variety of modern large telescopes.

This final figure (Figure 9) displays the power of NGOS on a 4-meter telescope in the era of 8-meter facilities. The vertical axis is a parameterization of the data collection capability of the instrument combining spectral signal with the field of view divided by image quality as a parameter for the number of objects that the instrument is capable of observing. Note the factor of 50 improvement for NGOS over the current RC spectrograph due to the higher efficiency and larger field of view for NGOS. Also note that the much larger field of view provided by the Mayall 4-meter with NGOS over that of GMOS on Gemini makes NGOS a faster instrument by factors of two to three for objects brighter than magnitude 21 AB. We also point out that the IMACS instrument outperforms all 8 and 10 meter class instruments due to the large field of view offered by the smaller 6.5-meter Magellan telescope.

9. REFERENCES

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