Recommendations of the NGST Detector Requirements Panel

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Executive Summary

Detector arrays will be a truly critical element of the Next Generation Space Telescope. The enormous scientific potential of such a cooled, large-aperture space telescope can only be realized if very high-sensitivity, very large-format arrays are successfully developed and demonstrated, and if they can be produced within schedule and cost constraints.

This panel has explored a wide range of detector topics, extending the breadth and depth of previous NGST detector technology plans. This report defines a clear rationale for deriving detector characteristics from the latest, prioritized science objectives, and from the low, estimated photon backgrounds. Imaging and spectroscopy objectives drive detector requirements toward increased formats (nominally 64 – 80 million pixels for the NIR) and reduced total noise (of order a few electrons).

Detector parameters are discussed in detail, by wavelength region (near-IR, mid-IR, visible). Based on science drivers, the pacing parameters are listed in priority. The near-IR range, owing to its central role in the scientific program, and to the particularly-challenging detector standards that are indicated there, is identified as highest-priority for development and investment. Important, lower-priority, development thrusts are identified for the mid-IR.

A number of NGST detector issues can be further defined by improved system-level definition, and by system studies. In addition to providing updated values for the top-level detector parameters such as format, noise, & quantum efficiency, the panel identified additional factors that must be included for NGST. These include, for example, the effects of cosmic radiation, latent images, thermal stability, and charge-diffusion effects within the detectors that could degrade system modulation transfer function.

A set of Requirements and even more ambitious, highly-challenging Goals was defined for each wavelength region. Requirements are dominantly based on the needs of imaging systems, up to a spectral resolution of ~10 (with a reasonable chance of attainment in 2-3 years); Goals address many of the extraordinary standards implied by planned spectroscopic investigations.

Detailed characterization of candidate NGST detector technology and focal planes is critical. This will require specialized low-background laboratory equipment and expertise, observational tests (when NGST-applicable), and the careful review and open exchange of performance data.

Among the panel's recommendations are: augment funding for detector development; give priority to NIR developments; balance investments in improving sensitivity vs. those which enhance format / producibility; regularly involve detector experts to support system analyses and help guide detector development and characterization; and improve understanding of radiation effects in candidate detectors.

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Section I. Introduction

Infrared detector array and focal plane technology is a crucial and enabling element of the planned NGST mission concept. As the field of detector technology has advanced, and as the mission studies and designs for NGST have matured, the need has arisen for a fresh, comprehensive look at detector requirements and science drivers. This report is an update and expansion of the original (December 1996) NGST detector development plan and requirements document. It was developed by a broadly-based panel with interests and expertise in astronomy, science planning, instrumental concepts, technology development, project planning, device characterization, and astronomical observing & testing.

This report describes developmental goals and requirements which incorporate findings and recommendations from the Ad Hoc Science Working Group (ASWG), the teams defining potential instruments for the NGST Integrated Science Instrument Module (ISIM), collaborators in industry, and review panels such as the NGST Standing Review Board. It includes ideas, data and recommendations presented by a number of speakers at the April 20-21, 1999 NGST Detector Workshop, and at the September 13-16, 1999 NGST ("Woods Hole") Science and Technology Exposition.

The detector requirements were directly derived from the planned science topics and programs, as defined by the latest version of the NGST Design Reference Mission (DRM). Subject to additional technical progress and revised project planning guidelines, we expect these detector requirements and recommendations will be useful in shaping both near-term development activities -- up to the competitive selection of NGST science teams, and the focal plane suppliers -- and also far-term developments of flight focal plane assemblies.

Section II. Objectives

II.A Report Objectives

A key objective of the report is to review the latest scientific objectives for NGST (primarily the latest, prioritized list of DRM programs), and to provide a clear rationale for deriving detector requirements from these science objectives. We worked to identify the highest-priority detector parameters, both those that have the greatest direct influence on science programs, and those that require the greatest emphasis in near-term technology developments and characterization. We present a general assessment of the present developmental state of the art for candidate focal plane arrays, including the status of work by industrial focal plane vendors, and by astronomical groups engaged in utilizing arrays on telescopes. We also aim to provide useful and clear definitions of detector characteristics, and to suggest conventions for collecting and reporting data.

Note that the assessments and prioritizations presented in this report are intended to help guide the project's planning and conduct of the technology development phase, and are *not* meant to define the subsequent detector selection process.

For reference, the committee's charter is listed in Appendix D, Section VIII.

II.B Detector Development Program Objectives

So that the tremendous potential of NGST is realized, the development program must be responsive to science needs, and timely and effective. A summary description of the current and planned NGST detector development program was provided at the April 1999

Detector Workshop (see http://www.ngst.stsci.edu/detector_conf99/proc/mccreight.pdf). The program basically supports the development of two technologies for the near-IR (NIR), 1 - 5 µm; three technologies for the mid-IR (MIR), 5 - 10+ µm, with test data being produced at the three companies and four outside (university or Government) labs.

Throughout the three years until focal plane vendor selection, this program must:

- Support multiple sources of supply of focal planes for the infrared wavebands (NIR and MIR).
- Prove that focal plane technology has both the required sensitivity and the required format and packaging concepts (via mosaicing) for NGST applications.
- Demonstrate reproducible, proven, independently-verified technologies in time for the selection of focal plane vendor(s).
- Involve experts within the astronomical community, in development and demonstration. Try to assure that potential investigators and potential system contractors are familiar with the technology and the industrial focal plane suppliers.
- Assure that the project and the science community has an independent, flexible test & demonstration capability, by supporting multiple lab groups in a coordinated test & characterization activity.
- Incorporate knowledge and heritage from previous space missions & ground-based work, while allowing for new approaches and innovation.

Section III. Derivation of Detector Requirements from NGST Science Objectives

We now examine how the NGST science objectives drive the facility's observing parameters and detector requirements. We approach this topic by considering broad and general observations and effects, with minimal focus on specific observing programs, telescope architectures, or instruments.

III.A. Science Requirements

We start by distilling the general expected observational requirements from the five NGST broad science themes:

1. Cosmology and the Structure of the Universe
2. Origin and Evolution of Galaxies
3. The History of the Milky Way and its Neighbors
4. The Birth and Formation of Stars
5. The Origins and Evolution of Planetary Systems

NGST will likely spend the majority of its observing time conducting large imaging and spectroscopic surveys with total integration times of 10^5 seconds or more per field. Approximately equal amounts of time will be spent in broad-band imaging ($R = \lambda/\delta\lambda \sim 3$ - 5) and spectroscopy. Much of the spectroscopy will likely be conducted at low resolution (R ~ 300), but a significant amount of time will be spent acquiring spectra at higher (R ~ 1000 - 3/5000) resolution. Imaging observations will be conducted over the observatory's entire wavelength range, from approximately 0.6 µm to well beyond 10 µm. Spectroscopic observations will be conducted from 1 µm or less to the long wavelength limit. Several key science programs require good response to at least 25 µm and benefit from sensitivity to 35 µm or beyond. Both spectroscopic and imaging observations are expected to be conducted at moderately undersampled to critically-sampled resolutions. Most NGST observations will require the highest sensitivities achievable, limited only by natural (zodiacal) and telescope background noises whenever possible. The maximum observable flux in each mode is not well established, but we desire bright end overlap with ground-based facilities as a goal.

A set of DRM proposals for NGST was drafted and prioritized by the ASWG in June 1999. The highest priority DRM proposals encompass a wide variety of observations over the entire anticipated NGST wavelength range. These top seven programs call for high resolution (Nyquist sampled -- 4 pixels per Airy disk diameter), wide-field (typically 4' x 4'), zodiacal light-limited NIR imaging and multi-object NIR spectroscopy. MIR wide-field imaging and multi-object spectroscopy are also required for these programs, but it is generally acceptable for the MIR sensitivity to be limited by noise from the telescope self-emission or sunshade scatter. We now list the observational parameters of these programs to give a concrete example of what high priority NGST observations are likely to require:

DRM Program	Major Required Instrument Capabilities	Comments
1. Deep Galaxy Imaging	Wide Field NIR Imaging (1/2) Wide Field vis & 10 μm imaging (1/2)	112 days with 4'x4' FOV
2. Deep Galaxy Spectroscopy	R=100, 1000, 5000 at λ=3.5 μm R=5000 at λ=10 μm	98 days 20 days
3. Dark Matter	Wide Field NIR Imaging	192 days for 4' × 4'
4. Probing the IGM	R=100 NIR spectroscopy	10 days
5. High *z* Supernovae	WF NIR Imaging & some spectroscopy	uses data of DRMs 1 & 3
6. High *z* Obscured Galaxies	λ=8 – 35 μm Wide Field Imaging R=300-1000 Multi-object MIR spectroscopy	54 days / FOV ≥ 2'x2' 10 days
7. Physics of Protostars	λ=15 – 35 μm Imaging R≥3000 spectroscopy λ=6 – 28 μm)	40 days 35 days

This set of programs pushes detector performance by requiring ultimate sensitivities, wide fields, very long exposures, wide wavelength coverage, and a wide range of background fluxes. Programs 6 and 7 push the long-wavelength limit, which will ultimately be set by cooling technology and the finite resources available for detector development. These two programs are still compelling even with a 28 μm cutoff and with realistic observatory backgrounds (as listed in section III.B). These programs are generally representative of the overall science program envisioned for NGST, with the additional provision that most spectroscopy would be best done at R ≥ 300 resolution. The remainder of this section discusses how these and other observational requirements are related to specific detector parameters.

III.B. Observatory and Natural Backgrounds

We start to quantify specific detector requirements by examining the expected photon background flux incident on each detector pixel at anticipated wavelengths and spectral resolutions. Since the final point spread function (PSF) of the telescope is not known, we assume Nyquist sampling so that each pixel subtends λ/2D angular size on the sky in each dimension at all wavelengths λ. Actual instruments are expected to have fixed magnifications, so wavelengths shorter than their Nyquist ones will be somewhat undersampled, and longer ones will be somewhat oversampled. We also assume that the optical throughput is 50% in imaging (R=5 below) and 30% in spectrographs (R≥100 below).

The following table lists these expected photon backgrounds <u>incident</u> on NGST detectors in units of photons/s/pixel given the above assumptions:

Wavelength (μm)	R=5	R=100	R=1000
1	0.18	0.0053	5.3E-4
3	0.54	0.016	0.0016
5	3.8	0.11	0.011
10	320	9.5	0.95
20	2.9E4	870	87
30	2.7E5	8200	820

We derived these fluxes from a background model which includes the Hauser et al. COBE DIRBE sky background empirical model (south ecliptic pole zodiacal reflection, zodiacal emission, and galactic emission) plus thermal emission from an 8 m diameter 40 K telescope with 3% emissivity, scattered emission from a 100 K sunshade with an effective emissivity of 3% which is scattered into the telescope with an efficiency of 0.002. These parameters and computed background fluxes are consistent with those distributed by the NGST project when one accounts for plate scale differences. Source confusion at NGST sensitivities is largely unknown and will likely set NGST's ultimate detection limits. Therefore the above values represent an estimate of the *minimum* likely NGST backgrounds.

It is most straightforward to relate the above backgrounds to detector performance requirements for direct imaging or dispersive spectroscopic instruments. The photon backgrounds incident on the detectors of such instruments are simply the above tabulated values. This assumes that the dispersive spectrographs are designed so that their slit widths equal the Airy disk diameter which covers 4 pixels; reducing sampling by a factor of 2 in each dimension (for 2 pixels per slit width) would increase the background per pixel by a factor of 4. Other instrument schemes may not have such a direct relation between their incident detector fluxes and detector noise requirements. For example, the incident photon backgrounds of imaging Fourier transform spectrographs (FTSs) are typically set by their spectral ranges and not their effective spectroscopic resolutions. Hence the detector well size and noise requirements of different instrument types operating in the same effective observational modes (e.g., wavelength, R, spectral range) can vary somewhat.

III.C. Observational and Technical Drivers

For simplicity we shall primarily consider the cases of low R direct imaging and high R dispersive spectroscopic instruments in examining how observing modes drive detector requirements. The above background values show that the NIR detectors must have very low noise values to achieve the goal of natural background-limited sensitivities even in direct imaging or low resolution spectroscopic observations. (In this report, noise is taken to be the quadrature sum of read noise and fluctuations in dark current signal and/or mux glow signal.) There is strong motivation to achieve this goal since integration time for a given limiting flux is generally proportional to $(\text{noise})^2$. Furthermore, very large format detectors or mosaics will be required to image wide fields at critically-sampled resolutions; 8 k x 8 k pixels critically sample a 4' x 4' field at a wavelength of 2 μm. Large formats are also required to observe as many objects as possible at high spectroscopic resolutions with large (~ 1 octave) spectral ranges with dispersive multi-object spectrometers. Mosaicing multiple smaller detector arrays (i.e., the Sensor Chip Assemblies, or SCAs) to fill the required focal plane area should be minimized in order to avoid gaps in spatial or spectral coverage. However, pixel sizes must not be reduced to the point where the modulation transfer function (MTF) of the system is degraded via crosstalk. Thus the NIR NGST detectors must be produced in the largest possible SCA formats consistent with optimal pixel size and with very low noise. These requirements are somewhat less severe for the MIR detectors since they operate under higher backgrounds and subtend larger angular sizes.

Long exposures will be required for NIR spectroscopic observations to be background noise limited. We estimate that the practical limit to exposure times will be on the order of 1000 s, set by the cosmic ray flux (approximately 4 cm^{-2} s^{-1} at solar minimum). For 27 (18) μm pixels, this flux corresponds to *direct* hits of 2.9 (1.3)% of the pixels of a detector array, assuming that its active layer is considerably thinner than its pixel pitch. If the detectors are largely unshielded, and/or considering the occurance of secondary events from peripheral angles, then the hit rate may rise to 2 – 3 times this level. Detectors with larger pixels will detect more cosmic rays and therefore may have shorter maximum exposure times than ones with smaller pixels. Signal-to-noise is directly proportional to exposure time for read-noise-limited spectroscopic exposures (R > ~100–1000), so smaller pixels may allow higher signal-to-noise or less total integration time for these observations. The shortest exposures will be for very long wavelength broad-band imaging; the high thermal background will require that exposures be on the order of 1 s to prevent full well saturation at 30 μm wavelength. Cosmic ray detections will also drive the pixel operability requirement; it makes no sense to require a high operability (e.g., greater than 0.99) if up to 10% of the pixels were to detect cosmic rays (and thus become effectively useless) in a 1000 s exposure. Distributed defects are generally required to be random for minimal scientific impact, particularly for imaging. Limitations on clusters of bad pixels or bad rows / columns need to be specified in terms of the technical limitations (gap sizes) in butting together SCA arrays to form a composite focal plane array (FPA) estimated to be 4 k × 4 k pixels in size.

In addition to these constraints, it is highly important that NGST strive to develop detectors which are well-behaved, and as nearly ideal as possible. Experience on HST and other missions has shown that implementing post-launch corrections and calibrations can be very complicated and costly. NGST detector technology development programs should thoroughly characterize, and then refine the detectors, so that they will achieve these objectives.

Required signal-to-noise ratios of observations will drive detector stability and instrument flat field requirements. Most programs considered in the current NGST DRM require only moderate signal-to-noise, S/N < 100. These values have been routinely achieved with various space and ground-based NIR array instruments. However, several DRM programs (e.g., stellar populations, planetary searches, and astrobiology) require more precise photometry, high contrast imaging, or detection of very weak spectroscopic features. These observational conditions require signal-to-noise ratios of 1000:1 or greater for best results. Thus the NGST detectors along with their warm electronics and instrument optical trains must strive for stability at the 0.1% level. High photometric accuracy also drives sampling and fill factor requirements.

Interpixel crosstalk (including electrical & optical components) will be driven by the spatial or spectral sampling scales of the instruments and is described here in terms of the MTF. Spatial or spectral resolution will be compromised if crosstalk is sufficiently high in instruments which do not sample at the Nyquist frequency; this effect will be lessened with better spatial sampling. Determining the impact of interpixel crosstalk on spectral or spatial resolution requires understanding the details of how other observatory and instrument components also affect resolution and MTF. The fill factor must be high even in Nyquist-sampled instruments for good detective and responsive quantum efficiency. Furthermore, the flat field pixel response must also be understood as a function of position on the array to ensure photometric accuracy.

Other detector requirements will be driven by the mission's technical constraints. The short wavelength limit ultimately will be set by the observatory's optical performance (PSF and reflectivity). The long wavelength cutoff will be determined by the detector's cooling requirements and available cooler technologies. Quantum efficiency (QE) ultimately is limited by the carrier diffusion lengths at the operating temperature as compared to achievable thicknesses. Non-ideal broadband anti-reflection (AR) coatings can also limit QE. The number of independent electrical leads – bias & clock lines, signal outputs per detector array, and reference lines – should be minimized. This reduces power dissipation and cost of warm electronics, simplifies cabling, and minimizes heat loads. Pixel pitch will be set by the telescope f/number (to adequately sample with reasonable instrument optics), crosstalk (MTF), and the conflicting optical design requirements of sub-pixel spot sizes and large fields of view. Operating temperatures of the various detectors will be set by the detector material and the required dark current performance, as well as the observatory's thermal design and cooling capabilities. Power dissipations will depend strongly on the number of reads required to meet noise performance requirements. Thus, low single read noise is important since it enables less power dissipation as well as less data processing and / or reduced telemetry bandwidth. It is fortunate that the longest wavelength detectors see the highest backgrounds; this relaxes their noise requirements, enabling fewer reads and less power dissipation for these devices which must be operated at the lowest temperatures.

III.D. Summary

The following table summarizes how NGST detector requirements are driven by its observational parameters and technical constraints:

Detector Requirement	Drivers
Format	imaging field, spectral range, number of slits, few gaps
Read Noise	background, spectroscopic resolution, power dissipation, processing power and telemetry bandwidth
Dark Current Noise	background and spectroscopic resolution
Well Capacity	dynamic range, thermal background, & bright limit
Exposure Time	cosmic rays, pixel area, thermal background
Operability	cosmic ray detections, randomized flaws with small cluster size, FPA gaps (limit bad rows/columns)
Detector Stability	signal-to-noise, radiometry, temperature stability
Crosstalk / MTF	sampling (pixel scale), optics performance
Fill Factor	sampling, optics, photometry, S/N, QE
Pixel Pitch	crosstalk/MTF, optics performance, S/N, FOV

Wavelength Range	science, optics performance, backgrounds, cooling
Quantum Efficiency	detector thickness & doping, diffusion length at operating T, AR coatings
Number of Leads	power dissipation, electronics cost, desired frame rate
Operating Temperature	detector material, cooler technology, thermal design
Low Power Dissipation	thermal control, cryogenics

(We acknowledge that these scientific and technical considerations ultimately must be carefully considered in the light of budget and risk limitations and realities.)

These detector requirements are examined in greater detail in subsequent sections. When appropriate we also note how different instrument applications (imaging, spectroscopy, IFTS, etc.) alter these requirements.

Section IV. Key Detector Parameters

There are a range of assumptions and science requirements which drive the specification of the detector array systems. In this section we discuss these in a general way. The specific wavelength regimes will be discussed; this is followed by a section (IV.D) which discusses parameters which apply in common to all anticipated NGST regimes. Summary goals and recommendations are presented in Section IV.E.

In Section III the expected minimum photon backgrounds for an effective critically-sampled diffraction PSF at each wavelength is calculated. The NIR background photon fluxes incident on the detectors are always less than 3.8 photons/s/pixel and for most wavelengths and spectral resolutions, much less. This clearly defines NGST as a very low background system, which dictates that the large focal plane arrays be populated by excellent, low-background detectors.

Considerations of pixel pitch, PSF, and MTF apply, particularly for the shorter (i.e., visible and NIR) wavelength bands of NGST. In general, the MTF of the detector element can impose a limitation to overall system performance, and it becomes a more serious concern with smaller pixels. It may be a particularly important consideration in the NIR. MTF will be addressed below, in Sec. IV.A.

An important point to be remembered in trade studies for NGST arrays is this: SIRTF experience with (very much less difficult) array specifications tells us that *all* parameters specified must be verified on one demonstration array. A full, consistent data set, including results for all important parameters, must be compiled and evaluated for each detector array. That is, it will not be sufficient to realize mux performance on one sample array, show good quantum efficiency on another, and acceptable radiation performance on a third.

Another important point to be remembered is that any specification must also apply to some large percentage of pixels. A "bad pixel" is a pixel out of specification for *any* parameter - and ultimately the number and distribution of bad pixels will have to be specified, and will affect yield.

Note that after each of the following sections (NIR, MIR, visible), comments are included about the state-of-the-art. Some of this material also includes *expectations* of performance to be achieved by ongoing developmental activities. As will be discussed in Sec. V (characterization), and the report's recommendations (Sec. VI), it is essential that all of these projected advancements be experimentally validated through careful low-background measurement program.

IV.A. Near-IR Detector Parameters

1. Introduction

NGST is designed as a premier IR facility, with most sensitive operation required from 1 - 5 μm. The NIR detector arrays are a crucial component of the NGST instrument complement, and the performance required for the key parameters poses major challenges.

We assign highest priority to four NIR parameters: 1) the number of detectors/format, 2) overall detector noise, 3) quantum efficiency, and 4) pitch.

2. Key Parameters - Highest Priority

2.1 Number of Detectors / Format. Telescope field of view requirements dictate a NIR FPA format of approximately 16 M pixels**,** consisting of four or five such FPAs built of individual SCAs with a minimum array size of 1k x 1k ; these FPAs do not have to be closely-packed.

2.2 Noise. Noise is a very high priority parameter, since it bears directly on achieved NIR sensitivity. In the ideal case, overall detector noise is composed simply of contributions from (a) the shot noise in the dark current and (b) the read noise, added in quadrature. Hence, both dark current and read noise are highly important, and, although their relative contributions vary with exposure time (read noise is fixed whereas the charge due to dark current increases with time), they will be considered together in this section.

It is important to note that the overall noise is only determined by the sum of the dark current and read noise components if all other sources of noise such as system noise, multiplexer (mux) glow, 1/f noise and noise due to thermal fluctuations across the array are negligible.

For a Nyquist-sampled, 2 μm diffraction-limited PSF, 1000 s exposure at a resolution of 5, with a QE of 100%, one estimates a zodiacal background noise of 13.4 e^- at 1 μm. Thus the detector noise (mux and dark current shot noise) must be a small fraction of 13.4 e^- for background-limited operation. The lowest detector dark currents measured in either InSb or HgCdTe are slightly below 0.01 e^-/s; in a 1000 s exposure the shot noise in this dark current is $\leq$ 3.2 e^-. (Note that $\sqrt{n}$ statistics may not always hold – noise may be less for some types of dark current.) Mux read noises of 3 e^- are optimistically projected, so that the quadrature sum noise would be < 5 e^-, consistent with (close to) background limited operation. However detector noise will dominate for most dispersive spectroscopic observations in the NIR since it is comparable to zodiacal background noise at resolution R = 100. Dispersive spectroscopy thus drives the detector read noise and dark current to the lowest levels achievable.

Appropriate muxes must be developed for extremely low read noise at the temperature of operation, and detector material must be developed for ultra-low dark current.

2.3 Quantum Efficiency (QE or η). Driven by the need to reach requisite signal/noise ratios efficiently, QE of at least 80% is needed throughout the 1 - 5 µm range. QE is a high priority parameter. It enters sensitivity calculations as $(QE)^{1/2}$ for background-limited (imaging) conditions, and linearly for detector-limited (spectroscopic) conditions.

Note that in this report we have chosen to report the quantum efficiency (QE or η) - the fraction of incoming photons producing signal – rather than the RQE (responsive quantum efficiency) or the DQE (the detective quantum efficiency). Formal definitions may be found in Appendix B, Section VIII. The reasons for this choice are dictated by the various detector types and the various background conditions that will be encountered in NGST instruments. On the one hand, the NIR devices have no photoconductive gain, but the MIR IBC devices may. Thus the gain factor and the gain dispersion which are part of the RQE and DQE definitions respectively, cannot be defined, except in the case where the gain is unity. If there were no other signal or noise degradation compared with the ideal case, then DQE = QE = RQE for the NIR devices. When the NIR devices are background limited, then this double equality is true. For very low backgrounds, however, the read noise is degraded with respect to the background fluctuation noise encountered, and the DQE is lower than the QE or η. On the other hand, the QE (η) is an intrinsic property of the device at a given wavelength, and depends only on such factors as the AR coating on the back-side, the diffusion length as compared with the thickness, the absorption depth at each wavelength, and the fill factor. MTF is also a function of diffusion length, but high QE need not be inconsistent with good MTF.

2.4 Pitch. The panel understands that in the NIR there are no system considerations which favor a particular a particular pitch within the 15 - 30 µm range. For a specific detector material and process and array architecture, key noise parameters such as dark current, capacitance (and hence read noise) and cosmic ray hit rate are reduced for smaller pixels; theoretically they all scale with with pixel/diode implant area. Smaller pixels will however exhibit higher 'optical' crosstalk and any smearing of the image profile will degrade the system MTF (see Section VIII/Appendix A). It is critically important to set both requirements and goals for the detector component of the overall budget for degradation of the theoretical telescope PSF (the Fourier transform of the theoretical MTF). This would allow trade-off between resolution and sensitivity within the space between requirements and goals. Alternately, a slower optical system could be utilized than that selected for an ideal detector in order to maintain image quality, necessitating even *larger* array formats to maintain a given FOV. This would require a different set of trade-offs, e.g., greater power dissipation.

3. Key Parameters - High Priority

3.1 Minimum Wavelength, Maximum Wavelength. 1 µm minimum (or 0.6 µm if extending into visible). >5 µm maximum. Both InSb (with appropriate 4-layer AR coating) and HgCdTe (with substrate removal) have reasonable response above 0.6 µm, without degrading IR capability. The actual maximum wavelength is a low priority, as long as it is >5 µm. IBCs can work at 5 µm [~50% of peak response (RQE = gain x QE)] for Si:As with or without appropriate AR coating. This cut-over wavelength can be considered in future trade studies but must not impact the 1 (0.6) - 5 µm performance of the NIR arrays.

3.2 Temperature. Should be close to, but larger than, achievable passively-cooled focal plane temperature if no mechanical coolers used. (Note that an 8 m^2 diameter radiating area is required to achieve 30K). Technically, it would easier to provide a somewhat higher temperature via radiative cooling, but in the end, performance issues for detector arrays will dictate the temperature required. For example, for InSb, lower dark current is achieved at higher temperature for higher doping – this needs to be optimized while retaining reasonable thickness. It is also desirable that detector array technologies have an adequate thermal performance margin relative to NGST system concepts. That is, arrays should have enough operating margin that long-term shifts or degradations in focal plane operating temperature do not result in degraded or noisy operation.

Heating the arrays to higher temperature for short periods following radiation damage may be required. A requirement would be for fast (e.g., 5 min) recovery to operating temperature for efficiency.

4. Key Parameters - Important

4.1 Frame Time. $\leq$ 12s is required. Current European NGST instrument studies specify a value of 5 s. All of the multiplexers currently under consideration use shift registers to sequentially address pixels, and the settling time is no less than a few μseconds. Thus with a single output amplifier, readout of a 1k x 1k takes at least several seconds and a 2k x 2k with a single output amplifier takes four times longer. Utilization of parallel output amplifiers, which in many muxes can be activated by software, both reduces the time to read the array and increases the power dissipation during the read, approximately in direct proportion. The output amplifiers and shift registers are powered down when not reading the array, so for a given number of reads during an exposure, the average power is, to first order, independent of the number of output amplifiers. The use of parallel output amplifiers does slightly increase calibration requirements.

DRM science requirements may impose a requirement/goal for short frame times. Modest gains (a factor of 4 - 128) are feasible using multiple amplifiers. Further improvements would require sequential readouts of subarrays, rows/columns or even individual pixels and can drive the reset architecture of the multiplexer along with substantial increases in operational complexity.

5. Some Comments on Present NIR State of the Art:

Format: HgCdTe: Rockwell has produced 2 k x 2 k arrays with 2.5 μm-cutoff PACE HgCdTe, and 1 k x 1 k arrays with 5 μm cutoff MBE/CdZnTe HgCdTe. They plan to design a derivative of the 2048 x 2048 HAWAII-2 mux with the same one or eight software-selectable outputs per quadrant. The NGST mux allow for reference pixels to be incorporated into the perimeter of the array. The existing digital support circuitry of the HAWAII-2 mux will be constrained to two adjacent sides, to allow close butting of the other two sides. An NGST 4k x 4k FPA assembled from these SCA's would consist of 4 arrays, closely butted on two adjacent sides. The butting gap would be 10 to 20 rows/columns (0.2 - 0.4 mm), corresponding to a total dead space within the mosaic of 0.1 to 0.2%.

InSb: Raytheon has produced 412 x 512 arrays. They have designed and fabricated a prototype NGST mux, the SB-226 (1024 x 1024 with 4 outputs, although a single output is feasible). Hybrids are being fabricated. Raytheon would design a 2048 x 2048 mux if the NGST project deems that essential. The SB-226 mux has two reference channels. A 2k x 2k module has been built from 4 SCAs close-butted (~0.75 mm) on two sides. Using the mesa approach, close-butting could be reduced by approximately a factor of 3 in future designs. The modules would then be close-butted on 3 sides, and on the fourth side butted with 2 mm spacing to form a 4k x 4k. A working first-cut version of a

4k x 4k FPA was demonstrated by Raytheon at the Science & Technology Exposition.

Quantum Efficiency: InSb: Raytheon, UR, and GSFC have measured the QE of SIRTF InSb arrays at ~3.5 and 4.5 µm (single layer AR coating optimized for 3.5 µm). Of eleven candidate arrays for IRAC, nine exhibit QE (3.3 µm) > 93% at 15K and for those measured at 30K, a similar value. Because a single-layer AR coating was used, the QE at 4.5 µm is 90% of that at 3.3 µm, and there are wavelengths between 1 and 3 µm where the non-AR coated value (65%) is obtained. With a 4-layer coating, the entire band would be at QE > 93%. UR has also determined QE at λ < 1 µm (see visible section, below), and has further determined that for the long-wave limit of the SIRTF arrays, the QE drops below 50% at 5.2 µm. The precise wavelength for the 50% cut-off is detector thickness dependent.

5 µm HgCdTe: Rockwell has measured the QE of uncoated 5 µm MBE material to be 74% from 1.3 to 4.6 µm. Application of an AR coating is expected to yield QE of 80 - 90%. UH has verified that the QE of this material does not measurably change (to within <1%) from 82 to 59 K, and will extend relative measurements down to 30K. The experimental database on these MBE devices is expanding, since many devices have just recently been delivered, and the initial measurements are quite recent.

Noise and Dark Current: 5 µm HgCdTe: For 5 µm MBE material hybridized to a HAWAII mux, UH has measured the noise over the range 58 < T (K) < 90 in 1250 second and 5,000 second ramps and has also estimated the dark current in these ramps using the method described by Gert Finger (European Southern Observatory, ESO) (cf., http://www.ngst.stsci.edu/detector_conf99/proc/finger.pdf). The dark current measured at 60 K was ≤0.02 e^-/s, and the measured noise was consistent with that predicted for the shot noise in this current. The double correlated read noise is measured to be < 10 e^-, reduced to < 5 e^- by eight Fowler samples. Noise in the HAWAII-2 mux is expected to be further reduced and, if read noise is still a limiting factor, there are opportunities for further noise reduction in the design of the derivative mux for NGST. UH has verified that the arrays remain functional down to 30K.

InSb: Gert Finger has demonstrated a dark current level of 0.004 e^-/s on InSb at 25 K. For SIRTF, the dark current specification was < 1 e^-/s, and UR found an upper limit of 0.1 e^-/s for selected arrays utilizing the method of recording dark charge as a function of exposure time. For InSb on a SIRTF mux, multiply sampled (16 Fowler samples) gives a noise of 5 e^- for short integration times (1/f noise limited). The SIRTF CRC-744 mux is optimized for low noise & deep cryogenic performance (<10 K). Raytheon's new SB-226 mux is also designed for low noise, as well as cryogenic operation. Raytheon has reported hybrid array (27 µm pixels) data indicating lower read noise than the SIRTF CRC-744 for 1 Fowler pair.

Well Capacity: InSb: Candidate SIRTF arrays depart from linearity by 5% at full wells of 120,000 - 180,000 e^-, with an applied bias of 450 mV (actual diode bias ~320 mV). If required, larger well capacities can be achieved with increased reverse bias, and some dark current penalty. For NGST the front-side passivation on the InSb would be optimized for lower well capacity, and in turn, lower dark current.

5 µm HgCdTe: HAWAII arrays utilizing 5 µm MBE material provide linear, reverse biased well capacity of 60,000 e^- at 220 mV reverse bias. If required, larger well capacities can be achieved with increased reverse bias.

Latent or Persistent Images: 5 µm HgCdTe: Measurements of recent MBE-process arrays indicate latent images of a few tenths of 1% of full well, for the first read after a saturating integration. The magnitude of this latent image varies with mux operating parameters, indicating the latent image may be associated with the mux. There is no detectable latent image at the << 0.01% level in subsequent exposures.

InSb: SIRTF/IRAC devices also exhibit a few tenths of 1% of full well latent image, for the first read after a saturating integration, decaying away with multiple time constants ranging from 1 to 800s. Front-side passivation improvements at Raytheon are being developed to prevent minority carriers in the InSb from reaching the interface and getting trapped. In addition, InSb optimized for higher temperature operation than 15K is easier to passivate, leading to much lower latent images and dark currents.

Power Dissipation: InSb: Raytheon prescribes a rule of thumb power dissipation of 2 njoules/pixel/sample for their multiplexers. So, for an 1024 x 1024 SCA using this rule of thumb, they estimate a power dissipation of 0.2 mW per array at a 10 s frame rate. A specific thermal model predicts 0.11 mW. Note that halving the frame rate doubles the power dissipation. Obviously, the 2k x 2k composite will exhibit a model power dissipation of 0.44 mW at a 10 s frame rate. Raytheon multiplexers do not require a cold off-chip resistor.

5 µm HgCdTe: Rockwell prefers a configuration where the load resistors are located off-chip, at the same temperature as the SCA, but optically baffled to suppress self-radiation. With this configuration, and assuming video waveform settling to ten time constants, Rockwell projects a maximum (total, cold) power dissipation of 0.5 njoule/sample for each 2048 x 2048 NGST HgCdTe array. Sampling up the ramp, a 10 s read interval translates to average power dissipation of 0.21 mW, independent of the number of reads actually used to read the signal, and this is reduced to below 0.1 mW for a 25 s read interval. Rockwell's measured power dissipation for the HAWAII-2 mux is as predicted and is similar to these values. Although the total power dissipation, including the video loads, will be somewhat higher depending on the current source design selected, properly matching the settling time to the read interval should result in only minimal increases over these estimates.

Pitch: 5 µm HgCdTe: The 18 µm pitch of the HAWAII-2 mux is a slight reduction from the 18.5 µm pitch of the HAWAII mux. The use of the 18 µm pitch has allowed utilization of a process which has resulted in acceptably high yields on 2048 x 2048 muxes and it would be Rockwell's preference to continue with this proven process. However Rockwell has the capability to scale pitches up to 27 µm, if required. Rockwell has measured MTF's for both 18.5 µm and 27 µm pixel arrays and obtained values of approximately 38% and 56%, respectively, which are comparable to InSb. However the HgCdTe MBE process provides the ability to control parameters such as the layer thickness and the doping profile and band gap passivation within the unit cell to optimize MTF.

InSb: Raytheon has presented extensive analyses of the MTF for InSb as a function of pitch, at both the Detector Technology Workshop, and at the Science & Technology Expo. UR has verified experimentally their analyses for the SIRTF arrays. At present, Raytheon has designed 27 µm pitch NGST arrays. It would be Raytheon's preference to maintain the 27 µm pitch, but they are willing (and they have a path) to design and build 18 µm pitch arrays if a full system trade analysis by NGST indicates this to be desirable. Smaller pixels lead to more image smearing, compared to their ideal response profile, which makes those pixels behave like larger pixels in an MTF analysis. As a result, a slower optical system is required than would be selected for an ideal detector, in order to maintain image quality. Specifically, instrument optics for 27 µm pixels can be f/24 (1:1 reimaging). For similar values of both the MTF and the FOV, instrument optics for 18 µm pixels should be f/19 rather than f/16 suggested by scaling pixel sizes. This requires a factor of 1.4 more pixels than for 27 µm pixels. (See full discussion in Sec. VIII/Appendix A). In general, small pixels of a given material have smaller dark current, and smaller radiation hit probability; however the required larger number of small pixels leads to a factor of 1.4 larger power dissipation.

Wavelength Coverage: InSb: With appropriate multi-layer AR coating InSb has reasonable response above 0.6 microns; degradation of NIR capability has not been observed in such material. InSb's long wave cutoff is fixed at 5.2 µm.

5 µm HgCdTe: Rockwell has entirely removed the CdZnTe substrate on large-format (640 x 480 x 27µm pitch) arrays and has measured QE in the range of interest, without AR coating, down to λ = 0.5 µm. The process removes only the CdZnTe substrate, leaving the surface as deposited. This allows full Double-Layer Planar Heterostructure (DLPH) 'surface' passivation of the material exposed by the thinning. The bandgap, and hence the cut-off wavelength of HgCdTe, can be precisely controlled and Rockwell has experience with layers with cut-off wavelengths from 1.7 µm to 14 µm. The dark current is a strong function of cut-off wavelength, varying a factor of 1.5 for each 1% change in wavelength for 5 µm material. The long wavelength cut-off is thus a crucial factor in determing dark current in HgCdTe arrays.

Linearity: The absolute linearity is not terribly critical. Of far more importance is the ability to calibrate the curve, so that the response can be linearized in the data reduction to better than 99% (up to some predefined cutoff which is a significant fraction of the total well depth). See comments above, under Well Capacity.

Reset Options: Whether an SCA is reset by row, or array depends on the details of the mux utilized.

5 µm HgCdTe: Reset options include global reset, sub-array reset, row or column (only one) reset or individual pixel reset. These are progressively more operationally complex and time consuming but offer the ability to observe much brighter sources, some interesting observing techniques and the potential to guide on a source within a sub-array. All options are available within a HAWAII-2 derivative multiplexer, in principle until final design of the flight multiplexer, but should be finalized as early as possible to allow thorough evaluation of the devices.

InSb: SB-226 reset options include global reset, and reset by rows. Raytheon chose to exclude individual pixel reset in this multiplexer design.

IV.B. Mid-IR Detector Parameters

1. Introduction

For a “typical” direct imaging MIR instrument with a spectral passband of 10% (such as the 10 µm “silicate” filters which are very commonly used in ground-based MIR instruments), the zodiacal emission will dominate all other sources over the wavelength range from 5 µm to roughly 16 µm. At these wavelengths, thermal emission from the telescope primary and/or scattered light from the sunshade begin to dominate. For an instrument with 0.07 arcsec pixels (the platescale required to Nyquist sample the image at 5.5 µm, where the MIR instrument would presumably pick up from the NIR instruments), we predict a photon flux of a few photons/s at 5 µm, climbing rapidly to a few hundred photons/s in the range 9-16 µm, and then climbing again to a few thousand photons/s around 25 µm.

It is clear that the short wavelength end of this instrument places the greatest stress on the detector noise requirements and that even for an R=10 imager, the dark current must be well below 1 e^-/s for zodical-limited performance at 5 - 7 µm; for an R=3000 spectrograph, this requirement is approximately 0.003 e^-/s. This requirement scales with both spectral resolution and platescale: one can parameterize this a bit by saying that to first order, the dark current must be less than $0.5(10/R)(a/0.07)^2$ e^-/s where R is the spectral resolution of the instrument, and a is the angular size of the pixel in arcseconds.

The read noise requirement, though it arises primarily from the multiplexer rather than the detector material, is equally stressed by the short wavelengths. Individual on-chip integrations will likely be limited to 1000 s, in order to avoid significant impact by cosmic ray hits. We might expect to collect a few tens of photons in this time with 5 µm high resolution spectroscopy, which places a requirement of 2-3 electrons on the read noise. Similar to the previous expression, this requirement will scale with the spectral bandwidth and pixel scale: $\sim 3\ (a/0.07)\ (1000/R)^{1/2}$.

These two quantities are the most obvious noise requirements, but many second order effects can masquerade as one of these two, and they must be adequately accounted for. Examples include temperature instabilities, electronic instabilities (1/f noise in particular), FET glow, etc.

On the other hand, the desire to work at wavelengths where the telescope background becomes significant (> 15 µm) will require deep wells and fast readout rates, goals which are at first glance incompatible with low noise. Broadband imaging at 30 µm will fill the wells of currently available devices ($\sim 10^5$ e^-) in less than 0.5 seconds. Fortunately, a noise increase at fast readout rates can be tolerated as long as the photon noise continues to dominate.

We base the “Requirements” in this section and in Sec. IV.E on an R=10 imager which is zodiacal-background-limited from ~7-15 µm; such an instrument will satisfy a majority of the DRM observations which require MIR capabilities. The MIR “Goals” will address the possibilities of achieving zodi-limited high resolution spectroscopy and/or telescope-limited broadband imaging at wavelengths > 20 µm.

2. Key Parameters - Highest Priority

2.1 Number of Detectors / Format. The power of NGST will lie in its ability to critically sample large areas of the sky in a single field-of-view. Detector arrays of at least $\underline{1024^2}$ are therefore required to fulfill this potential. For spectroscopy, such an array would allow observation of an entire octave at R=500. Two high priority DRM desire to observe an octave at R=1000, thus larger formats could be justified (but since these programs are focused on single object spectroscopy, the spectrum could be cross-dispersed across a 1024^2 array). The number of outputs should be determined by tradeoff between a rapid readout rate (for bright sources) vs. total electronics complexity.

2.2 Noise. As discussed above, the mean read noise, through whatever sampling scheme (Fowler, up-the-slope, etc.) needs to be in the vicinity of $\underline{3\ e^-}$ for high resolution spectroscopy near 5 µm. It is expected that the dark current, as a contributor to noise, must be no higher than 0.5 e^-/s for imaging, and perhaps as low as 0.01 e^-/s for spectroscopy (but see above discussion for scaling factors). For our imager, the *total* noise requirement is $\underline{20\ e^-}$ in a 1000 s exposure utilizing a “many-sampling” scheme; the goal is $\underline{3\ e^-}$ to enable zodi-limited spectroscopy. Note that the MIR detectors may imply significant temperature stability requirements. For example, in the generation-recombination limited regime for Si:x detectors, the functional dependence of dark current on temperature can be extremely sharp, viz., an order of magnitude increase in dark curent for a 1 kelvin temperature rise.

Thus the allowable temperature fluctuation must be determined so that this varying dark current does not appear as excess noise.

2.3 Quantum Efficiency (QE). Because read noise overwhelmingly dominates all other noise sources at 5 μm we need the best QE possible. Current detectors are capable of 70% peak QE, we expect similar performance for NGST. Our requirement is therefore 70%, with a goal as high as possible.

2.4 Pitch. The pitch will be set by a trade between small pixels to improve dark current, capacitance, and radiation cross section, and large pixels to ease optical design and allow adequate room for readout transistors of the appropriate geometry for good noise performance. A careful study needs to be made to determine the optimum size, particularly in regard to the radiation cross section, given that Si:x IBC detectors are much thicker than the NIR detectors and thus may suffer a higher hit rate and a higher incidence of multipixel hits. We therefore choose not to set a requirement at this time, but note that currently available pixel sizes from 18-27 μm will likely bracket the final choice. [See additional comments in the visible & NIR sections.] Note that regarding the MTF (for Si:x detectors, at least), we believe that the carrier diffusion concern is much less significant than it is for the NIR. For these MIR detectors, favorable electric fields are present at the sites where photons are absorbed, so charges are directed to the desired collection gates. (This is opposed to the situation for photovoltaic devices, which rely upon only carrier diffusion in locations far from the p-n junction.) We recommend that these impressions be verified by experiment before the final choice of pixel size is made.

3. Key Parameters - High Priority

3.1 Minimum and Maximum Wavelength. The mid-infrared instrument will "take over" from the NIR instruments. Thus, reasonable observing efficiency must be available at 5.0-5.5 μm. We therefore require that the 5 μm efficiency be no less than 1/2 the peak response, with a goal of equal response. The maximum MIR wavelength requirement is 10 μm (per the DRM deep galaxy MIR imaging program), with a long-wavelength goal of 30 μm (per other MIR programs such as hidden star formation and protostar studies). As indicated below, the "10+ μm" limit will be heavily influence by the assessment of cooler technology.

3.2 Temperature. (See discussion of cooler technology below.) We set no requirement at this time, but acknowledge that the NGST program is not seriously considering any cooler < 6 K. Whatever the final temperature, the temperature must be sufficiently stable so that variations in the detector responsivity and dark current do not mimic read noise or dark current shot noise. Note that some MIR technologies for NGST may not require the complexity and power penalty (for an active system) imposed by a ~6 K cooler system.

3.3 Power Dissipation. The requirement for minimum power dissipation is primarily an instrument design issue. Because the MIR detectors will likely be actively cooled, minimizing total power (to minimize the size of the cooler) is critical. However, parasitics and other thermal loads (e.g., wiring, filters, detector enclosure) are likely to be significant (several mW). In this case, a detector dissipation below 1 mW per 1024^2 pixels is required, with a goal of perhaps 0.1 mW.

3.4 Frame Time. The readout time is driven by the ability to read out quickly to avoid saturation on objects which can be observed from the ground and to allow broadband imaging at > 20 μm, while not requiring a prohibitive amount of power or unreasonably deep wells. The greatest majority of such observations can be accomodated with a read time of 10 s, which we set as the requirement, but the longest wavelengths or brighter objects will push the goal to < 1 s.

4. Some Comments on Present MIR State of the Art & Material Options:

4.1 State-of-the-Art

The following table lists the detector materials with the greatest promise for meeting the demanding performance levels required by a MIR instrument on NGST. We recognize that MIR detector choices may be severely limited by NGST system design & cost considerations, and acknowledge that the present NGST system planning supports cooling only to a minimum temperature of 6 kelvin. Unlike the visible & NIR where passive cooling is baselined, the MIR detector selection will depend critically on the cooler technology chosen. The doped silicon materials (Si:x) listed below all assume a impurity band conduction (IBC, equivalent to blocked impurity band, or BIB) structure, while HgCdTe is a more traditional photovoltaic structure.

Material	Wavelength Range (µm)	Temperature (K)*	Approximate Dark Current (e-/s)	Approximate QE (%)	Comments
Si:Ga	4-17	~14 (about 4 – 5 K higher than Si:As)	~<1 at 14 K?	~50 - 70%?	Relatively new IBC dopant; under material development. First hybrids in 6-12 months
Si:As	5-28	6 - 8	<0.1 at 6-8 K	~70 %?	Baseline Material. Most mature MIR material. Flight applications
Si:P	5-35	~6? (anticipated to be about 2 K lower than Si:As)	~<1 at 6 K?	~50 -70%?	New IBC material; first lot of detectors grown. Under test at Boeing.
Si:Sb	12-40	~4 (based on SIRTF data)	~1 at 4 K	~50 -70%?	Moderately mature. Application on SIRTF/IRS.
HgCdTe	4-12	25-35 anticipated	100 – 1000 at 30 K?	80-90%	$Hg_{1-x}Cd_xTe$, x=0.21, tunable. Goal is to reduce leakage with MBE structure.
QWIP	Completely tunable	25-35 anticipated	30-100 at 30 K?	20% peak; limited spectral range	GaAs/AlGaAs quantum wells. Relatively new development.

*Panel's projection of the temperature needed to achieve the 0.5 e^-/s level for Si:x detectors. Experimental data are clearly needed.

Maturity of MIR Detectors: Si:As IBC is by far the most mature technology. Arrays of these detectors have flown on ISO, COBE, WIRE, and Spirit III/MSX, and are featured prominently in SIRTF. Arrays with performance nearly adequate for NGST are already available, and 1024^2 arrays are under development by two vendors. Operationally, the largest drawback is the fact that these arrays need to be cooled to below 10 K to meet the performance specifications.

Because the response of Si:As arrays drops precipitously at 28 µm, they are not suitable for efficient observations of the 28.2 µm H_2 rotational ground state line. Should such observations be desirable, or if simply a longer wavelength cutoff is desired (e.g., to observe forsterite at 33 µm), Si:Sb is an option. Large Si:Sb arrays have been available and characterized for ~5 years, with spectral coverage to about 40 µm. With its smaller bandgap, a lower operating temperature (~4 K) is required.

A new, intermediate longwave material option, just now being investigated, is Si:P. It is demonstrated to have spectral response to 35 µm, with a cooling requirement about 2 K below that of Si:As.

Si:Ga could be attractive if the coolers cannot provide sub-10 K cooling but can provide 10-14 K levels, and if low-leakage, large-format hybrids can be fabricated. The Si:Ga cutoff wavelength is approximately 17 µm, which is adequate for much of the science to be done with the MIR instrument, although a significant portion will be lost without the extension past 20 µm.

It is anticipated that HgCdTe or quantum well infrared photoconductors (QWIPs) detectors would be considered if cooling below 30 K is deemed infeasible. HgCdTe array technology, with cutoff wavelength of 10 µm or greater, is being widely pursured for non-astronomy applications. In efforts to adapt this technology for NGST, material purity issues have been identified. Although progress is being made, UR data on available diodes show leakage currents which significantly exceed NGST goals and requirements. The QWIP detectors are a relatively recent development. They have inherently narrow passbands (10% is typical, although 50% bandpass devices are under development) and low peak quantum efficiency, but they may provide an alternative in addition to HgCdTe if sub-30 K cooling is not available. They have been demonstrated in astronomical obserations. These higher temperature alternatives can be made to cover from 5 to 10 µm (or portions of this range, in the case of QWIP) with degraded performance, thus partially addressing the current desire for NGST to extend to “10 plus” µm. Clearly, the loss of science which requires wavelengths longer than 10 µm would be significant.

Format: Si:As: Raytheon: 412 x 512 arrays recently produced & tested; SB-226 1024 x 1024 cryoCMOS readout fabricated, 256 x 256 on SIRTF/IRAC. Boeing: 1 k x 1 k array mated to HAWAII mux and tested at 10 K; 128 x 128 on SIRTF/IRS. 1 k x 1 k mux optimized for Si:x operating temperatures now being designed & developed. NGST FPA built from these SCAs would likely involve a single 1 k x 1 k SCA, or four 512 x 512 arrays. Four outputs is typical of modern devices and is probably adequate for NGST.

Si:Sb: Boeing: 128 x 128 on SIRTF/IRS & MIPS.
Si:P: one 256 x 256 IBC array.
10 µm HgCdTe: 256 x 256 under test at UR.
GaAs/AlGaAs QWIP: 640 x 480, with larger formats under development.

Quantum Efficiency: Si:As IBC: Peak DQE around 70% has been achieved for SIRTF (AR coated). Si:Sb IBC: 30%**.** QWIP: 20% demonstrated in a ground-based 8.5 µm, $\Delta\lambda$=1 µm device.

Noise: Si:As IBC: multiply sampled noise ~8 e^- for SIRTF/IRAC. 412 x 512 shows lower read noise, by about 20%. Si:Sb IBC: 30 e^-**.**

Dark Current: Si:As: <1 e^-/s at 6 K for SIRTF/IRAC. Si:Sb: <40 e^-/s at 5 K for SIRTF/IRS.

10-µm-HgCdTe: Recent single-diode measurements at UR have shown most devices exhibited less than 1000 e^-/s, and one 100 e^-/s dark current, at 30K. Array tests are underway (256 x 256 format), but these have been hindered by zero-bias variations within the available multilplexers. Progress is being made on other related Rockwell programs, but data on presently-available 10 µm arrays show dark currents of <1000 to 5000 e^-/s.

Well Capacity: Si:As and Si:Sb IBC: 2E5 e^-.

Latent or Persistent Images: Si:As IBC: Similar to NIR data, measurements of Si:As 256 x 256 arrays indicate latents of a few tenths of 1% of full well, for the first read after a saturating integration. Decay times of minutes are typical. Si:Sb: < 2% of full well.

Power Dissipation: Si:As IBC: ~0.3 mW per 256 x 256 array on SIRTF, very similar to NIR InSb data (same mux). Raytheon 1024^2 mux < 1 mW.

Pitch: Raytheon presently has reluctance to push pixel size to below 25 µm, but could go to 20 µm if needed. Rockwell Si:As IBC is being tested on HAWAII (18.5 µm pixel) mux. Si:Sb: SIRTF/IRS arrays are 75 µm pitch.

Wavelength Coverage: See materials table above.

Fill Factor: Current technologies reach nearly 100%. We expect this to true for NGST as well.

4.2 Recommendations for Future MIR Development

We recommend that the following actions be taken in the near term to present the broadest range of detector options to the project (in order of priority):

1) Ensure that 1024^2 multiplexers optimized for < 10 K operation become a reality.

   Several vendors either have or are developing the first generation of these multiplexers. These developments should be carried to completion, and the characteristics (especially read noise) of the resulting multiplexers should be verified experimentally.

2) Refine Si:As IBC material to ultimate performance.

   Currently-available Si:As material is to meeting NGST ‘requirements’ levels. However, more work in lowering dark current and reducing second-order effects (persistence, radiation susceptibility) is highly desireable.

3) Develop alternate materials to the point where they can be fairly compared against Si:As.

   Si:P IBC is a very attractive alternative as it allows science capabilities to 35 µm for only a 2 K temperature penalty. Si:Ga IBC is appealing if coolers can only achieve 12-14 K levels. HgCdTe and QWIPs might represent backups if active cooling is not an option for NGST. However, none of these materials has been developed to the same level of maturity as Si:As. It is simply not known whether NGST can truly take advantage of any of them. All these options should be carried as close to maturity as possible until the final instrument and detector selections are made.

4) Measure MTF of candidate detector arrays thoughout the MIR spectral range.

   These data will be very important in guiding final MIR designs (and selection of pixel pitch). In addition to uncertainties about carrier diffusion within MIR detectors, there is a concern that MTF will be degraded if pixel pitch is comparable to or shorter than wavelength of the incident radiation.

IV.C. Visible Detector Parameters

1. Introduction

Although NGST has been defined as primarily an IR facility, several science programs would be enabled through extending wavelength of performance to 0.6 μm. Certain science programs wish to sample at the effective diffraction limit at 0.6 μm: thus, unless the image scale is magnified, a perfectly matched array would require considerably smaller pixels than a NIR array.

In this section, we shall explore whether the NIR and visible arrays might be one and the same array, despite the larger pixels of the latter. Another related option is the use of Si p-i-n diode arrays, hybridized to IR-developed cryogenic muxes, which has yet to be demonstrated. A third option entails monolithic, front side illuminated CMOS Si devices (CCD arrays with appropriately sized pixels exhibit known difficulties and operate only at considerably higher focal plane temperatures; they will not be considered in detail here).

If the visible arrays have the same pitch and format as the NIR arrays then either the visible images will be severely undersampled or, if the image scale is magnified to allow λ/2D sampling at 0.6 μm, the FOV will be reduced by a factor approaching ten in area. The detector MTF is likely not to be an issue in the visible as the PSF is expected to have broad wings around a sharp core and will require extensive restoration, even if λ/2D sampled.

2. Key Parameters - Highest Priority

2.1 Number of Detectors / Format. Telescope field of view requirements dictate visible FPA format either that of the NIR arrays (if the same detectors are used) or at least one <u>4 k x 4 k</u> pixel focal plane (if separate detectors are used).

2.2 Noise. (This assessment is very similar to that for the NIR. Please refer to Sec IV.A.2.2). Noise is a very high priority parameter, since it bears directly on achieved visible sensitivity. If Si is used as the detector material then its higher band gap and much lower capacitance will result in much lower dark current and read noise than the NIR arrays, even if the same muxes are used. Otherwise the noise will be as for the NIR arrays.

2.3 Quantum Efficiency (QE). Driven by the need to reach requisite signal/noise ratios efficiently, QE of <u>80%</u> is needed throughout the 0.6 - 1 µm range.

2.4 Pitch. If the NIR arrays are used in the visible then the pitch, which is then relatively unimportant at visible wavelengths, will be determined by NIR considerations. If monolithic Si detectors are used then the pich may be driven to 5 μm to allow λ/2D sampling at 0.6 μm.

3. Key Parameters - High Priority

3.1 Minimum Wavelength, Maximum Wavelength. <u>0.6 - 1</u> µm. Note that 1 μm is the wavelength where the InSb/HgCdTe range presumed to begin, if NIR arrays are not assumed to provide visible response.

3.2 Temperature. Compatible with passive-cooled system approach; nominally <u>30 K</u>. The visible array temperature should be that of NIR arrays, if separate visible arrays are used. Note that the system needs headroom for temperature anneals to ameliorate cosmic ray damage.

4. Key Parameters - Important

4.1 Frame Time. < 12s is required. The visible-range frame time should be the same as for the NIR detector arrays. Frame times of ~ 1 s would require larger numbers of outputs (this should be easily achievable with 4 outputs per 256 x 256 section). However, power dissipation is higher for shorter frame times. DRM science requirements may dictate minimal frame time; if so, a trade study would be required.

5. Some Comments on Present Visible State of the Art:

Format: HgCdTe and InSb: As described in IV.A, above.

Hybrid CMOS: Rockwell has delivered five types of Si p-i-n arrays on CMOS muxes, including the HyVis array, which employs a CTIA mux (640 x 480). Si p-i-n arrays have also been hybridized to 1024 x 1024 HAWAII muxes for evaluation for NGST applications. Rockwell's HyVis array currently employs a CTIA mux (640 x 480) and a 1024 x 1024 version soon will be available. Raytheon also has a Si p-i-n diode hybrid array on a video mux, with similar properties.

Monolithic CMOS: Rockwell has fabricated large format, front side illuminated CMOS detector arrays which hold promise for NGST. Pixel sizes down to 4 µm and formats > 4k x 4k are within current technology.

Active Pixel Sensors under development. An emerging technology with modest quantum efficiency, which has not been used in astronomical applications.

CCDs: Small pixel, large format options abound, up to 8 k x 8 k (UH). Most are not rad hard, and have response over limited range of wavelengths at high QE. These devices exhibit ultra-low dark current (<0.0028 e^-/s) and noise (<4 e^-). However, they operate at quite high temperatures. Some ideas for low-temperature CCDs have been aired, but these have not been developed.

Quantum Efficiency: HgCdTe: Rockwell has measured visible response on a 640 x 480 array, on which the CdZnTe substrate was entirely removed. QE measurements of about 45% at 500 & 600 nm were reported. The overall sensitivity performance, and the imaging properties, have been measured. The thinning does not appear to impact other detector parameters and should not reduce yield, as the thinning process is extremely benign.

InSb: UR measurements of a SIRTF array with a single-layer AR coating (designed for peak response at 3.5 µm) were made at visible wavelengths. This array exhibits excellent RQE and DQE at wavelengths longer than 480 nm - with interference dips to 65% because of only 1 AR layer. The results were reported by collaborator Paul Hickson at the Science & Technology Expo. Four- and 8-AR-layer models predict excellent performance (above 80% DQE longward of 480 nm) and the model for the 1-layer situation matches experiment well. In general the RQE is about 10-20% higher than the DQE. The maximum DQE is about 1 at 570 nm and the minimimum is about 0.65 at 500 and 650 nm (that expected for bare InSb). Below 480 nm there is a rapid drop off in RQE and DQE. Imaging properties appear to be excellent, based on both UR measurements, and reports from a previous application (Navy's HYDICE system). InSb, with an appropriate 4-layer AR coating on the back-side, is a viable candidate for visible work as well. No change in IR performance is expected or was observed. The only IR impact is that filters will need excellent short wavelength rejection, and in all probability a dual filterwheel will be required.

CMOS Hybrid: Rockwell: The responsive QE is >60% from 460 - 1000 nm, with maximum of 90% on the HyVis device which operates at high T (>250K). Rockwell projects QE > 80% over the 0.6 to 1 µm interval on AR coated material hybridized to HAWAII muxes. Device is instrinsically rad hard. Raytheon: with AR coatings they have achieved flat response from 500 - 900 nm. The device can be bonded to any CMOS mux, and QE > 80% has been verified

CCDs: have response over limited range of wavelengths at high QE. For example, CAT-C (Steward) is >80% from 460 - 800 nm; WFPC2 >70% from 440 - 900 nm. To maintain buried channel operation, high (>~120 K) focal plane temperatures are required.

Noise: Noise obtained for InSb (256 x 256), multiply sampled is 5 e^- at 30K with CRC744 mux. CRC226 mux noise performance is better (Raytheon measurement) so 3 e^- is a reasonable upper limit for that mux.

To our knowledge, data on CMOS arrays or Si p-i-n arrays at 30 K are not available.

Well Capacity: InSb: While not explicitly measured at visible wavelengths, the well capacity of InSb devices utilized at 0.6 - 1 μm, should be similar to that projected for the NIR. See section IV.A.5.

Although the capacitance of Si is much less than the 5 μm materials, the higher band gap allows higher reverse bias to compensate, maintaining well capacity.

Latent or Persistent Images: Measurements on InSb & 5 μm HgCdTe indicate latent images of a few tenths of 1% (at 15K for InSb), for the first read after a saturating integration. Multiple decay times of (1 - 800) s for InSb. InSb designed for 15K operation has a factor of 10 higher latent images at 30K. UR has not tested devices specifically designed for 30K operation - in that case, higher doping density renders passivation easier, leading to much reduced dark currents and latent image response.

Latent behavior is unknown for Si p-i-n devices, hybridized or monolithic.

Power Dissipation: The power dissipation for the muxes used with 5 μm detector arrays, should be unchanged or slightly reduced with Si p-i-n arrays. The monolithic devices have lower power dissipation.

Pitch: The pitch of Si p-i-n diodes to be matched to cryo-muxes by Rockwell and Raytheon. CCD pixel pitch very small - e.g., 5-10 μm.

Linearity: The absolute linearity is not terribly critical. Of far more importance is the ability to calibrate the curve, so that the response can be linearized in the data reduction to better than 99% (up to some predefined cutoff which is a significant fraction of the total well depth).

The linearity of Si CMOS devices is unknown but should be very good.

Reset Options: As for NIR detector arrays - see section IV.A.

IV.D. Detector Requirements Common to All Wavelength Bands, 0.6 – 10+ μm

We have identified the following important requirements, which apply similarly to the visible, NIR, and MIR regimes. To minimize duplication, we discuss them here as a group:

1. Well Capacity. Refer to sec III and IV.A. The requirement depends on dynamic range required, which in turn depends upon the specific instrument approach. For non-FTS

applications, 0.6 - $1x10^5$ e^- is adequate. The detector well capacity is a function of bias across the device.

2. Latent or Persistent Images: A very high priority parameter, which impacts data processing and photometry. As an objective, the longest-lived latent images should decay to the noise levels above in < 5 s. These effects arise from decaying traps within the detector, and are temperature dependent. One can ameliorate this to some degree by proper choice of applied bias; dark current is also bias dependent, as is well depth.

3. On-chip reference channels of potentials. On-chip reference channels on NGST detector arrays will be essential to account for mux instabilities, so that ultra-low dark curent and total noise can be achieved.

4. Electrical crosstalk should be < 1%. Optical crosstalk is a function of pitch, fill factor, and diffusion length, as well as thickness of detector and degree of lateral collection (can be minimized via design). We believe this quantity is best specified as a maximum tolerable percentage degradation of MTF. See MTF section below.

5. Fill Factor. >95%. Must be close to 100**%.** Large fill factors are required to achieve the highest QE. Also, close to square intra-pixel response is important at short NIR wavelengths, where one critically-samples at the diffraction limit. At longer NIR wavelengths, pixels are oversampled, so this is less important. Essentially all pixels within the array should also have the same intra-pixel response function. Furthermore, it is important to minimize gap size between SCAs, and to design the gap geometry & surface treatment or coating to avoid distributing reflected light adversely throughout the ISIM.

6. Radiation Immunity. The requirement is to have only minimal effects during exposure to the space radiation environment, which involves the cosmic galactic background flux and the effects of solar activity. Over the mission life (5-10 years) one expects a dose of ~ 6 krad(Si). Individual hits during "normal operation" should not affect photometry following reset (i.e., the array should reset cleanly, and the stability of the system should not change in response to a cosmic ray hit). Amplifiers must respond to these transients promptly, and without ringing. The system recovery depends on dose (e.g., solar flare can cause upset). Large doses or accumulated doses may necessitate amelioration: restoring detector operating point via temperature anneal, and possibly a bias change. Following anneal, the system should recover within 1% of baseline sensitivity within TBD (5 min?).

7. Radiometric Stability. To support DRM science, the detector array system should be stable over 1 hour, 1 month to ~1 %, 1 year and 10 years to TBD. We note that most devices will degrade over 10 years, and specifications should adequately anticipate and address this.

8. Exposure Time. Exposure time of 1000 s derives from cosmic ray flux considerations - for this time, a tolerably low (~3%) fraction of the array is expected to be hit by radiation. Plans for detector sampling must include multiple sampling to achieve lowest noise as well as 1000s exposure time. This is also important in reducing the possiblity of glow, with no more than 10% of time devoted to reading out the array.

9. Frame Time. The optical time constant of the detector material should be fast enough to settle to 16 bit accuracy in a frame readout time. Assuming a 10 s readout, the time constant needs to be ~ 1 s.

10. Pixel Operability. A large fraction of the array (~98-99%) pixels need to satisfy all key requirements. However, a modest number of dead rows or columns can be tolerated, consistent with the dead space represented by the gaps between SCAs. Clusters of inoperable pixels should not have dimensions larger than the FPA gap size.

11. Linearity. The absolute linearity is not terribly critical. Of far more importance is the ability to calibrate the curve, so that the response can be linearized in the data reduction to better than 99% (up to some predefined cutoff which is a significant fraction of the total well depth, such as 90%).

12. Reset Options: Reset by pixel, column, or array. Resetting by pixel requires substantial power, and generates noise. Resetting by column leads to differing integration times, but not nearly so bad as resetting by array. Note that it would be very helpful for ongoing technology developments, and for system studies, to define a reference readout scheme for NGST arrays.

IV.E. Requirements and Goals

The panel recognized the desirability of recommending (1) a reasonable, hopefully achievable standard of performance that the mission really *must* have (the "Requirement"), and (2) a second, significantly-more-challenging, yet desirable standard that would provide substantially more scientific return (the "Goal"). We tried to balance the needs articulated in the prioritized DRM science program with our practical view of what the technology providers could reasonably be expected to deliver in the ~3-year NGST instrument-selection time frame.

Our approach centered on the key NIR regime. This rationale was then extended into the MIR (and to a lesser extent, the visible). Starting with scientific objectives, it is clear that the NIR imaging programs envisioned for NGST are truly crucial; the corresponding Requirement would be to achieve zodiacal background-limited performance for imaging, up to a resolution $\lambda/\Delta\lambda$ of 10, at 2 μm. Goals would go beyond this, addressing higher-resolution imaging, and the needs of spectroscopy. In determining levels for the Goals, we tried to identify ambitious and intentionally-optimistic numbers.

Our Goals in some cases stopped short of the most extraordinary background-limited performance levels associated with the shorter-wavelength, highest-resolution spectroscopy. We recognize and emphasize the crucial nature of spectroscopy for NGST, and hope that developers will push as hard as possible at this critical stage in the program to try to meet or exceed even the challenging Goals. Now is an ideal time for focused investments and detector innovations, which can yield major NGST system benefits and cost savings.

As a compromise, we have tried to offer reasonably realistic but challenging numbers for Requirements, and optimistic, highly challenging values for Goals. We believe that the combination of these Requirements and Goals embraces the great majority of NGST science objectives, and represent a very powerful potential capability with which very high resolution measurements, although detector-noise-limited, would be very productive.

Note that in the crucial area of noise, we chose not to specify read noise and dark current levels in this section. We believe it is important for detector developers, and instrument teams, to have as much flexibility as possible, in apportioning these noise components. The important result, of course, is the combined noise total.

The following tables summarize NGST Requiremeents and Goals, by wavelength regime:

1. NIR

Parameter	Requirement	Goal	State of the Art
1. DETECTOR-DRIVEN			
Number of Detectors / Format	FPA: 4 k x 4 k	FPA: 4 k x 4 k	
Total Noise[1]	10 e^- rms	3 e^- rms	
Read noise			7 e^- (InSb); 5 e^- HgCdTe. Both Fowler sampled.
Shot noise in dark current			Not well known. Dark current <0.1 e^-/s (InSb); ~0.02 e^-/s at 60 K (HgCdTe)
QE	>80%.	95%	>90% (InSb); 74% (uncoated) HgCdTe
Well Capacity	6E4 e^-	2E5 e^-	2E5 e^- InSb; >6E4 e^- HgCdTe
Latent or Residual Images[2]	order of 0.1% (1st read after saturating exposure)	0%	Few tenths of 1% InSb and HgCdTe
Min / Max Wavelength	1 – 5 µm	1 – 5 µm	HgCdTe: 1 – 5 µm. InSb: 1 - 5.2 µm
Fill Factor	>95%	100 %	~100 %
Radiation Immunity[3]	Causes minimal effect	No effect	minimal for InSb; TBD for HgCdTe.
Frame Time	<12 s	<12 s	tbd
2. SYSTEM-DRIVEN			
Temperature	32?	30	-- Need better definition of system capability. 30 K workable for HgCdTe and InSb.
Power Dissipation (at FPA temp)	1 mW per 1 k x 1 k array	0.1 mW per 1 k x 1 k array	-- Need better definition of system capability. <<2.2 mW/1k^2 InSb. ~0.2 mW for HgCdTe FPA (proj'd).
Pixel Pitch	15 - 30 µm / tradeoff	15 - 30 µm / tradeoff	-- Need better system definition. HgCdTe: 18 µm; InSb: 27 µm
MTF	TBD (% degradation of total)	TBD	Need better system definition. Need to assign FPA portion of budget. Lumped parameter, to include crosstalk.
Exposure Time	1000 s	>1000 s	Defined by radiation & system effects. 1000 s feasible with present arrays.

[1]Quadrature sum of contributions from read noise, shot noise on dark current, shot noise

on glow, 1/f, timing fluctuations, temperature drifts, temperature gradients across array, etc.

[2]It is important to measure the latent/residual image at the same integration time as was used to saturate.

[3]Need minimal or no effect on key parameters like responsivity, read noise, dark current.

4. Overall Note: Requirements set to meet NIR zodiacal background-limited performance for $R \leq 10$ at 2 μm. Also, the 'System Driven' parameters can be considered independent variables. The temperature, power dissipation, pixel pitch, MTF, and exposure time characteristics are either determined by overall system designs, or are within the range of reasonable detector design / tradeoff /optimization space.

2. MIR

Parameter	Requirement	Goal	State of the Art
1. DETECTOR-DRIVEN			
Number of Detectors / Format	FPA: 1 k x 1 k	FPA: 1 k x 1 k	Si:As: 1 k x 1 k on HAWAII mux; 412 x 512 on cryoCMOS mux
Total Noise[1]	20 e^- rms	3 e^- rms	
Read noise			Si:As: 8 e^-, Fowler 32
Shot noise in dark current			TBD. Dark current <0.1 e^-/s at 6 K (Si:As)
QE	70%	>70%	Si:As: >70%
Well Capacity	1E5 e^-	>2E5 e^-	~2E5 e^-
Latent or Residual Images[2]	order of 0.1% (1st read after saturating exposure)	<0.1%	Si:As: order of 0.1%
Min / Max Wavelength	5 - 10 µm	5 – 30 µm	Si:As: 5 – 28+ µm. Si:Sb: >5 - 40 µm
Fill Factor	~100 %	100 %	~100 %
Radiation Immunity[3]	Causes minimal effect	No effect	minimal
Frame Time	10 s	<10 s	tbd
2. SYSTEM-DRIVEN			
Temperature	6-8	10+?	-- Need better definition of system capability.
Power Dissipation (at FPA temp)	1 mW per 1 k x 1 k array	0.1 mW per 1 k x 1 k array	-- Need better definition of system capability. 0.2 mW for 256 x 256 array (Si:As)
Pixel Pitch	18 - 30 µm / tradeoff	18 - 30 µm / tradeoff	-- Need better system definition. Boeing: 18.5 µm; Raytheon: 27 µm
MTF	TBD (% degradation of total)	TBD	Need better system definition. Need to assign FPA portion of budget. Lumped parameter, to include crosstalk.
Exposure Time	1000 s	>1000 s	Defined by radiation & system effects. IRAC Si:As - 200 s.

[1]Quadrature sum of contributions from read noise, shot noise on dark current, shot noise on glow, 1/f, timing fluctuations, temperature drifts, temperature gradients across array, etc.

[2]It is important to measure the latent/residual image at the same integration time as was used to saturate.

[3]Need minimal or no effect on key parameters like responsivity, read noise, dark current.

4. Overall Note: Requirements set to meet MIR zodiacal background-limited performance for $R \leq 10$ at 5 µm. Also, the 'System Driven' parameters can be considered independent variables. The temperature, power dissipation, pixel pitch, MTF, and exposure time characteristics are either determined by overall system designs, or are within the range of reasonable detector design / tradeoff /optimization space.

3. VISIBLE[5]

Parameter	Requirement	Goal	State of the Art
1. DETECTOR-DRIVEN			
Number of Detectors / Format	FPA: 4 k x 4 k	FPA: 4 k x 4 k	8 k x 12 k CCD
Total Noise[1]	10 e^- rms	3 e^- rms	
Read noise			7 e^- (InSb); 5 e^- HgCdTe. Both Fowler sampled.
Shot noise in dark current			Not well known. Dark current <0.1 e^-/s (InSb); ~0.02 e^-/s at 60 K (HgCdTe)
QE	>80%.	95%	>90% (InSb); 74% (uncoated) HgCdTe
Well Capacity	6E4 e^-	2E5 e^-	2E5 e^- InSb; >6E4 e^- HgCdTe
Latent or Residual Images[2]	order of 0.1% (1st read after saturating exposure)	0%	Few tenths of 1% InSb and HgCdTe
Min / Max Wavelength	0.6 – 1 µm	0.5 – 1 µm	Si p-i-n: 0.4 – 1 µm; HgCdTe: 0.5 – 1 (5) µm. InSb: 0.5 – 1 (5.3) µm
Fill Factor	>95%	100 %	~100 %
Radiation Immunity[3]	Causes minimal effect	No effect	minimal for InSb; TBD for HgCdTe. Issues with CCD.
Frame Time	<12 s	<12 s	tbd
2. SYSTEM-DRIVEN			
Temperature	32?	30	-- Need better definition of system capability. 30 K workable for HgCdTe and InSb.
Power Dissipation (at FPA temp)	1 mW per 1 k x 1 k array	0.1 mW per 1 k x 1 k array	-- Need better definition of system capability. <<2.2 mW/1k^2 InSb. ~0.2 mW for HgCdTe FPA (proj'd).
Pixel Pitch	15 - 30 µm / tradeoff	15 - 30 µm / tradeoff	-- Need better system definition. HgCdTe: 18 µm; InSb: 27 µm
MTF	TBD (% degradation of total)	TBD	Need better system definition. Need to assign FPA portion of budget. Lumped parameter, to include crosstalk.
Exposure Time	1000 s	>1000 s	Defined by radiation & system effects. 1000 s

[1]Quadrature sum of contributions from read noise, shot noise on dark current, shot noise on glow, 1/f, timing fluctuations, temperature drifts, temperature gradients across array, etc.

[2]It is important to measure the latent/residual image at the same integration time as was used to saturate.

[3]Need minimal or no effect on key parameters like responsivity, read noise, dark current.

4. Overall Note: Requirements set to be consistent with NIR zodiacal background-limited performance for R ≤ 10 at 2 µm. Also, the 'System Driven' parameters can be considered independent variables. The temperature, power dissipation, pixel pitch, MTF, and exposure time characteristics are either determined by overall system designs, or are within the range of reasonable detector design / tradeoff /optimization space.

[5]Due to limitations of time and of technical expertise, the visible specifications in this table are largely considered as deriviatives of the NIR arrays. Additional study is warranted.

Section V. Characterization

Section IV is filled with references to missing or desirable data, on existing and anticipated devices. A strong NGST testing and characterization program is clearly needed to address these needs. Detector characterization is critical to the success of both the mission's detector technology and flight detector development programs. Lessons from previous missions indicate that both of these programs must involve teaming among industry, academic, and government researchers in order to achieve the needed skill set, and that these teaming relationships must be maintained through launch. The challenge these teams will face can be divided into two broad categories: design verification and production testing.

1. Design Verification

The goals of this program are: [1] determine, to what extent, a given detector design satisfies NGST mission requirements, [2] improve the quality of manufacturer in-house tests through benchmarking against independent test, [3] advance the art and science of relevant test methodologies, and [4] generate an independent knowledge base and technology assessment in advance of the NASA solicitation for NGST flight detectors.

Laboratory tests conducted under this program will typically involve a small number of devices. As a consequence, it is anticipated that facilities geared toward single unit testing will suffice. These tests will focus on performance characteristics inherent to a specific design rather than questions of sample-to-sample variation and manufacturing process. Examples of design characteristics include: quantum efficiency, power dissipation, operating temperature, noise, dark current, radiation hardness, MTF, image persistence, radiometric stability, intra-pixel response, etc.

To enable these tests, all NGST detector development contracts and grants will require delivery of device samples to NGST that have been characterized by manufacturer in-house testing. It is envisioned that NGST will fund a number of scientist-lead community and government teams to conduct independent design verification tests on these samples. Program experience from space programs (SIRTF, IRAS, NICMOS, many others) and ground-based development projects has proven that the approach of using a small number of expert, experienced groups which work in coordination but with critical, independent approaches, is highly effective in producing definitive data, and in uncovering limitations or subtle behaviors. Lab groups within the astronomical community (universities, some NASA Centers, national observatories) have clearly demonstrated their ability to greatly enhance, to significantly higher levels of sensitivity, data taken in-house by the detector vendors. These groups have the time, and the expertise, to critically probe very deeply into the details of device performance, at the very low flux levels. The SIRTF program provided a valuable precedent in this regard. On SIRTF, vendors conducted screening and initial tests on candidate arrays to modest sensitivity levels, but the final low-background verification of specifications, flight part selections and detailed data sets on subtle or irregular effects came from experiments done in outside (university or government) PI or Co-I labs. We anticipate that this type of partnership will be an essential aspect of the success of the overall NGST program.

We wish to emphasize the point that extensive, specialized expertise and experience are needed. NGST needs data from characterization lab groups (to be competitively selected against objective criteria) which are fully familiar with the measurement and interpretation of 'regular' performance parameters such as noise, dark current and quantum efficiency, and are thus in a position to recognize and study the subtle but potentially pivotal second-order effects which will undoubtedly emerge. These lab groups need to stay in close communication, so that their data on the same devices are consistent or readily comparable. They should ideally be equipped to conduct unbiased tests on samples of competing array technologies from different suppliers, particularly in the key NIR band. They must collect and report data toward consistent, objective standards.

All test data derived from this program will be publicly disseminated; we believe that free and complete publication of data and test methodology promotes the best overall understanding of detector performance, and the best overall utilization of these detectors in NGST instruments, NGST will retain ownership of these test samples and will implement round-robin testing, as necessary, to facilitate calibration of results among the laboratories involved. Regarding round-robin testing, the use of a 'transfer standard', i.e., testing the same device at multiple labs, and carefully cross-comparing data, is a very effective means of establishing relative and absolute test accuracy and validity. Because demonstration of key parameters demands state-of-the-art testing facilities (including difficult to achieve dark current and noise levels; the ability to optimize clocking while monitoring a host of parameters; etc.), it is important that NGST solicitations for this task stress the demonstrated competence of the testing teams as well as the quality of their lab facilities.

Example challenge areas that would benefit from grass-roots innovation by academic community astronomers, experimentalists, and device physics experts during the design verification phase include:

- experimental methods for extremely low background high precision radiometry
- experimental methods for high precision detector temperature control
- automated techniques for full frame data analysis
- astronomical testing using ground-based and airborne imaging spectrometers
- methods to mitigate effects of particle radiation
- electronic designs and/or operating methods to ease temperature stability requirement
- electronic designs and/or operating methods to ease limitation on analog cable length

2. Production Testing

The goals of this program are to: [1] develop automated high volume test methods and facilities for screening production SCAs, [2] develop automated high precision test methods and facilities for characterization and selection of flight SCAs from a pre-screened set, and [3] develop methods and facilities for performance verification of integrated FPA assemblies.

The NGST project schedule requires delivery of flight FPAs 2 to 2.5 years after manufacturer selection. It is anticipated that these FPAs will incorporate roughly 20 – 80 flight NIR SCAs. As a consequence, screening tests conducted under this program will involve at least several hundred units. Hence, all aspects of production testing must be highly time efficient. It is anticipated that detailed performance testing on pre-screened flight SCA candidates, and FPA assemblies, will utilize previously developed design verification facilities and teams (Sec. V.1). However, single point responsibility for all aspects of science instrument performance assurance will rest with its Principal Investigator.

Section VI. Recommendations

1. Substantially increase detector technology development funding levels, to accelerate progress toward meeting requirements and goals. Detectors are critical to mission success, and improvements have very high system leverage

The performance requirements and goals for NGST detectors are highly challenging, particularly in the NIR region. The important goal of achieving background-limited spectroscopic investigations at high resolution clearly drives these standards to extreme limits. The present development program supports a promising mix of candidate technologies and experts. While a useful foundation has been laid and important progress is being made, we believe that the program is not adequately funded. An increased level of investment, ideally doubling the annual level at this early stage of the project would dramatically accelerate technical progress. We believe that now is the time for the detector program to be pushing as hard as possible toward performance goals, since large system and project benefits would result. Every percentage reduction in detector noise, for the spectrometers, would produce that same percentage reduction in required observing time (and in associated operating costs). This augmentation seems an excellent means of reducing risk in a critical area. The magnitude of such an early investment would be insignificant in the long run, but is very likely to enable a far more powerful scientific capability, and a far more producible, affordable critical flight subsystem.

2. Assign highest priority to NIR detector technology development – particularly in noise reduction and scaling up to large formats.

The priorities of the NGST detector technology development program must be aligned with the priorities of the planned science program. Since the NIR imaging and spectroscopic observations remain truly central to the NGST mission, and because the identified requirements for focal plane format and sensitivity are especially challenging in the NIR, it is essential that developments in this region be successful. Of the wavelength ranges considered for NGST, the largest gap between available sensitivities and formats, vs. identified goals, exists in the NIR. For these reasons, NIR technology should be given the highest overall priority. Strong efforts should be made in the NIR to address the pacing parameters – principally to reduce noise (read noise and dark current contributions), and to fully demonstrate that 16 Mpixel FPA formats can be produced and qualified. The expert detector group (Recommendation 11) should advise the project on relative funding priorities, particularly with respect to emphases within the NIR, and on NIR vs. MIR investments.

3. Maintain strong support for MIR detector technology development – particularly in reducing read noise and dark current

MIR detector requirements for NGST are challenging as well; they are not satisfied by the present state-of-the-art. Improvements in detector performance would clearly enable compelling mission science. The panel advocates concerted development projects in this area, at a somewhat lower priority level than those in the NIR. Development efforts should attack the pacing MIR parameters of dark current and read noise, and readout format. There are a number of potentially attractive but less mature MIR detector material alternatives, which we recommend be pushed, so that these options are better understood, and more established.

Mindful of the cost constraints of the overall project, the panel recommends the visible focal plane technology should be viewed as an adjunct of the NIR program, at a lower priority level than the NIR or the MIR. Subject to advice from this oversight panel and further definition of the NGST scientific program, it does not appear that a significant development program in visible detectors is warranted.

4. Maintain balance between investments to improve sensitivity, and investments to establishing producibility and large formats. Support potential vendors in efforts to establish adequate packaging and manufacturing/yield technology to meet NGST needs (including costs)

The panel supports the plan to help prepare the potential detector vendors for production of the very large planned NGST arrays through manufacturing technology (mantech) and packaging technology tasks. This is an important complement to the efforts to improve device sensitivity and SCA formats. Consistent with Recommendation 2, we believe that emphasis should be placed on FPA packaging and mantech tasks for the NIR. In addition to the process optimization and yield improvement tasks, the mantech work should also develop efficient, low-cost means of quickly yet accurately testing and screening large numbers of candidate SCAs. We also note that significant expertise is emerging in universities and other institutions with regard to very large-format arrays (e.g., 8 k x 12 k CCDs); the NGST packaging programs should be broadly based, to involve these experts and their approaches.

5. Assure stability & continuity of support for development and testing teams (given demonstration of good progress)

The NGST detector development tasks must be periodically reviewed to assure technical quality, reasonable progress, and responsiveness to the latest mission requirements. Assuming a given group passes periodic review, it is very important that it be given sufficient time, and uninterrupted funding, to bring their approaches to fruition. Technical progress in this technology is difficult to achieve; it requires a dedicated team, sufficient resources to retain the right mixture of skills and experience, and long-term commitment. This applies to all elements of the development program, including the design, processing, fabrication, and in-house testing at the vendors, as well as the testing and characterization work at outside university or Government laboratories.

6. Establish a small, coordinated network of low-background characterization labs to verify detector characteristics and establish technology readiness

It is essential that developmental devices be characterized as thoroughly and widely as possible, both before, and after, selection of the instrument teams and the focal plane vendors. Definitive low-background measurements are extremely difficult to make. Experience has shown that the best data result from careful outside lab work by the astronomical community, working in concert with colleagues in industry. We recommend an expansion in both the scope of activity and the number of (competitively selected) lab groups, to provide this critical data. In the near-term, this widely-available data will be essential to support sound NGST instrument proposals and system tradeoff studies and analyses. In the farther term, substantial data on SCA performance and full focal plane arrays must be available to guide selection of parts for flight instruments, and to help design of flight data analysis systems. A careful definition of the specific types of measurements, and the associated timing -- where and when such measurements will be needed – has not yet been completed. This needs to be done, with the involvement of the advisory committee.

This represents a significant technical challenge to a community that includes only a small number of expert groups. We emphasize that extensive, specialized expertise and experience are needed to successfully satisfy this need. Data must be widely disseminated. The lab groups need to stay in close communication, so that their methods and equipment produce data that are consistent or readily comparable. They should be prepared to conduct unbiased tests on samples of competing array technologies from different suppliers, particularly in the key NIR band, and collect and report data toward consistent standards.

7. Conduct ground-based testing of candidate arrays, when NGST-like conditions can be produced

In addition to low-background laboratory data, it is important to gain observational experience and data from candidate NGST arrays, where practical. Astronomical testing is warranted *if* NGST-like flux conditions can be created (this may be difficult at the longer wavelengths). Experience has shown that a number of subtle detector effects are only revealed when arrays are exercised in astronomical applications from the ground or from an airborne platform. Obviously, if direct observational experience with the latest devices can be gained by potential investigators in the near-term, better instrument proposals, and a better overall understanding of technical issues, will be gained.

8. Include detector experts in the overall system engineering process. Conduct analyses to confirm system-level compatibility of detector requirements, and to provide better focus for detector developments & optimization

There are clear couplings between detector characteristics and overall NGST system parameters. Examples include detector contributions to overall MTF, electronics and temperature stability requirements, and the requirements placed on the cryogenic cooler system. We believe it is essential that detector experts are directly involved in the system engineering process. Such expertise, and the latest data, will allow the project make the best design decisions. It will also provide very useful guidance to the teams developing and optimizing candidate detector technologies and in defining instrument concepts. It is important to verify that the science-driven detector requirements are compatible with overall system designs.

We recommend that the project develop an overall focal plane reference design and observing scenario, to further guide detector development and characterization activities.

For detectors, an important and fairly complex optimization and tradeoff area is the issue of pixel size. A number of factors, including MTF considerations, noise, radiation effects, yield, and dark current (including glow), are involved. Note that we have not identified any external drivers that would preclude use of NIR pixels within the present range of consideration (~15 to 30 µm). Better system definition and tradeoff results would greatly assist the final optimization of pitch, and other key detector parameters.

9. Improve analyses and understanding of radiation environment and effects for NGST

Radiation effects can be a significant factor in selection of detectors, and in design of system accommodations to minimize them. We recognize that relevant experience will be accumulated though SIRTF and other missions. But we stress the importance of developing a detailed understanding of the radiation environment (energies, rates) associated with the anticipated L2 NGST orbit, and better characterization of the response of detectors in this anticipated environment. The instantaneous response of detectors (and associated amplifiers) to individual ionizing events must be studied, as well as the effects of exposure to anticipated total mission dose levels.

10. Test NIR arrays in guider-mode to establish feasibility or limitations

The yardstick-mission concept of using the NIR arrays with broadband filters for guiding must be considered with care. As is the case with many other recommendations, data are needed to guide decisions and analyses. Tests should be conducted on existing and emerging large-format NIR arrays. One should determine how much interference is produced between a small ‘guider’ subarray (clocked with high frame rate) and the remainder of the array devoted to science (and operated at slow frame rate). Such data would greatly help determine overall feasibility, and identify technical issues. Ongoing studies of separate guider instruments should continue as well. We recognize that the necessary measurements on the NIR arrays, and the subsequent choice of guider implementation, must be made in the relatively near term.

Should the NIR concept be pursued, the choice of filter (e.g., at the shortest available wavelength) for guiding could impact the basic NIR science capabilities. The need for rapid frame rates could create high levels of glow, which, without redesign of the readout, could generate undesirable dark current or thermal heating/dissipation effects. There is clearly a need for much deeper understanding of the performance characteristics and operating (e.g., clocking) tradeoffs involved.

11. Form a permanent NGST detector advisory panel

We strongly recommend that a permanent, broadly-based expert detector group (involving scientists and technology specialists) be formed to advise the project on a range of topics. This idea was discussed at the April ’99 Detector Workshop, where it received broad support. The detectors and focal planes will clearly be a crucial element of NGST, and project and technical decisions will clearly benefit from the advice of such experts. The project has significantly matured in recent years, and focal plane concepts have also expanded beyond the scope the baseline approach; it is time to establish a readily-available expert resource to provide guidance.

We anticipate that this committee could address a range of topics. These would involve support of system analyses and tradeoffs, as mentioned above. In the area of detector and focal plane technology development, this panel could greatly help assure that development tasks are responsive, and that they remain consistent with the latest project and science requirements; that the pivotal detector parameters are receiving the most attention; that detector characteristics are being measured with the best methods; that the overall focal plane technology investment is properly prioritized, balanced, and focused; etc. This panel could also help organize annual detector workshops for NGST.

To best utilize such a resource, the NGST project should carefully determine the best position for this multi-disciplinary detector advisory group within the overall project advisory structure.

VIII. Appendices

A. MTF - Modulation Transfer Function.

(References: Davis et al. SPIE 3379, 288 (1998); Schroeder "Astronomical Optics")

1. Definition:

The MTF is the real part of the OTF (Optical Transfer Function): the system OTF is the product of the separate OTFs. The system OTF is the Fourier transform of effective PSF (point spread function). In the absence of aberrations such as coma causing lateral shift in the intensity pattern on the image surface, the OTF = MTF.

The MTF can be thought of as the ratio of the contrast in the image to the constrast in the object (at a specific spatial frequency f); thus the system MTF is a measure of the spatial resolution of the entire system.

For NGST, the system MTF is the product of the detector array MTF, the instrumental optics MTF, and the telescope MTF (Fourier transform of the PSF).

2. Detector MTF:

The detector MTF is itself the product of two independent MTFs. One, the so-called aperture MTF, is related to the pixel or detector size. If one takes the Fourier transform of a "box" response, i.e. response 1 from -p/2 to +p/2 and 0 everywhere else, where p is the pixel pitch (assuming perfect square response profile when pixel is spot scanned), the MTF = sinc(f p).

Physically, as the frequency of the contrast in the scene gets very high, the pixel will no longer register the contrast, but just the average of the highs and lows in contrast. For Nyquist sampling, $f_N = 1/2p$, the detector aperture MTF is always the same, namely $2/\pi = 0.64$. This is the maximum MTF the detector array, hence the system, will ever have, if Nyquist sampling is assumed.

But the detector array is also subject to the detective or diffusion MTF_{det}, due to diffusion of the charge carriers laterally into neighboring regions. This tends to "smear" closely spaced contrast in the scene, i.e., it degrades the overall MTF at higher spatial frequencies. The detective MTF depends on several detector parameters, including diffusion length, detector thickness, absorption coefficient, the relative junction size as compared with p, and backside passivation (much more so than the frontside passivation). The primary dependences are the diffusion length L (only parameter assumed [incorrectly] in Davis et al.) and the "thickness" - actually the distance from electron/hole generation to the depletion region. For any given detector, this varies with wavelength - e.g., for InSb at 30K, the absorption depth is ~5 µm at a wavelength of 5 µm, and ~0.7 µm at a wavelength of 2 µm. Annoyingly, the diffusion MTF increases for smaller L while the DQE increases for larger L. Obviously, the detector MTF asymptotically approaches 0.64 for large detector pixel pitch p.

A graph of total detector MTF vs. Detector pitch was presented by Raytheon for 7 µm thick InSb at the NGST Detector Workshop (see chart 15 in A. Hoffman's presentation http://www.ngst.stsci.edu/detector_conf99/proc/hoffman.pdf) for wavelengths shorter than 4 µm (where the absorption depth effect is inconsequential). It shows that the asymptotic detector MTF = 0.64 has not been realized even for 50 µm pixels: it is 0.48 for 27 µm pixels, and 0.37 for 18 µm pixels. In this calculation, L was assumed to be 100 µm (Alan Hoffman, private communication), consistent with maximum DQE. A more recent calculation by Raytheon, utilizing a smaller value of L and other more realistic assumptions, confirmed the earlier results.

3. Instrument Considerations:

For detector array pixels with a pixel pitch of p = 27 (18) µm, the detector Nyquist frequency $f_N = 1/2p$ = 18.5 (27.8) cycles/mm. The optical cut-off frequency f_c in cycles/mm at the focal plane for an instrumental system (assuming angular separation of diffraction rings of λ/D) is $1/(\lambda \times f/\text{number})$. For example, at 2 (3.5) µm wavelengths, and f/24, the f_c is 20.8 (11.9) cycles/mm.

To maintain the MTF as well as the FOV, a larger array than might be expected is required. What might be surprising is the magnitude of the effect: to maintain the performance achieved by a 27 µm pixel with f/24 reimaging optics, an 18 µm pixel requires not f/16 optics (proportional to pixel size) but f/19 reimaging optics and the number of pixels needs to increase by a factor of 1.403 (Raytheon, private communication) over simple expectations. Thus instead of a 1024 x 1024 element array of 27 µm pixels to cover the field of view, an 18 µm-pixel array would need 1213 x 1213 elements covering the same field of view. Since power dissipation is proportional to the number of pixels, a trade may be required.

4. Conclusion:

The detector MTF has been discussed above for InSb. To maintain constant MTF, and the same field of view, a larger number of pixels is required for 18 µm pixel arrays than for 27 µm pixel arrays.

Experiments on HgCdTe MTF conducted by Rockwell are noted in section IV.A, and confirm the expectation that the two detector types behave similarly. Rockwell notes that a path to improving the MTF for a given pixel pitch is possible in principle since MBE growth of HgCdTe allows control of the thickness and doping profile. Similarly, Raytheon has indicated that InSb detector MTF might be improved by design and process changes.

B. Definition of Terms / Recommended Standards for Data Reporting

Read Noise: The level of noise which results from each interrogation or read of a pixel with a given sampling technique or algorithm. Since read noise can be significantly improved by a number of methods (like multiple sampling, e.g., Fowler sampling) and non-destructive read techniques, experimental data must clearly report the number and method of such sampling.

Photon noise: The standard deviation in the average photon fluence. It is the fluctuation of the number of photons incident on the detector caused by the photons being discrete and not arriving at a uniform rate.

Shot noise: The noise associated with the variance in a dc current flowing across a junction due to the discreteness of the quantized electronic charge. The current shot noise is given by the expression $I_{sh} = (2*q*I*\Delta f)^{1/2}$. If I is solely the result of photons, that is, a photocurrent, then the noise of the detector is photon-noise limited and I_{sh} is the detector shot noise created by the photons through mediation of a photocurrent crossing the detector's junction.

Quantum Efficiency (QE or η): The (internal) average conversion efficiency of carriers produced per incident photon. When describing the collection of these carriers in an external circuit, the product Gη applies, where G is the gain.

Dark Current: The current observed in a device with neglible photon flux incident.

Point Spread Function (PSF): Point spread function is the normalized intensity as a function of position P from image center for point source illumination.

Nyquist criterion for discrete sampling: Two samples per resolution element. For a linear separation at the Rayleigh limit given by λ*f/number, the Nyquist criterion corresponds to pixel size p (radians) = λ/2D.

Critical sampling: Four samples per Airy diameter to first zero.

Optical Crosstalk: The signal measured on an un-illuminated detector when an adjacent detector is exposed to a given photon flux. It is usually expressed as a percentage of the signal that would be generated if the un-illuminated detector were subjected to the same photon flux.

Fill Factor: The ratio of a detector's active area to a pixel's area. It is expressed as a percent, and may vary somewhat depending on the definition of active area.

Well capacity: The number of carriers that a potential well can hold before it is completely filled. The well is usually a capacitor, so the charge it can hold is voltage dependent. Useful well capacity may be defined as a percentage of full well capacity.

C. Acronym and Abbreviation List

ALADDIN	Advanced Large Area Detector Development for InSb (1 k x 1 k InSb array for ground-based astronomy)
AR	Anti-Reflection
ASWG	Ad Hoc Science Working Group for NGST
BIB	Blocked Impurity Band
CCD	Charge-Coupled Device
CMOS	Complimentary Metal Oxide Semiconductor
COBE	Cosmic Background Explorer
CTIA	Capacitive Transimpedance Amplifier
DIRBE	Diffuse Infrared Background Explorer, instrument on COBE
DLPH	Double-Layer Planar Heterostructure
DRM	Design Reference Mission
ESO	European Southern Observatory
FOV	Field of View
FPA	Focal Plane Array
FTS	Fourier Transform Spectrometer
GSFC	Goddard Space Flight Center
HAWAII	HgCdTe Astronomical Wide Area Infrared Imager (HAWAII is the 1 k x 1 k HgCdTe array technology; HAWAII-2 is the 2 k x

	2 k technology)
IBC	Impurity Band Conduction
IGM	Intergallactic Medium
IRAC	Infrared Array Camera, a SIRTF instrument
IRS	Infrared Spectrograph, a SIRTF instrument
ISIM	Integrated Science Instrument Module for NGST
ISO	Infrared Space Observatory
MBE	Molecular Beam Epitaxy
Mux	Multiplexer
MIPS	Multiband Infrared Photometer for SIRTF
MIR	Mid Infrared
NICMOS	Near Infrared Camera/Multi Object Spectrograph; instrument on HST
NIR	Near Infrared
OTF	Optical Transfer Function
pixel	Picture element; element of a detector array
PSF	Point Spread Function
R	Spectral Resolution, $\lambda/\delta\lambda$
rms	Root-mean-square
SCA	Sensor Chip Assembly
SIRTF	Space Infrared Telescope Facility
S/N	Signal-to-Noise
SOA	State-of-the-Art
FTS	Fourier Transform Spectrometer
QE	Quantum Efficiency
QWIP	Quantum Well Infrared Photoconductor
UH	University of Hawaii
UR	University of Rochester
WIRE	Wide-Field Infrared Explorer
WFPC2	Wide Field Planetary Camera 2, HST instrument

D. Panel Charter

An advisory committee formed at the request of the NGST Project Scientist is chartered to revisit the NGST visible, NIR, and MIR detector requirements and attributes. The composition of the committee was chosen to include representatives of the instrument concept study teams, those involved in previous missions (HST & SIRTF), detector technology, and to also have a even distribution between institutions.

The objective is to revisit the detector charactersitics listed in the “Black Book” (The Next Generation Space Telescope: Visiting a Time when Galaxies Were Young, June 1997), and those discussed at the April 1999 NGST Detector Workshop, to verify that the appropriate parameters have been identified, that the associated goals are reasonable and consistent with the latest understanding of science requirements, and to explore whether other parameters or characteristics should be included.