Wide Field UV/Optical Spectroscopy on TMT

K. Taylor[1], M. C. Britton[1] and D. J. A. Jones[2]

[1]California Institute of Technology, 1200 E. California Blvd. Pasadena, CA 91125, USA, E-mail: kt@astro.caltech.edu, mbritton@ astro.caltech.edu

[2]Prime Optics, 17 Crescent Rd., Eumundi, Qld 4562, Australia, E-mail: opticsfx@bigpond.net.au

Abstract: As the aperture (**D**) of ground-based telescopes becomes larger, the more we are required to justify the scientific advances that are predicted to flow. This is especially true of ELTs, not just because their cost will be so large, but because no significant benefits are likely to come from the development of superior ground-based sites. This issue is captured in quantifying the signal-to-noise ratio (SNR) gains as a function of aperture; the so-called $\mathbf{D}^{\mathbf{N}}$ gain. It is a commonly held belief that a $\mathbf{D}^{4}$ gain is a unique characteristic of diffraction-limit science and hence the emphasis for all ELT programs on achieving the diffraction limit through Adaptive Optics. We analyse here the variation of **N** as a function of fundamental instrumental parameters such as spatial and spectral resolution in order to better understand and quantify these gains in realistic noise conditions. Our primary motivation is to better understand the case, if it exists, for seeing-limited spectroscopy on ELTs with special regard to the 30m TMT project.

1. INTRODUCTION:

For seeing-limited science on TMT, a $\mathbf{D}^{2}$ gain may be sub-critical. A factor of ~9 in sensitivity gain over the 10-m Keck telescopes may not be enough to justify the substantial cost of building a 3-times scaled up version of a multi-slit spectrograph such as DEIMOS[1]. While a factor of 9 may appear compelling in an historical context, it has to be balanced by a number of detrimental considerations. Primary amongst these are:

- The field of view (FoV) of a classical multi-object spectrograph is inversely proportional to **D**, all else being equal. FoV, or more specifically object multiplex, is a major component of metrics which quantify the information gathering capacity of such a spectrograph. This has the potential for completely negating the $\mathbf{D}^{2}$ advantage.
- The cost per night on an ELT is a steep, though poorly quantified, function of **D**. Such increased costs will inevitably translate into reduced access for a given science program.

Unless seeing-limited spectrographs for TMT are scaled, at great cost, both in beam-size and FoV, to mitigate these factors, the science they can do is likely, in many cases, to be eclipsed by the current 8-10m telescopes.

It is a fact, however, that $\mathbf{D}^{2}$ sensitivity gains in the UV/optical, outside the wavelength régime where AO-correction is currently possible, are themselves significant and hence such arguments cannot be used to rule out seeing-limited, multi-object spectrographs for ELTs completely. Nevertheless it is clearly imperative that great care be taken to optimize these facilities through appropriately targeted strategies and through harnessing the unique attributes that ELTs have to offer.

1. THE $\mathbf{D}^{4}$ ADVANTAGE:

In the simplest terms, object flux is $\propto \mathbf{D}^2$ while the spatial resolving power at the diffraction limit, $\boldsymbol{\Gamma}_{\mathbf{DL}}$ $(=\mathbf{D}/\lambda) \propto \mathbf{D}$. It is clear, therefore, that sky-background flux ($\propto \mathbf{D}.\boldsymbol{\Gamma}_{\mathbf{DL}}{}^2$ is independent of **D** and hence sensitivity is $\propto \mathbf{D}^4$. This assumes, however that the observations are sky-background noise limited and, more critically, that the objects under study are unresolved at the diffraction limit (DL). Neither of these assumptions are universally valid and hence let us look more closely at the SNR derivations.

It is immediately apparent that there are two cases to be considered; the spatially resolved ($\mathrm{SNR_R}$) and spatially unresolved ($\mathrm{SNR_{UnR}}$) case. Hence:

$$\mathrm{SNR_R} = (\boldsymbol{\sigma}.\mathbf{D}^2.\boldsymbol{\tau}.\boldsymbol{\Gamma}^{-2} \,.\, \{\, [\boldsymbol{\sigma}.\mathbf{D}^2.\boldsymbol{\tau}.\boldsymbol{\Gamma}^{-2}] + [\mathbf{S_{Bg}}.\mathbf{D}^2.\boldsymbol{\tau}.\boldsymbol{\Gamma}^{-2}] + [\mathbf{N_{De}}.\boldsymbol{\tau}]\}^{-½} \qquad (1)$$

while:

$$\mathrm{SNR_{UnR}} = (\boldsymbol{\sigma}.\mathbf{D}^2.\boldsymbol{\tau} \,.\, \{\, [\boldsymbol{\sigma}.\mathbf{D}^2.\boldsymbol{\tau}] + [\mathbf{S_{Bg}}.\mathbf{D}^2.\boldsymbol{\tau}.\boldsymbol{\Gamma}^{-2}] + [\mathbf{N_{De}}.\boldsymbol{\tau}]\}^{-½} \qquad (2)$$

where:

$\boldsymbol{\sigma}$ is the object flux;

$\boldsymbol{\tau}$ is the exposure time;

$\mathbf{S_{Bg}}$ is back-ground flux;

$\mathbf{N_{De}}$ is the detector noise.

The 3 bracketed noise terms in the denominators are from object, sky-background and detector. Here the long exposure (faint object) limit is assumed where the detector noise (read plus dark) is taken as approximately proportional to exposure time, τ.

From equations (1) & (2) we can construct the following matrix (Table 1).

		Spatial Resolving Power		
Noise condition	**Spatially …**	$\boldsymbol{\Gamma}_{\mathbf{SL}}$	Transition	$\boldsymbol{\Gamma}_{\mathbf{DL}}$
Source-limited	Resolved	$\mathbf{D}^2$	↔	$\mathbf{D}^0$
	Unresolved	$\mathbf{D}^2$	↔	$\mathbf{D}^2$
Sky-limited	Resolved	$\mathbf{D}^2$	↔	$\mathbf{D}^0$
	Unresolved	$\mathbf{D}^2$	↔	$\mathbf{D}^4$
Detector-limited	Resolved	$\mathbf{D}^4$	↔	$\mathbf{D}^0$
	Unresolved	$\mathbf{D}^4$	↔	$\mathbf{D}^4$

Table 1: SNR dependences on aperture, **D**, as a function of noise conditions and spatial resolution. The extremes of spatial resolution at the seeing-limit (SL) and diffraction-limit (DL) are given.

Table 1 clearly demonstrates that the $\mathbf{D}^4$ advantage is not universally confined to the diffraction-limit (DL). Also, at the DL, the index N varies over the full range from 4 to 0. For the purposes of clarity we limit ourselves to the faint object case and hence ignore the source-limited régime. In this context, it is useful to define a critical spatial resolving power, $\boldsymbol{\Gamma}_{\mathrm{C}}$, (= $\mathbf{D}/\boldsymbol{\lambda\eta}_{\mathrm{C}}$) where $\boldsymbol{\eta}_{\mathrm{C}}$ (<1) defines the value of $\boldsymbol{\Gamma}_{\mathrm{C}}$ where detector noise ($\mathbf{N_{De}}$) and sky-background noise ($\mathbf{S_{Bg}}.\mathbf{D}^2.\boldsymbol{\Gamma}^{-2}$) are equal. Table 1 can thus be summarized as follows:

- **When $\eta > \eta_{\mathrm{C}}$ (including DL, where η=1):** Observations of spatially resolved objects go as $\mathbf{D}^0$, whereas observations of faint, spatially unresolved objects go as $\mathbf{D}^4$.
- **At the seeing-limit (SL):** All observations go as $\mathbf{D}^2$, unless they are detector-noise limited (eg: at very high dispersion) where they go as $\mathbf{D}^4$.

A natural question then arises: What spectroscopic conditions define the critical spatial resolving power, $\boldsymbol{\Gamma}_C$, which itself defines the transition from a SL to DL dependency? Clearly the balance between detector noise ($\mathbf{N_{Dc}}$) and sky-background noise ($\mathbf{S_{Bg}}.\mathbf{D}^2.\boldsymbol{\Gamma}^{-2}$), at which η_C is defined, is a function of system and observational noise parameters but, once these are defined, η_C is principally a function of spectral resolution.

As an example, let us assume the following spectroscopic parameters:

- Telescope Aperture = 30m
- Detector read-noise: (CCD) = 2.5e- (rms) ; (HCT) = 7e- (rms)
- Dark-count: (CCD) = 0.001 Hz/pixel ; (HCT) = 0.02 Hz/pixel
- Pixel-size: (CCD) = 15μm ; (HCT) = 18μm
- Binning: (CCD) = Optimal defined by Nyquist sampling ; (HCT) = No binning
- Camera speed limit slower than f/2 (otherwise 2-pixels per spectral element)
- Anamorphism = 1
- System efficiency: (B,V,R,I) = 30% ; (U,J,H,K) = 20%
- Integration time = 4 hours with 8 detector reads
- Standard values for sky background flux

For such parameters we can now calculate the value of $\boldsymbol{\Gamma}_C$ (or the corresponding η_C) as a function of spectral resolution (**R**) as given in Figure 1; while Figure 2 shows the variation in $\boldsymbol{\Gamma}_C$ as a function of wavelength (λ) for a particular spectral resolution, **R**=4,000. With reference to Table 1, one way of interpreting Figure 2 is to recognize that, for faint spatially unresolved objects, the critical spatial resolving power, $\boldsymbol{\Gamma}_C$, defines the transition from a $\mathbf{D}^2$ to a $\mathbf{D}^4$ dependency. For the case of TMT, assuming standard spectroscopic parameters (as listed above) and a spectral resolution of **R**~4,000, critical spatial resolutions of typically 100mas are indicated. Significantly coarser than this, one is in a sky-background noise, $\mathbf{D}^2$, régime while significantly finer than this, one is in a detector noise, $\mathbf{D}^4$, régime. Now for TMT, a 100mas spatial resolution (at $\lambda \sim 1\mu$m) is equivalent to η_C ~0.07 and hence is a very long way from the diffraction-limit (DL). The notion that $\mathbf{D}^4$ science is the exclusive preserve of the diffraction limit is therefore quite inappropriate.

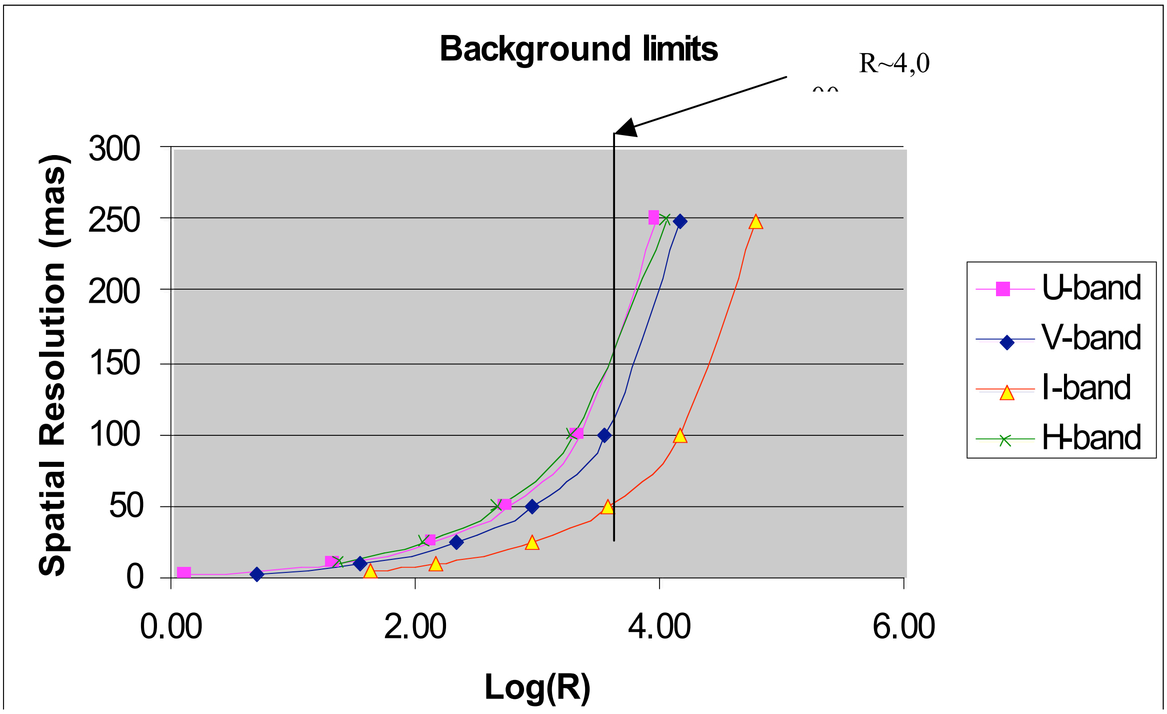

Figure 1: In this plot the ordinate (or y-axis) defines Γ_C in terms of spatial resolution (in mas) for a range of spectral resolving powers (**R**) for four photometric bands

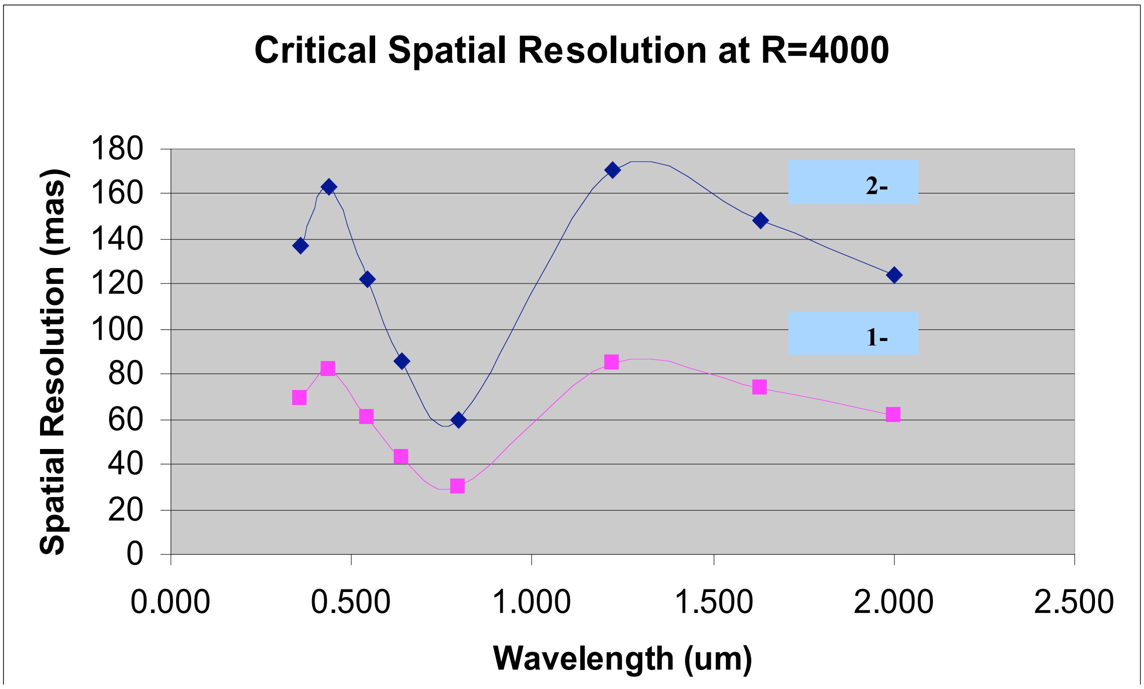

Figure 2: As in Figure 1, the ordinate defines Γ_C in terms of spatial resolution (in mas) but now for a fixed spectral resolution (**R**=4,000) for all wave-bands from U through K. The improvement in spatial resolution (Γ_C) obtained in the case of under-sampled spectral information (eg: 1-pixel per spectroscopic slit) is highlighted.

2. SEEING-LIMITED SCIENCE ON ELTS:

We have demonstrated in the above analysis that it is not necessary to achieve the diffraction-limit in order to be in the $\mathbf{D}^4$ science régime; a factor of ~10 coarser spatial resolution may be sufficient in many circumstances however, in order to achieve such intermediate $\boldsymbol{\Gamma}$s, near-DL adaptive optics (such as promised through techniques such as MOAO[2]) may be sufficient. Nevertheless, seeing-limited, UV/Optical, spectroscopy at intermediate (R~5,000) spectral resolution is firmly in the $\mathbf{D}^2$ régime even if enhanced through some variant of Ground-layer AO. So how can it be defended?

It is an undeniable fact that UV/Optical spectroscopy on ELTs is scientifically compelling, however in order to justify a significant investment in such instrumentation we are required to optimize sensitivity and object multiplex in a manner which takes maximum benefit from the increased aperture. Furthermore, such instrumentation is simultaneously required to be maximally efficient for single object spectroscopy. One way of achieving such ends is to take advantage of the simplest AO configuration (SLGLAO). As demonstrated in our accompanying paper[3], very significant sensitivity enhancements (factors >7) can be achieved in *typical* atmospheric turbulence conditions, well in advance of the more normally invoked GLAO. Indeed, in exceptional circumstances improvements down into the UV can be achieved. Most importantly however, the FoV over which such corrections can be effected is directly proportional to **D**. Thus SLGLAO is uniquely suited to ELTs and we conclude that seeing-limited spectroscopy should be configured to allow for such correction when the atmospheric conditions permit.

Inspired by this realization, the TMT **MILES** concept was born. **MILES** is a 4-shooter multi-slit UV/optical spectrograph which uses a focal reducer as a fore-optics relay to increase field of view (FoV), reduce the size of the multi-slit units and, most importantly, to facilitate SLGLAO by hosting a deformably mirror at a relayed pupil image in each of its 4 arms. In almost all observing conditions the SLGLAO facility permits sensitivity enhancement by concentrating the point spread function and permitting the use of narrower spectroscopic slits. The analysis presented here (and in our accompanying paper [3]) suggests that such a SLGLAO capability should always be considered as a part of any ground-based UV/Optical spectroscopic or imaging facility.

3. ACKNOWLEDGEMENTS:

This paper was prepared as part of the work of the Thirty-Meter Telescope (TMT) project. TMT is a partnership of the Association of Universities for Research in Astronomy (AURA), the Association of Canadian Universities for Research in Astronomy (ACURA), the California Institute of Technology, and the University of California. The partners gratefully acknowledge the support of the Gordon and Betty Moore Foundation, the U.S. National Science Foundation (NSF), the National Research Council of Canada, the Natural Sciences and Engineering Research Council of Canada, and the Gemini Partnership.

4. REFERENCES:

1. James et al., "DEIMOS: a wide field faint object spectrograph" *SPIE* Vol. 2871, pp 1107-1115, (1996)
2. D. Gavel, “Tomography for Multiconjugate Adaptive Optics Systems Using Laser Guide Stars”, *Advancements in Adaptive Optics, Proceedings of the SPIE,* Volume 5490, pp. 1356-1373 (2004).
3. M.C.Britton and K.Taylor, “SLGLAO”, These Proceedings