NGST NIR Spectrograph Study

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For the NGST Ad Hoc Science Working Group

NIR Spectroscopy Panel:

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Contents

List of Figures

List of Tables

Executive Summary

Arguably the most important goal of NGST is to explore the astrophysics of the early universe, including the assembly of galaxies and the formation of the earliest stars. These processes lie at the very root of human existence. A significant fraction of the Design Reference Mission for NGST is based on near-infrared (1-5 μm) spectroscopy, where the telescope and instruments should have tremendous advantages over both previous space-based and modern ground-based telescopes. These advantages come about because a cooled space telescope both avoids the huge atmospheric and telescopic thermal background of a ground-based system and samples the complete spectral range unhampered by atmospheric absorption and emission.

The panel reexamined the scientific program in the DRM and other interesting near-infrared spectroscopic science and distilled what we think are the simplest and most basic capabilities desirable for NGST NIR spectroscopy. Several decisions on spectrograph parameters are driven by relatively simple scientific trades which also depend on as yet to be finalized detector and telescope characteristics. For example the dark current critically drives the optimal pixel sizes for limiting spectroscopy.

We believe that the NIR spectroscopic science mission will be best served by an instrument or instruments that have the following general characteristics:

	Wide-Field Mode	High Resolution Mode
Wavelength Coverage	1-5 microns	1-5 microns
Pixelation	0.1-0.15" *	0.030"
Resolution (R)	500-2000 req 500-5000 goal	500-5000 req 500-10000 goal
Field of View (FOV)	3'x3' req 4'x4' goal	few arcsec squared
No. of Objects/Field	300	> 3000 **

* depends on dark current

** number of individual spectra in the FOV

For wavelength coverage, because it is critical to cover features as they pass through all redshifts, the full spectral range should be observable. We recognize that in dispersive spectrographs this is likely best done in octaves with appropriately blazed gratings.

For pixelation, which relates to spatial resolution, a significant fraction of both the galactic and extragalactic science is critically enhanced if observations can be made at the diffraction limit of the telescope, 0.069" at 2.2 microns. Nyquist sampling of the FWHM ($\sim$ 0.057" at this wavelength) implies 0.030" pixels in the spatial dimension. This is the parameter that drives the high spatial resolution channel. For the ultimate sensitivity for *integrated* galaxy spectra, in the wide-field mode, we are driven to pixel sizes defined by the maximum sizes of faint galaxies and by the match between detector noise (primarily dark current) and the background zodiacal light. S/N is maximized by increasing the spatial pixel size until you either run out of galaxy light or you become background noise dominated. The optimal pixel size is wavelength dependent, and we have made the choice at 2-3 microns.

For spectroscopic resolution, the choice of resolution is driven strongly by the astrophysical problem to be solved and the natural widths of the spectroscopic features to be detected. We believe that most of the very low resolution spectroscopy in the DRM (e.g. that which requires only crude redshifts) should not drive the spectrograph design. There is a growing body of evidence that reasonably good ($\delta z \sim$ 0.03-0.05) photometric redshifts can be obtained by imaging in medium or even broad band filters. Quantitative spectroscopy, for example, measuring the galaxy-galaxy velocity correlation function at high redshift or studying the internal kinematics of galaxies, requires velocity accuracies better than 100 km/s and thus requires resolutions of 500 or more. High spatial resolution programs often also require high spectroscopic resolution, driven by the intrinsic physics of the phenomena to be studied (narrow emission line regions, weak absorption lines, kinematics at 10-30 km/s velocity resolution, etc.)

For FOV, we were driven in two competing directions. Some of the most important goals of the DRM require the widest possible field. However, the ISIM itself is specified to provide only a 4'x4' FOV for the spectrograph, and this should be the goal of whatever wide-field mode is constructed. At the same time, the ultimate field is driven by the combination of detector size (number of pixels) and the optimum pixel size needed to obtain the best S/N on the faintest galaxies (extended sources). If large pixels can be used without significant degradation of the S/N due to zodiacal background, then the FOV will be determined strictly by the ISIM specification. If $\sim$0.1" pixels are optimum, as we discuss below, then the FOV is driven by the detector size — a 2048^2 array with 0.1" pixels will cover only a 3.4' diameter field. Note also that based on HDF source counts, non-cluster cosmological programs are not likely to require spectroscopy of more than 300-400 objects per field. The field "filling" factor for deep galaxy surveys is less than 10%.

Detector size drives the high spatial resolution mode as well. A design that is diffraction limited at the shortest wavelength we consider, 2 microns, requires ~ 0.03" pixels for spatial Nyquist sampling. Thus, if the spectrograph were to use a 4096^2 array in an integral field mode with one dimension fully covered by the dispersion direction, the maximum field of view obtainable would cover at most $4096 \times 0.030"^2 = 4$ square arcseconds. This choice is actually well matched to the sizes of individual objects to be studied with NGST, e.g. galaxies, young stellar disks, and star clusters in nearby galaxies. We have compared these requirements to three generic instrument concepts, Integral Field (IFS), Multi-Object (MOS), and Fourier Transform (FTS) spectrometers.

- **1. The high resolution mode (primarily high spatial resolution but also likely higher spectral resolution) would be best served by an integral field spectrograph that would enable efficient (single exposure) full spatial coverage**

- **2. Based on the concepts in hand, the optimal choice for the wide-field mode is a MOS spectrograph, probably based on micro-mirror array technology. Although we have not been asked to comment directly on engineering issues, a dispersed FTS with a MOS front-end appears to be roughly equivalent to a MOS spectrograph in sensitivity, but brings a degree of complexity beyond the grating MOS that is not offset by suitably large gains in capability. The ultimate decision on the wide-field mode must await the technological readiness of the various front end choices.**

- **We believe that it is imperative to have two spectroscopic channels that, combined, are capable of carrying out the DRM as well as a significant amount of additional and related science. The spectrograph should have, like the cameras on HST, both a wide-field and a high spatial resolution mode.**

1 Spectroscopic Science and the NIR Spectrograph Requirements

The choice of instruments for NGST is driven both by the obvious technical advantages of a diffraction limited, IR optimized cooled 8-meter space telescope and by the scientific programs that will be forefront when it is launched and operating. In this report, we have endeavored to derive the optimal design parameters for the NGST Near Infrared (NIR) spectrograph based on the instrument parameters outlined in the telescope definition study, the scientific requirements for the programs outlined in the Ad Hoc Science Working Group (ASWG) Design Reference Mission (DRM) and more general and broad scientific and technical considerations.

1.1 Scientific Overview

The scientific overview is divided into two sections, the first of which covers the science programs in the DRM for which spectroscopy in the NIR plays a key role, while the second adds to these programs some science objectives that arose during the committee's deliberations.

1.1.1 Spectroscopy in the DRM

The science discussion for programs in the DRM is based on, and structured to be consistent with, the recent ASWG ranking of the DRM science programs. This ranking is shown in Table 1, taken from the ASWG Minutes, meeting #7, and the identification number for each science discussion section is that from that table.

Note that we do not comment directly on programs that are in whole imaging (e.g. the highest ranked DRM program on imaging galaxies in the early Universe) or that are clearly spectroscopy in the mid-infrared range. We have, however, included in our consideration those spectroscopic programs that have a 3-10 micron component, in part because, especially at high spectral resolution, the NIR spectrograph may be the best instrument to accomplish the science goals of those programs, and, in part because the long wavelength cutoff of some of the NIR detectors under consideration may extend to 8-10 microns.

(# 2) – Formation and Evolution of Galaxies – Spectra.

Table 1: **The ASWG Ranking of DRM Programs.**

Rank	DRM Title	Scientific Capabilities
1	Form. & Evol. Galaxies- Imaging	2 micron dif.-limited imaging, wide FOV, 8-m sensitivity, 0.6-5 microns
2	Form. & Evol. Galaxies- Spectra	NIR multiplexed spectroscopy, 1-5 microns, R = 100-3000, 5-10 MIR spectroscopy, R=3000
3	Mapping Dark Matter	Widest FOV, stable PSF
4	Searching for the Reionization Epoch	Very sensitive NIR spectroscopy, R = 100-300
5	Measuring Cosmological Parameters	Ability to follow fields over months
6	Form. & Evol. Galaxies- Obscured Stars & AGN	MIR (10-28+microns) imaging and spectroscopy, R = 300
7	Physics of Star Formation: Protostars	MIR (10-28+microns) imaging and spectroscopy, R = 3000+
8	The Age of the Oldest Stars	Low scattering in PSF
9	Detection of Jovian Planets	5 micron coronagraph
10	Evolution of Circumstellar Disks	MIR spectroscopy, R=30000+
11	Measuring the Rates of Supernovae	Ability to followup imaging with weeks
12	Origins of Substellar Mass Objects	Core NIR imaging and spectroscopy
13	Form. & Evol. Galaxies- Clusters	Core NIR imaging and spectroscopy
14	Form. & Evol. Galaxies near AGN	Core NIR imaging and spectroscopy
15	Cool Field Brown Dwarf Neighbors	Core NIR & MIR spectroscopy
16	Survey of Trans-Neptunian Objects	Core NIR imaging
17	Properties of KBOs	Ability for slow linear tracking, MIR imaging
18	Evolution of Organic Matter in ISM-Astrobiology	Core MIR spectroscopy
19	Microlensing in the Virgo Cluster	Overall Field stability
20	Ages and Chemistry of Halo Pops.	V-band imaging desirable
21	Cosmic Recycling in the ISM	Core MIR spectroscopy
22	IR Transients from GRBs and Hosts	Targets of Opportunity - 4 day replanning
23	IMF for Old Stellar Populations	Core NGST angular resolution & sensitivity

Table 2: Scientific Capabilities of the Ranked Program. The Core Programs (1-7) are shaded.

The goal of this program is simple but challenging – to obtain spectroscopic redshifts as faint as possible, so as to probe the highest redshifts, and thus the earliest epochs of galaxy formation. More explicitly, such spectra can be used to i) determine and study the evolution of metallicities, stellar ages, star formation rates, and dust extinction levels from low redshifts $z \sim 1$ to redshifts $z > 5$, and ii) measure the kinematics of the gas and stars in order to establish the mass scales for galaxies as a function of epoch. A related, but more focused, program is to study the physical conditions of star formation at different locations within a galaxy in a small sample of morphologically complex systems.

From deep NGST imaging observations, photometric techniques can be used to estimate redshifts based on spectral regions exhibiting large-scale spectral features or continuum breaks (e.g., the Lyman limit or the break at Lyα). Such techniques need to be validated by spectroscopic redshift confirmation as faint as practical, so as to inspire confidence in the technique at flux levels where spectroscopy is impractical.

Spectroscopy provides additional unique information. For example, metallicities can be measured using rest frame visible [OIII] to Hβ line ratios. Star formation rates can be estimated using ionizing photon rates obtained from Hα measurements, or, with less accuracy, from [OII], and from UV rest frame continuum fluxes at $\lambda \sim 1600$ Å. Stellar ages can be determined using measurements of continuum breaks (e.g., Ca H+K at 4000Å, Mg 2799), though metallicity effects can result in degeneracy. Preferred techniques involve measuring absorption line indices in the rest frame blue (from ∼4000–5200 Å) combining metallicity sensitive indices such as λ4668 Å with H-line indices such as Hβ and Hδ. Dust reddening can be determined using Hα/Hβ flux ratios, checking for consistency with UV rest frame continuum slopes, again around 1600 Å. For lower redshift objects, Pα (1.6 microns) observations can also be used.

To study the kinematics of the gas and the stars in galaxies, appropriate emission and absorption features can be used. For example, for the gas, Hα and other emission lines such as [OII], [OIII] etc., provide measures of rotation curves, and characteristic velocity widths if the objects are unresolved, as well as outflows in high SFR objects. While much harder to measure, absorption lines can also be used to obtain stellar velocity dispersions and rotational velocities, or characteristic velocities if the objects are unresolved and/or the spectra are of low S/N. Feature such as the the CO 2.3 micron band head, the Ca triplet, Mg‘b’, and the G-band are all potentially useful features depending on redshift and S/N.

The requirements imposed by these various programs on the characteristics of the spectrograph depend on the specific program, but range from R∼500 for redshifts suitable for large scale structure studies to (rest frame) R∼5000 for velocity measurements on low mass proto-galactic "clumps," with the other scientific goals falling at resolutions between these limits The most demanding observations, those of stellar absorption features, require S/N $\sim$ 20, but many of the others can be achieved with significantly lower S/N requirements (few–10).

While the focus of this science program is on surveys of large numbers of high redshift objects, the ability to map a smaller number of distant galaxies in some detail is highly desirable. Such mapping can be used to characterize their kinematic structures, as well as measure other diagnostics of the gas and stellar components (metallicities, SFRs, etc.). Thus a high spatial resolution, small-field IFS is of particular value, with spectral resolutions in the range R $\sim 500 - 5000$.

(# 4) – Searching for the Reionization Epoch.

The objective of this program is to determine the epoch at which the intergalactic medium (IGM) was reionized. This is a crucial milestone in the thermal history of the Universe, with significant implications for the development of proto-galactic structures at very early epochs. The process for establishing the reionization epoch involves searching for characteristic signatures from the Lyα foreground absorption in the spectra of UV bright sources at z >5. The Lyα forest falls within the 1-5 micron core spectral region of NGST for redshifts 7.2< z <40, coinciding with the likely range for the redshift of the reionization epoch.

More specifically, this program involves the measurement of the depth and profile of the intervening intergalactic Lyα absorption out to progressively larger redshift, and the measurement of the redshift beyond which the optical depth becomes large, and the damping wing of the Gunn-Peterson trough appears. The strongest limits could be set on rest frame UV-bright sources at redshifts $z > 5$ with a combination of low resolution, moderate S/N spectroscopy at the lowest resolutions being proposed (i.e. R $\sim$ 500 or even less), and high S/N photometry.

(# 5) – Measuring Cosmological Parameters – with High Redshift SNe.

The increased sensitivity to cosmological parameters at higher redshifts makes the observations of standard candles, like SN Ia, with NGST, critical. Light curves of SN Ia in the redshift range $z \sim 1-1.5$ provide added leverage, compared to what can be done presently at $z < 1$, for distinguishing between various cosmological models, particularly for differentiating between $\Lambda \neq 0$ cosmologies and the "conventional" low $q_0, \Lambda = 0$ or $\Omega_M = 1$ cosmologies. In particular, the effects of cosmology can be more clearly separated from those of stellar age, composition, interstellar and intergalactic dust.

The basic detection of the SNe arises through the distant galaxy deep imaging survey, but requires complementary spectroscopic observations to derive the SN host galaxy redshift and to confirm the SN type. Operational constraints arise from the time-critical aspects of this program, but the instrumental requirements are not demanding, since low resolution spectra (R $\sim$ 500 is satisfactory) at modest S/N ($\sim$ 10) of only about 50 faint objects are required. The surface densities are low, being of the order of one object per 3 arcmin^2.

(# 6) – Formation and Evolution of Galaxies – Obscured Star Forming Regions and AGNs

While this core program from the DRM is explicitly listed as requiring mid-IR spectroscopic capability, the committee noted that the recent SCUBA and optical results together suggest that the degree of obscuration in distant galaxies varies quite dramatically, both between and within galaxies, and that NIR spectroscopic observations would complement the mid-IR observations being considered for this program. The importance of the mid-IR was not questioned; it was just noted that observations of galactic/AGN spectral features over a wide wavelength range, through the NIR into the mid-IR, would provide scientific returns, particularly given the wide redshift range over which NGST will be studying such sources. The same spectroscopic capabilities, particularly the wide-field mode, identified for # 1 above and # s 13 and 14 below are suitable for this program. An additional capability that could prove to be particularly valuable for dusty AGNs (and other dusty objects, or objects with significant non-thermal components – e.g., radio galaxies) could be a spectropolarimetric unit for the spectrograph. While not baselined, some assessment of its cost-benefit could be made.

(# 7) – Physics of Star Formation: Protostars

Again, as for # 6, this is listed as a mid-IR program. However, there are evolutionary phases for protostars during which the extinction can be significantly lower, and the environs of such objects may have lower extinction, such that NIR spectroscopic observations would be of considerable scientific value. Thus the committee felt that it was important to note that the NIR spectroscopic capability should also be considered when evaluating the scientific program on protostars. The high resolution IFS mode could be of particular value for this scientific program.

(# 11) – Measuring the Rates of Supernovae

SNe are central to heavy element enrichment and are probes of star formation regions at high redshift. The goal of this program is to study type I and II SNe at redshifts $z \sim 2 - 5$. Because some progenitor populations have not had time to be created in the early universe, the results would be useful for constraining the progenitors for both types I and II SNe. While faint, the type II SNe should be observable with the low resolution spectroscopic system – the frequency is high, being about 20 Type II SNe per 4x4-arcmin field.

(# 12) – Origins of Sub-stellar Mass Objects.

Deeply embedded young clusters can be used to establish the low mass end of the IMF (0.1-0.001 $M_\odot$), since the likelihood of detection and the rate of occurrence of low mass objects are both expected to be high in this environment. A specific issue is whether there is a turnover in the distribution of stellar masses between the hydrogen burning limit (0.08 $M_\odot$) and the minimum mass for fragmentation of a molecular cloud ($\sim$0.01 $M_\odot$).

The imaging survey is expected to yield more than 10^3 objects per 4x4 arcmin field, per cluster, providing a large sample for low resolution multi-object spectroscopic follow-up. The spectroscopic observations would establish temperatures and allow the generation of an H-R diagram for the low mass sequence. Only a fraction of the likely low mass objects could be spectroscopically studied; these spectra could be used to develop a calibration such that the photometric measurements of the remaining objects could be utilized to add them to the H-R diagram. Higher resolution spectroscopy (at R$\sim$3000) over 2.5-5 μm of atmospheric components such as CO, OH, H_2O, CH_4, SiO, and NH_3 could be used to derive gravities and abundances. The goal here is to do a smaller number of the more luminous objects per cluster. Studying a number of clusters and dynamical environments would provide constraints on the universality of the derived low mass IMFs.

(# 13) – Formation & Evolution of Galaxies: Clusters

Galaxies in clusters evolve (and perhaps form) quite differently from those in the field. Early-type (E/S0) galaxies are far more frequent in clusters. Environmental differences play a key role. Study of galaxies in dense environments may provide clues to the importance of processes that are much more subtle and harder to study in the field. The observational goals and requirements of this program mirror those of the first ranked program (i.e., # 1 here) on field galaxies at redshifts $z \sim 1-5$, with the explicit difference that now many cluster/dense environments need to be explicitly chosen over this redshift range. The science goals, and the corresponding resolution and S/N ranges also apply, though the survey may be initially done at higher resolution $R \sim 1000$ since the relative velocities in the substructures of interest within the clusters may be quite small.

Clearly a number of clusters are required (of order 20 or more), since both a range of redshifts and space densities are involved, and so this program could be substantial if the goal of sampling galaxy formation and evolution in the dense intersections of the galaxy cellular structures is met.

(# 13) – The Formation and Evolution of Galaxies near AGN

In addition to galaxies in dense environments, another class of galaxies merits special consideration – and that is the study of AGN host galaxies. The larger samples that can be studied at higher redshifts may provide insight into the AGN phenomenon, its development, timescale and fueling (on galactic scales – not the detailed nuclear scales), particularly when such samples are compared to the field samples of DRM # 1 and the cluster samples of DRM # 12. This program is strongly coupled to both these surveys, and would identify particular objects from the field and the cluster environment for spectroscopic follow-up at moderate spectral resolution. This requires wide-field capability to build up suitable samples since the density of objects will be low.

(# 15) – Cool, Field Brown Dwarfs and Companions

A number of surveys over the next few years (the Sloan Digital Sky Survey SDSS, the 2-Micron All-Sky Survey 2MASS, and the Deep Near IR Survey DENIS) will be identifying field brown dwarfs. The goal of this NGST program is to measure the physical properties of these objects, including temperatures, surface gravities, and rotation rates, as well as atmospheric processes such as dust and cloud formation and mixing. Other issues include searching for evidence for disks, planets and magnetic activity, and associated low mass companions. While the primary focus of the spectroscopic observations is in the mid-IR at $\lambda > 5\mu$m, some of these issues can be addressed with the NIR spectroscopic capability.

1.1.2 Spectroscopy not in the DRM

Although the DRM describes much of the key science that justifies NGST, we decided, in determining the properties of the NIR spectrograph, to examine more broadly scientific programs that could be carried out with a capable spectrograph. In doing so, we recognized a number of interesting science programs unique to NGST which are not explicitly mentioned in the DRM. These items have not been developed in any detail, but provide some potential additional interesting studies that could be carried out.

(# N1) – Quasar Absorption Line Systems

QSO absorption line system have provided remarkable insight into the nature of the neutral components and proto-galactic structures in the IGM. NGST provides opportunities to extend such studies to higher redshifts, and/or to provide continuous coverage that is not possible to obtain from the ground in the near-IR. For example, metal lines of Lyman-limit and damped Lyman alpha systems (e.g., Zn and Cr lines from $z \sim 3.9$) can be studied to higher redshifts, allowing an analysis of star formation histories and the connection between metal line absorbers and protogalaxies/galaxy halos. As higher redshift quasars/AGNs are discovered, it will also be possible to observe the Lyman alpha forest, enabling the study of cloud properties, clustering along the line of sight, and large-scale structure across lines of sight at earlier epochs. The wavelength coverage and sensitivity of the NIR spectrographs being considered for NGST are well-matched to this program, with the exception of the spectral resolution – resolutions $R \sim 10000$ would be better than the baseline 5000.

(# N2) – Young Stellar Objects and AGNs

These disparate objects would both benefit from high spatial resolution two-dimensional spectroscopy at moderate (or in the case of YSOs, as high as practical) spectral resolution. Accretion and outflow processes could be mapped using a variety of diagnostic features available through the near-IR (including, e.g., H_2, HI, [FeII], [SII]).

(# N3) – ISM Chemistry

NGST provides opportunities for studying the chemistry of the ISM along lines of sight toward stars located behind molecular clouds, using moderate spectral resolution measurements of, e.g., CO/H_2 ratios in a number of different environments.

(# N4) – Non-optical/IR Selected Samples

There will continue to be demand to follow up with spectroscopic study of objects selected in surveys at other wavebands (e.g., deep radio, sub-mm, FIR or X-ray surveys). Existing deep surveys (e.g., VLA, SCUBA, ISO, ROSAT) identify many optical/NIR counterparts that are so faint that they cannot be studied spectroscopically by current ground-based 8–10 m telescopes. In those cases where the positional accuracy or astrometry is not accurate enough to pinpoint a unique optical/NIR counterpart an imaging spectrograph that can observe many faint objects at once can lead to a rapid identification of the source.

(# N5) – Cool Star Abundances

The NIR spectroscopic capability in the 2.0 to 2.35 μm region allows for the determination of accurate metal abundances for cool stars and for star clusters with ages between $\sim$1 Gyr and 10-15 Gyr, i.e., for an age range between that for intermediate age Magellanic Cloud clusters and Galactic globular clusters. The goal would be to extend observations to individual stars and star clusters well beyond the local group, especially since this technique can be applied to the integrated light of star clusters, in addition to individual giant stars. The features that need to be measured are the Na and Ca lines in the K band, and the strength of the first CO band head at 2.29 microns. The calibration would be made using ground based spectroscopic observations at the same resolution and high S/N ratio of bright giants in globular clusters, of Galactic bulge fields, and of the integrated light of globulars and clusters in the Magellanic Clouds. The expectation is that such a calibration would reproduce the best optical [Fe/H] values to an accuracy of 0.1 dex or better. The resolutions required match those of the baseline spectrograph, namely R$\sim$ $1000 - 1500$. The required S/N is high at 40–50 (and ideally 100), and so fields with multiple targets allow for the most efficient use of the MOS capability.

(# N6) – Serendipity

As with any new facility operating in a new wavelength regime with greatly enhanced sensitivity, the opportunity exists for serendipitous discoveries. While this normally occurs through imaging programs, the spectroscopic observations provide comparable opportunities, even though the time-integrated areal coverage is small. For example, the spectroscopic surveys (even using targeted slitlets) allow for the discovery of high-redshift emission line galaxies with very large equivalent widths. Such objects are are strongly preselected against in wide-band photometry. Instruments which maximize areal coverage for spectroscopy have an advantage in this area, but this has to be balanced, of course, against the targeted observation capabilities outlined previously.

(# N7) – "Mainstream Science"

The panel also recognized the existence of "mainstream science" that may not have been mentioned explicitly in the DRM, but to which a considerable amount of NGST observing time surely will be allocated. Within our Galaxy an example is high resolution, multi-object spectroscopy of embedded star clusters and the galactic center region, to determine stellar kinematics to provide measures of dispersion, bulk expansion/contraction, and rotation rates. Additionally, study of 3μm (and, in the mid-IR, 10μm) dust features at moderate-to-high spectral resolution and high spatial resolution, is likely in order to understand the chemistry in environments as varied as circumstellar disks and external galaxies with varying amounts of UV radiation. Another possibility is identification of faint stars in the solar neighborhood, which may be potential targets for TPF, and follow-up observations at low spectral resolution to determine temperatures, and at high spectral resolution to measure rotational velocities, surface gravities, and metallicities. In the extragalactic area, many individual objects or rare classes of objects, such as mergers, massive star formation regions, radio sources etc., will be targeted explicitly, given the unique capabilities of NGST and its NIR spectrograph. Of particular interest could be the properties of the nuclei in starburst galaxies, and galactic black holes with relativistic jets.

1.1.3 Summary

We recognize that many key scientific issues will evolve over the next 8-10 years, and the scientific focus will invariably shift with time. One could be concerned that by coupling the instrument concepts strongly to the science of today we will be unable to tackle the issues of 2010. However, we would alleviate this concern in two ways. First, the spectroscopic capabilities that are discussed in this document are versatile and will prove themselves amenable to working on a large range of scientific problems, some of which presumably will be the key scientific issues of the day in 2010. Second, many of the issues that are addressed by the DRM are fundamental, unchanging questions about our universe that provide the *raison* *d'être* for this project – no other planned facilities will be able to tackle these problems as well within the next decade.

1.2 Spatial Resolution

The baseline NGST "Yardstick" architecture provides for the ISIM to deliver high Strehl ("diffraction limited") images at 2.2 microns and longer. At 2 microns the PSF will have a FWHM of ~ 57 mas. The challenge for the near-infrared spectrograph is to provide adequate sampling of these images, while also covering a substantial fraction of the field provided by the telescope optics, within the constraint of the baseline 4096×4096 detector format.

To exemplify the tradeoffs that must be made, consider the case where the NIR spectrograph optics are structured to provide Nyquist-sampled images at 2 microns, i.e., the pixel scale is set up to be $\sim$2 pixels per FWHM. The maximum field that would then be covered by the typical MOS designs under consideration, or an FTS, would be 4096×30 mas = 123 arcsec, or 2 arcmin, well under the nominal 4×4 arcmin field of view of the ISIM. This assumes that sparsely-filled sampling of the FOV as provided, for example, by movable fiber positioners remains impractical for space applications. To cover a larger FOV with the types of systems under consideration requires that one move to poorer sampling than that needed for Nyquist-sampling. To cover a 4×4 arcmin field would require that each pixel of a 4096×4096 detector array be an (undersampled) $\sim$60 mas, and that the MOS resolution unit be $\sim$120 mas for 2 pixel sampling. A full field FTS also can cover the 4×4 arcmin field with comparable resolution. While this resolution represents a noticeable degradation from what the telescope is capable of, some of the difference may be restorable by one-dimensional dithering.

In some concepts, e.g. those involving integral field devices, the dense sampling leads to even smaller FOVs for a given pixel scale. For example, an integral field unit that assigns one spatial resolution element per two rows on the detector would give a FOV of only 3.8 arcsec for the same 60 mas pixels. This can be significantly increased in two ways, namely by (i) increasing the pixel size, or (ii) using low spectral resolution so as to stack several spectra along each row in the spectral direction on the detector. For example, if 4 spectra are stacked per row, and the resolution increases to 300 mas with the same 2 pixels per spatial resolution element (i.e., the pixels are 150 mas), then the FOV can become 19 arcsec. Clearly if field coverage is a primary component of the figure of merit, then IFS systems have an intrinsic disadvantage. However, their ability to provide detailed two-dimensional mapping on small scales can provide unique opportunities for measuring structure over the whole of an extended object.

The question of the pixel size thus becomes a key issue for the NIR spectrograph design concepts, as do issues about filling factors of objects, and the importance of wide-field capability. In all of this it is worthwhile to note that trades may have to be made that involve the issue of "unique science" versus "systematic statistically-robust science" programs. Both play a role in furthering science understanding, but they need to be distinguished – as has been noted in peer review situations: "just because it is unique does not make it important."

The scientific goals for the mission, as enumerated in the DRM, provide a means by which the tradeoffs can be evaluated and a suitable compromise found. The DRM science can be broadly separated into two categories, namely wide-field studies of distant galaxies and of stellar populations in nearby galaxies, including regions of the Milky Way, and detailed studies in smaller fields of one or a few objects, which typically will be unresolved or have unresolved components.

In the NGST DRM very high priority has been given to studies of distant galaxies. While it is recognized that exploring the limits of the very faintest detectable galaxies will become the realm of multi-band imaging through photometric redshifts, spectroscopy of substantial samples of distant galaxies will also be required to the faintest practical limits — in the case of NGST to $\sim$29-30 AB mag. At these magnitudes, the density of objects is $\sim$200-300 per square arcmin. In a 4$\times$4 arcmin field this sets the likely number available for MOS/FTS spectroscopy at about 3000-5000 objects.

Recent studies (e.g., Gardner & Satyapal 1999) suggest that such m_{AB} = 29-30 objects typically have FWHM of about 200 mas (half-light radii of $\sim$100 mas). While this can set a scale for deriving the spatial sampling resolution element for the NIR spectrograph, it is important to note that galaxies are not "top-hats!" The centrally-concentrated surface brightness distributions of real galaxies do require a more sophisticated analysis to establish the optimum sampling size.

However, all these numbers may not reflect the sizes and scales of the most desirable subset of objects, namely those very high redshift objects at z>5. These objects are rarer, and may well be smaller or have structure on scales that could be unresolved by NGST (cf. the gravitationally-lensed z=4.92 galaxy in the cluster Cl1358+62 which has star-forming "hotspots" that are 10^{10}-10^{11} solar luminosities, yet are only hundreds of parsecs or <50 mas in size — Franx et al. 1997). Note that 1 kpc $\sim$ 140 mas for an Ω_M = 0.3, Ω_Λ = 0.7, H_0 = 75 universe at z$\sim$5 . Such clumpy objects with "point sources" may require observational strategies which differ significantly from those designed to optimize the acquisition of galaxies with surface brightness distributions more typical of lower redshift objects. This is especially so if one of the goals is to derive some spatially resolved velocity and chemical information, though the value in a statistical sense of obtaining global averages for a large sample should not be underestimated (cf. Tully-Fisher studies, Fundamental Plane studies, etc.).

These results suggest that a careful and thorough analysis of the spatial pixelation of a MOS or IFS system is required, as it is for an FTS, though the tradeoffs are somewhat different for such systems. A critical factor will be the dark current since studies to date suggest that this will be the dominant noise source. While preliminary studies, albeit with rather simplistic models for high redshift galaxy surface brightness distributions and structures, suggest that the optimum scale in terms of S/N for the spatial sampling is large, at 200-300 mas, it is important to recognize that this could limit the amount and scientific value of the resulting data. A more sophisticated analysis with realistic simulations is desirable, with "actual" high redshift galaxies. A slight loss in S/N for an "average" observation may be desirable if additional scientific returns can be obtained with sampling at higher spatial resolution.

Since most of the data being used for the modeling of distant galaxy scales, structure and light distributions comes from HST, it is worthwhile to note that the data quality should improve in the next two years. The limitation of the current poor sampling of HST should be removed when the HST Advanced Camera, the ACS, becomes operational in 2001. It will have twice the sampling of the current WFPC2 and substantially higher throughput, and so should provide much higher resolution, higher S/N data on high redshift galaxies.

However, even if the structure and spatial scales extant in high redshift galaxies do require sampling at the diffraction limit provided by the telescope at 1-2 microns, technical and/or cost considerations may limit the wide-field survey instrument to lower spatial sampling than provided by the PSF. If so then every effort should be made to provide a smaller-field Nyquist-sampled instrument for the single complex object components of the DRM. The committee's discussions strongly highlighted the importance of minimizing noise sources in the detectors and instruments so that the observations become source/background noise limited at the high spatial resolutions possible with the NGST "Yardstick" architecture.

The consensus recommendation of the committee is given in the Summary, but a key step in arriving at that recommendation involved estimating the optimum sampling for distant galaxies. Given the importance of the DRM programs on such galaxies, particular emphasis should continue to be given to careful, thorough and realistic modeling and simulations of z $\sim$ 5 and beyond objects.

1.3 Spectral Resolution

The issue of the spectral resolution required for the NGST NIR spectrograph is intimately tied to the astrophysics in the science programs. Studying the distribution of galaxies at high redshift to understand the formation and evolution of galaxies is the highest ranked spectroscopic program in the DRM. The science associated with this program can be broken into three parts: the luminosity function of galaxies (or pieces thereof) in the early universe; clustering, clusters and large-scale structure; and detailed studies of the internal properties of individual galaxies. The first of these programs may well be best addressed by multicolor imaging. Recent studies (Steidel et al. 1999; Hogg et al 1998; Koo 1999; Simpson and Eisenhardt 1999) have shown that intermediate band colors are usually sufficient for deriving a 5-10% redshift estimate for all but the most unusual objects, primarily because broad and strong spectral features, like the CaII H+K break at low and intermediate redshift and the Lyman break at high redshift, are easily measured. Highly accurate redshifts are not a necessity for the purpose of studying the evolution of number density or even average spectral type.

The next level of the problem, studying clustering, does however require accurate redshifts/relative velocities, as shown by the vast improvement in small scale clustering and velocity field studies brought on by surveys such as the CfA and SSRS2 redshift surveys. Velocity accuracy of ~ 35 km/s allows accurate measurement of the relatively cold motions of field galaxies with respect to the Hubble flow as well as the velocity dispersions of small galaxy groups. This level of accuracy requires a resolution of several hundred in moderate to low S/N spectra — R $\approx$ 1500. The velocity accuracy required is not possible with observations at resolutions less than 300-500 at any of the redshifts of interest, especially since most models of structure formation predict that the correlation length and galaxy-galaxy velocity dispersion are smaller in the past than at present.

The last level of the problem, studying the internal kinematics and chemistry of forming galaxies, requires higher resolution still. If we want to understand how galaxy disks are assembled, the expected internal velocity dispersions of forming galactic disks are in the tens of km/s (e.g. Hartmann, Huchra & Geller 1986). Such measurements are likely to be made by observing the gaseous kinematics using emission lines with intrinsic widths of 10-20 km/s. The spectral resolutions required to measure faint absorption features such as the FeII lines in giant stars are driven by the line widths in the stellar atmospheres and the stellar velocity dispersions of the forming aggregates, again probably measured in the high tens of km/s. The detection and measurement of such features, even with noisy detectors, improves until the features become resolved. Thus these observations would be best done at R $\approx$ 10,000 in the redshift range of interest, but sufficiently accurate velocities could be obtained with lower resolution, R $\sim$ 3,000 if the S/N is large enough to allow centroiding to a tenth of a resolution element.

After the formation and evolution of galaxies, the next highest ranked spectroscopic program in the DRM is the search for the reionization epoch, z_i. At redshifts approaching the neutral era, a broad cumulative damping wing from high column density absorption is predicted at the redmost edge of the Gunn-Peterson trough (Miralda-Escude 1998), which can be used to infer both z_i and the neutral gas density. To measure the shape of the wing, low resolution (R = 100-300) and very high sensitivity are required, so a tunable filter system combined with the NGST imager, rather than the spectrograph, may be the most effective way to address this problem.

Measuring cosmological parameters via type Ia supernovae calls for low resolution spectroscopy. Here a redshift and a diagnostic spectrum are required to estimate the distance and age of the supernova, with R $\approx$ 300-500.

Also ranked highly in the core mission of the DRM are two mid-infrared spectroscopic programs. If the NIR spectrograph is extended to have mid-IR capabilities, then studies of obscured star formation in high-z galaxies (ULIRGs and AGN) will become possible. A spectral resolution of R $\approx$ 500 will be barely adequate to identify and study spectral features that may differentiate starbursts (e.g. PAH features) from hard UV sources (e.g. coronal lines such as SiVI). Higher resolution, R=1500, is desirable.

Another mid-IR spectroscopic program in the core DRM is the physics of protostars. Here R$> \approx$ 3000 is required to detect narrow spectral diagnostic features. Because the lines are unresolved, lower resolutions are undesirable – in fact at R=1000 the time required to do the observations goes up by more than a factor of 10.

A number of spectroscopic programs we considered mentioned resolutions in the range 10,000-30,000. With the exception of QSO absorption line studies, almost all of these concentrated on mid-IR spectroscopy. On consideration of scientific goals, we felt that almost all of the NIR science could be done with a spectrograph, especially in the high spatial resolution mode, that reached R=5,000, which we recommend be the requirement for one channel of the spectrograph. A small number of programs, such as QSO absorption line studies or detailed kinematics of protoplanetary disks, would be enhanced with sightly higher resolution, therefore we recommend that a goal be to provide the capability of NIR spectroscopy at R=10,000.

1.4 Spectral Coverage

Continuous spectral coverage over the 1-5 micron region is critical for a number of DRM programs. Of note are the following: any of the cosmology proposals where redshift is not known a priori, quasar absorption line studies, brown dwarf atmospheres, and studies of the low mass initial mass function. The 3-5 micron region is especially important for redshifts beyond z=3.5 where Hα is shifted into this regime, and for studies of CO and H_2 in circumstellar disks.

We have limited our discussions to the 1-5 micron spectral range, excluding wavelengths below 1 micron where NGST does not provide substantial improvements in background over earth-orbiting telescopes, and above 5 microns where separate mid-infrared instrumentation for NGST is expected to exist.

1.5 Field of View

As discussed above under Spatial Resolution, FOV is in part determined by the pixel size and number of pixels in the detector and in part determined by the type of spatial sampling (integral field or multi-object) and the possibility of "stacking" low resolution spectra.

Several key DRM projects call for surveys of objects at such faint flux levels that the spectrograph must have multi-object capability in order to complete the DRM within the mission timeframe. For multi-object studies, maximizing the field of view of the NIR spectrograph is important primarily so that there are sufficient objects of the appropriate type to take full multiplex advantage of the spectrograph. Ideally the spectrograph should be capable of obtaining at least 300 objects simultaneously. Not every object in the field will be desirable as a target, so a field of view containing about 3000 objects is a reasonable goal.

From this goal and the density of sources on the sky we can derive minimum field sizes. For example, a substantial portion of the NGST spectroscopic program is contained in the deep galaxy spectroscopic survey. The Hubble deep field observations, figure 1, indicate that there are $\sim$ 30 and 300 galaxies/arcmin^2/mag at AB mag of 25 and 30 respectively. Assuming we wish to observe all galaxies at a particular magnitude, then our goal implies a spectrograph FOV of 10'$\times$10' for an AB mag of 25 or 3'$\times$3' for an AB mag of 30. Given the ISIM NIR spectrograph limitation to 4'$\times$4', this calculation suggests a minimum acceptable FOV of 3'$\times$3' and preferably the maximum 4'$\times$4'.

Note also that for these deep DRM programs on field galaxies, the filling factor for the spectrograph field (give by the number of objects to be observed times their average size divided by the FOV) is less than 10% (Gardner & Satyapal 1999).

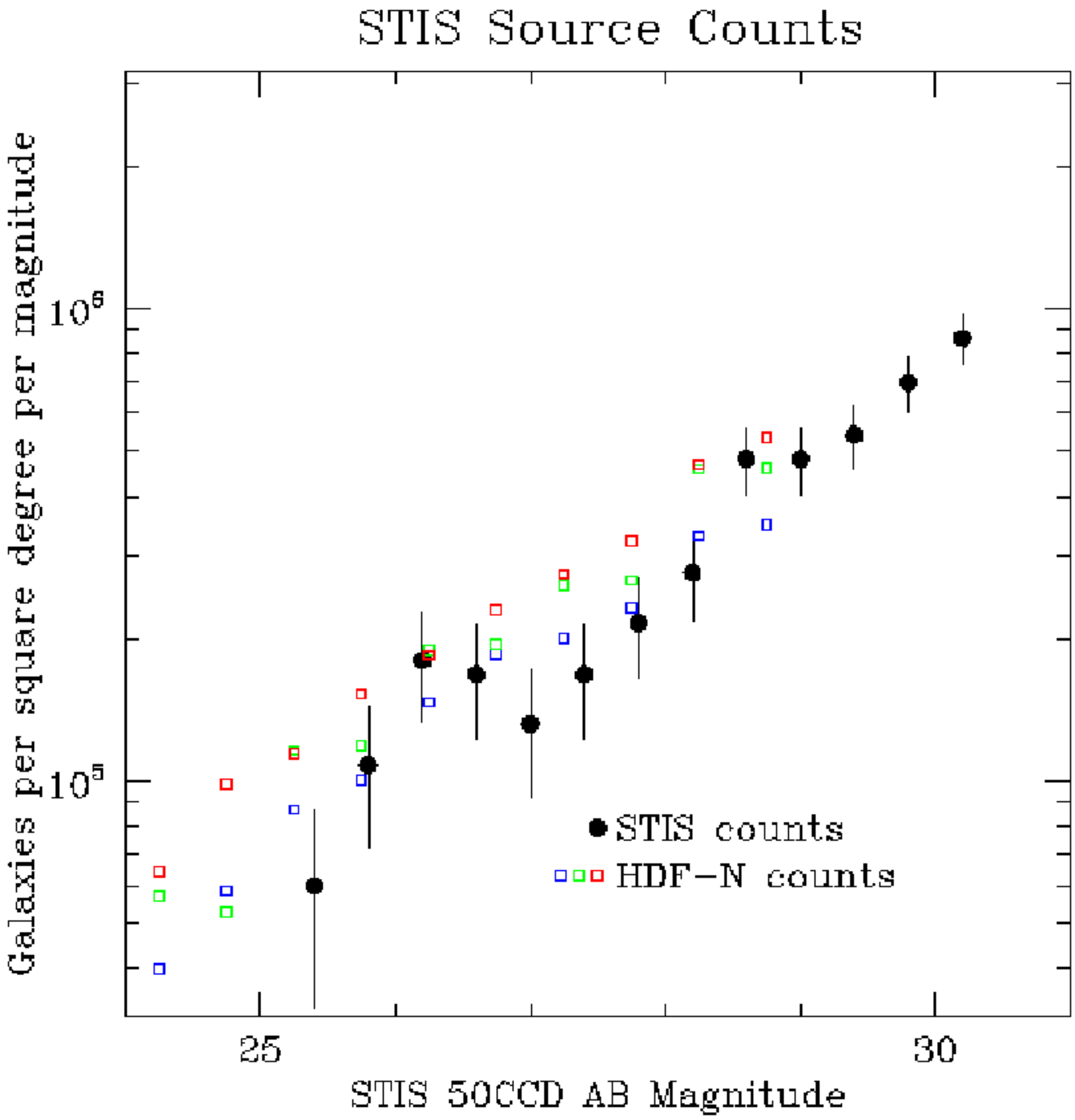

Figure 1: Source Counts in the Hubble Deep Fields. STIS CCD counts in wide open mode in the HDF-S, and WFPC2 counts in approximately B, V and I. (from Gardner & Satyapal 1999).

Among extragalactic targets, the largest dynamical systems are individual clusters of galaxies. X-ray diameters at z=0.5 are observed to be of order 1 arcmin. For $H_o = 68$, the minimum angular scale factor (occurring typically at a z of 1-2) is 0.1-0.15 arcsec/transverse kpc. For clusters of galaxies, with a core radius of 0.4 Mpc, this corresponds to a 40-60 arcsec radius, suggesting the minimum field to observe the objects in a rich cluster should be of order two arcmin. This is compatible with the above multi-object FOV calculation although multiple exposures may be required to get all the objects in the field.

Note that for programs involving Galactic or local group objects, it is unclear that there are sharp discriminators in size. The only such NIR spectroscopic program with a requirement for field size is the program involving embedded stellar clusters, which have apparent sizes that are well matched to a 4'x4' FOV spectrograph. Globular clusters, open associations, and HII regions are too large to contemplate for observation with single pointings.

For individual objects requiring complete spatial sampling such as a dense stellar core, a high redshift galaxy whose detailed kinematics is the object of study, or a nearby star cluster, it is desirable to include as much of the object as possible, in order to sample different physical regions. In these cases one is limited by the desire for high spatial resolution (at the diffraction limit) and the detector format. A field of 2"×2" critically sampled in two dimensions at the diffraction limit will produce >3000 spectra that must be recorded simultaneously.

1.6 Serendipity

Given that the raw sensitivity of any near-IR spectrograph on NGST will exceed that of spectrographs on ground-based 8 meter telescopes, it is worthwhile to consider strategies to facilitate and exploit serendipitous discoveries. The strategy is not straightforward since the best strategy depends on the nature of the object. If the object cannot easily be detected by broadband imaging, the figure of merit for serendipitous discovery is the number of spectra which can be taken. An example of the type of object that might be discovered in this fashion would be the detection of a population of high-redshift clouds which emitted predominately in a single line, such as H_α. On the other hand, if, as has been predominantly the case in the past, most serendipitous objects are first detected and identified as interesting in imaging programs, then the exact design of the spectrograph should not be driven by serendipity. To the extent that serendipity is a discriminator, the very best spectrograph would be the one which obtains the largest number of spectra over the widest field with moderately low spectral resolution.

2 A Strawman Spectrograph

Based upon the discussion above, it is possible to distill the scientific requirements from the DRM and what we think are other important programs into a strawman design, "Strawspec."

For wavelength coverage, because it is critical to cover features as they pass through all redshifts, the full spectral range should be observable. We recognize that in dispersive spectrographs this is likely best done in octaves with appropriately blazed gratings, or volume phase holographic gratings if they become available (see Appendix A).

For pixelation, which relates to spatial resolution, a significant fraction of both the galactic and extragalactic science is critically enhanced if observations can be made at the diffraction limit of the telescope, 0.069" at 2.2 microns. Nyquist sampling implies 0.035" pixels in the spatial dimension. This is the parameter that drives the high spatial resolution channel. For the ultimate sensitivity for *integrated* galaxy spectra, the wide-field mode, we are driven to pixel sizes defined by the maximum sizes of faint galaxies and by the match between detector noise (primarily dark current) and the background zodiacal light. S/N is maximized by increasing the spatial pixel size until you either run out of galaxy light or you become background noise dominated. The optimal pixel size is slightly wavelength dependent, and we have made the choice at 2-3 microns (see the section on Sensitivity).

For spectroscopic resolution, the choice of resolution is driven strongly by the astrophysical problem to be solved and the natural widths of the spectroscopic features to be detected. We believe that most of the very low resolution spectroscopy in the DRM (e.g. that which requires only crude redshifts) should not drive the spectrograph design. There is a growing body of evidence that reasonably good ($\delta z \sim$ 0.03-0.05) photometric redshifts can be obtained by imaging in medium or even broad band filters. Quantitative spectroscopy, for example, measuring the galaxy-galaxy velocity correlation function at high redshift or studying the internal kinematics of galaxies, requires velocity accuracies better than 100 km/s and thus requires resolutions of 500 or more. Furthermore, it is important that this spectral resolution be provided over the full spectral range.

High spatial resolution programs often also require higher spectroscopic resolution, driven by the intrinsic physics of the phenomena to be studied (narrow emission line regions, weak absorption lines, kinematics at 10-30 km/s velocity resolution, etc.) Although it would be advantageous for some programs to be able to utilize a spectrograph that enabled high spatial resolution spectroscopy of multiple objects in the field, almost all of the specifically high spatial resolution programs described in section 1 are single-object programs (although in some cases, such as star clusters in nearby galaxies, "single" actually means a complex collection of single objects).

Table 2: **Strawspec**

	Wide-Field Mode	High Resolution Mode
Wavelength Coverage	1-5 microns	1-5 microns
Pixelation	0.1-0.15" *	0.030"
Resolution (R)	500-2000 req 500-5000 goal	500-5000 req 500-10000 goal
Field of View (FOV)	3'x3' req 4'x4' goal	few arcsec squared
No. of Objects/Field	300	> 3000 **

 * depends on dark current
** number of individual spectra in the FOV

Thus, for FOV, we were driven in two competing directions. Some of the most important goals of the DRM require the widest possible field. Given that the ISIM itself is specified to provide only a 4'x4' FOV for the spectrograph, this field should be the goal of whatever wide-field mode is constructed. However the ultimate field is driven by the combination of detector size (number of pixels) and the optimum pixel size needed to obtain the best S/N on the faintest galaxies (extended sources). If large pixels can be used without significant degradation of the S/N due to zodiacal background, then the FOV will be determined strictly by the telescope/ISIM. If ∼0.1" pixels are optimum, as we discuss below, then the FOV is driven by the detector size — a 2048^2 array with 0.1" pixels will cover only a 3.4' diameter field in multislit mode.

Detector size drives the high spatial resolution mode as well. A design that is diffraction limited at the shortest wavelength we consider, 2 microns, requires 0.035" pixels for spatial Nyquist sampling. Thus, if the spectrograph were to use a 4096^2 array in an integral field mode with one dimension fully covered by the dispersion direction, the maximum field of view obtainable would cover at most $4096 \times 0.035''^2 = 5$ square arcseconds.

The obvious conclusion is to recommend two spectroscopic channels that, combined, are capable of carrying out the DRM as well as a significant amount of additional and related science. The spectrograph should have, like the cameras on HST, both a wide-field and a high resolution mode. The parameters of these modes are given in Table 2.

3 Instrument Concepts

At present, there are three generic concepts under discussion for the NIR spectrograph and it is likely that any new concept will be related to one of these. Two are dispersive and are distinguished primarily by their front ends and one is interferometric. The dispersive designs use either fixed format focal planes, which are called Integral Field Units (IFU), or positionable slits, apertures or fibers, in which case the system is called a multi-object spectrograph (MOS). The interferometric designs are usually based on a Fourier Transform Spectrometer (FTS). The panel obtained descriptions of the existing U.S., European and Canadian NIR spectrograph concept studies; final versions of all the U.S. instrument studies including the ISIM and Coronagraphic Science study are available on the web and are listed in the references (Bally et al., Ennico et al., Graham et al., MacKenty et al., Moseley et al., Trauger et al.)

3.1 Integral Field Spectrographs

Integral field spectrographs are those with which a spectrum is simultaneously obtained for every pixel in the FOV of the instrument. There are a variety of ways to implement integral field spectrograph designs. These include both designs which use image slicers to rearrange the focal plane on the spectrograph entrance aperture and also fiber-based designs. The front ends of both types of system are called IFU's.

Depending on how the IFU pixels are utilized, one can design spectrographs with various combinations of spatial sampling, field of view, resolution, and spectral range. We assume a 16 Megapixel detector (4k×4k) For an assumed low resolution baseline (namely R=500 spectra, simultaneous coverage of 1 octave, and 2 CCD pixels per spectral resolution element), one can (in principle) image a 120×120 IFU pixel region on the sky, by stacking spectra along the dispersion axis of the CCD. At the diffraction limit (0.035" at 2 microns) this corresponds to a 4.2"×4.2" region of the sky. To obtain a larger field of view, one must sacrifice a combination of resolution, simultaneous wavelength coverage, and spatial resolution. For example, increasing the pixel limit to 0.2×0.2 arcsec (matching slits to the expected size of galaxies in the deep exposures), and reducing the spectral resolution to 300, one can increase the field of view to of order 33"×33".

The integral field spectrograph design that has been worked out in most detail for NGST uses an image slicer approach. The design, produced by a European team led by O. LeFevre, actually contains two independent channels: one designed for low spectral (R∼150) resolution, relatively wide-field (46"×40") spectroscopy and the other designed for relatively high spectral (R∼3000) and spatial (0.050") resolution.

Integral field spectrographs are ideally suited to observations in which one desires to obtain a spectrum of every pixel in the field of the spectrograph, and in which field size is not a dominating criterion. The obvious example of such a program in the DRM is the studies of quasar host galaxies, but other possibilities include studies of individual globular clusters in nearby galaxies and the nuclear regions of galaxies. Integral field spectrographs are ideal when every pixel in the field will produce a useful spectrum, e.g. for K+M stars in nearby galaxies, for circumstellar disks, and for the cores of Galactic globular clusters, even if in these cases the relevant scale of the object may be considerably larger than the field of view. Also, as a direct result of the fact that an integral field spectrograph obtains a spectrum of every pixel, they are excellent choices in situations in which it is difficult to identify the interesting part of a field or in which the target astrometry is relatively poor (e.g for SCUBA sources).

Since the throughput of an integral field spectrograph can approach that of a simple slit spectrograph, integral field spectrographs can also be used effectively for single object spectroscopy. Since such spectrographs have few (or in some cases no) moving parts, background subtraction and other calibration should be straightforward. Furthermore, integral field spectrographs tend to have few grating settings (especially in image slicer designs where it is tricky to lay the spectra out on the detector so they don't interfere), and hence dithering may be easier with these spectrographs than with some competing approaches.

Integral field spectrographs are less well suited to "sparse-field spectroscopy." Examples of such spectroscopy in the DRM programs include the deep galaxy survey, the studies of clusters of galaxies and the studies of the low mass end of the initial mass function, which, as noted earlier, are observations of objects extended on a scale of several arcmin.

That integral field spectrographs are less well suited to "sparse-field" spectroscopy is not surprising because they are optimized for situations in which (nearly) every position in the FOV is interesting. Since detector real estate is expensive, integral field spectrographs necessarily involve compromises in terms of resolution, simultaneous wavelength coverage and FOV. The European low resolution channel is an excellent example of an attempt to find the appropriate compromise. The pixel size in this spectrograph is well-matched to that required to carry out the extragalactic science program. The low resolution channel of this design requires 24×10^6 pixels, somewhat but not too much greater than the fiducial 4k×4k arrays we have assumed elsewhere. However, consistent with our own "back of the envelope" estimate above, the resulting FOV is smaller than optimal for most of the low spectral resolution DRM science and the spectral resolution of 150 is less than desirable for the bulk of wide-field NIR spectroscopy on NGST.

For these reasons, while the committee felt that the integral field spectrograph approach is the best approach we have seen for high spatial resolution spectroscopy, we found it less compelling for wide-field spectroscopy.

3.2 Multi-Object Spectrographs

Generally what is meant by a Multi-Object Spectrograph (MOS) is a spectrograph capable of observing a significant number of selectable objects simultaneously over a large field of view, comparable in size to the maximum FOV obtainable in the focal plane of NGST. Common examples of such an instrument use positionable fibers or multi-slit systems.

The advantages of a MOS include the maximization of the accessible FOV, flexibility in the selection of objects to observe, optimal use of the detector pixels by obtaining data only for the objects of interest while rejecting blank sky and overly bright objects, high total throughput and sensitivity, and the fact that the effective slit size can be increased to trade spectral resolution for higher throughput.

We have considered in some detail a MOS concept (MacKenty et al) that employs the developing technology of micro mirror arrays (MMA). Three specific advantages of the MOS-MMA concept over one or more of the other proposed concepts are the minimal dead space between mirrors permitting dense spatial sampling (particularly important for extended objects), the ability to synthesize arbitrarily shaped and oriented apertures, and the fact that, since sub-arrays can be read out during long exposures and individual elements in the MMA can be rapidly reconfigured, some of the mirrors can be reoriented in the course of an exposure to observe additional objects.

The MOS-MMA is especially well suited for the execution of the core programs of the DRM. In particular, this instrument concept is ideal for the top ranked spectroscopic program on galaxy formation and evolution. More generally, the MOS-MMA will be quite effective in carrying out all of the programs in the spectroscopic DRM that require observations of multiple objects over a wide FOV at spectral resolutions of R$\sim$3000 or less. These observations can be made while taking advantage of the full FOV proposed by MacKenty et al. since the FOV is not dependent on the spectral resolution. Preservation of field size is particularly important for sparsely distributed objects.

The science goals for NGST near-IR spectroscopy that require resolutions of 5000 to 10,000 are aimed primarily at single or few object per field studies. Thus, these programs would benefit from a cross-dispersed mode. This would avoid the need for multiple gratings. High resolution and wide spectral coverage could be achieved simultaneously in a cross dispersed mode. Cross-dispersed spectra of several objects or of multiple positions within the same object can be stacked in the same exposure. In addition, most of the high spectral resolution programs also require high spatial resolution, i.e. at the diffraction limit of NGST.

In order to Nyquist sample at 0.035"/pix on a 4096 array, a 2048 square micro-mirror array is needed. Each mirror needs to sample 0.07" which is close to the NGST-MOS "enhanced" design presented by MacKenty et al. in which each of the MMA mirrors subtends 0.08 arc seconds, yielding a 4.1$\times$2.7 arcmin FOV. This samples a larger FOV than does the IFS.

A small advantage of the multiple fiber approach over the MMA is that it is more flexible in positioning on the sky — with micro-mirrors one cannot obtain spectra of objects that lie along the dispersion direction with respect to each other.

At higher resolutions, a problem with the MOS approach becomes the number of gratings required to achieve full spectral coverage unless: a) a cross dispersed mode is implemented; b) the gratings can be tilted (see also the appendix on VPH gratings for a third alternative).

Because of low background, one can synthesize lower spectral resolution in order to gain photons by adding together light from neighboring micro-mirrors. One gives up spatial resolution with this technique, however. For extended ($\geq$0.07") objects one is forced to trade off between spectral resolution and total light captured if the entire front end were made to properly Nyquist sample at 0.035".

Object pre-selection is required for either micro-mirror arrays or movable fibers whereas it is not required for integral field or either an FTS or a Fabry-Perot (FP) mode. However, integral field mode can be simulated by "stepping" through sets of parallel columns with the MMA concept, with some loss of efficiency. Except at the lowest spectral resolution, the effective FOV with an MMA-MOS is about half of the actual FOV because the spectra must be arranged without overlap.

The IFS and the MOS used with the same spatial resolution have similar chances of making serendipitous discoveries since the number of detection elements is the same.

Note that for faint object spectroscopy, the sky background must be accurately subtracted. This requires excellent calibration of the relative flat-field response. This is a well known problem for fiber systems as the sensitivity of a fiber will be a function of how a fiber is stressed. Thus repeatability may be an issue. Similarly, issues of repeatability may be important for the MMA system, particularly if the sky background is obtained from separate mirrors from the ones covering the object. How accurately can the flat field response and sky subtraction be calibrated?

One last issue for the MMA is the question of how diffraction from the regular spacing of the micro-mirrors and the dead spaces in between mirrors affects the performance of such a system. This may need further study.

3.3 Fourier Transform Spectrographs

An imaging Fourier transform spectrograph forms a spatial image of the instrument's field of view on the detector, spectrally sampling one Fourier component of the spectrum of each point in the image. Changing the path length difference of the interferometer samples a different Fourier component of the spectrum. By taking a series of images at different path lengths, a data cube is built up that provides, upon Fourier transform, the spectrum of each point in the image. In addition to preserving the diffraction limit of the telescope, this technique allows unbiased spectroscopy since there is no preselection of objects. FTS instruments trade their spatial multiplex gain against the spectral multiplex advantage of grating instruments. Thus the richness of the observation scene largely dictates the advantage of an FTS against dispersive designs. The FTS is most efficient for low spectral resolution

(R $<$ 100) observations of extremely crowded fields (N $>$ 1000 sources).

Many observational targets will contain a limited number of objects in the field of view, particularly in high spectral resolution modes where relatively bright objects are required. In this circumstance, a standard FTS is inefficient compared to a dispersive design. To partially compensate, a dispersed FTS (DFTS) mode can be implemented. Here a focal plane mask (micro-mirrors, micro-shutters, etc.) selects the objects for study, and a dispersive element is inserted into the collimated beam of the FTS. The mask prevents overlap of the dispersed images on the detector. DFTS reduces the number of Fourier samples needed to attain a given spectral resolution, at the expense of incomplete sampling of the focal plane. DFTS requires the elements of a MOS design (focal plane mask device and dispersive element inserter) in addition to the FTS mechanism, and is thus mechanically more complex than a MOS or IFS.

For targets where a spectrum is required at each (high spatial resolution) point in the image, an FTS is ideal. However, a single FTS cannot be used to provide both low and high spatial resolution without a camera change. Therefore if low spatial resolution information is desired (e.g. integrated galaxy spectra), the FTS and DFTS over-sample the image plane at decreased sensitivity relative to other instrument concepts. At high spectral resolution (R$>$1000) DFTS is not competitive with cross-dispersed designs, since there are too few objects in the field of view to utilize the detector pixels effectively.

Since an FTS measures all the flux in a particular Fourier component across a relatively broad spectral range, it is always photon noise limited. Thus it is a particularly attractive design if detector read noise or dark current cannot meet the NGST specifications. Conversely, if there are strong emission lines in the spectrum, their larger photon noise contributes to each spectral sample, degrading the sensitivity to continuum and absorption line measurements.

In a four-port FTS design, such as those investigated by Graham and Moseley, broad-band imaging is produced "for free" simultaneously with the spectroscopic measurements. Thus if there is to be only one NIR instrument on NGST, an FTS is a strong contender, since it can perform both the imaging and spectroscopic roles. On the other hand, if separate imagers and spectrographs are provided, the competing spectrograph designs will certainly outperform the FTS alone in accomplishing the spectroscopic portion of the DRM. A DFTS mode can in principle be implemented, which would recovers much of the sensitivity, but this adds considerably to the complexity of the instrument concept.

4 Instrument and Detector Trades

In this section, we discuss the effects of detector characteristics, such as read noise and dark current, on the choice of instrument concept. Spectrographs generally consist of a front end, a dispersive system, a camera and detector, and several of the concepts presented can be modified by changing front ends while keeping the rest of the system fixed (e.g. using a MOS and cross-disperser as the front end of an FTS system). We address those trades as well. Finally, we also discuss other spectrograph options such as a coronagraph and the ability to do polarized and time resolved spectroscopy.

4.1 Detector Characteristics and Effects on Spectroscopy

We discuss the impact of detector parameters on spectrograph performance, with a specific emphasis on those factors which impact the choice of spectrometer. The focal plane array will be characterized by the following parameters: 1) detector noise, including read noise and dark current, 2) quantum efficiency 3) wavelength coverage, 4) array format, 5) pixel pitch, 6) well capacity and dynamic range, and 7) detector stability. Detector quantum efficiency and wavelength coverage will affect all spectrographs similarly and is therefore not relevant to the choice of spectrometer.

For dispersive-based spectrometers and tunable filters, the detector noise affects the ultimate sensitivity possible with NGST. Due to the cosmic ray rate of ~ 4 cm^{-2} s^{-1} at L2, typical exposure for the NIR detectors will be 1000 s in duration. For this integration time and a modest resolution of 100, the noise per pixel (assuming 30 mas pixels to critically sample the diffraction limited PSF at 2 microns) due to zodiacal background is $\sim$15 e- at 5 microns and 3 e- at 1 micron. This implies that, for all dispersive spectrographs, at *any* of the spectral resolutions we consider, the spectra will generally be detector noise limited. In order to be limited by the zodiacal background, the detector noise must be less than these values. If the read noise of the detector array is 2 e-, for example, the dark current must be less than 0.005 e-/s, substantially lower than current values. For higher resolution spectroscopy with dispersive spectrographs, the challenge on detector noise requirements is clearly even more severe. For pure FTS spectrometers and current detector specifications, the detectors are always operating under photon noise limited conditions since each pixel views the entire pass band. Detector noise therefore has no effect on the sensitivity in this case. The impact of detector noise on spectrograph sensitivity is illustrated in Figure 2. As shown, if detector noise performance is comparable to that available in current InSb arrays, an FTS will approach the point source sensitivity limits of a dispersive-based spectrograph

Table 3: **Assumptions for Signal-to-noise Calculations**

Telescope Area	= 8 meter
Detector Size	= 4k x 4k
Plate scale	= 0.03"/pixel (critically sampled for diffraction limited performance at 2 microns)
Detector dark current	= 0.02 electrons/s
Detector read noise	= 3 electrons
Detector quantum efficiency	= 0.90
Wavelength coverage	= 1-5 microns
Background	= Zodiacal background model from DIRBE
Maximum single exp time	= 1,000 s (determined by cosmic ray rate)

at low spectral resolutions.

Since most spectroscopic observations with NGST will require long exposures, detector stability is critical. In the case of dispersive-based spectrographs, the spectrum is obtained simultaneously or with only several exposures at specific grating settings. In the case of an FTS, detector responsivity drifts taking place during a scan will contaminate the reconstruction of the full spectrum. However, with a four-port interferometer, detector instabilities can be removed by acquiring a differential measurement between spectra of sources at the primary input and spectra of a calibrator at the secondary input.

Finally, while cosmic ray removal will be possible with all spectrograph concepts, a cosmic ray glitch in an FTS spectrograph will affect the entire interferogram. Interpolation schemes can however be implemented. We have not fully explored the impact of cosmic rays on observing complexity for each of the spectrograph concepts.

4.2 Sensitivity

We have investigated quantitatively the sensitivity trades between the following fundamental instrument concepts: a Fourier Transform Spectrometer, a dispersive-based multi-object spectrometer, an integral field "image slicer," and tunable filters or a Fabry-Perot (FP). The assumptions used for all calculations in this document are summarized in Table 3.

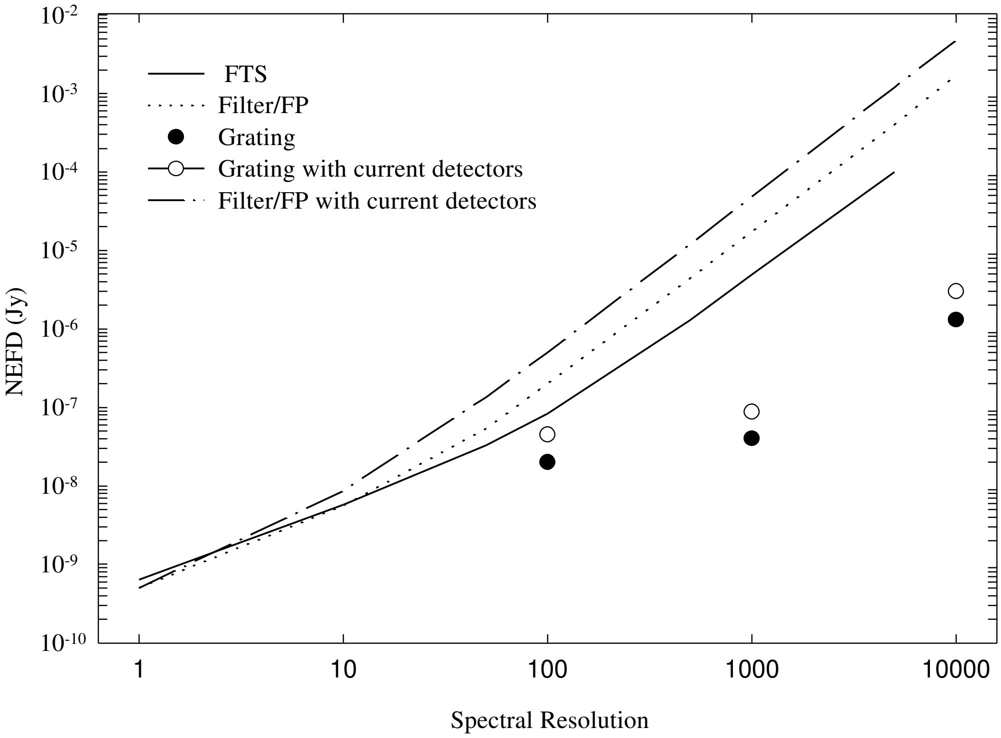

Figure 2: Noise equivalent flux density for S/N=10 as a function of spectral resolution for a 10^5 second integration determined at 3 microns for the three generic spectrograph concepts. We show the effect of detector noise on spectrograph sensitivity. For the goal NGST detectors, we assumed a read noise of 3 electrons and a dark current of 0.02 e/s. For current detectors, we assumed a read noise of 15 electrons and a dark current of 0.1 electrons per second. As shown, the sensitivity of an FTS is independent of detector noise performance.

4.2.1 Dispersive Spectrographs

The sensitivity of a long slit grating-based spectrometer is given by:

$$SNR = \frac{S_\lambda \Delta\lambda \frac{\mathrm{t}}{N}}{\left(\left[(N_R^2 + I_{\mathrm{dark}}\frac{\mathrm{t}}{N})n_{pixpsf}(\lambda)\right] + \left(S_\lambda \Delta\lambda \frac{\mathrm{t}}{N}\right) + B_\lambda \Delta\lambda \frac{t}{N} n_{pixpsf}(\lambda)\right)^{1/2}} \qquad (1)$$

Where S_λ and B_λ are the source and background photon rates including instrument throughput and grating efficiency (which are strong functions of wavelength), N_R is the total effective read noise from the multiple ~ 100 second exposures required at each grating setting (for cosmic ray removal and not to saturate the detector), I_{dark} is the detector dark current, t is the total integration time, and $n_{pixpsf}(\lambda)$ is the number of pixels in the point spread function. In the IFS case this is simply given by the match to the spatial resolution; in the MOS case (or long-slit case) it is related to the number of pixels in the 1-D psf along the slit times the slit width in pixels. Here N is the number of grating settings/gratings required to obtain the entire spectrum, and $\Delta\lambda$ is the effective bandpass per dispersed pixel. The assumptions on the grating efficiency are summarized in Table 4.

4.2.2 Imaging Fourier Transform Spectrometers

A Fourier Transform Spectrometer (FTS) acquires a full 2 dimensional image of the entire field of view observed. Successive images corresponding to different positions of a moving mirror are acquired and the Fourier transform of the resulting interferogram yields a spectrum of every pixel in the array. The signal-to-noise ratio in this case is given by the expression:

$$SNR = \frac{\frac{\sqrt{N}}{M}\left(\int \frac{S_\nu t}{N} d\nu\right)}{\left(\left[2(N_R^2 + I_{\mathrm{dark}}\frac{t}{N})n_{pixpsf}(\lambda)\right] + \left(\int S_\nu \frac{t}{N} d\nu\right) + \int B_\nu \frac{t}{N} n_{pixpsf}(\lambda) d\nu\right)^{1/2}} \qquad (2)$$

Here, S_ν is the signal photocurrent including instrument efficiency (assumed to be flat across the frequency interval), B_ν is the background photocurrent, N_R is the read noise, I_{dark} is the detector dark current, t is the total integration time, N is the number of samples in the interferogram, $n_{pixpsf}(\lambda)$ is the number of pixels in the point spread function, and M is the number of spectral channels required for the desired spectral resolution. The derivation of the above expression is given by Bennett (1999). The factor of two in the detector noise

Table 4: **Grating Assumptions**

```
Case A: R=100
  . 1 grating can cover whole spectrum
  . Band average efficiency is approximately 50%
  . Grating density: 2.96E-03 mm-1
  .    Incidence angle: 8.74 deg
  . Nominal blaze angle: -0.143 deg
Case B: R=1,000
  . 2 gratings can cover whole spectrum; 1 setting each
  . Band average efficiency is approximately 83%
  . Grating density: 5.45E-02 mm-1 , 2.44E-02 mm-1
  .    Incidence angle: 6.43967 deg, 6.43984 deg
  . Nominal blaze angles: -2.183 deg, -2.186 deg
Case C: R=10,000
  . 2 gratings can cover whole spectrum; 8 settings each
  . Band average efficiency is approximately 84%
  . Grating density: 4.86E-02 mm-1 , 2.084E-02 mm-1
  .    Incidence angle: 8 different values for each grating
  . Nominal blaze angles: -19.2277 deg, -19.2313 deg
```

term arises for dual port interferometers, where all photons are collected using two focal plane arrays. The spectral resolution of an FTS is determined by the maximum scan length of the moving mirror and is constant with respect to frequency. For a Nyquist sampled spectrum, N is twice the spectral resolution. As can be seen from equation (2), an FTS views all photons within its pass band simultaneously. In photon noise limited operation, and in the absence of band reducing filters, the detectors are also subject to the associated shot noise from the entire pass band.

4.2.3 Imaging Tunable Filters

As in the case of the FTS-based spectrograph, the entire FOV in an imaging tunable filter-based spectrograph is viewed at once. The full spectrum is obtained by imaging the field with successive filters, or by tuning a Fabry-Perot (FP). Here the signal-to-noise ratio is given by:

$$SNR = \frac{S_\lambda \frac{\lambda}{R}\frac{t}{N}}{\left(\left[(N_R^2 + I_{\rm dark}\frac{t}{N})n_{pixpsf}(\lambda)\right] + \left(S_\lambda \frac{\lambda}{R}\frac{t}{N}\right) + B_\lambda \frac{t}{N}\frac{\lambda}{R} n_{pixpsf}(\lambda)\right)^{1/2}} \quad (3)$$

The total integration time again is denoted by t, and N is the number of filters or FP settings required to obtain the entire Nyquist-sampled spectrum. S_λ and B_λ are the source and background photocurrents, respectively, including instrument throughput. As can be seen, the detectors in an FP-based system receive reduced signal compared with the FTS case since only those photons from the source within the bandwidth of the filter at each setting are passed. However, the associated shot noise is also reduced compared with the FTS case. Under background limited operation and assuming identical instrument throughputs, the sensitivity of an FTS and an FP are equal.

4.2.4 Single and Multiple Point Source Spectroscopy

In Figure 2, we plotted the point source sensitivity as a function of spectral resolution to obtain the full 1-5 micron spectrum with an FTS, a grating (for the detector size stated in Table 3), and an FP. The flux density is given at 3 microns for a signal-to-noise ratio of 10. As can be seen, the grating system is the most sensitive to detect a point source for R$\geq$100.

While the sensitivity of an FTS (or FP) is not competitive for point source detections, as the number of sources in a given field of view is increased, dispersive-based spectrometers are limited by the number of simultaneous spectra that can be obtained in a single exposure with a given detector array size. In Figure 3 we include the impact of the anticipated number counts in the NGST field on observing efficiency for the three instrument choices. Specifically, the integration time required to obtain a 10 σ detection on 10 nJy sources in the entire 3'×3' FOV is plotted versus spectral resolution. The predicted integrated number counts in the NGST spectrograph FOV at 3 microns is $\sim 4\times103$ (Gardner 1998, Gardner & Satyapal 1999).

At R=100, a multiple slit spectrograph can obtain spectra of all sources simultaneously with a 4 k×4k detector. At R=1,000, we assume that the spectrum of approximately 1,000 sources can be obtained at once. The total time to achieve the stated sensitivity at 10 nJy is calculated. We have not included in this calculation the added overhead in target pre-selection. As can be seen from Figure 3, at higher resolution, the efficiency of the grating-based spectrograph in obtaining full spectra of the NGST galaxy field is most evident. It should be noted that in the case of an FTS, while the efficiency in obtaining spectra of all galaxies in the full FOV at resolutions > 100 is lower than that of the multi-object spectrograph, very deep broad band images are simultaneously acquired. Since the top ranked science program on galaxy formation and evolution includes both wide-field imaging and spectroscopy, an FTS-based spectrograph allows for both objectives to be simultaneously executed.

4.2.5 Hybrid Approaches: Dispersed FTS's

As can be seen, while the single object sensitivity obtainable at any resolution with an FTS is not competitive with dispersive-based spectrographs, a hybrid concept involving a dispersive element together with an FTS can offer the sensitivity advantage of dispersive spectrographs with the largest field of view and highest multiplex advantage possible for a given detector size. The sensitivity disadvantage for a pure FTS arises because you only acquire the spectrum one Fourier component at a time, so a large number of exposures is required. If a prism of relatively modest dispersion ($\sim$100) is inserted into the collimated space of an FTS spectrograph and a slit mask exists at the focal plane, the photon flux reaching each detector can be reduced until the detectors become detector noise limited. The FTS, operating in a high resolution mode can then be used to obtain higher resolution (determined by the scan length of the moving mirror of the FTS) full wavelength coverage spectra. Since the spectral bandwidth viewed by each pixel is narrow (determined by the resolution of the prism), it is not necessary to sample the interferograms as densely as for the case in which broad band light is incident on a pixel. This dispersed FTS concept would generate a spectral datacube

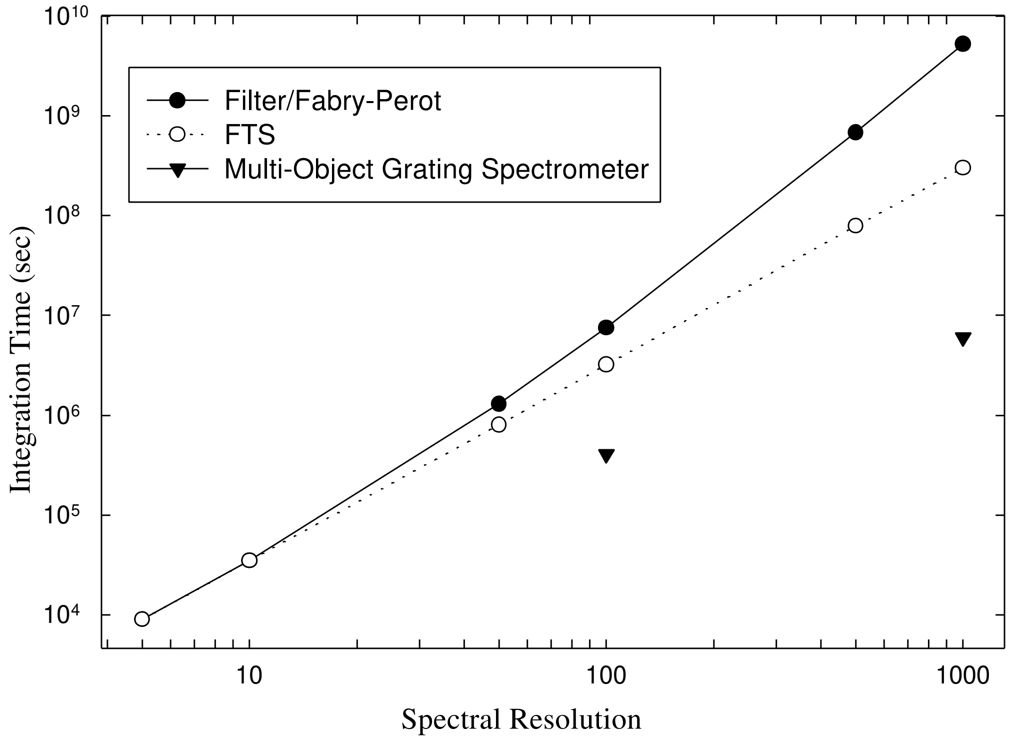

Figure 3: Integration time required to obtain 1-5 micron spectra of 4000 galaxies of $F_{3\mu} =$ 10 nJy (AB=28.9 mag) at 10 σ over a 3'×3' FOV. At very low spectral resolution, filters and an FTS take the same amount of time to obtain a spectral data cube of the entire FOV. At R=100, the multi-object spectrometer can obtain spectra of almost all 4,000 galaxies at once and therefore takes the least time. Overhead in initial imaging observations and target preselection for the MOS observations is not included.

with spectra that are tilted at an angle with respect to the z-axis. The point source sensitivity of such a hybrid approach is comparable to that obtainable with a pure multi-object spectrograph (see Bennett 1999). However, the number of simultaneous spectra that can be obtained over the FOV is higher. Using our requirement on the minimum spectral resolution for the wide-field galaxy survey work of 500, a MOS + FTS spectrograph can view ~ 5 times as many galaxies at a time as a pure MOS spectrograph. At the very deepest exposures, the faintest objects observable spectroscopically with NGST will approach 10 nJy (AB$\sim$30 mag). At these flux levels a pure multiobject spectrograph with a 4K$\times$4K detector array will require only two separate exposures to acquire spectra of all 4,000 galaxies (Gardner & Satyapal 1999) in the FOV. A MOS+FTS spectrograph, on the other hand, can acquire spectra of all galaxies simultaneously. At higher spectral resolutions, the multiplex gain of the MOS+FTS concept is greater but the actual number of galaxies in the field bright enough for high resolution spectroscopic observations is lower. At R=1,000, a pure MOS spectrograph with a 4K$\times$4K detector array can stack only 1 object spectrum in the dispersion direction, and can obtain a total of approximately 1,000 simultaneous objects in the FOV, comparable to or even larger than the anticipated counts at the limit of R=1,000 spectroscopy with NGST. Therefore, while the MOS+FTS concept allows theoretically for the most effective use of detector "real estate," the anticipated number counts at the flux limit of NGST suggest that the actual gain in observing efficiency compared to a pure MOS spectrometer is marginal.

4.3 Wide-Field Observations of Very Faint Galaxies

The optimum choice of plate scale for the wide-field spectroscopic survey work is a function of the light distribution of faint galaxies at high redshift, the zodiacal background, and the detector noise. Background cannot be neglected if the aperture is to be opened up to increase the signal from extended objects. To determine the optimium aperture sizes, we use the recent estimates of the radial light profiles of high z galaxies from the HDF-South STIS images (Gardner & Satyapal 1999, Figure 4), which suggest that half-light radii of ≥ 100 mas are likely to be appropriate. We then calculate the signal-to-noise ratio as a function of pixel size to detect an AB=28 mag galaxy in 10^5 seconds of total integration time. Figure 5 shows the result as a function of wavelength. We assumed a detector dark current of 0.02 e/s, consistent with the anticipated dark current goal for NGST detectors, and the recent zodiacal background models from COBE (Bely 1999). For the scientific goal of maximizing the detection rate of high z galaxies, the optimum pixel scale is between 100 and 150 mas, almost independent of wavelength over the range 2-4 microns. As the background increases, the optimum aperture size and pixel scale decreases.

We note that the optimum pixel scale is dependent on the detector dark current and, in some cases, the read noise. If we assume a dark current of 0.1 e/s and a single frame read noise of 15e, consistent with current InSb detector arrays, the pixel scale for optimum signal to noise at 3 microns for R=2,000 becomes 0.2".

4.4 Spectropolarimetry

As part of our evaluation of NIR spectroscopy, we have considered the utility of adding a spectropolarimetric capability to the NGST spectrograph. Scientific areas of interest at low redshift include studies of grain physics, of magnetic field structures in dusty disks around stars, evolved stars, and AGN, and of warm dust in the vicinity of the Galactic center. At high redshift, polarimetric studies would be of significant importance for understanding the physics of AGN in the context of the unified scheme, especially in searches for hidden broad-line regions. If a spectropolarimetric capability could be easily incorporated into, for example, a high spatial resolution integral field spectrograph, significant and interesting AGN science could be done. This would require the provision of an upstream filter assembly capable of incorporating three wire grid analyzers. Since the greatest sensitivity gains over the ground for spectropolarimetry would be obtained in the mid-IR ($\geq$3 microns) and the DRM does not identify polarimetry as cornerstone NIR science we do not believe that it is essential to include a polarimetric capability in the NIR spectrograph. Modest imaging polarimetric capabilities, but not spectropolarimetry could be easily incorporated into the NIR imager by including wire grids into its filter complement and would be desirable.

4.5 Time Resolved Spectroscopy

A wide variety of programs involving time resolved spectroscopy could be carried out using NGST. On longer timescales (>1 day), potential programs include studies of the afterglows of gamma-ray bursts, of variability in AGN, of variability in T-Tauri systems, and of long-period variables. Such programs would place few if any additional requirements on a spectrograph designed appropriately for single-object spectroscopy on NGST, assuming that individual images were sent to the ground on timescales of a few thousand seconds.

NGST should be an excellent observing platform for such studies, given its location at L2 and the fact that space-based instrumentation is generally well-calibrated and stable. The main requirement for such observations will most likely be scheduling flexibility in order to space observations properly or to coordinate scheduling with other observatories.

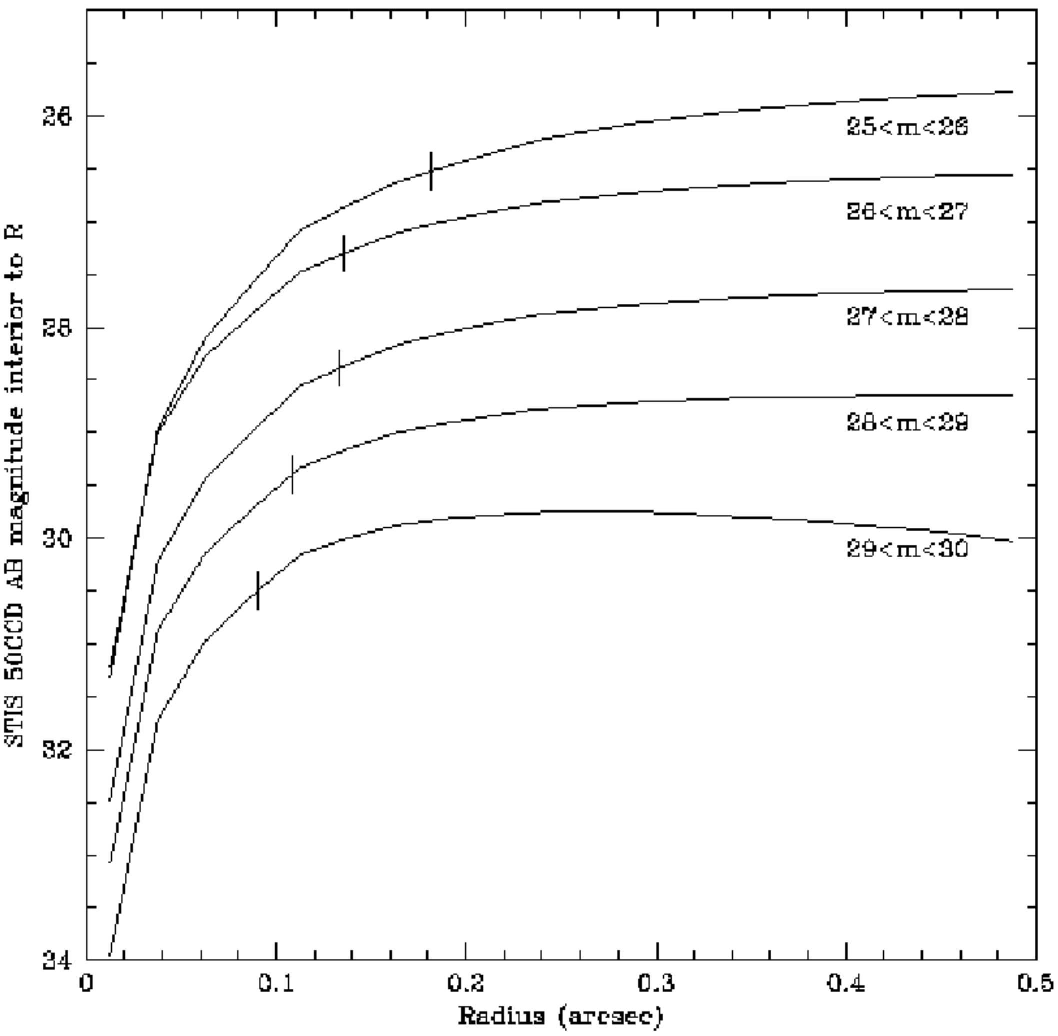

Figure 4: Galaxy Size versus Apparent Magnitude (from Gardner & Satyapal 1999). The vertical bars refere to the mean half-light radii for galaxies in a given magnitude range. As expected in most cosmologies, galaxies do not generally get significantly smaller with magnitude (or distance).

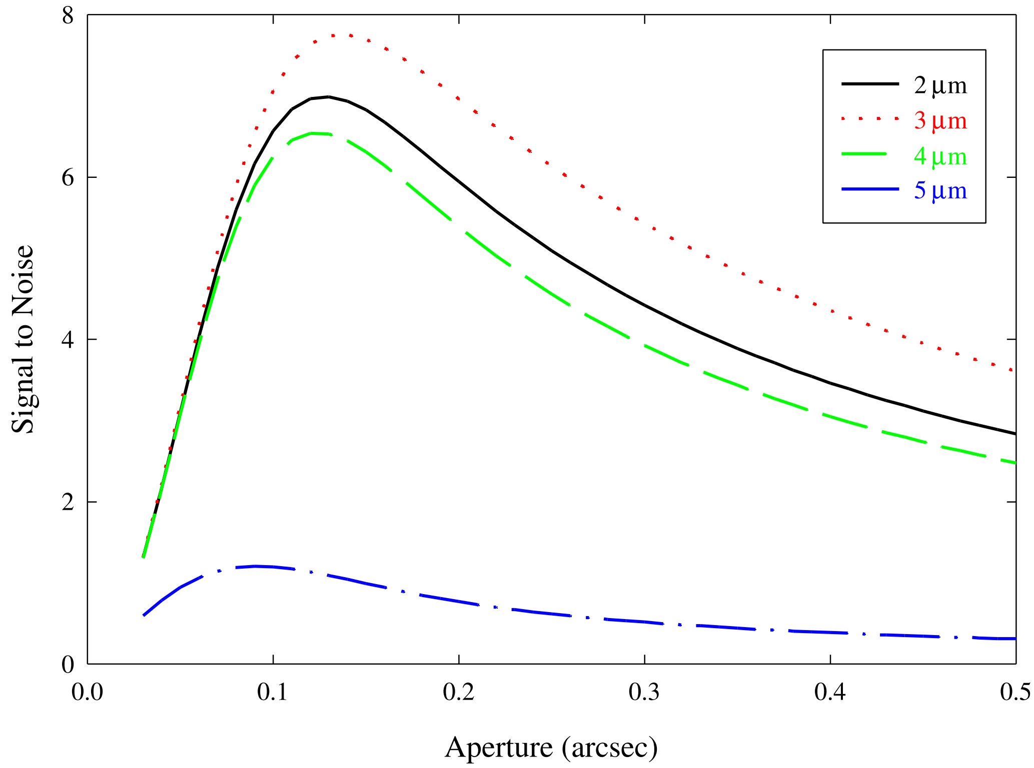

Figure 5: Signal-to-noise ratio versus pixel size for an observation of an AB=28 mag galaxy in 10^5 seconds of integration time at R=500 for various wavelengths assuming a dispersive-based spectrograph. We assumed two pixels per slit width, a dark current of 0.02e/s, a maximum single exposure time of 1,000 seconds and a read noise of 3 e- per frame. The optimum signal-to-noise ratio at 3 microns occurs at a pixel scale of 0.14" at R=500. At R=2,000, the optimum pixel scale is 0.16".

There are also programs which would necessitate shorter time-scales. These include studies of the physics of blazars and BL Lacs, such as 3C66A, and microquasars, such as GRS 1915 and of flares in late-type stars. NGST could be used very effectively for spectroscopically decomposing the outer disks of dwarf novae in eclipsing systems, and for determining the the nature of the secondary stars of black hole binaries. The primary requirement implied to enable these studies would be a capability to acquire accurately sampled object spectra on timescales of 10 seconds or less, and either to buffer sufficient data on board for later transmission or to provide a high-bandwidth transmission channel to keep up with the data rate.

The "best" time variable objects tend to be rare. NGST's potential is that it expands the distance range over which these types of studies can be considered. For example, NGST can in principle acquire a S/N 10 R=500 spectrum of a 20th magnitude object in 5 seconds. This is significantly better than the current performance of NIRSPEC at Keck which provides S/N 10 R=2000 spectra of a 20th magnitude object in $\sim$ 3000 seconds.

4.6 Coronagraphic Spectroscopy

A coronagraph or other means of suppressing the scattered and diffracted light from bright sources to enhance detectability of nearby fainter source(s) or extended structure would be an attractive option. Coronagraph-type spectroscopy on NGST would enable science programs such as spectroscopy of cool (e.g. brown dwarf and planetary) companions to nearby stars located at small angular separations, spectroscopy of the inner regions of circumstellar accretion disks and of the bases of jets in circumstellar outflows, and spectroscopy of the circumnuclear regions of AGN.

It will be difficult to implement an effective coronographic mode within a general-purpose multi-object NIR spectrograph. A focal plane occulting spot (or equivalent with the micromirror or fiber designs) will not eliminate the diffracted light from the bright source, and thus will have an insufficient contrast ratio to allow the types of studies mentioned above (see Trauger et al. 1999 for a detailed discussion). A full coronograph requires both a focal plane occulting spot and a pupil plane Lyot stop.

Fiber designs cannot image the primary after the fiber scrambling, and thus cannot incorporate the Lyot stop within the spectrograph. A separate coronographic module is required, where the coronograph's output focal plane is the spectrograph's input focal plane. All the other spectrograph designs presumably could incorporate both the focal-plane and pupil-plane stops within the spectrograph. Cross-dispersing elements cannot be located before the Lyot stop. Most designs place dispersive elements at the pupil plane, so there is likely to be competition with the Lyot stop. The additional diffraction from image slicing elements in IFS designs and from micro-mirror structures in MMA-MOS designs will not be suppressed by a standard coronograph.

In summary, coronographic requirements may well escalate the complexity of the NIR spectrograph, and also lead to compromises that degrade both the coronagraphic and non-coronographic performance of the instrument. If the science goals of a coronagraphic spectrograph are essential for the NGST mission, it may be better to include a separate coronographic spectrograph or incorporate a spectroscopic mode into a coronographic camera.

5 Summary

The panel reexamined the scientific program in the DRM and other interesting NIR spectroscopic science and distilled what we think are the simplest and most basic capabilities desirable for NGST NIR spectrographs. Several decisions on spectrograph parameters are driven by relatively simple scientific and technical trades which also depend on as yet to be finalized detector and telescope characteristics. For example, the dark current critically drives the optimal pixel sizes for limiting spectroscopy. Similarly, it is extremely important to simulate (or measure!) the sizes and shapes of real high redshift galaxies to determine both the optimum aperture sizes and also the type of spatially resolved spectroscopy that can be obtained for young galaxies.

Table 5 summarizes our conclusions regarding the required spectroscopic parameters for the observations in the DRM and the supplementary programs discussed in section 2. For each program we list the required spectral resolution, spectral range, required field of view, object density, and spatial resolution. Note that the first zero of the Airy pattern, 1.22 λ/D, for an 8 meter at 2.2 microns is at 0.069 arc sec, and at 1.0 microns this is 0.031 arc sec. The ordering of the programs follows the ASWG's ranking (Table 1), and the spectroscopic observational parameters have been derived from the DRM proposals and the panel's scientific and spectroscopic expertise.

With few exceptions, programs require a *minimum* spectral resolution in the range 500-1000. Those that could be done at lower resolution can also be done sufficiently well with broad to intermediate band photometric imaging. Programs also tend to segregate into high spatial resolution observations of individual objects (from protoplanetary disks to the kinematics of individual high-redshift galaxies) where every spatial resolution element in two dimensions is crucial, and lower spatial resolution observations of hundreds (but not thousands) of objects per field of view.

We believe that the NIR spectroscopic science mission will be best served by an instrument or instruments that have the characteristics of the strawperson spectrograph, "strawspec," described in section 2.

Based on inputs from the various spectrograph definition teams, we have examined three basic NIR spectrograph concepts, IFS, MOS and FTS, including narrow and wide-field versions of the integral field concept and dispersed versions of the FTS concept. We compared the performance of each of these instrument concepts to the spectroscopic requirements listed in Table 5. The suitability was graded from excellent to poor (and also un-doable), and these grades are shown in Table 6. In this table IFSW = Integral Field Wide-Field Mode, IFSH = Integral Field High Spatial Resolution Mode, and DFTS = Dispersed FTS Mode.

For example, under the DRM program on the formation and evolution of galaxies and large scale structure at high redshift, there are three different spectroscopic programs: the study of large-scale structure including clustering statistics, spectroscopic diagnostics of galaxies such as those necessary to study integrated chemistry, and the study of the internal kinematics of galaxies including rotation curves for disk systems and the determination of the fundamental plane. These three programs have different requirements. The first two require observation of large samples (thousands), the third requires high spatial and spectroscopic resolution on a relatively small number of objects (dozens). The first requires reasonably accurate redshifts, thus moderate to low spectral resolution (500-1000), while the second requires higher resolution to detect and measure narrow features like [OIII]4363Å emission or Hβ absorption. The first would be well done (E) with a MOS or its equivalent, the dispersed FTS. It would be less well done with either the wide-field mode of an integral field unit (G) or an FTS (G to F). In the first case this is due to the probable poorer match to spatial resolution (a really wide field IFS would have to have very coarse pixels given our constraints on detector size), and in the second this is due to the much poorer throughput of the FTS for moderate resolution spectroscopy if the field is only partially filled.

The high spatial resolution IFS would be a very poor match to the first galaxy program, but it is exactly the instrument of choice for the third program, the internal kinematics of high redshift galaxies. For that program, both high spectral resolution and high spatial resolution are at a premium. The FTS is a poor choice because of its exremely poor throughput at high resolution, the MOS and DFTS are G-F, depending on the MOS aperture size, and, again, wide-field IFS is poor.

Similarly, the DRM program on protostars, essentially observations of the ISM structure (disks, jets, outflows) around single, highly reddened objects, is best done with the high resolution mode of the IFS, especially if the NIR spectrograph detectors can be pushed to longer wavelengths. All of the other instrument concepts are significantly poorer matches to the necessary observations.

The comparison of the scientific spectroscopic requirements to the three generic instrument concepts, Integral Field (IFS), Multi-Object (MOS), and Fourier Transform (FTS) spectrometers and their variations supports the following recommendation:

- **The high resolution mode (primarily high spatial resolution but also likely higher spectral resolution) would be best served by an integral field spectrograph that would enable efficient (single exposure) full spatial coverage at moderately-high-to-high spectral resolution of individual objects. The exact geometry of such a system (square, rectangular etc. FOV) requires further study to optimize the match to object geometry (e.g. if most objects are disklike, a rectangular geometry might be favored if roll angle is only a minimal observational constraint).**

  While FTS systems are attractive for very low resolution spectroscopy and may represent the best choice for a near-IR imager, their generally poor sensitivity for spectral resolution R=500 and higher, and their lower efficiency for observations of objects that sparsely fill the field, argue against their use for the wide-field mode of the NIR spectrograph. In principle, these deficiencies may be reduced by adding complexity, namely a micro-mirror or other multi-slit array and a dispersing element to the FTS.

- **We believe that the optimal choice for the wide-field mode is a MOS spectrograph, probably based on micro-mirror array technology. The ultimate decision must await the technological readiness of the various front end choices.**

- **We believe that it is imperative to have two spectroscopic channels that, combined, are capable of carrying out the DRM as well as a significant amount of additional and related science. The spectrograph should have, like the cameras on HST, both a wide field and a high spatial resolution mode.**

- An FTS, a tunable-filter, or a FP system appears to be very attractive for the NIR imager.

Table 5: **Recommended Spectrograph Parameters for Science Programs**

Program	Spec Res	$\lambda\lambda$	FOV	Obj Den	Spat Res	Notes
High Priority Programs						
Galaxy Formation+Evol	500	1-5	Max	100	0.1	Luminosity Functions, Evolution of Very Large-Scale Structure
Galaxy Formation+Evol	2000	1-5	Max	100	0.03	Spectral Diagnostics
Galaxy Formation+Evol	5000	1-5	Max	100	0.03	2-D Internal Kinematics
Reionization Epoch	3-500	1-5	Min	<1	0.1	Lyα at very high z's
Cosmology with SN	3-500	1-5	Min	1	0.1	Redshifts of SN gals, SN Spectra
Protostars	3000	2-35	Min	1	0.1	Disks and Jets
Other DRM Programs						
Oldest Stars	1500	2-3	Max	10	0.015	Globs in nearby gals
Extrasolar Planets	1000	1-20	Min	1	0.03	Coronagraphic Spectroscopy
Circumstellar Disks	30000	2-30	Min	1-10	0.015	Kinematics+T(r)
Circumstellar Disks	1500	3-30	Min	1-10	0.015	Dust features
SN Rate Evolution	500	1-5	Mod	1	0.1	Redshifts of SN II Gals
Sub-stellar Objects	3000	1.8-5	Max	10	0.1	Atmospheres, g, Fe/H
Galaxies in Clusters	1000	1-5	Max	300	0.02	Spectral Diagnostics
Galaxies in Clusters	5000	1-5	Max	300	0.02	2-D Internal Kinematics
AGN Galaxy Connection	1000	1-5	Mod	1	0.02	AGN Host Spectral Diagnostics
AGN Galaxy Connection	5000	1-5	Mod	1	0.02	2-D AGN Host Kinematics
Brown-Dwarfs + Companions	500	1-5	Min	1	0.03	Coronagraphic Spectroscopy
Brown-Dwarfs + Companions	30000	1-20	Min	1	0.03	Coronagraphic Spectroscopy
KBO+TNO Properties	3-500	1-5	Min	1	0.1	Albedo, Atmospheres (if $\exists$)
Halo Populations	1500	2-3	Mod	100	0.03	K+M stars in nearby gals
ISM Dynamics+Evol	30000	1-5	Min	1	0.1	ISM in absorption in highly reddened areas
ISM Dynamics+Evol	5000	1-5	Max	1	0.1	ISM in emission regions
Gamma Ray Bursts	500	1-5	Min	1	0.1	Host redshifts
Gamma Ray Bursts	3000	1-5	Min	1	0.1	Evolution+chemistry
Beyond the DRM						
High-z QSO Absorbers	10000	1-5	Min	1	0.1	Cloud properties
Dense ISM Outflows	3000	1.6-5	Min	1-10	0.015	2-D Stellar winds
Radio/X-ray/etc ID's	3-500	1-5	Max	100?	0.1	Unknown objects at other λ's
Serendipity	1000	1-10	Max	100?	0.1	Unusual objects
Cool Brown Dwarfs	10000	4-10	Min	1	0.05	Atmospheres+Rotation+B?

Obj Dens = Object density in number/arcmin^2
Spec Res = Spectroscopic resolution
Spat Res = Spatial sampling/resolution in arsec, specified at 2.2 microns
FOV = Field of view
$\lambda\lambda$ = Wavelength Coverage in microns

Table 6: **Performance of Spectrograph Concepts by Science Program**

Program		IFSW	IFSH	MOS	FTS	DFTS
High Priority Programs						
Galaxy Formation+Evol	Luminosity Functions, Evolution of Very Large scale Structure	G	P	E	G	E
Galaxy Formation+Evol	Spectral Diagnostics	P	G	E	P	E
Galaxy Formation+Evol	2-D Internal Kinematics	P	E	G	P	G
Reionization Epoch	Ly a at very high z's	G	G	G	P	G
Cosmology with SN	Redshift of SN gals, SN Spectra	G	P	E	P	G
Protostars	Disks and Jets	F	E	F	F	F
Other DRM Programs						
Oldest Stars	Globs in moderately nearby gals	F	E	E	P	E
Extrasolar Planets	Coronagraphic Spectroscopy	P*	E*	P*	G*	G*
Circumstellar Disks	Kinematics+T(r)	F	E	F	P	F
Circumstellar Disks	Dust features	F	E	F	F	F
SN Rate Evolution	Redshifts of SN II Gals	G	P	E	P	G
Sub-stellar Mass Objects	Atmospheres, g, Fe/H	P	F	E	P	E
Galaxies in Clusters	Spectral Diagnostics	G	P	E	P	E
Galaxies in Clusters	2-D Internal Kinematics	P	E	G	P	E
AGN Galaxy Connection	AGN Host Spectral Diagnostics	F	E	G	P	G
AGN Galaxy Connection	2-D AGN Host Kinematics	P	E	G	P	G
Brown-Dwarf Companions	Coronagraphic Spectroscopy	*	*	*	*	*
Brown-Dwarf Companions	Coronagraphic Spectroscopy	X	X	X	X	X
KBO,TNO Properties	Albedo, Atmospheres (if $\exists$)	E	G	G	P	G
Halo Populations	K+M stars in nearby gals	F	F	G	E	G
ISM Dynamics+Evol	ISM in absorption in highly reddened regions	P	F	P	G	G
ISM Dynamics+Evol	ISM in emission regions	P	P	P	F	P
Gamma Ray Bursts	Host redshifts	E	F	E	P	G
Gamma Ray Bursts	Evolution+chemistry	E	E	G	P	G
Beyond the DRM						
High-z QSO Absorbers	LSS, Cloud properties	P	E	E	P	E
Dense ISM Outflows	2-D Stellar winds	E	E	G	G	P
Radio/X-ray/etc ID's	Unknown objects from other λ's	G	P	E	F	E
Serendipity	Unusual objects	Y-	P	Y-	Y+	Y-
Cool Brown Dwarfs	Atmospheres+Rotation+B fields	E	G	E	P	E

E = Excellent, This instrument made for this problem
G = Good, Instrument will do a good job (~x5 less than E)
F = Fair, (~x10 less than G)
P = Poor, (~x10 less than F)
X = Probably can not be done with any of the "strawspec" designs
* = Requires Coronagraph
Y = Can be done (+ = very well, - less well)
Z = Observations primarily outside wavelength range considered here

APPENDIX

A Emerging Technologies

Our focus in this report has been on clearly stating the scientific goals for NGST near-IR spectroscopy and in turn the instrument parameters that these goals imply. We have commented only briefly on the specific technical difficulties of the currently proposed designs, believing that such a discussion would be most fruitful in the context of a full instrument proposal review.

Nonetheless, it is clear that both emerging technologies and new instrument concepts that cross the IFS/MOS/FTS boundaries may play a major role in determining which design can accomplish the most science at reasonable cost. Two examples highlighted in the instrument studies are MMA technology and dispersed FTS designs. Here we briefly describe two other key areas of technology development, primarily to flag them for future consideration.

A.1 Volume Phase Holographic Gratings

We recommend further exploration of the potential of volume phase holographic (VPH) gratings as a high-efficiency alternative to conventional ruled gratings. In VPH gratings, the refractive index within a transparent layer of dichromated gelatin is modulated periodically. Light is diffracted by passing through the volume, according to the principles of Bragg scattering. The gelatin is sandwiched between layers of glass, which may be shaped and anti-reflection coated. VPH gratings promise *extremely high efficiency*, ∼90-95%, in comparison with traditional gratings, ∼70% (Barden, Arns & Colburn 1998).

Another advantage of VPH gratings is that they effectively have a "tunable blaze" — a single grating may substitute for several traditional gratings, because rotating a VPH grating allows for peak transmission efficiency of a different range of wavelengths. To take advantage of this capability, the camera must be movable to accommodate a variable camera-collimator angle, so the mechanical complexity is comparable. At any angle, the width of the efficiency peak is similar to the width of the peak for a traditional grating. For extremely large FOVs, one must also consider the decrease in efficiency for large angles off-axis, but this should not come into play significantly for the FOVs considered here.

At present, VPH gratings are available and easily customized to any ruling with diameters up to ∼200 mm. However, they have not yet been used in an astronomical spectrograph, and a variety of issues need to be explored first, including temperature sensitivity and performance at high dispersion. Of more importance, the current substrate transmits only to 2.8 microns, so some exploration of alternative materials will be necessary before VPH gratings become a practical option for NGST. People currently exploring the potential of VPH gratings include Sam Barden (NOAO), Chris Clemens (UNC), and Keith Taylor (AAT). The largest difficulty with the use of a VPH in NGST is likely to be the need to articulate the camera.

A.2 Infrared Transmitting Fibers

Infrared transmitting fibers represent another possibly important emerging technology, currently under study by the Canadian MOS design team. Although silica-based fibers do not transmit past ∼2 microns, a variety of materials (fluoride-based, chalcogenide and chalcohalide, silver halide, etc.) have recently been developed that transmit in the near to mid-IR, and research on new materials is currently quite active due to commercial applications in the photonics industry, especially laser and medical applications. Presently available fibers from Infrared Fiber Systems transmit over the entire 1-5 micron range considered in this report, although data on losses between 4-5 microns has not yet been made available. A variety of core diameters and materials are available. Reflex Analytical Systems also supplies infrared transmitting fibers over a number of wavelength ranges. Key issues in considering these fibers for use in space will be their throughput and robustness. They are generally more fragile and temperature sensitive than silica fibers, and it will be critical to measure their response to mechanical stress and evaluate the impact on throughput and background subtraction.

B Backgrounds

Zodiacal Background at the ecliptic pole from DIRBE data (obtained from Pierre Bely) in photons per sec per pixel (assuming .035" pixels)for a 20% bandpass (assuming 8 m telescope, yardstick design:

Table A1. Zodiacal Background

wavelength	ph/sec/pix
1 micron	1.80E-01
2	1.20E-01

3	6.90E-02
4	1.60E-01
5	1.10E+01

The thermal emission from optics is much lower in the near-IR

Table A2. Telescope Thermal Emission

wavelength	ph/sec/pix
2 microns	1.83E-71
3	9.27E-45
4	1.77E-31
5	2.39E-22
6	4.30E-17
8	1.43E-10
10	1.06E-06
12	3.80E-04
15	1.26E-01
18	5.64E+00
20	3.67E+01
25	9.91E+02
30	8.25E+03

C Working Group Process and Charge

NIR Spectrograph Study Charter

The NGST Ad Hoc Science Working Group (ASWG) has developed the general scientific goals of the mission into strawman observing programs, as represented in the Design Reference Mission. Most of the DRM programs were tailored for the NGST Yardstick instrument complement described in "Visiting a Time When Galaxies Were Young," Stockman et al., 1997). However, various NIR spectrograph designs have been suggested and/or are being studied for carrying out this science mission. Altogether 12 instrument studies are funded by NASA, ESA, and the CSA, and there are unfunded studies in progress as well. The reports from the funded studies will be presented at the Woods Hole NGST meetings Sept. 13-16, 1999, and final reports are due Sept. 30. The proposed spectrometers include multi-object spectrographs, integral field spectrographs, and Fourier transform spectrometers. In addition, tunable filters are under development and Fabry-Perot interferometers could be considered, along with various hybrid devices (grisms, post-dispersed Fourier spectrometers, and so forth).

Because of the necessity to apportion the instrumentation among the U.S. and the international partners for NGST in spring 2000, the ASWG is charged with recommending the desired instrument complement, based on scientific value. A technical review panel will provide input to the ASWG based on review of the study reports. Based on the ASWG work and the instrument studies, the Project Scientist will issue a public statement in January 2000, recommending a conceptual instrument complement to meet the most important science goals. There will be time for community comment before presentation to NASA, ESA, and the CSA, and ample time for learning from the experience of previous missions such as SIRTF, ISO, and HST.

To help this process, the STScI is chartering a committee to carry out an independent study of the various spectrograph options. Specifically, this committee should, at a minimum, answer the following questions:

1. Which of the various spectrograph concepts can best carry out each portion of the Design Reference Mission for NGST?

2. What are the strengths and weaknesses of the various near-IR spectrograph options for carrying out the science described in the DRM? Are there portions of the DRM which could not be carried out with one or more of the spectrograph designs?

3. Are there important discriminators among the spectrograph options in terms of expected overall sensitivity, complexity, or flexibility in enabling the broad range of science expected to be relevant in the NGST time frame, even if not necessarily contained in the DRM?

4. Are there specific characteristics (e.g. spatial or spectral resolution, field of view, throughput, detector dark current) that are relatively more crucial for a specific choice of spectrograph?

5. Is there a single spectrograph concept that provides adequate coverage of the entire near-IR spectroscopic part of the DRM? Are the capabilities of different concepts so compelling that some way must be found to include more than one, sacrificing some performance of each to make the combination affordable?

6. Are there alternative criteria besides the ability to complete the DRM that should be considered by the ASWG?

The committee is expected to deliver a written report or "white paper" to the STScI Associate Director for NGST, Ethan Schreier, by August 31, 1999. This report will be forwarded to the NGST Project Scientist, John Mather, for consideration by the Ad Hoc Science Working Group at their September meeting in Woods Hole, to assist in their discussion of which spectrograph designs being studied best suit the NGST science mission.

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