XMS and NG1dF: Extreme Multiplex Spectrographs for Wide-Field Multi-Object Spectroscopy

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ABSTRACT

Two feasibility studies for spectrographs that can deliver at least 4000 MOS slits over a 1° field at the prime focuses of the Anglo-Australian and Calar Alto Observatories have been completed. We describe the design and science case of the Calar Alto eXtreme Multiplex Spectrograph (XMS) for which an extended study, half way between feasibility study and phase-A, was made. The optical design is quite similar than in the AAO study for the Next Generation 1 degree Field (NG1dF) but the mechanical design of XMS is quite different and much more developed. In a single night, 25000 galaxy redshifts can be measured to z~0.7 and beyond for measuring the Baryon Acoustic Oscillation (BAO) scale and many other science goals. This may provide a low-cost alternative to WFMOS for example and other large fibre spectrographs. The design features four cloned spectrographs which gives a smaller total weight and length than a unique spectrograph to makes it placable at prime focus. The clones use a transparent design including a grism in which all optics are about the size or smaller than the clone rectangular subfield so that they can be tightly packed with little gaps between subfields. Only low cost glasses are used; the variations in chromatic aberrations between bands are compensated by changing a box containing the grism and two adjacent lenses. Three bands cover the 420nm to 920nm wavelength range at 10Å resolution while another cover the Calcium triplet at 3Å. An optional box does imaging. We however also studied different innovative methods for acquisition without imaging. A special mask changing mechanism was also designed to compensate for the lack of space around the focal plane. Conceptual designs for larger projects (AAT 2° field, CFHT, VISTA) have also been done.

Keywords: wide-field astronomy, multi-object spectroscopy, galaxy redshift surveys

1. INTRODUCTION

In the past few years there has been increasing appreciation of the contribution that small aperture telescopes with wide fields of view can make to astronomical imaging surveys. The Pan-STARRS project is one example. However, there has been less appreciation of smaller telescopes for wide-field multi-object spectroscopy. But the idea of étendue applies just as much to spectroscopic surveys as to imaging surveys and the cheap cost of CCD detectors makes possible a huge increase in the field for spectroscopy as well as imaging. Here we describe the basic concept, the full design and the science case for an extreme multiplex spectrograph for wide-field 4-m telescopes. The beauty of this instrument design is that there are a number of already existing 4-m telescopes with a 1° field or more where this instrument could be cheaply implemented. With a 1° field, a rate of ~4000 spectra an hour or ~30 000 spectra per night is achievable. With a 3 deg² field surface area, ~12 000 to 14 000 spectra per hour or ~100 000 spectra per night would be possible. These rates make many surveys possible, especially for cosmology. And the rates that are achievable may be competitive with much more expensive instrument proposals like WFMOS+SKA.

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We shall therefore begin by describing the optical design concept of our proposed wide-field spectrographs, and then give some examples of the powerful science that might be addressed by these instruments.

2. XMS/NG1DF CONCEPT

The fundamental technology driver here is the cheap cost of CCDs, which now makes it possible to tile a large focal plane cheaply and, coupled with an efficient optical design, still retain high image quality. As noted above, imaging surveys such as Pan-STARRS are already exploiting the étendue of small aperture telescopes with wide fields of view. Here we propose similarly to take advantage of the large étendue of 4-m class Ritchey-Chretien telescopes for extreme multiplex spectroscopy.

2.1 Number of slits

The conceptual design of the Extreme Multiplex Spectrograph (XMS) instrument for the Calar Alto 3.5-m and the Next Generation 1° Field (NG1dF) instrument for the AAT 4-m exploits this promising combination of aperture and field of view to allow slits to be placed on ~4000 targets. This estimate assumes 1.5" width and 5" to 10" length depending of the bandwidth and resolution used; far more slits could be targeted if the 10" slit width was reduced to a 1.5" aperture, with a few hundred such sky slots to map the sky over the whole mask. The estimate of 4000 targets also assumes that the spectra would have a length of 100 to 200 slit width images on the detector depending on the bandwidth and resolution.

![Figure 1. The field of view of XMS for the Calar Alto 3.5-m, similar to that to NG1dF for AAT 3.9-m (100% vignetting at 1.38°). The 1° field is divided into four rectangular subfields of 25' x 30'.](image)

2.2 Spectrograph at prime-focus

To use the large 1° field or more, the spectrograph must be at the prime focus. This put some constrains on its characteristics, mostly putting some limits on its weight and length. A unique spectrograph would easily be too large and too heavy so an array of smaller spectrographs was chosen instead. Our design contains 4 spectrograph units in each of

Proc. of SPIE Vol. 7735  77351Q-2
XMS and NG1dF. Each unit has its own detector. A larger number of units would be used at a site of exceptional seeing and/or a telescope with a larger field corrector. Figure 1 shows one of the studied designs for XMS although the baseline has gaps of about 4% of the total field width. The subfields are 100 mm x 120 mm wide at the corrector focus which corresponds to 25' x 30' on the sky. This size was designed for 4k x 4k detectors giving pixels of 0.44''.

Figure 2. The design of a single spectrograph unit for XMS; four of these are needed to cover the 1° field shown in Fig. 1. The box containing the disperser is changed when changing of bandwidth or spectral resolution or for imaging.

The spectra are 2.5' to 5' long depending on the bandwidth and resolution. For XMS, the distance from corrector focal plane to detector could not be more than 600 mm and only 50 mm more for NG1dF. The optics were therefore designed for these lengths. While there is some vignetting outside the 1° field, there is still a lot of light getting through in the 4 corners of the spectrograph so this region is not lost.
One difficulty when many spectrograph units are present is to place these units near each other to minimize the gaps in the field. Ideally, all optics in a spectrograph unit would be smaller than the subfield width. This would permit to pack the units tightly. This is achieved in our design by placing a field lens as near as possible to the input focal plane to bend the beams toward the centre (fig. 2). This also helps to make the spectrograph more compact. Mechanically, the spectrograph can be made as one structure or each unit can be a separate structure. A combination of both is also possible. While a unique structure would make the spectrograph more rigid for a specific weight and less expensive because simpler mechanically, it makes alignments more difficult.

2.3 Low cost spectrograph

For this concept to be practical, it is necessary that the price is maintained sufficiently low. A first part of the solution is to avoid the complex mechanism, size and spectrograph shape that comes with reflective gratings. A transparent disperser combining a transparent grating, as a grism or a VPH, with prisms permits to make the units straight (fig. 2) and makes it possible to place optics very near the disperser which in turn reduces the size of the spectrograph and reduces the aberrations. Different dispersers will have different prism angles and materials depending on the band and spectral resolution. For low spectral resolution, a grism or a grism plus a prism would do. For high resolution, VPH glued to prisms would be the preferred option.

The second part of the solution is to use low cost glasses. This however makes it difficult to design the spectrograph achromatic. To resolve this problem, we take advantage of the need to change the disperser when changing of band or spectral resolution. In our solution, two lenses are changed with the disperser. These lenses can be made small and thin and would fit in a small box with the disperser (fig. 2). A special care must be taken when designing them to avoid the need of tight alignments of the disperser boxes which would increase the cost. In our design, the tolerances have values of about 30 µm which standard precision. Also, the box tolerances can be relaxed if the other tolerances are made slightly tighter. One or more of the boxes can be made of lenses only and used for imaging; alternately, the disperser alone could be replaced by some optics in each box. We made one independent imaging box in our design.

![Image](image-url)

**Figure 3. Interchangeable disperser boxes of XMS.**
2.4 Spectral resolution and wavelength range

To fit different scientific projects, the designs of both XMS and NG1dF was made with 4 disperser boxes:

- Blue band: 0.42 µm to 0.52 µm with 10Å resolution with a 1.5" slit.
- Intermediate band: 0.52 µm to 0.72 µm with 10Å resolution with a 1.5" slit.
- Red band: 0.72 µm to 0.92 µm with 10Å resolution with a 1.5" slit.
- HR: 0.847 µm to 0.874 µm (Calcium triplet) with 3Å resolution with 1" slit.
- Imaging: 5% bandwidth around 0.62 µm.

The priority is the intermediate band at 10Å resolution. Figure 3 shows the optical design of the 5 boxes for XMS. Note the increase in the prism angles with spectral resolution to compensate for the larger beam deviation of the grating.

Much higher resolutions are also possible but request some significant changes to the design. The camera and collimator could not be maintained in a straight line; the camera would need to be at an angle. This is feasible with a spectrograph that has no more than 6 units but would be more difficult with a larger number of units where some are completely encircled by other units.

A minimum design would have only 2 bands, for example the intermediate and red band. This would permit to simplify the design, improve image quality and reduce cost. The other boxes could have more lenses and be added in a 2nd phase.

2.5 Changing mechanism

To maintain a low cost, there must be as little mechanisms as possible. The basic concept is to use only one disperser per night and to have it changed by hand during the day. It may however be necessary to have some imaging capability for acquisition. If no practical alternative method can be found, it would be necessary to have a changing mechanism with 2 positions, most probably a slide. Both the studies of XMS and NG1dF include such a mechanism. We also studied different alternative methods of acquisition without imaging.

Figure 4. Transmission of XMS including telescope and detector but excluding the atmosphere; NG1dF transmission is very similar.
The problem is different for the mask; many of them are necessary every night. The 2 main alternatives are a wheel or a jukebox like mechanism as in GMOS. The wheel would support a smaller number of masks than the jukebox but is a simpler mechanically. Since we expect to need up to 9 mask per night, a jukebox was designed.

3. PERFORMANCES

The present design gives good transmission and image quality but these must be considered as minimums because much can be done to improve the design. While there is some vignetting, it is limited.

3.1 Transmission

The transmission of the whole system from primary to and including the detector (but excluding the atmosphere) is significantly higher than the typical transmission of fibre spectrographs (fig. 4). It is around 40% for our main bandwidth. The transmission in the blue drops quite fast toward the shortest wavelength but this is mostly because no effort was made at this stage of the project to take transmission into account when designing the optics. The transmission at the shortest wavelength can be increased by changing the glasses with worst transmission in that region and by optimizing the thicknesses of the lenses.

3.2 Image quality

Table 1 shows the image quality of the latest design of XMS. While the PSF width is significantly smaller than the slit width, it is still quite large compared to an optimum system considering that there are other sources of image blurring as misalignments and surface errors. The design is far from being at its limit however, different strategies can be adopted to improve it:

- Add one or 2 lenses to the HR disperser box: the whole design is drove by the difficulty to give a good image quality using this box. In figure 3 for example, we can see that the first lens is quite far from the disperser. It was right by it when the preliminary design was made with only the 3 normal resolution bandwidths. Adding lenses to the HR box would decouple it from the others which would improve the resolution of all bands.
- The design was started with 2 bands, then the 3rd was added and then the high resolution. Restarting the design from scratch with all boxes from the beginning may very well converge to a different design. In other words, the optimization process may be trapped in a local minimum in the space of all possible designs.
- Split doublets.
- Add one or 2 lenses to the whole spectrograph.
- Add aspheric surfaces (only one in the present design).
- Change glasses.

The image quality will definitely be better in the final design.

Table 1. Image quality at the detector

<table>
<thead>
<tr>
<th>Type of grism box</th>
<th>50%EED</th>
<th>50%EED</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>average</td>
<td>arcsec</td>
</tr>
<tr>
<td>4200A to 5200A</td>
<td>0.68</td>
<td></td>
</tr>
<tr>
<td>5200A to 7200A</td>
<td>0.72</td>
<td></td>
</tr>
<tr>
<td>7200A to 9200A</td>
<td>0.71</td>
<td></td>
</tr>
<tr>
<td>High resolution</td>
<td>0.70</td>
<td></td>
</tr>
<tr>
<td>imaging</td>
<td>0.53</td>
<td></td>
</tr>
</tbody>
</table>
3.3 Vignetting

Some of the light is lost through vignetting in 2 different ways. First, there is some vignetting in the corrector at a radius larger than 0.5°. Second, there is some vignetting at the field lens just after the corrector/mask focal plane if the spectrograph sub-fields are placed near each other as in figure 1. The resulting distribution for XMS is given in table 2. Very little surface area is of low throughput.

<table>
<thead>
<tr>
<th>Transmission</th>
<th>Percentage of field</th>
</tr>
</thead>
<tbody>
<tr>
<td>100%</td>
<td>80.3%</td>
</tr>
<tr>
<td>50% to 100%</td>
<td>16.1%</td>
</tr>
<tr>
<td>less than 50%</td>
<td>3.6%</td>
</tr>
</tbody>
</table>

Table 2. Total vignetting distribution for XMS

4. MECHANICAL DESIGN

The mechanical designs of XMS and NG1dF follow different basic ideas. While the design of XMS is highly modular, the design of NG1dF has significantly less individual pieces.

Figure 5. Modular mechanical design of XMS.
4.1 XMS

The basic idea behind the XMS mechanical design is that the spectrograph units must be completely independent in order to be assembled, aligned and tested independently. They would be integrated into one instrument only at the end. To simplify the complexity, each spectrograph unit is also made of modules that are relatively easy to assemble (fig. 5). This makes it easier to assemble each unit. As shown by figure 6, XMS is a small instrument considering its capability. A complete description of the mechanical design is given in [7].

Figure 6. Global view of XMS showing how small the instrument is.

Figure 7. Mask mechanism with the mask in its position just after insertion (left) and in its final position on the focal plane (right).
Figure 8. Global view of NG1dF (left); view of the focusing mechanism (right).

Figure 9. NG1dF on the top end of the AAT with the 1º corrector.
4.2 XMS mask unit

The space between the corrector and the spectrograph, and around the spectrograph, is quite tight for XMS. A special mask unit had to be designed. Contrary to usual designs, the mask is inserted lower than the focal plane, then pushed up into position (fig. 7).

4.3 NG1dF

In Ng1dF, each set of 4 identical lenses are on a unique mount. While this makes alignments more complex, it significantly reduces the complexity of the mechanical design so the cost of the instrument. A carefully studied alignment plan would have to be developed. Figure 8 shows a global view and the focusing mechanism. It moves separately each doublet just after the disperser box. This lens was chosen for focusing because it gives much higher precision and image quality than moving the detector or another lens. Figure 9 shows NG1dF on top of the corrector. Again, we can see that it is a small instrument as XMS.

5. UPGRADES

While XMS and NG1dF are powerful instruments, future improvements are possible to significantly increase the capabilities of these instruments.

5.1 Multi-IFU masks

In this option, sturdy masks would be made in which small IFUs could be plugged-in. The holes in the mask would be for holding the input IFUs and their output small slits. Figure 10 shows one of these IFUs. It has an input of 10 x 10 lenslets feeding fibres each 0.6" in size. The output slit would be only a few mm long. The mask could theoretically hold 200 of these although 50 would already give some very interesting science.

![Design of a mini-IFU button to be plugged in a multi-IFU mask](image)

Figure 10. Design of a mini-IFU button to be plugged in a multi-IFU mask; note the scale of 1 mm at the bottom which shows how small these IFUs are compared to a mask of 250 mm x 210 mm.
5.2 Microslice system with hundreds of thousands of spaxels

An exciting possibility would be to transform the spectrograph into a huge integral field spectrograph with many arcmin$^2$ of surface area. This would use the technology of microslice systems which are made of cross-cylindrical microlens arrays that are similar to system as TIGER and SAURON but with 4 to 6 times more spectra for the same spectrograph. With the present spectral resolution of 10Å and length of 2000Å, the system would have 60 000 spaxels (so spectra). With small spectral length of 300Å, 300 000 spaxels would be available on a field of 9.1' x 6'.

6. OTHER PROJECTS

We made a proposal for an extreme multiplex spectrograph for the 2° field of the AAO that we called NG2dF and another for a similar but smaller instrument on the CFHT that we called MegaMOS (fig. 11). NG2dF would permit 12 000 to 14 000 spectra simultaneously compared to the 4000 of XMS/NG1dF. MegaMOS would give at least 8000 because of its better seeing. We were also approached for a next generation instrument for VISTA using a future very large visible corrector of 2.6°. It would give 19 000 to 24 000 spectra simultaneously.

![Fig. 11. Fields of view of other projects using the basic design of XMS/NG1dF. Even with these complex field shapes, the sky can be mapped without losses of field (bottom left with MegaMOS field).](image)

7. SCIENCE CASE

There are many science goals for an instrument of this sort, ranging from galaxy surveys for cosmology at low resolution (R~400) to stellar radial velocity and abundance surveys at 10x higher resolution (R~4000). Here we concentrate on the low resolution cosmological aspects which form our particular interest in the science from these instruments.

7.1 Emission and absorption line galaxy redshift surveys at z~0.7.

A prime cosmological goal for the NG1dF/XMS instruments is based on their ability to measure 4000 galaxy redshifts per hour for i<21 absorption-line and i<22 emission-line galaxies at z~0.7 (see Fig. 12). 4000 emission/absorption redshifts an hour means ~30000 redshifts a night or ~6 x10$^9$ galaxy redshifts in a 200 night survey. Such a survey could cover 1000-2000 deg$^2$ of sky and enable powerful new investigations of the clustering of galaxies to be made over a wide range of scales (0.1-1000h$^{-1}$Mpc). Deeper surveys to z~1 would also be possible with a smaller total number of galaxies.
A prime aim would be to measure the scale-length of Baryon Acoustic Oscillations (BAO) as detected in galaxy clustering power spectra and correlation functions. These features are seen as an oscillation in the power spectrum and as a spike in the galaxy correlation function. These features can be used as standard rods and allow tests of cosmological models. In particular, such observations will allow us to probe the equation of state of the vacuum energy, $p=w\rho$. Currently, the spike in the correlation function is tentatively detected in the 2dF Galaxy Redshift Survey of 250 000 $z<0.1$ galaxies and also in the SDSS redshift survey of $\sim 75$ 000 $z<0.35$ Luminous Red Galaxies. In the future, bigger galaxy surveys will be needed to measure the BAO scale at higher redshifts and hence track any evolution in the vacuum energy equation of state with redshift. Instruments like NG1dF/XMS therefore will have a crucial role to play in the future of observational cosmology.

There are enough galaxies at the magnitude limits quoted above to fill $\sim 4000$ NG1dF/XMS slits since galaxy count data suggest that there are $\sim 4000$ galaxies per square degree at $i<21$ and $\sim 9000$ at $i<22$, 5000 of which will show emission lines. The $\sim 9000$ absorption and emission line galaxies available in total will make it more possible to place slits on a subset of $\sim 4000$ galaxies. The future for BAO studies is to identify systematics caused by non-linearity in galaxy power spectra that may result in different scale-lengths being measured for different types of galaxy. The high multiplex of NG1dF/XMS will, for example, mean that a choice will no longer have to be made between emission-line galaxies and luminous red galaxies for BAO measurement since both can be observed simultaneously in the same volume and the BAO results compared. Similar comparisons can be made as a function of morphology and luminosity class, given the high numbers of galaxies available.

Other cosmological applications of redshift surveys containing millions of $z<0.7$ galaxies will include measuring the rate of growth of structure using galaxy clustering redshift-space distortions. Here the flattening of galaxy clustering in redshift-space caused by dynamical infall is used to provide a measure of the infall parameter $\beta=\Omega_{\text{m}}^{0.6}/\beta$ and measuring $\beta$ at different redshifts gives the gravitational growth rate. This provides a test of Einstein’s gravity independently of geometrical cosmological tests using standard candles and rods, such as BAO. Redshift distortion results can also be used to give an estimate of the masses and hence mass-to-light ratios of galaxy group haloes in CDM models. These allow new tests of the efficiency of the process of galaxy formation as a function of halo mass environment. There are too many examples of other galaxy redshift survey-based projects to detail here. These include the vast array of results that will be available on the topic of the dependence of the galaxy stellar mass and luminosity function on environment and redshift.

### 7.2 Lyman break galaxy redshift surveys at $z<3$.

More ambitiously, it may be possible for 4-m telescopes to compete effectively on surveying the Universe of galaxies at redshift, $z<3$. In 4x3hr exposures, spectra for $\sim 4000$ $r<25$ Lyman break galaxies at $z<3$ (fig. 13) can be measured, producing 100 000 $z<3$ galaxy redshifts in a 50 night survey. Although the exposure time is long, a single mask will produce as many redshifts at $z<3$ as are currently known from larger telescopes. A prime scientific aim would then again be to measure the BAO scale in the LBG clustering, allowing the first constraints on the dark energy equation of state at $z<3$. Furthermore, measuring redshift space distortions in the galaxy clustering would give constraints on the gravity model at $z=3$ and also allow the dependence of the halo M/L ratio on redshift to be estimated and hence the evolution with time of the efficiency of the galaxy formation process. In terms of a survey plan that would include the lower redshift $z<0.7$ galaxies discussed in Section 3.1, in a total survey time of 250 nights, flexible scheduling might allow the 50 nights with the best seeing to be used to observe fainter LBG targets with 1 arcsec wide slits and the remaining 200 nights could be used for the $z<0.7$ galaxy redshift survey where 1.5-2 arcsec wide slits might be used. This 250 night survey plan might then realize redshifts for 100 000 $z<3$ LBGs as well as for $\sim 6$ million $z<0.7$ galaxies.

### 7.3 Calibration of photometric redshifts

A prime use of galaxy surveys like both of those above will be the calibration of photometric redshifts. These are needed to support satellite surveys such as SNAP and also EUCLID which is the new ESA dark energy mission resulting from the merging of SPACE and DUNE. For example, it has been suggested that up to $\sim 100$ 000 spectroscopic redshifts may be needed to calibrate the large photometric redshift surveys planned in the case of the SNAP satellite. Large numbers of galaxies are particularly needed where large galaxy redshift training sets are needed as in the case of Artificial Neural Network (ANN) photometric redshift codes. The NG1dF/XMS absorption and emission line galaxy redshift surveys described above will be uniquely placed to satisfy this huge demand for spectroscopic redshifts for photo-z calibration and would complement the work of these satellites, for example EUCLID would not observe galaxies at a redshift smaller than 0.7.
7.4 Stellar velocity and abundance surveys

In its higher resolution mode (R~4000) NG1dF/XMS can also be used for a variety of other purposes. At low Galactic latitudes and in the Galactic bulge, stars brighter than $i=15$ will have sky densities larger than 4000 per deg$^2$ and can therefore be efficiently observed with this instrument. At these magnitudes, 1-2hr observations will yield an S/N per Angstrom $> 50$ and thus allow stellar radial velocities and abundances of useful accuracy to be achieved. This will allow...
Galactic archaeology projects searching for stellar streams in the Galactic bulge and thick disk to proceed. Although the velocity accuracy will not be high enough in nearby dwarf galaxies, stellar abundance studies will certainly be possible in the higher resolution mode of NG1dF/XMS.

Fig. 13. Seven spectra of Lyman break galaxies at z~3 from a VLT VIMOS survey. Two faint QSO spectra from the same survey are also shown. These spectra taken with the VIMOS LR Blue grism have lower resolution (~20 Angstroms) and show that such surveys will be perfectly possible with the default 10 Angstrom resolution of the NG1dF/XMS spectrographs.

8. CONCLUSIONS

Clearly, spectrographs such as NG1dF/XMS have huge potential impact in terms of the significant science goals they address. There are many ground-based optical and near infra-red imaging surveys coming up such as Pan-STARRS, VST ATLAS+KIDS, ALHAMBRA/PAU, Dark Energy Survey, VISTA Hemisphere Survey and VIKING surveys and also LSST. These will inevitably need spectroscopic follow-up and NG1dF is ideally designed to do this. This spectroscopic follow-up will include the major science programs described above including the measurement of the BAO scale and the measurement of the evolution of the gravitational growth rate. These address major science questions including the nature of dark energy and its evolution and whether Einstein’s gravity can explain the observed growth of large-scale structure. However NG1dF/XMS are not “niche instruments” because of the wide variety of science goals they can pursue, of which we have only noted a few examples here.

A major driver is that these instruments can exploit already existing 4-m telescopes with large fields of view and therefore this helps keep costs low. The modular spectrograph design is also aimed at being relatively low-cost as well as maintaining high throughput over a wide field of view.

We conclude that the future for classically designed 4-m telescopes with large fields may be bright if they are armed with spectrographs such as NG1dF/XMS. Indeed, such telescope-instrument combinations may offer a very cost-effective solution to pursuing the large-scale cosmological surveys that are needed to address the fundamental questions of the dark energy and its evolution with redshift and one which is competitive scientifically with more ambitious projects such as WFMOS and SKA.
REFERENCES


