1- Introduction

In the baseline concept of the NGST-NIR spectrograph, MEMS are used to create the focal plane slit masks necessary for multiobject spectroscopy. When a unit of the MEMS array (hereafter, facet) is ON, the corresponding portion of the sky is selected and imaged (through the spectrograph) on the focal plane detector array.

In this note we will discuss how the pixel scale at the detector and the slit dimensions (width and length) affect the performance of the NIR-SPEC.

This discussion requires to analyse how the different sources of noise (zodiacal, detector, etc) interplay for the different designs. The key tool for this analysis is the Exposure Time Calculator (ETC). The most complete NGST-ETC is included in NMS (NGST Mission Simulator: Samsom and Petro, 2000). However, that ETC does not include the slit effects which are important for the discussion outlined above.

Therefore, as a first step we have developed a new ETC optimized for spectroscopy (Spectroscopic ETC; hereafter S-ETC) which takes into account the slit effects (i.e. slit losses; changes in the zodiacal light) and updates other relevant issues (Section 2). In Section 3 we discuss the figure of merit. In Section 4 we discuss how the sensitivity of the spectrograph changes for different choices of slits and pixels. In Section 5 the global efficiency (speed) for multiobject observations is analysed as a function of the pixel scale. In Section 6 the implications for the facet geometry and size are briefly commented. In Section 7 we outline the main preliminary conclusions.

A 6.5m. telescope (diffracted @ 2 µ) will be assumed through all this note. Two spectral resolutions (R=100 and 1000) will be discussed. DRM15 (Deep spectroscopic survey) is considered the science program leading the NIR-SPEC design.

2- Spectroscopic ETC

The main assumptions of S-ETC are:

i) PSF. Based on the simulated PSFs generated by Bely et al. (2001, NGST-Monograph nr. 7), transformed for a 6.5m telescope (diffr. at 2 µ). For the present calculations we have selected a PSF with low-frequencies of 0.144 µ (rms) in wavefront and the same
mid-frequencies as the Hubble. This PSF just fulfills the optical requirements for the OTA as established by Bely et al.

ii) Zodiacal. Based on the revised COBE data by Giavalisco et al (2001, private comm.).

iii) Slit. Slit losses assuming the above PSF (point sources) and changes in the zodiacal background depending on the slit width.

iv) Detector. For long exposures (DRM15) the dark current is the major contributor to the detector noise. A value of 0.02 e/s is considered.

v) Extraction. For the NIR-SPEC spectrum extraction techniques are going to be relevant, as the wings of the PSF will carry a relatively important part of the flux. S-ETC uses both the standard extraction procedure (no weights), and the ‘optimal extraction’ method (weights based on the variance: Horne, 1988, PASP, 98, 609). The successful application of these techniques depends on a detailed knowledge of the background, the detector noise, and the optical distortions of the spectrograph. For the results presented here it is assumed that this will be the case.

vi) Monte Carlo simulations of the central position of the object within a particular detector pixel.

### 3 Figure of merit

The ASWG ranked *ultimate sensitivity* as the first priority for the NGST instrumentation. Specifically, for the particular case of the NIR-SPEC, and because high redshifted galaxies in DRM15 will appear as point (or barely resolved) sources, sensitivity should be favour over resolution.

However, for multiobject observations the performance of the spectrograph will be measured by its *speed observing ‘interesting’ galaxies (at the required S/N) per unit of observing time*.

Initially, we will look for the pixel scale (and slit width) that maximizes sensitivity. Later we will analyse the speed of the spectrograph as a function of the pixel scale.
4 Sensitivity = F (pixel scale, slit)

4.1 Case slit = 2*pixels

R=1000

Initially we will consider the standard assumption that the slit width (*no the facet*) is sampled by two pixels on the detector.

Using S-ETC we have generated Figure 1 (top) which shows the S/N obtained in an arbitrary amount of observing time as a function of the pixel size in the detector. Further assumptions are indicated in the figure, but we highlighted that this was for R=1000.

The conclusion from figure 1 (top) is clear: If the slit is sampled by two detector pixels and R=1000, a scale of about 0.16 arcsec/pixel maximizes the S/N for a single observation, under the assumptions mentioned above. However, this selection is not critical, and values in the range 0.14-0.20 arcsec/pixel give virtually the same results.

Using a similar methodology Petro and Stockman (2000; http://www.ngst.stsci.edu/nms/main/docs.html) – for a 8m telescope, and without considering slit effects – found that a value of 0.11 arcsec/pixel maximizes S/N (minimizes Exp. t) for the NIR spectrograph. Taking into account the scale factor due to the mirror diameter, both analysis agree very well.

To better understand the behavior shown in Figure 1 (top) the other two panels indicate, independently, how the signal (middle panel) and the noise (bottom panel) change with the pixel size.

The behavior of the signal is rather obvious: Larger pixel implies larger slit width, then less light losses (more signal).

In the panel at the bottom the total noise (continuum line), as well as its breakdown into the individual noises is represented (dots: poissonian from the source, small dashes:detector, large dashes: zodiacal). The poissonian noise is clearly related to the signal from the source. The zodiacal light increases with the slit width. Detector noise is more important for smaller pixels, because this implies a larger number of pixels to cover the object along the slit. Note, however, that the zodiocal and detector noises have not a linear behaviour with the number of pixels, since the weights applied according to the ‘optimal extraction method’ imply a reduction of these noises (more important if many small pixels sample the spectrum along the slit).

\[ \text{Strictly speaking we are representing \( S/N/\sqrt{t} \) as a function of the pixel size. However, the factor \( \sqrt{t} \) has not relevance in the present discussion as it does not affect the shape of the curve.} \]
Figure 1: Top. $S/N$ (per $\sqrt{t}$) as a function of the pixel size \(2\times\)pixel size, for \(R=1000\).

Other assumptions are indicated in the upper right corner. Middle. Variation of the signal with the pixel size. Bottom. Variation of the noise with the pixel size. dot line: poissonian from the source, small dashes: detector, large dashes: zodiacal, continuum line: all noises combined

- **6.5m (PSF$^f$, 44; Bely et al. 2001)**
- 2 microns
- point source $K_aB$ = 27
- Slit length = 0.6 arcsec
- Mean Zodi. (Giavalisco 2001–WFC3)
- Dark current = 0.02 e/s
- Optimal Extraction (Variance)
- \(R=1000\)
- Slit width = $2\times$(pixel size)
Figure 2: Top. S/N (per $\sqrt{t}$) as a function of the pixel size (slit=2*pixel size), for R=100. Other assumptions are indicated in the upper right corner. Middle. Variation of the signal with the pixel size. Bottom. Variation of the noise with the pixel size. dot line: poissonian from the source, small dashes: detector, large dashes: zodiacal, continuum line: all noises combined
R=100

In figure 2 we present similar figures for the case R=100. Because in this case the zodiacal light is much more important, the advantage of having a reduced number of pixels (large pixel scale) is not compensated by the increase in the zodiacal light (due to the large slits).

The conclusion here is: If the slit is sampled by two detector pixels and R=100, a scale of about 0.085 arcsec/pixel maximizes the S/N for a single observation, under the assumptions mentioned above. However, values in the range 0.07-0.12 arcsec/pixel give virtually the same results.

**Dependence on the assumptions**

How the result inferred from Figures 1 and 2 will change with other assumptions?

**Wavelength:** the longer wavelengths, the larger the pixel scale that maximizes S/N (as a first approach a linear behaviour with $\lambda$ can be considered).

**Background:** The smaller the zodiacal background, the larger pixel scale which maximize S/N (and viceversa).

**Dark current:** If dark current is larger than the one considered (0.02 e/s) the pixel scale should be larger (and viceversa).

**Extraction:** If the standard extraction method (no weights) is applied, the detector and zodiacal noises are more important for small pixel sizes and, therefore, a larger pixel scale is obtained.

**Object Size:** If the object is extensive the pixel scale should be larger.

4.2 Case slit width $\neq 2*pixel$: Effects of the slit width

High-redshifted galaxies are expected to be point sources (or barely resolved) with typical sizes of 0.2 - 0.3 arcsec. Under these circumstances, large slit widths (say, for instance, 0.4 arcsec or larger) may imply only a modest lost in spectral resolution (as the image of the object is nearly equally sampled onto the detector independently of the slit width). Larger slit widths do imply, however, a larger amount of zodiacal noise, but it may also imply a (modest) increase in the signal. Observations with relatively wide slits are equivalent to 'slitless' observations of a relatively small region of the sky. Because observations at R=1000 and R=100 happen at very different regimes (i.e. detector limited, and zodiacal limited, respectively), the effects of the slit width are different in both cases.

In this subsection we will analyse the case in which the slit width and the pixel are not coupled.
Figure 3: $S/N$ (per $\sqrt{t}$) as a function of the pixel scale onto the detector, for three slit widths (0.3, 0.45, 0.6 arcsec), and $R=1000$. Other assumptions are indicated in the figure. Lower panels show the relative importance of the different noises for the three slits (dot line: poissonian from the source, small dashes: detector, large dashes: zodiacal, continuum line: all noises combined)
Figure 4: S/N (per $\sqrt{t}$) as a function of the pixel scale onto the detector, for three slit widths (0.1, 0.2, 0.3 arcsec), and R=100. Other assumptions are indicated in the figure. Lower panels show the relative importance of the different sources of noise for the three slits (dot line: poissonian from the source, small dashes: detector, large dashes: zodiacal, continuum line: all noises combined)
R=1000

Using S-ETC we have generated Figure 3 which shows S/N - (pixel size) curves considering three fixed values for the slit widths (0.3, 0.45, 0.6 arcsec).

We can see that relatively large slit widths ($\sim 0.3-0.45''$) give the highest sensitivity, with pixels scales in the range 0.12-0.2 arcsec/pix. [Note that these sensitivities are larger than the case slit=2*pixels for both small pixel scales (because the slit collects more light from the object) and large pixel scales (because the background noise is smaller)].

The reason for the relatively large slits inferred from Figure 3 can be understood intuitively: When we are observing point sources in a detector limited regime, the use of relatively large slits implies a net gain of signal (flux in the wings of the PSF), while the negative effects due to the increase in zodiacal light are not so relevant.

According to Figure 3 for slits $\sim 0.3-0.45''$ a scale of 0.1 ''/pixel imply a moderate loss in S/N ($\sim 5\%$) with respect to the maximun, but it may have other advantages (see below). A scale of 0.05 '' the loss is more relevant ($\sim 20\%$ in S/N). In addition, the results for small pixel scales depend more on the extraction techniques which, in practice, are subject to uncertainties no considered here (Sect. 2).

R=100

In figure 4 we present the S/N-(pixel scale) curves for R=100, and three fixed values for the slit width (0.1, 0.2, 0.3 ''). Because in this case the observations are zodiacal limited, relatively large slits have an important impact in the S/N. Optimal values are obtained for slit widths in the range 0.2-0.3 '', with a pixel scale in the range 0.05-0.1 ''/pix.

5 Speed = F (pixel scale, slit)

Slit length: Effects on Multi-object observations

The effects of the slit width have been analysed in the previous section. Regarding the slit length, beyond the dimension of the object, an increase in the slit length has not any effect in *single* object spectroscopy (just more pixels are used to record the background). However, for multiobject observations a larger slit length implies more severe crowding effects (as the background of one object may overlap other object’s spectrum).

Due to the fact that observations at R=1000 and at R=100 happend at different regimes, the effects of overlapping are also very different in both cases.

In figure 5 we present the impact on the required observing time, when the background is increased by a factor 2 and 3 (which simulates the overlapping of 2 and 3 spectra), as a function of the pixel scale. There are two main conclusions from this figure:
Figure 5: Exposure time required (normalized to the one for a scale of 0.1''/pixel, mean background) for one, two, and three times the mean background for $R=1000$ and $R=100$.

i) an increase in the zodiacal light is less relevant for $R=1000$ than for $R=100$.

ii) an increase in zodical light is less relevant for small pixel scales, because they are in a more strict 'detector limited' regime.
Figure 6: Speed of the spectrograph as a function of the pixel scale for three cases: i) no overlap allowed, ii) overlap of two spectra is allowed, and iii) overlap of three spectra is allowed. The speeds are normalized to the value corresponding to ‘no overlap’ for scale=0.1″/pixel. For cases ii) and iii) the level of background is higher (see figure 3), and therefore require larger exposure times for reaching a given S/N, but this is compensated for R=1000 by the fact that more galaxies are observed. This is not the case for R=100, for which a sequential procedure is more efficient.
Therefore, **the smaller pixel scale and/or the larger spectral resolution, the less the important the overlapping of several spectra is.**

**Speed of NIR-SPEC (an approach)**

The detailed modeling of the multiplexing gain and sensitivity as a function of the pixel scale and slit dimensions is complex (zodiacal light is wavelength/positional dependant, and the crowding requires Monte Carlo simulations – and it is dependant on the density of objects and the type of observations (continuum/emission) –, geometry of the detector/MEMS, etc).

For the present discussion we will assume some reference values based on previous simulations for the crowding for a density of 100 objects/′². In particular we will consider that for R=1000, the 31%,56%,and 74% of the galaxies in the focal plane can be observed in 1, 2, and 3 exposures with out allowing overlap. For R=100, 45%, 65%, and 80%, for 1, 2, and 3 exposures. These values can be significatively different in practice, but they give us a reference for the present discussion, which does not require detailed inputs at this respect.

In figure 6, we represent the speed of the spectrograph as a function of the pixel scale for R=1000, and R=100, considering three cases: i) no overlap allowed, ii) overlap of two spectra is allowed, and iii) overlap of three spectra is allowed. The speeds are normalized to the value corresponding to ‘no overlap’ for scale=0.10′′/pixel. For cases ii) and iii) the level of background is higher, and therefore require longer exposure times for reaching a given S/N. In the case of R=1000, this is compensated by the fact that more galaxies are observed. However for R=100, simultaneous observations of overlapped spectra have a more dramatic consequences, and the longer exposure time required is not compensated by the multiplexing gain.

In summary, the preliminary conclusions from Figure 6 are:

i) For R=1000 and multiobject observations, the scale which maximizes global efficiency (speed) is somewhat smaller (∼ 0.1 ″/pixel) than the one which maximizes sensitivity (∼ 0.16 ″/pixel).

ii) For R=1000, a scale of 0.05″/pixel implies a loss in speed of about 30% with respect to the one for 0.1″/pixel.

iii) For R=1000, multiobject observations are more efficient allowing the overlap of 2 or 3 spectra.

iv) For R=100, multiobject observations are more efficient if done in a sequential way (not overlap).
6 Facets

As a slit is built up with facets, the facet size should be always equal or smaller than the expected slit. On the other hand, the larger the facet, the smaller the number of facets to cover a certain FOV, and the smaller diffraction and inter-facet losses.

So far the number of facets in a MEMS array has been considered to be tied to the number of pixels at the detector through a 1-1 or 1-2 projection. However, there is not any reason for that. Just the contrary: previous sections indicate that, if the detector is built up with (many) relatively small pixels, the observations will be in a more strict ‘detector limited regime’ and therefore, the slits can be larger (in length and width) which relax the requirements for the MEMS’ facets (they can be less and larger), especially for R=1000.

An other conclusion is that the two dimensions of the facets do not play the same role. While the dimension along the spectral dimension is important to adjust the slit width, the facet dimension across the spectral dimension can be relaxed and it could be larger than considered so far (e.g. 0.2″ or larger), which would reduce the number of facets as well as diffraction and interfacet losses. (Note that longer facets along the cross-dispersion direction do not imply a lost in spatial (or spectral) resolution)

Regarding the dimension along the spectral direction values of 0.1″ seem reasonable provided that R=100 requires slit widths of the order of ~ 0.2″. However, if finally R=100 is implemented in the NIR camera, and NIR-SPEC (R=1000) is only planned to be used for DRM15-like observations (i.e. point sources at a ‘detector limited regime’), the requirements for the MEMS dimensions can be relaxed even more (i.e. ~ 0.15″ x 0.3″).
7 Conclusions

Under the assumptions mentioned along this note we conclude:

1- Pixel Scale

At the detector, a scale of 0.1″/pixel seems the best option, as: i) it maximizes sensitivity and speed for R=100, ii) it maximizes speed for R=1000, and iii) it gives more than 90% sensitivity for R=1000. A scale of 0.05″/pixel gives a nearly optimal sensitivity and speed for R=100, but it implies substantial losses in sensitivity and speed for R=1000 (exposure times longer by 30-40%).

2- Slit dimensions

For R=1000 and DRM15-like observations (i.e. [nearly] point objects, detector limited), slit widths as large as 0.3-0.4″ optimize S/N.

For R=100 and DRM15-like observations, the slit widths of ∼ 0.2″ optimize S/N.

3- Facet dimensions

The two dimensions of the facets do not play the same role.

Across the spectral direction the facet dimension could be larger than considered so far (e.g. 0.2″ or larger), which would reduce the number of MEMs facets (for a given FoV) as well as the diffraction and interfacet losses. (Note that this does not imply a loss in spatial (or spectral) resolution).

Regarding the dimension along the spectral direction values of 0.1″ seem reasonable provided that R=100 requires slit widths of ∼ 0.2″. However, if finally R=100 is implemented in the NIR camera and the NIR-SPEC (R=1000) is planned to be used only for DRM15-like observations, the requirements for the MEMS dimensions could be relaxed even more (i.e. ∼ 0.15″ [spectral] x 0.3″ [spatial]), which would reduce substantially the number of MEMs facets, as well as the diffraction and inter-facet losses.

Acknowledgements: Thanks to John Trauger and Mauro Giavalisco who provided the NGST-PSFs and updated values for the zodiacal light, respectively.