NGST Detectors: What We Need

Knox S. Long (STScI), Matthew Greenhouse (NASA/GSFC), Craig McCreight (NASA/Ames) and Bernard Rauscher (STScI)

Abstract

The instrumentation currently planned for the Next Generation Space Telescope will require an unprecedented number of low background, high efficiency IR arrays spanning a total wavelength range 0.6-28 μ. To obtain these arrays, NASA is funding basic research and manufacturing technology efforts in two NIR materials, one based on HgCdTe and the other on InSb, and one mid-IR material Si:As. In this brief report, we summarize the current detector requirements and some of the considerations that are evolveing into a better definition of those requirements.

Introduction

The NGST science mission is intended to address very basic questions concerning the formation and evolution of the first stars and galaxies in the Universe, the reionization of the intergalactic medium by those stars, the nature and structure of highly-obscured, high redshift galaxies, and the physics of protostars. To carry out this mission, the NGST Project Scientist and the Ad-hoc Science Working Group for NGST have recommended a core complement of instruments consisting of a 4’ x 4’ 0.6-5 μ NIR camera, Nyquist sampled at 2 μ, a 3’ x 3’ 1-5 μ NIR multiobject R~1000 spectrograph, and a 2 x 2’ 5-28 μ MIR camera/spectrograph (Mather, et al. 2000). Detectors are the heart of each of these instruments. The NIRCAM and NIRMOS require arrays totaling 8 k x 8 k pixels and 2 k x 2 k pixels respectively. The NIRCAM will most likely be constructed from 4 2 k x 2 k focal plane arrays. The MIR Cam/Spec requires an array with 1 k x 1 k pixels.

Requirements

The NGST project has been developing requirements and goals for these arrays based on the need to carry out NGST’s science goals as represented in a design reference mission and our increasing understanding of the rest of the NGST architecture, including operational constraints. Philosophically, we have chosen to base our requirements on the imaging portion of the science program while our more challenging goals result from the needs of the spectroscopy portion of the program. Most of the requirements, such as the noise specification of 10 electrons in a 1000 s exposure in the NIR, are close to being satisfied in existing devices, although work is required to show that all the requirements are satisfied in single devices. The goals are more challenging. However, as indicated by some of the talks in this conference, rapid progress towards achieving them is being made. A summary of some of the more important requirements and goals is presented in Table 1, below:

Table 1

	NIR		MIR	
Parameter	Requirement	Goal	Requirement	Goal
Format	FPA : 2k x 2k	FPA : 2k x 2k	FPA : 1k x 1k	FPA : 1k x 1k
Noise	10 e^- (rms)	3 e^- (rms)	20 e^- (rms)	3 e^- (rms)
λ range	0.6-5 μ	0.6-5 μ	5-27 μ	5-30 μ
QE	>80%	>95%	70%	70%

Cosmic Ray upsets	<18%	<6%	<18%	<6%
Pixel Pitch	15-30 μ	15-30 μ	15-30 μ	15-30 μ
Max. Exp Time	~ 1000 s	1000 s	~ 1000 s	1000 s
Guide Window	10 x 10 pix @ 100 Hz	10 x 10 pix @ 100 Hz	None	None

Most of these requirements are discussed extensively in the report prepared by the NGST Detector Working Group (McCreight et al. 1999). We expect that NIR focal plane arrays of total size 2 k x 2k will be required for NGST, but the focal plane arrays may be constructed of a single device or mosaiced from 1 k x 1 k devices. Dithering will be used extensively for NGST observations and so small gaps can be tolerated between the individual sensors in the NIR instruments. In the MIR, we assume that the array will be constructed of a single chip; the required 1 k x 1k device is only a small scale-up from the sizes available on SIRTF.

The NIR devices must be sensitive to a short wavelength cutoff of 0.6 μ because we do not believe we can afford to develop or accommodate a separate visible technology within the 30 K integrated science instrument module. While we would like the MIR detector response to extend to and beyond the 28.3μ line of H_2, the materials needed for this would require considerable development and would require temperatures lower than can be easily supported in the 30 K environment of the ISIM.

Our noise specification represents the total noise, including that due to read noise and dark current. Because the "sky" background is low a L2 where NGST will be located, frame times, i.e. the time between detector resets, will be much longer than is typical for ground based astronomical observations. Thus our noise requirements are based on 1000 s exposure times.

We currently believe that by altering the f-ratio of the telescope to match the NIR pixel size, NGST will be able to accommodate pixel sizes ranging from 15 – 30 μ. This allows the detector manufacturers to select a pixel size with which they are comfortable and one that optimize other characteristics of the detector.

For mass, power, and especially cost reasons, we hope to use the NIR cameras to provide a fine error signal to the attitude control system for NGST. Therefore, it must be possible to select any one of the sensors in the NIR camera and to read and centroid the signal in a portion of that sensor at rates as high as ~ 100 Hz.

Since that the Detector Working Group Report was written, we have continued to refine the requirements as our understanding of NGST and its environment has increased:

Cosmic Ray Effects

The mean cosmic ray flux at L2 is estimated to be 5-10 cm^{-2} s^{-1}, which is considerably larger than low earth orbit outside of the SAA (Barth & Isaacs 2000). Based on proton tests of the SIRTF/InSb detectors as well as on in-orbit measurements with NICMOS, a typical cosmic ray deposits several thousand electrons in the brightest pixel associated with that cosmic ray. However, at the noise limit, even cosmic rays normally incident to the detector are likely to affect more than one pixel. Rauscher, Isaacs & Long (2000) have concluded that at this limit, the typical cluster size of the SIRTF/InSb detectors is ~5. For this cluster size, a cosmic ray rate of 5 cm^{-2} s^{-1}, and 27 μ pixels, ~18% of the pixels would be affected in 1000 s. Although one can compensate for the loss of these pixels by additional exposures, this is an efficiency loss that we need to minimize. As a result, we have now set both requirements and goals for the susceptibility of the NIR and MIR detectors to the short-term effects of cosmic rays. Detectors with smaller pixel sizes may be less susceptible these cosmic rays, assuming the cluster size can be kept small, but this requires verification. Shorter frame times reduce the inefficiency caused by cosmic ray "upsets" as well. But shorter frame times increase the overall noise. Furthermore, if the frame times were shorter and all of the frames were transmitted to the ground, it would increase the total data rate required to support the detectors.

Readout Efficiency

In our original description of the requirements, we did not directly specify a required sensitivity. Instead we specified quantum efficiency (QE) and noise (N) goals and requirements. This was in part to allow flexibility in the readout approach and also to make the requirements easy to interpret. However, it is clear that two detectors both with the same quantum efficiency and noise specification will reach different sensitivity limits if the effective exposure time, given by the frame, or "wall-clock", time (t_{frame}) minus the read out time (t_{read}), differs since

$$\frac{S}{N} \sim \frac{Flux \times QE \times (t_{frame} - t_{read})}{N} = \frac{Flux \times QE \times (\eta \times t_{frame})}{N}$$

In calculating the sensitivity of NGST with the NGST mission simulator, a sample rate of 5 μs pixel^{-1} and Fowler 16 has usually been assumed. In that case, for 1 k x 1k readouts and frame time of 1000 s, the first set of 16 Fowler reads give the signal at 42 s and the last set gives the signal at 958 s implying an efficiency η of 92%. The same efficiency can be obtained if the noise specification can be reached with Fowler 8 sampling and a sample rate of 10 μs pixel^{-1}. By contrast, a detector that required Fowler 32 and 12 μs pixel^{-1} sampling would have an exposure efficiency of 62%. To indicate the importance of readout efficiency as well as the ultimate noise performance, we have updated the current specifications for NGST detector development to indicate that we would like the noise specification to be measured using 12 μs pixel^{-1} sampling and Fowler 8.

Modulation Transfer Function

The modulation transfer function for an ideal detector with square pixels is 0.64. However, no detector is ideal and therefore we have evaluated how critical the MTF is in the overall performance of the observatory (Rauscher 2000). For imaging, our current working requirement is that 60% (85%) of the flux at 2 μ falls within and encircled radius of 0.06" (0.20"). Given that the NIRCAM is intended to be Nyquist sampled at 2 μ, MTFs as low as 0.4 are sufficient for imaging. If the spectrograph is designed so that two detector elements correspond to one resolution element of the spectrograph, then spectroscopy requires a higher MTF of ~0.53.

Summary

For NGST, the astronomical community will require substantially more IR pixels than have flown on any previous space mission, and the associated detectors must be affordable. On the current schedule, these detectors must demonstrate technology readiness by the mid-20003. To assure this, NASA is funding basic research on IR detectors in the community and manufacturing technology and cost analysis programs with several detector manufacturers. For the NIR, where the detector challenge is greatest, the NASA effort is supporting both HgCdTe and InSb-based efforts. For the MIR, Si:As, due in part to its development for SIRTF, seems the clear choice and as a result is the only technology for which the NGST project is providing funding.

Documentation on the detector program and on the NGST detector studies, including significantly a proposed read out design architecture for the detectors on NGST (Boyce et al. 2000), is available from the NGST web site (ngst.nasa.gov).

References

Barth, J., & Isaacs, J. C. 1999, NGST Doc 570, The Radiation Environment for the NGST

Boyce, L. et al. 2000, Doc. 703, ISIM Detector Readout Design: Cycle 1

Mather, J., Jacobsen, P., Lilly, S., & Stockman P. 2000, NGST Doc. 549, NGST Science Instrument Recommendations

McCreight C. et al. 1999, NGST Doc. 538, Recommendations of the NGST Requirements Panel

McCreight C. 2000, NGST Doc. 641, Technology Development Specification for NGST Detectors

Rauscher, B 2000, NGST Doc.662, NGST – A Note on Detector Modulation Transfer Function Guidelines

Rauscher, B., Isaacs, J. C., & Long, K. S. 2000, NGST Doc. 649, Cosmic Ray Management on NGST 1: The Effect of Cosmic Rays on Near Infrared Imaging Exposure Times