Performance modeling of an upgraded NIRSPEC on Keck

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ABSTRACT

NIRSPEC is a high-resolution near-infrared (1-5 micron) echelle spectrometer in use on the Keck II telescope. We are designing an upgrade to the spectrometer, and here we present modeling for the expected performance of the upgraded system. The planned upgrade will (1) replace the Aladdin III science detector with a Teledyne H2RG, (2) update the slit-viewing camera (SCAM) detector to an H1RG and replace the optics, and (3) upgrade the instrument control electronics. The new spectrometer detector has smaller pixels but a larger format, and its improved noise characteristics will provide a dramatic increase in sensitivity, especially between OH lines in H-band and shorter wavelengths. Optical modeling shows that the upgraded system is expected to achieve higher spectral resolution and a larger spectral grasp. Also, preliminary modeling of the SCAM optical design aims to permit operation from 1-5 μm, overcoming a limitation with the existing system.
Keywords: Telescopes: Keck; Spectrometers: NIRSPEC, Infrared

1. INTRODUCTION

NIRSPEC is a NIR cross-dispersed spectroscopic instrument on the Keck II Telescope at W.M. Keck Observatory in Hawaii. NIRSPEC was commissioned in 1999 by the IR Lab at UCLA (PI Ian McLean)[1,2]. Since its commissioning, NIRSPEC has proven to be one of the most versatile and useful instruments at Keck. NIRSPEC has contributed to over 350 refereed papers in such diverse science areas as water production rates in comets[3]; the characterization of the coolest brown dwarfs from WISE[4]; the discovery of water in the terrestrial planet forming zone of a protostellar disk[5]; the identification of a low redshift host galaxy of a GRB[6]; and the study of gravitationally lensed Lyα emitters at $8.5<z<10.4$[7]. However, infrared array technology has improved significantly over the past 15 years, and the NIRSPEC detectors and electronics are now outdated. We plan to upgrade the current science detector from an Aladdin III InSb 1024x1024 array to a Teledyne HAWAII-2RG (H2RG) HgCdTe 2048x2048 array, which will have smaller pixels and is expected to have higher sensitivity. Additionally, the current SCAM design will be upgraded from its current 256x256 PICNIC array (which only operates over 1-2.5 μm) to a Teledyne H1RG 1024x1024 array optimized for 1-5 microns. Finally, we will replace the current readout electronics with the Teledyne SIDECAR ASIC readout and control board.

1.1 Current design

Light enters the NIRSPEC vacuum chamber and is reflected from an off-axis parabola (OAP) and fold-mirror assembly (similar to a K-mirror), which acts to both collimate the f/15 beam and fold the light path to reduce the size of the cryogenic vacuum chamber. This moveable K-mirror also acts as an image rotator to counteract the rotation of the sky on the slit plane while observing. Collimated light then passes through a filter wheel module, followed by a second (stationary) K-mirror assembly, which refocuses the light path as f/10 onto a slit wheel. Both K mirror assemblies are powered. The slit wheel contains mirrors tilted at 12° with slits of varying width and length cut into each surface. Slits of 1, 2, 3, 4, and 5 pixel widths are available at lengths of 12″ or 24″. The science detector has a pixel scale of 0.144″ per 27-μm pixel in the dispersion direction and 0.193″ per 27-μm pixel in the spatial direction in the high-resolution mode. The front face of each slit is a highly reflective gold surface that reflects light back onto the fold flat of the second K-mirror and into the Slit-Viewing Camera (SCAM).

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The SCAM optical system consists of three lenses made of BaF_2 and LiF, and a 256x256 HgCdTe PICNIC array capable of 1-2.5 μm detection. The SCAM allows for easy alignment of faint targets onto the slit when observing at these wavelengths.

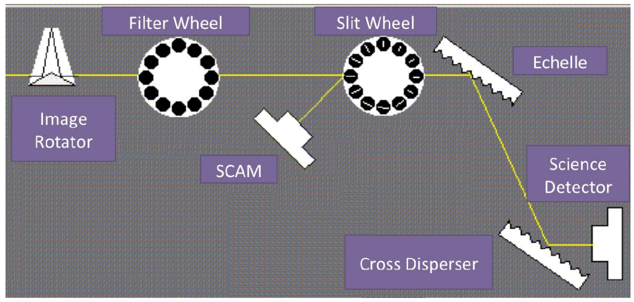

Figure 1. Simplified layout of the NIRSPEC design. Credit: W. M. Keck Observatory.

Following the slit plane, an OAP mirror is used to re-collimate the light into a 120mm beam towards the grating turret. For the high-resolution mode, the echelle grating is selected in the grating turret and is used in conjunction with a cross-dispersing grating to produce $R=\lambda/\Delta\lambda$ ~20,000, which is then imaged by a three-mirror anastigmat camera onto the Aladdin III detector. For low-resolution mode, a flat mirror is selected in the turret, and the cross-disperser grating alone provides R~2,000 spectral resolution.

The readout electronics for both the SCAM and spectrometer detectors, as well as the electronics used to control the instrument's various moving mechanisms, are implemented using Inmos Transputer based single-board computers.

1.2 Design limitations

The main limitations of the current design are the outdated detectors and readout electronics, which are much noisier than can be achieved with current infrared array technology. The transputer boards used for controlling the instrument's mechanisms and detector readouts, as well as the boards used for system housekeeping, are obsolete. There is cause for concern that if any of the current electronics required repair, they would be quite difficult or impossible to replace. Science detections are currently detector noise limited between sky lines, and spurious increases in noise on the science detector reduce efficiency during observations by up to a factor of $\sqrt{2}$. Additionally, the slit-viewing camera (SCAM) is only viable in the 1-2.5 μm regime, which poses difficulty for aligning targets on the slit while taking observations in the *L* and *M* bands.

2. PLANNED UPGRADE

In order to mitigate the limitations of the current design, we are planning several improvements to the instrument. Specifications for the current instrument and the planned upgrade are listed in Table 1 below.

2.1 Replacement science detector

The proposed upgrade will first replace the Aladdin III detector with a Teledyne H2RG with 5 μm cutoff material. The current science detector has much higher read noise and dark current than can be expected from the newest H2RG. In particular, read noise will decrease from 23 e- to 4.5 e- (16 Fowler samples), dark current will decrease from 0.7 to 0.01 e-/s, and the quantum efficiency (QE) is expected to increase from ~70% to >95%. Currently, high-resolution detections are detector-noise limited between OH lines. We expect the reduction in the dark current and read noise will allow detections to become background limited. The result of these improved noise characteristics are an increase in limiting magnitude of >1mag, or more than a 6.25 times reduction in integration time required to achieve a given signal-to-noise ratio (SNR). We also expect a 5 to 10-fold increase in efficiency in the *L* and *M* bands from increased QE and lower dark current and read noise.

The pixel size will decrease from 27 μm to 18 μm, while the format of the detector will increase 4-fold in pixel count, from 1024x1024 to 2048x2048 pixels. The increased detection area and decreased pixel size will increase both spectral sampling and spectral range. Optical modeling in Section 3 suggests that spectral resolution may also be increased if smaller slits are used. With the smaller pixels of the H2RG, the pixel scale will decrease to 0.096″ per pixel because the OAPs and gratings will remain unchanged. Smaller pixels and better sampling will allow for longer integration times before detections reach the background limit, also increasing the efficiency of observations. The replacement detector will allow NIRSPEC to continue in its status as a workhorse instrument for the Keck II telescope for at least the next decade.

Table 1. System specifications for the current instrument and planned upgrade

	CURRENT SYSTEM	PLANNED UPGRADE
Wavelength Coverage:		
Science Detector	0.9-5.3 μm	0.9-5.3 μm
Slit Viewing Camera (SCAM)	0.9-2.5 μm	0.9-5.3 μm
High-Res mode resolution	~25,000 (0.28″ slit)	~35,000 (0.192″ slit)*
Science Detector	Aladdin 3 InSb 1024x1024 27 μm pixels	Teledyne H2RG HgCdTe 2048x2048 18 μm pixels
SCAM Detector	PICNIC HgCdTe 256x256 40 μm pixels	Teledyne H1RG HgCdTe 1024x1024 18 μm pixels

* Increasing the resolution of the high-res mode is possible, but will require use of a smaller slit. We are currently investigating the performance of the optical system as built to determine how much of an increase in resolution we can obtain, and whether or not we will need to replace any of the slits in the current instrument with smaller slits matched to the H2RG.

2.2 Replacement SCAM detector

The second major component of the upgrade will be the replacement of the Slit-Viewing Camera (SCAM) detector. The 256x256 PICNIC array can only observe in the 1-2.5 μm regime, which is a drawback for the current design. Currently observations conducted in *M* band require switching filters to *K* band to acquire the target, before taking exposures with the *M* band filter. Having to switch the filters decreases efficiency by a factor of ~50%. Additionally, differential refraction between ~2 μm and ~4 μm makes it difficult to properly align targets on the slit. The replacement of the SCAM detector with a 1-5 μm H1RG (1024x1024 pixels) will be a great improvement for observations conducted in *L* and *M* bands. It will become much easier to align targets on the slit plane using SCAM after the upgrade, and the longer wavelength response will greatly increase efficiency when observing in these bands. This replacement also allows for the opportunity to redesign the SCAM optical system. The lenses have anti-reflective coatings viable for 1-2.5 μm and thus will have to be replaced. Also, the focal ratio of the system is matched to the PICNIC array. Replacing the PICNIC with a H1RG provides the freedom to redesign to optimize for such things as sensitivity, sampling, and field of view.

2.3 New readout and control electronics

The final component to the upgrade will be a complete overhaul of the computing system. The transputer electronics used for reading out, controlling mechanisms, and housekeeping are now obsolete. Replacement of the readout electronics for both the SCAM and spectrometer detectors with the Teledyne SIDECAR ASIC will provide NIRSPEC with a modern system with much less readout noise that will also be free of the systematic noise present in the current readout electronics. Control hardware will be replaced with more modern hardware currently implemented by Keck Observatory in other IR instruments such as MOSFIRE and OSIRIS. NIRSPEC will be able to share spare electronics with MOSFIRE, and its new user interface software will also take advantage of improvements implemented with the MOSFIRE instrument at Keck[8].

3. OPTICAL MODELING OF THE SCIENCE DETECTOR

The smaller pixel size of the H2RG will allow for 50 % better sampling and longer integration times, which greatly increases the sensitivity and usefulness of the instrument for doing groundbreaking science across many astronomical fields, including high red-shift galaxies, protostellar disks, brown dwarfs, and exoplanets. Because the H2RG has a larger format, we studied how the RMS spot size behaves at the corners and along the edges of the new detector.

We used ZEMAX to study the performance of the proposed detector upgrade. We studied the focal plane of NIRSPEC for both the current and proposed designs to quantify throughput and spot size across the detector. In Figures 2 and 3, we show estimated RMS spot size as a function of order and location on the detector to compare the Aladdin III and H2RG detectors in the J band (~1-1.3 μm) in high-resolution mode. The physical sizes of the detectors are shown in Figure 2 as dotted vertical lines and the one and two pixel sizes of each detector are marked in horizontal dashed lines. With the exception of the corners, the spot sizes are small enough to have 80% encircled energy fall within one or two pixels of the H2RG. We expect similar performance in other NIR spectral bands.

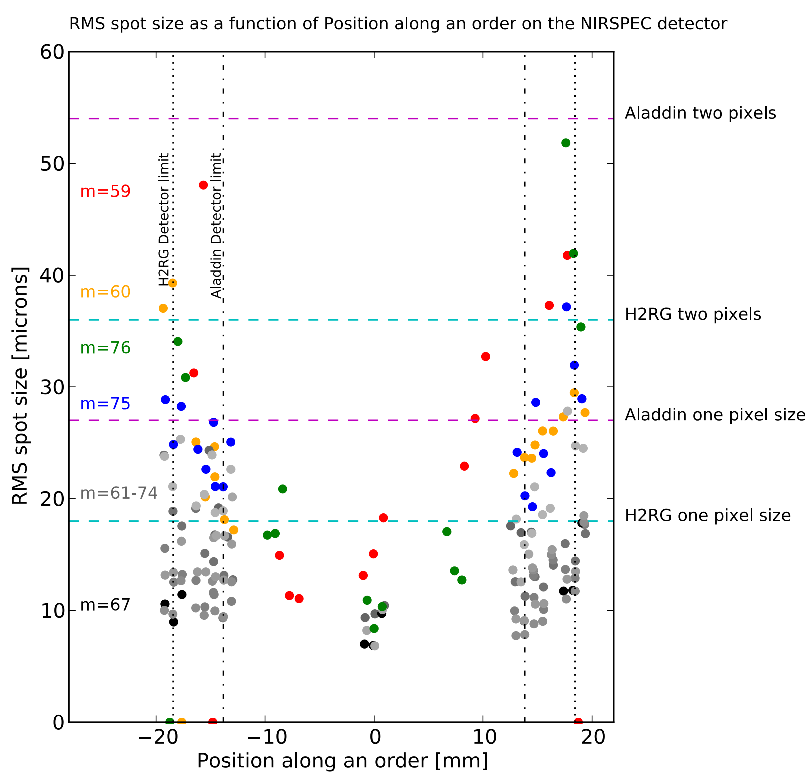

Figure 2. RMS spot size vs. position along an order (dispersion direction) on the detector. Different spectral orders are represented by different shaded dots. Spectral orders at the top and bottom of the detector are highlighted in color, because the edges of the detector are where we expect the poorest optical performance. The majority of the spot sizes are smaller than 2 H2RG pixels, indicating that we can expect much better pixel sampling with the H2RG than we currently see with the Aladdin III. Analysis was performed for the *J* band (~1-1.3 μm, echelle orders 59-76) but is expected to produce similar results for the other NIR bands.

Figure 3 shows the results of our ray tracing, plotted as an image of the NIRSPEC focal plane. Shading of the blue dots represents percent throughput of the light. Lighter spots have lower throughput. Spots are enlarged to demonstrate the impact of location on RMS spot size. An example spot with 80% throughput and a 10 µm spot size is shown in the bottom center as a reference. Boxes are drawn to denote the boundaries of the Aladdin III and H2RG detectors. Spectral orders are marked, along with the approximate lines they trace out on the detector. The slits are tilted because of the quasi-Littrow configuration of the spectrometer. From Figure 3, it is clear that the H2RG will offer a significant improvement over the current detector. Each order will have a larger spectral coverage, with acceptable spot sizes everywhere except the corners of the detector. All of the central orders have spot sizes smaller than 2 H2RG pixels; the majority of the spot sizes are under 30 µm. Throughput is also quite high; with the exception of the corners of the H2RG, throughput is greater than 80%.

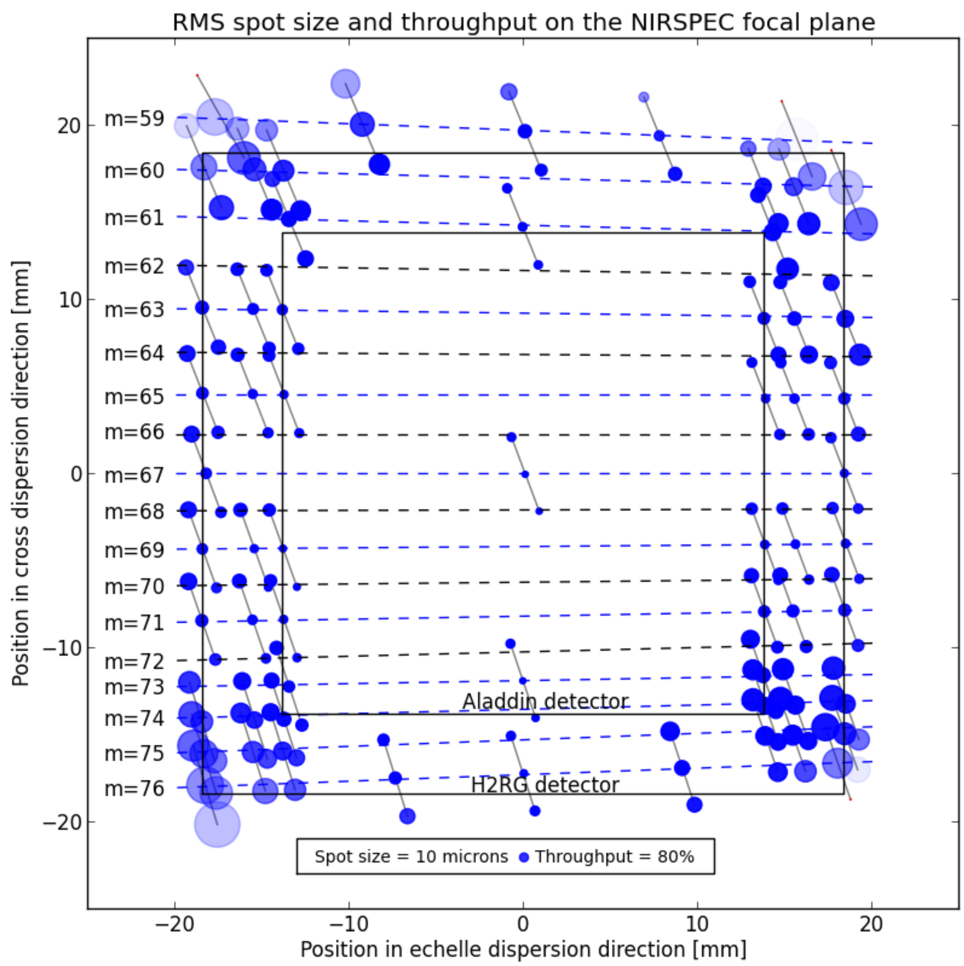

Figure 3. RMS spot size as a function of location on the NIRSPEC focal plane in *J* band (~1-1.3 µm, echelle orders 59-76). Spot sizes were calculated at three locations along 30″ slits along each order (tilted vertical lines). Lighter shaded dots have lower throughput, and red dots are completely vignetted by the instrument. Spot sizes are enlarged, but the majority of spot sizes fall within one or two pixels (18 or 36 µm for the H2RG). The slits are tilted because of the quasi-Littrow configuration of the spectrometer. Only the corners of the H2RG field have significantly lower throughput and larger spot sizes, but the overall improvement in spectral range is evident. We expect similar performance in the other NIR bands.

4. SCAM UPGRADE MODELING

We have performed preliminary modeling of the IR sky background to estimate performance of the Slit Viewing Camera in the 1-5 μm regime. SCAM shares the same wideband spectroscopic filters as the science detector. With carefully chosen anti-reflective coatings or additional filters, it will be possible to observe with SCAM in the *L* and *M* bands without saturating in the minimum exposure time of the newer detector. Observations will be background limited, however, and thus achieving a SNR of ~10 for faint targets will require many co-additions of short exposure images. Despite these difficulties, extending SCAM to 5 μm is a great improvement over the current setup, in which 3-5 μm observations with SCAM are not possible, affecting the observer's ability to efficiently position a target on the spectrometer slit.

Figure 4 shows our estimations of the total overall noise and signal-to-noise (SNR) vs. exposure time for bright and dim sources in each of the 5 NIR bands that SCAM will observe. *L* and *M* bands are entirely background limited, as expected. With carefully chosen anti-reflective coatings or additional photometric filters, it will be possible to image in *L* and *M* bands without saturating in the minimum exposure time. To prevent saturation we will need a shorter minimum exposure time than can currently be obtained with the H1RG (1.45 seconds with a 100 kHz clock, full-frame).

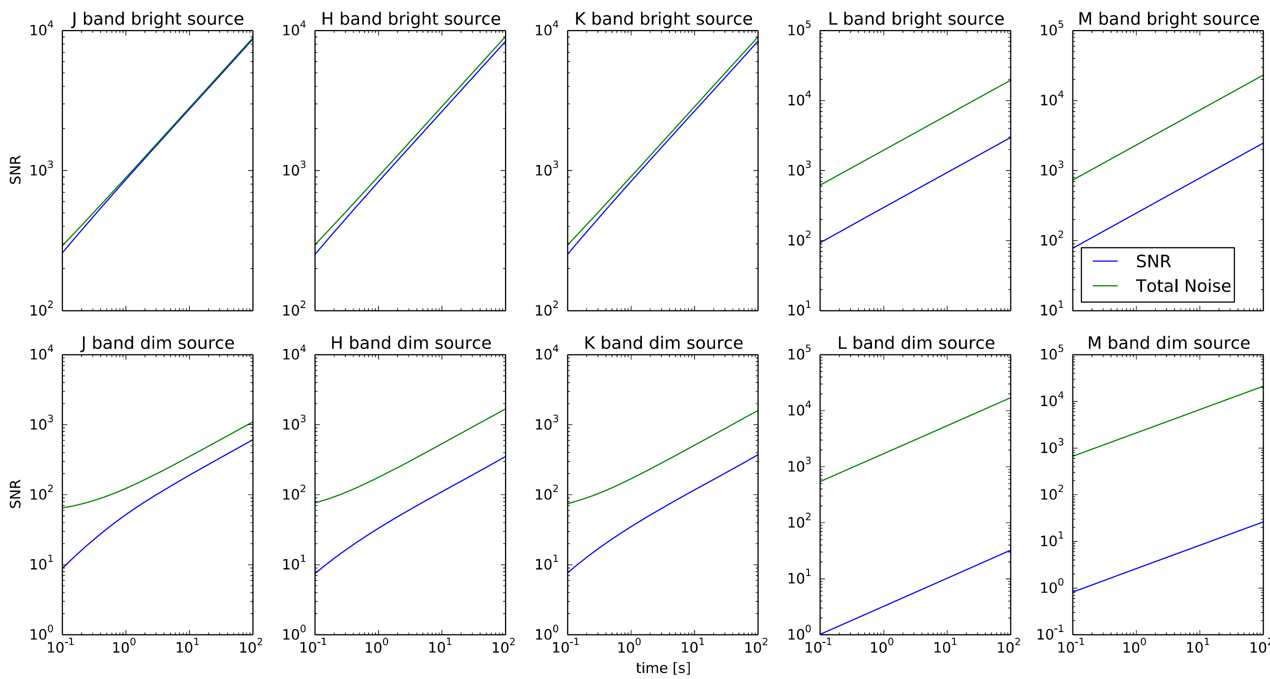

Figure 4. SNR and Total Noise vs. exposure time for *J,H,K,L*, and *M* bands as observed by SCAM for bright and dim sources. "Bright" sources are 100 times brighter than the *J* band background, while "dim" sources are the same brightness as the *J* band background. SNR is calculated using point-source photometry on the modeled SCAM H1RG setup. In actual observations, SCAM guiding will only be observing the light that does not go down the slit, and thus will not be a point source. *J,H,* and *K* bands are initially read noise limited, and then photon noise limited. *L* and *M* bands are entirely background limited.

5. CONCLUSIONS

We have presented optical modeling of the proposed upgrade for NIRSPEC on the Keck II Telescope. We have shown that the upgrade will significantly improve the quality of the science that NIRSPEC is capable of, by providing a new science detector, new SCAM detector, and new readout electronics. The new science detector will have increased spectral range and smaller pixels, allowing NIRSPEC to achieve higher resolution spectroscopy. The new SCAM detector and optics will allow imaging of the slit in *L* and *M* bands, providing easier acquisition of targets in these bands. Additionally, the new readout electronics will have much lower noise and result in higher sensitivity observations.

We are currently in the process of cold testing the readout electronics and detector head assembly in preparation for testing an engineering-grade H2RG. The new detector head assembly is designed to be completely modular in order to allow for quick replacement of the old detector and readout electronics, with minimal down-time and impact on observatory operations.

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