THE SELECTION, MOUNTING, AND INTEGRATION OF AN INFRARED
PHOTON-COUNTING APD MODULE FOR J-BAND ASTRONOMICAL
PHOTOMETRY ON THE NMSU HSP

BY

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A thesis submitted to the Graduate School
in partial fulfillment of the requirements
for the degree
Master of Science

Major Subject: Astronomy

New Mexico State University
Las Cruces New Mexico

???? 2012
“The Selection, Mounting, and Integration of an Infrared Photon-Counting APD Module for J-Band Astronomical Photometry on the NMSU HSP,” a thesis prepared by Leland R. Wehland in partial fulfillment of the requirements for the degree, Master of Science, has been approved and accepted by the following:

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Committee in charge:

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Dr. Jason Jackiewicz  
Dr. Laura Boucheron
DEDICATION

To my wife Gladys, without her love, support and patience none of this would have been possible. With all my love, thank you!
ACKNOWLEDGEMENTS

I would like to express my appreciation and thanks to the following:

New Mexico State University and in particular the Astronomy Department faculty and staff for the opportunity and support.

Yu-Ping Tang, Caleb Sokoll, and Charlie Park of NMSU Manufacturing Technology & Engineering Center for Engineering and Manufacturing support.

Dr. Rik Van Gorsel of Boston Electronics U.S. representative of id Quantique and Léonard Widmer of id Quantique for their technical advise and support.

My committee, chaired by Dr. Thomas Harrison and included Dr. Jason Jackiewicz and Dr. Laura Boucheron, for their guidance and patience.

Thank you all and everyone that I’ve neglected to mention that helped me along the way, I have enjoyed the journey.

I would also like to acknowledge the funding provided via NSF grant AST-0519398.
ABSTRACT

THE SELECTION, MOUNTING, AND INTEGRATION OF AN INFRARED
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Dr. Thomas Harrison, Chair

The objective of this project was to attain a functioning near infrared data
channel for the New Mexico State University High Speed Photometer. The High
Speed Photometer is described, as it existed including the provisions for a sixth near
infrared channel. Defining requirements, developing options, analyzing the options
to the requirements, selecting a single option for implementation, has developed and demonstrated a solution for the sixth channel of the New Mexico State University High Speed Photometer. Implementation required integration into the High Speed Photometer via mounting of the device and attachment to the support systems. Testing was performed to validate the functioning of the solution. The sixth data channel for the High Speed Photometer was successfully implemented and is functional.
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1. INTRODUCTION

The objective of this project is to attain a solution for a sixth channel of the New Mexico State University (NMSU) High Speed Photometer (HSP) to collect data in the near-infrared J-band. Included will be requirements, options, final selection, engineering, manufacturing, integration, installation, and testing for the J-band detector. For the purposes of this project the J-band is defined as that of the Mauna Kea Observatories J-band, which is centered at 1.25 microns and a bandpass from 1.17 to 1.33 microns (Simons and Tokunaga 2002).

The following paragraphs of this chapter provide context for the subsequent chapters by presenting an overview of photometry including history, photometers, a technical description of three single channel detector technologies, and data use examples. Then the need for high-speed photometry is presented along with the NMSU HSP.

1.1 Photometry

The science of Photometry is the study of the brightness of stars and other astronomical objects. Objects of interest for photometry includes stars, galaxies, planets, comets, asteroids, nebulae, and any other astronomical objects that emit or reflect electromagnetic energy.

Historically, photometry was based on the human eye as a detector and how bright objects appeared in the sky. The measure used to describe brightness of an
object is magnitude. Stars were observed and their magnitude assigned by
corparison to a “standard” star of a known magnitude. Since the eye’s response to
brightness is logarithmic and not linear, the resultant magnitude scale is logarithmic.
Equation (1) is the expression for determining the differential magnitude between
two stars where $m_1$ and $m_2$ are the magnitude of star 1 and star 2 respectively. The
symbols $f_1$ and $f_2$ are the measured fluxes for star 1 and star 2 respectively. Flux is
defined as the energy from an object per second per unit area.

$$m_1 - m_2 = -2.5 \log_{10}[f_1/f_2] \quad (1)$$

For example, using equation (1), for stars to appear to the human eye to have
a magnitude difference of 5, the ratio of the stars fluxes must be 100.

Further, by historical convention, the fainter the object the higher (positive) is
its magnitude. Conversely, the brighter an object the lower (negative) is its
magnitude. An example is our Sun, which is the brightest object in the sky, and has
an apparent magnitude of -26.74.

1.2 Photometers

Photometers replaced the human eye in the science of photometry.
Photometers are instruments that determine the brightness of objects and do so by
measuring the flux from an object. Flux data from photometers is converted into
magnitudes using the historical scale as discussed above.
The major evolution in photometers came with the introduction of photographic film as a detector. Film allowed the development of consistent methods for determining magnitude. Photometers have evolved from film to using photoconductive cells, photodiodes, photomultiplier tubes (PMTs), charge coupled devices (CCDs), avalanche photodiodes (APDs), and other devices as detectors. Today’s photometry is primarily based on CCD technology and to a lesser extent PMT technology. APD technology has recently matured to the point that there have been limited deployments into the astronomy environment (Dravins 2000).

1.3 Current Detector Technology

CCD technology offers high quantum efficiency (QE), near 90% in some cases (Howell 2000), which makes them efficient at collecting photons. When in a proper operating environment (cooled) CCDs are low noise devices with noise levels of a few electrons. From a bandwidth standpoint Silicon based CCDs have a range of around 0.3 to 1.05 microns (Howell 2000) although improvement in design, materials, manufacturing processes, and coatings continue extending their range. Cost for astronomical grade CCDs is in the tens of thousands of dollars and up to hundreds of thousands of dollars depending on quality, noise, size, QE, readout speed, service environment, and other factors.

CCDs measure the flux from the object by measuring the charge stored in the CCD pixels associated with the object over some integration time (exposure).
Photons enter the CCD matrix, are absorbed, creating free electron and hole pairs. The electrons are collected within potential wells created by applying a positive voltage at each pixel location. This results in a charge being accumulated within the pixel that a photon struck. Once the exposure is complete the data is read and processed into counts. The readout process for a CCD can take tens of seconds to multiple minutes depending on the device. Depending on the CCD involved there are additional operational activities, like reading out the CCD prior to exposure to assure the pixels are emptied of charge. The cadence of CCD Photometers is limited by the total of setup time plus readout time plus exposure time which is the minimum time between exposures.

A single CCD can take data only in a single band at a time. When collecting data across multiple bands an exposure must be taken, read out and setup operations performed before a second exposure is taken in another band. The resultant data is not synchronized across the bands and key information, like relationships between the data in one band to another band, may be lost. The high cost of single CCDs limits the development of multi-channel CCD photometers.

In operation CCDs allow photometry of multiple objects at the same time that are visible in the same exposure. In addition, sky flux (background noise) can also be measured from the same exposure, which avoids telescope movements and its associated time consumption.
PMT technology offers high-speed data collection but low QE, below 30% in general (Howell 2000). They are preferred for photometry where high cadence or single photon detection is required. PMT technology is very low noise resulting in excellent signal to noise ratio. From bandwidth coverage standpoint PMTs have a range from 0.3 to 0.8 microns (Howell 2000). PMT technology evolution continues to improve QE and bandwidth. Costs for PMTs are often less than two thousand dollars.

PMTs detect flux when photons enter the tube and strike a photocathode releasing electrons. These electrons are accelerated via an electric field along a series of dynodes. As the electrons are accelerated they interact with the material of the dynodes freeing more electrons that are accelerated by the electric field and the process repeats itself creating a cascade of electrons. The resultant current is processed into counts. Detection cadence is limited by the “dead time” of the detector that, in the case of PMTs, is a few nanoseconds in duration. During the “dead time” no photons can be detected.

APD technology also offers high QE, in the range of 80% at maximum for Silicon based detectors (Renker 2006). They have more noise than CCDs or PMTs. Cooling is used to mitigate thermal noise. Silicon APDs are sensitive to light from 0.2 to 1.11 microns and are more sensitive than PMTs in this range (Hamamatsu 2004). Their cost is in the several thousands of dollars for the individual detectors.
APD are solid-state devices that are constructed in layers of semi-conductor materials much like CCDs, simple photodiodes, or solar cells. Specifically they are p-n junction semi-conductors. A photon of the proper energy range enters the device, is absorbed, and creates a free electron and hole pair (charge carriers). The internal electric field then separates the holes from the electrons and moves the electrons toward the cathode while the holes migrate toward the anode (depletion layer). At this point the APD differs from other photodiodes in that electrons are swept, via an internal electric field, toward a multiplication region designed into the device. The electrons are accelerated by a high electric field in the multiplication region to the point that they begin to produce additional free electrons by impact ionization. This process, which is similar to PMT, results in an avalanche of electrons (Hamamatsu 2004). The avalanche results in a detectable current (Renker 2006) that is processed into counts.

1.4 Photometer Data

As has been shown in the previous section the data output from all three different detector technologies is in the form of counts. Counts are converted to flux and magnitudes calculated via observational processes.

A common way to present photometry data is via a light curve plot. Figure 1 shows a typical light curve plot with magnitudes plotted against time. In this simple example the variation in brightness for an object is shown over several months. Each
data point is 6 days apart. The magnitude of the object varies from about 10 to 8.5 over a period of one month (June to July). It also appears that this variation might be periodic but more data is required.

Figure 1. Plots the brightness of an astronomical object viewed every 6 days over a few months in 1995 (Figure Credit: http://imagine.gsfc.nasa.gov/docs/science/how_l1/light_curves.html).

A second property that can determine from photometry data is color. Color is determined by comparing brightness of an object in two different bands by subtracting one magnitude from the other. This information can also be plotted as a light curve too. Light curves are a simple but useful way to analyze the output from photometers. The magnitude and color data provides information on the
environment and processes that are occurring within an object. For example, collecting data on the magnitude for a supernova over a period of days to create a light curve allows the rate and shape of the decay of the light output to be determined. The decay of the light curve allows identification of a supernova as either a type I or type II.

1.5 High-Speed Photometry

Photometry in general has been described but what is “high-speed” photometry? The general definition is photometry with a cadence of less than 10 seconds down to cadences of microseconds. Most CCD photometers cannot reach this level of temporal resolution.

There is a desire for “high-speed” photometry in order to study phenomena that occur on timescales of a few seconds or less. The short-lived phenomena are obscured in CCD based photometry due to the data collection cadence that can be many minutes long. By using high-speed photometry astronomers are able to study variable and dynamic phenomena of objects giving additional insight as to what processes are taking place within objects.

Figure 2 shows a high-speed light curve of the Crab pulsar showing its variations at the milliseconds scale. The individual variations (pulses) and their repeating pattern are easily discernable. Clearly this information would be lost if the data cadence was even a fraction of a second long.
Figure 2. Series of Crab pulses (Ryan et al. 2006).

Examples of types of observational subjects that could benefit from high-speed photometry include: eclipsing binaries, transiting exoplanets, variable stars, pulsars, and objects with accretion disks.
1.6 New Mexico State University High Speed Photometer

It is with the scientific motivation for studying variable and dynamic phenomena by examining the light output of objects, New Mexico State University (NMSU) proposed the creation of a High Speed Photometer (HSP). The NMSU HSP was further proposed to be multi-channel so that data could be collected simultaneously on several channels allowing correlation of phenomena between the channels. To this end the NMSU HSP was constructed and installed in September 2007 on the NMSU 1-meter research telescope at Apache Point Observatory (APO) in New Mexico. The HSP has five channels for data collection in the $UBVRI$ bands of the standard “Bessell” filter set and has a minimum time resolution of 0.01 seconds.

In order to do high-speed photometry detectors are required that collect data at a high cadence. As we have seen PMTs and APDs are two such devices while CCDs are not. The HSP uses two PMTs to collect data for the U-band between (0.365 micron midpoint) and B-band (0.455 micron mid point). Three Silicon APDs are used for the V-band (0.551 micron midpoint), R-band (0.658 micron mid point), and I-band (0.806 micron mid point) due to their higher QE at these wavelengths.

Figure 3 shows the layout of the HSP. The incoming beam enters the HSP from the telescope at the top right side of Figure 3. The incoming beam then passes through the aperture/guide mirror that is constructed of metal. The aperture/guide mirror assures that the light passing into the HSP is from the desired object.
Currently, a 15” (arcsecond) aperture is employed (a spare 10” mirror exists for future use).

Figure 3. Showing the internal light path, optics, and detectors of the NMSU HSP. Thick black lines represent dichroic mirrors, thin black lines are filters for various bands, and black rectangles are Fabry lenses.

After exiting the aperture/guide mirror, the beam passes through a collimating lens, resulting in a 25.4 mm collimated beam. The collimated beam then encounters 50-50 non-polarizing beamsplitter with a nominal wavelength range of
4000 Å to 8200 Å (0.4 to 0.82 microns). The beamsplitter reflects slightly more than it transmits at wavelengths shorter than 4000 Å. For wavelengths longer than 8200 Å the beamsplitter transmits slightly more than it reflects. This design results in the reflected beam that enters the left side of the HSP (left leg), containing U, V, and I wavelengths while the transmitted beam continues down the right side of the HSP (right leg), contains B, R, and near-IR (NIR) wavelengths.

The left leg beam encounters a U-band dichroic short pass mirror, oriented at 45° to the beam, which transmits all light of wavelengths shorter than 4200 Å (0.42 microns) and reflects everything else down the left side of the HSP. The transmitted (U band) light passes through a U filter, followed by a U Fabry lens and is focused onto the U band PMT. The reflected beam encounters a V-band dichroic long pass mirror, oriented at 45° to the beam, which reflects everything of wavelength shorter than 6500 Å (0.65 microns) toward the V-band APD. Since all light shorter than 4200 Å was previously removed the effective bandpass for the reflected beam is 4250 to 6500 Å (0.425 to 0.65 microns). The reflected V-band light passes through a V-band filter and Fabry lens before being focused on the V-band APD. The remaining transmitted light continues down the HSP, through an I-band filter and Fabry lens, finally being focused onto the I-band APD.

The transmitted beam from the beamsplitter, which continues down the right side of the HSP, contains B, R, and near-IR (NIR) wavelengths. The right leg encounters a B-band dichroic mirror, oriented at 45° to the beam, and reflects all
light with wavelengths shorter than 5500 Å through the B-band filter and Fabry lens to the B-band PMT. The right leg then encounters a dichroic mirror, oriented at 45° to the beam, and reflects all light with wavelengths between 5500 to 9250 Å toward the R-band detector. Finally the remaining transmitted NIR light is passed into the provisional J-band port.

This arrangement allows the HSP to deliver light to all five existing detectors and producing five channels of data simultaneously. It also provides NIR light to the sixth port in support of a NIR channel. Figure 4 shows the HSP with its top removed to allow viewing of the internal physical arrangement. This picture was taken prior to black anodizing, which was done before final installation to minimize internal reflections.
Figure 4. The HSP prior to anodizing is shown with the top removed. The existing detectors are shown with the vacant J-band port visible.

The HSP is currently mounted to the 1-meter telescope (see figure 5) at Nasmyth port #2. The HSP appears in the upper left quadrant of figure 5 and is the large black object in that quadrant.
Figure 5. Shows the HSP as mounted on the 1-meter telescope. The HSP is the large black box in the upper part of the picture connecting to the Nasmyth port number two on the telescope. Instrumentation is also shown mounted on the platform at Nasmyth port number two. Instrumentation is located below the HSP on the Nasmyth #2 platform.

With five data channels operating simultaneously, the HSP provides synchronized data collection allowing for comparison across the channels as well as within a channel. Figure 6 is plots of a light curve of the SX Phoenicis star CY Aquarii. The data for this plot was taken over a complete pulsation period of 88 minutes with all five channels. This data collection was part of the testing of the HSP and some guiding errors were encountered that were not corrected in a timely manner.
Figure 6. Five channel light curve from CY Aquarii produced by the NMSU HSP on the 1-meter NMSU research telescope. I-band data is at top the light curve and is followed by R, V, B, with U-band data at the bottom.

The NMSU HSP, as has been described above, has 5 data channels but, has light path and detector space for a sixth channel, namely a J-band detector. The rest of this document describes the process that resulted in a sixth channel installed on the HSP.
2. REQUIREMENTS

In order to develop a solution for the J-band detector a set of requirements were developed. These requirements, when met by a solution, provide a J-band detector that fulfills the needs for successful astronomical observations.

The requirements were broken into three categories, which were: 1) Detector, 2) Instrumentation, and 3) Project.

The detector category consists of the actual photon-sensing device. The detector component does not include the required electronic support capabilities, like counters or temperature controller, as these requirements vary based on the actual physical device that is chosen. The instrumentation category includes all the electronic support elements and can be either new or existing equipment like power supplies or counters. Project requirements are those non-technical requirements that must be met.

It is noted that requirements can evolve, as options are analyzed and selections made. For example: the decision on power requirements might impact the support requirements. These changes will be noted in the analysis of solution options. The following paragraphs will describe the primary requirements and give a rational for them. An identification number that is related to the three requirement categories precedes each requirement and will be used to identify specific requirements as needed.
The requirements for the detector cannot always be perfectly quantified with published information. The final solution will require compromises of some of the requirements but, where possible, these requirements were met. Optimization is an expected reality.

2.1 Detector Requirements

**D.1 Avalanche Photodiode (APD)** – APD is the required detector technology primarily based on their high QE, relatively low noise, cost, speed, and their high gain. It is the high gain that allows them to detect single photon events. The current HSP uses three Silicon (Si) APD detectors as previously noted.

**D.2 Sensitivity to J-Band photons** – In other words the detector must be able to detect light in the bandpass of 1.17 to 1.33 microns, which is the defined J-band of the Mauna Kea Observatories NIR filter set. This is a mandatory requirement.

**D.3 Detector size of 70 microns diameter minimum** – This is the minimum size that the 1 inch collimated beam that enters the HSP from the telescope can be comfortably focused down to. Detector size is also directly related to the noise, see requirement D.4, the smaller the detector the lower the noise. The existing Si ADP detectors are 300 microns.
D.4 Lowest possible noise – This requirement is not quantified. The interpretation is, that if multiple solutions exist that satisfy the other requirements then, the lowest noise solution is desired.

D.4.1 Lowest possible dark current - One of two sources of noise in APD detectors (Morath et al. 2004). Dark current arises form thermal and tunneling effects within the lattice of the detector. These can lead to avalanches that are indistinguishable from photon absorption events and hence noise ratio. Cooling of the detector reduces dark current increasing the signal to noise. Also, detector size impacts the dark current as a larger detector volume has more thermal and tunneling effects. The required dark current value is not quantified but should be minimized within the final solution.

D.4.2 Lowest possible afterpulsing - Second of two sources of noise in APD detectors (Morath et al. 2004). Afterpulsing results from trapped charge carriers within the detector matrix that over time will be released causing an avalanche event (afterpulse) that are indistinguishable from photon absorption events and hence noise. The charge carriers are trapped by impurities and imperfections in the detector matrix. The probability of afterpulsing is a function of time after an avalanche event. Detector size also impacts the afterpulsing as the larger the detector is, the more potential for impurities and imperfections resulting in more traps and more afterpulsing. This value was not quantified but should be minimized within the final solution.
D.5 Integrated Thermo-Electric Cooling (TEC) – Integrated TEC is the desired option. It is possible to provide cooling from external devices or by cryogenic methods but those solutions are more complex than desired. The operating temperature affects noise levels (see D.4 above), QE, and is critical for the performance of the device.

D.6 Geiger mode operation supported – The Si APDs of the HSP operate in linear mode with a maximum gain of around 200. But, operating the J-band detector in Geiger mode results in gain in the range of $10^5$ to $10^7$, which produces a detectable current, reducing required amplification and increases the sensitivity of the device.

D.7 Maximum Quantum Efficiency (QE) – This requirement was not quantified. By their nature APD have a high QE of generally higher than 50%. This exceeds the value for other detector types operating within the J-band, like PMTs that have QE at less than 5% (Hamamatsu 2004). The interpretation of this requirement is, that if a choice of QE is offered in the final solution, the highest is most desired.

D.8 Maximum count rate – The maximum count rate is one million counts per second or higher. If a maximum count rate of one million cannot be supported, then the best possible count rate affordable is the required solution.
D.9 Installation within and on the HSP – The detector solution chosen will be installable on the current HSP without design modification of the HSP or its mounting. The HSP cannot be removed as part of this activity.

2.2 Instrument Requirements

This section of the requirements has to do with the required instrumentation to support a given detector. These devices would include power supplies, square wave generators, temperature controllers, and discriminators if required by the detector solution.

I.1 Temperature control – The ability to control the detector TEC and maintain a desired detector temperature will be provided. Since sensitivity, dark current, and afterpulsing are all temperature dependent the ability to set and maintain and operating temperature is required to provide for reproducibility of the results.

I.2 Gain control – In the Geiger mode this is controlled by the reverse bias applied during the “on” part of the APD detector cycle. This value is selected to provide optimum event detection so it must be available to manipulation.

I.3 Gating control – Gating is required in the Geiger mode to support allow for optimizing the detector cycle including dead time for the detector.

I.4 TTL output – TTL output allows integration into the existing data taking system.
1.5 Mounting on the existing platform – Instrumentation must be sized such that it can be mounted on the Nasmyth port #2 of the NMSU 1-meter research telescope at APO.

1.6 Use available power sources – No special power requirements beyond what are available currently at the 1-meter telescope, which are 110 V and 220 V.

2.3 Project Requirements

The final category of requirements concerns the actual project and its expected goals.

P.1 Deliver within budget – Initial budget constraint was $8000. This was increased to a target of less than $20,000 for the detector in September 2011.

P.2 Deliver to schedule – Initial schedule was July 1, 2011 for equipment purchases with installation at a later date. The current final delivery date is prior to end of funding on July 1, 2012.

Table 1 summarizes the requirements.
Table 1. J-Channel Solution Requirements

<table>
<thead>
<tr>
<th>Identifier</th>
<th>Requirement Title</th>
<th>Comments / Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>D.</td>
<td>Detector</td>
<td></td>
</tr>
<tr>
<td>D.1</td>
<td>Avalanche Photodiode (APD)</td>
<td>High gain, low noise, fast, high QE.</td>
</tr>
<tr>
<td>D.2</td>
<td>Sensitive in the &quot;J&quot; band (1.24 Microns +/- 0.1 Microns)</td>
<td>InGaAs formulated APD are sensitive to this wavelength. Requires Mauna Kea filter for J-band.</td>
</tr>
<tr>
<td>D.3</td>
<td>Detector Size of at least 70 Microns</td>
<td>70 Microns considered the minimum size that the input beam can be focused to.</td>
</tr>
<tr>
<td>D.4</td>
<td>Lowest Possible Noise</td>
<td>Two sources of Noise in Geiger mode APD.</td>
</tr>
<tr>
<td>D.4.1</td>
<td>Lowest Possible Dark Current</td>
<td>Not quantified but selected device should be at low noise end of competitive products.</td>
</tr>
<tr>
<td>D.4.2</td>
<td>Lowest Possible Afterpulsing</td>
<td>Not quantified but selected device should be at the lowest value possible among competitive products.</td>
</tr>
<tr>
<td>D.5</td>
<td>Integrate Thermo-Electric Cooling</td>
<td>simplify solution design and manage noise.</td>
</tr>
<tr>
<td>D.7</td>
<td>Maximum Quatum Efficiency</td>
<td>Not quantified but selected device should have highest available QE.</td>
</tr>
<tr>
<td>D.8</td>
<td>Maximum Count Rate</td>
<td>1 million per second or higher</td>
</tr>
<tr>
<td>D.9</td>
<td>Installation within and on HSP</td>
<td>Installation will not require redesign of HSP itself.</td>
</tr>
<tr>
<td>I.</td>
<td>Instrumentation</td>
<td></td>
</tr>
<tr>
<td>I.1</td>
<td>Temperature Control</td>
<td>Stable control of temperature to assure consistency of measurements.</td>
</tr>
<tr>
<td>I.2</td>
<td>Gain Control</td>
<td>Stable control of gain to assure consistency.</td>
</tr>
<tr>
<td>I.3</td>
<td>Gating Control</td>
<td>Variable gating is required in Geiger mode to define correct detection cycle.</td>
</tr>
<tr>
<td>I.4</td>
<td>TTL Output</td>
<td>Required to integrate into existing counting device.</td>
</tr>
<tr>
<td>I.5</td>
<td>Mounting on the Existing Platform</td>
<td>Size must be accommodated by the Nasmyth port #2 of the telescope.</td>
</tr>
<tr>
<td>I.6</td>
<td>Use Available Power Source</td>
<td>Should not require different power sources than are existing at telescope.</td>
</tr>
<tr>
<td>P.</td>
<td>Project</td>
<td></td>
</tr>
<tr>
<td>P.1</td>
<td>Deliver within Assigned Budget</td>
<td>Solution must not exceed available budget.</td>
</tr>
<tr>
<td>P.2</td>
<td>Deliver to Schedule</td>
<td>PI established schedule should be met.</td>
</tr>
</tbody>
</table>
2.4 Selected Requirements Analysis

In this section selected requirements are further analyzed to provide a more complete understanding of their implications.

Requirement **D.2** specifies operation of the detector in the J-band. As we have seen Silicon APDs are not sensitive at the J-band wavelengths. So an APD with a different detector material is required. Research showed that Indium Gallium Arsenide (InGaAs) devices are sensitive in the J-band. InGaAs detectors are sensitive to the J-band wavelengths because the long wavelength cutoff, the longest wavelength that the detector responds to, is 1.654 microns as determined below.

Long wavelength cutoff is the result of the band gap of the semiconductor materials that the devices are made from. The band gap is the minimum energy required to move an electron from the top valance band to the bottom of the conductance band within a semiconductor. This is analogous to the energy required to disassociate an electron from the outer valance band of an atom.

For example: Si has band gap of 1.12 eV at room temperature (Hamamatsu 2004) and InGaAs has band gap of 0.75 eV at room temperature (Itzler 2011). It should be noted that the band gap is directly related to operating temperature and dependent on detector alloy formulation.

Using the expression for the energy of a photon:
\[ E = \frac{hc}{\lambda} \]  

Where \( E \) is the energy, in this case the band gap energy in eV, \( h \) is Planck’s constant = \( 4.13567 \times 10^{-15} \) eV s, and \( c \) is the speed of light = \( 3 \times 10^{16} \) \( \mu \)m/s.

Solving equation (1) for \( \lambda \) and substituting in the band gap values result in a long wavelength cutoff of 1.11 microns for Si detectors. Photons with energy lower (longer wavelength) than this value will NOT release an electron / hole pair. Repeating the calculation for InGaAs with a band gap value of 0.75 eV the long wavelength cutoff is 1.654 microns. As previously present the J-band is between 1.17 to 1.33 microns, which is well below the long wavelength cutoff for InGaAs but above the long wavelength cutoff for Si.

InGaAs APD solution meets requirements D.1 and D.2 and will be pursued.

Requirement D.3 specifies a detector size of 70 microns but assumes that the input beam will be focused via a lens onto the detector. The 70 microns is considered to be the smallest size that the available optics could achieve reliably. A size smaller than 70 microns could be acceptable if the input beam delivery to the detector was via a mechanism that does not require development of new optics.

Requirement D.6 calls for support of Geiger mode for the final solution. There are two modes of operation for APDs. The first is “linear” mode (used by the Si APDs of the HSP) and the second is “Geiger mode”.

25
When an APD is in the “linear” mode a reverse bias is applied to the APD that is below the breakdown voltage of the detector. When a photon is absorbed an avalanche occurs with a modest gain of less than \( (\text{Morath } 2004)1000 \) \((\text{Morath } 2004)\) depending of the material of the detector. Because of the modest gain this mode requires significant additional amplification to detect a photon event introducing noise.

When an APD is in the “Geiger” mode a reverse bias is applied that exceeds the breakdown voltage of the device. When a photon is absorbed a self-sustaining avalanche occurs which results in gains in the range of \( 10^5 \) to \( 10^7 \) (Renker 2006). It is these high gains that allow detection of a single photon without additional amplification. As the avalanche occurs from the absorption of a photon it produces a detectable current via the gain.

In the Geiger mode the detector has three states: 1) on, 2) conducting, and 3) off (Morath et al. 2004). Initially, the device is moved to the “on” state by quiescently raising the reverse bias above the breakdown voltage. Applying a square wave signal of sufficient voltage to raise the reverse bias above the breakdown voltage accomplishes this. If the device in the “on” state and absorbs a photon, a self-sustaining avalanche (“conducting”) occurs in the device. The avalanche is terminated and the reverse bias lowered below the breakdown voltage returning the device to the “off” state.
In order to terminate the avalanche three external actions need to be accomplish: 1) quenching, 2) hold off, and 3) reset.

Quenching is accomplished either passively or actively. In passive quenching a load is applied across the device that is sufficiently large to cause the bias to drop below the breakdown voltage (off state). This load is usually a resistor of sufficient value to cause the avalanche to decay over a short period of time. Active quenching detects the avalanche and drops the reverse bias below the breakdown voltage (off state) for a period of time to stop the avalanche.

Hold off keeps the reverse bias below the breakdown voltage for a sufficient period of time to allow trapped carriers to be emitted and not produce another avalanche (so called afterpulse).

Reset is accomplished by returning the reverse bias to above the breakdown voltage that returns the device to the “on” state.

No photons can be detected after the avalanche is initiated until the detector is reset to the “on” state. The timing cycles limit the maximum detection rate of the device. Signals with high counts will saturate the device.

In Geiger mode, optimizing the reverse bias, temperature, and detector dead time manages the QE, dark current, and afterpulsing and is the key design consideration.
3. SOLUTION OPTIONS

Most of the project time was devoted to consideration of solution options. This is a rapidly evolving technology where new products and capabilities are being offered almost continually. This nearly continuous evolution limits the lifetime (validity) of any analysis. For this reason the analysis of the options is only presented in summary form and not detailed as it may no longer be valid. The final solution was based on data available in September of 2011.

Based on the requirements, solution options were developed and analyzed. The following paragraphs will describe the various options and provide a summary as to their acceptability to the requirements. For reasons described previously, only solutions using InGaAs APDs are considered.

3.1 Option A: Single chip solution

This option used a single integrated device that included integrated TEC and TTL output. The Goodrich Corporation had announced the availability of a single photon counting InGaAs APD operating in Geiger mode for the NIR in 2006. These devices were considered to be available based on marketing information previously reviewed by the HSP Principal Investigator (PI). Conceptually this solution would integrate the detector into the light path of the HSP by lens. Existing external power supplies would power the device. The TTL output would be passed to an existing counter. External TEC control and gating would be required.
Although this device appeared to meet the detector requirements it was determined that this device was no longer available. A survey of other InGaAs detectors produced no other products with this level of integration. For example, there were available devices that had cooling integrated but TTL output was not offered. Investigation into this option was terminated.

3.2 Option B: Total solution

This option would provide a total solution. These solutions are instruments that include the detector, support circuitry for gain and temperature control, power supplies, counters, TTL output, and are generally offered as “single photon counting” devices. These solutions use fiber optics to provide the input signal. With any of these solutions a method of coupling the HSP collimated beam to the fiber is required.

Four vendors were identified that were offering solutions that appeared to meet the requirements. The vendors were: 1) id Quantique, 2) Princeton Lightwave, 3) Aurea Technologies, and 4) Voxtel. The Voxtel product was ultimately determined to not be available. The other three vendors offered multiple potential solutions. In the case of id Quantique four options were investigated but only two were potential solutions. For Princeton Lightwave two options were investigated but only one was considered due to its availability. Aurea Technologies offered two potential solutions that were investigated but only one was available.
It became apparent that although several of the potential solutions would fit the requirements they all exceeded the budget limit by three or four times. This option was abandoned at that point.

3.3 Option C: Use an existing Si detector module solution

This option would use an existing Si detector module, like those currently used on the HST, and replace the Si APD with an InGaAs APD. The electronics in the existing detector module would be used to control temperature, gain, and output TTL. By using an existing Si module the cost of the solution would be driven by the InGaAs detector and budget compliant solutions were available.

Numerous solutions were available for the InGaAs detector with an integrated TEC. The fatal issue became that the electrical characteristics of the Si detectors were not compatible with the InGaAs detectors. The existing Si modules were tightly packaged (sealed) and in some case highly integrated electronically making modification to the electrical circuitry and the detector mounting difficult if not impossible. This solution option was judged to be too high risk to pursue further.

3.4 Option D: Build it

This is similar to options A and B. Here the detector would be purchased with the TEC incorporated. The support electronics for the detector would be a mix
of existing equipment, purchased equipment, and locally manufactured as required. An apt description of this solution would be “home brew”.

Considerable effort was put into this solution. An acceptable detector was identified from Perkin Elmer. This detector used passive quenching integrated into the chip, which allowed reduction of the circuit complexity. The vendor also offered a prototype board which when properly powered would support the detector.

The conceptual design for this solution consisted of the detector (purchase), prototype board (purchase), and power supply (purchase), TEC controller (purchase), and a discriminator with TTL output (build/purchase).

Sources for all the conceptual components were identified except the discriminator. Options for the discriminator design/build were considered but never finalized. The cost of this approach was consistent with the available budget but there was considerable risk in meeting the budget constraint since the discriminator solution was not yet identified.

In addition to the cost risk, a second issue was identified with the detector. During technical conversation with the vendor it was discovered that the quenching time was of the order of 25 microseconds to lower the probability of afterpulsing to below 1% percent. With the Si modules on the HSP 32 nanoseconds are required for dead time to lower the after pulse probability to 0.5%. The longer time for quenching reduced the maximum count rate to below the desired one million counts per second. This terminated the investigation for this particular detector.
A search for another detector solution was terminated when additional funding allowed consideration of other options. See “Final Solution Selection” discussion, below.

3.5 Option E: Other solutions

Because of the risks of finding an InGaAs solution and the desire to show that the HSP could be used to gather NIR information in the J-band other solutions were investigated.

Among the solution considered where PMT with QE of 1 to 2%, amateur grade photometer that used an InGaAs detector, infrared cameras with InGaAs arrays instead of single detectors, and liquid nitrogen cooled devices. These solutions were considered against the requirements and no fully compliant solution was identified. These investigations were halted when additional funding became available and a final solution selected.

3.6 Final Solution Selection

When additional funding became available the viable options were those that met the requirements but did not meet the budget constraints. This resulted in renewed focus on Option B. Table 2 shows the comparison of the final 4 considered solutions for option B.
The analysis shows that all four sub-options do not meet all the requirements. Sub-option B-2 does not cover the frequency range. A request was made to the manufacturer to determine their potential interest in providing a customized solution and no response was received. Sub-option B-3 met the basic requirements but exceeded the cost limits. Sub-option B-4 was not available to support the schedule and it did not have a low noise model. None of the sub-options met the budget constraint. All of the sub-options require integration to the HSP beam via a fiber optics cable (see integration section for discussion).

At this point it was determined that sub-option B-1 would meet the requirements if the budget concern could be addressed. Price negotiations were carried out and the best available price was achieved for the id Quantique model id201. The delivered model consisted of the latest software revision and the low noise detector that provided improved performance over the other two competitors within the budgeted cost.
<table>
<thead>
<tr>
<th>Option :</th>
<th>B-1</th>
<th>B-2</th>
<th>B-3</th>
<th>B-4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Product:</td>
<td>id201 - id Quantique</td>
<td>id400 - id Quantique</td>
<td>PGA-600</td>
<td>SPD_A series</td>
</tr>
<tr>
<td>Source:</td>
<td>Boston Electronics</td>
<td>Boston Electronics</td>
<td>Princeton Lightwave</td>
<td>Aueria Technology</td>
</tr>
<tr>
<td>Origin:</td>
<td>Switzerland</td>
<td>Switzerland</td>
<td>U.S.A.</td>
<td>France</td>
</tr>
</tbody>
</table>

**Requirements:**

<table>
<thead>
<tr>
<th>D. Detector</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>D.1 APD</td>
<td>YES (InGaAs)</td>
</tr>
<tr>
<td>D.2 J-band support</td>
<td>YES - 0.9 to 1.7 Microns</td>
</tr>
<tr>
<td>D.3 Min size</td>
<td>NO - SMF and MMF input</td>
</tr>
<tr>
<td>D.4 Low Noise</td>
<td>Low Noise model available</td>
</tr>
<tr>
<td>D.4.1 Lowest Dark Current</td>
<td>Standard Detector Single Mode Fiber - &lt;1 x 10^-4 /ns of gate at SPDE = 10% and &lt;4.0 x 10^-4 /ns of gate at SPDE = 25% *</td>
</tr>
<tr>
<td>D.4.2 Lowest Afterpulsing</td>
<td>&lt;1% at trigger Frequency of 100 kHz</td>
</tr>
<tr>
<td>D.5 TEC Cooling</td>
<td>YES</td>
</tr>
<tr>
<td>D.6 Geiger</td>
<td>YES</td>
</tr>
<tr>
<td>D.7 QE</td>
<td>10 to 25%</td>
</tr>
<tr>
<td>D.8 Max Count Rate</td>
<td>NO</td>
</tr>
<tr>
<td>D.9 Installation</td>
<td>YES</td>
</tr>
</tbody>
</table>

**I. Instrumentation**

| I.1 Temp. Control | YES |
| I.2 Gain Control | YES |
| I.3 Gating Control | YES |
| I.4 TTL Output | YES |
| I.5 Mounting | YES |
| I.6 Use Available PWR | YES |

**A. Administrative**

| A.1 Meet Budget | NO - $20,397 ** |
| A.2 Meet Schedule | YES |

**Comments:**

* Lowest cost Model ** based on Feb 2011 quote Price exceeds id201. Low Noise unit to be announce in the future Lower noise device expected in near future

** Notes: **

Price exceeds id201. Lower noise device expected in near future

* Lowest cost Model ** based on Feb 2011 quote
3.7 Final Solution Description

Figure 7 shows the id 201, which was purchased as the solution to the J-channel for the HSP. This device is based on an InGaAs APD that meets requirements D.1 and D.2.

![Figure 7](image)

**Figure 7.** Shown is the front panel of the final J-channel solution, a single-photon detector module purchased from id Quantique. Note: this instrument is labeled as an id 200 model but is an id 201 model via upgrade to the software at the time of purchase.

The id201 does not meet requirement D.3 as the detector size is approximately 50 microns. But the input to the detector is via multi mode fiber optics (MMF) so this becomes an integration issue and is addressed in the following
integration Chapter. The smaller detector size does help address requirement D.4 as the smaller size has less dark current and afterpulsing. Additionally, the purchased device is the low noise model providing the best optimization for noise offered by the vendor for this device. Again addressing requirement D.4.

The detector design optimizes the operation of the detector in the Geiger mode by automatically adjusting the temperature and reverse bias based on the select single photon detection probability, gate width, and dead time. This eliminates the need for direct temperature and reverse bias control in the Geiger mode. This satisfies requirements D.5, D.6, D.7, I.1, I.2, and I.3.

The maximum count rate (requirement D.8) is not fully supported. None of the affordable options fully supported this requirement. The id201 is capable of count rates of over one million per second but this would not allow for any dead time to reduce the probability of afterpulsing. At a count rate of 100 kHz (1 microsecond dead time) the probability for afterpulsing is reduced to around 1%. Higher count rates are possible but with increasing probability of afterpulsing with increased dark counts (noise). The desire would be a low probability of afterpulsing at 1 MHz count rate. Table 3 shows the manufacture’s specification for the selected device and provides more information on the selected device.

The instrument has TTL output available on the front panel that satisfies requirement I.4.
The instrument power requirements and size are both accommodated within the existing Nasmyth port #2 of the NMSU 1-meter telescope satisfying requirements D.9, I.5, and I.6.

The instrument was purchased below the budget and installation met the end of project date satisfying requirements A.1 and A.2.

Table 3 shows the manufacture’s specifications for the id 201.
Table 3. Id201 Manufacture Specifications

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Min</th>
<th>Typical</th>
<th>Max</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wavelength Range</td>
<td>900</td>
<td></td>
<td>1700</td>
<td>nm</td>
</tr>
<tr>
<td>Fiber Optic Type</td>
<td>MMF</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Single Photon Detection Probability (SPDE)</td>
<td>10, 15, 20, 25, user-defined</td>
<td></td>
<td>%</td>
<td></td>
</tr>
<tr>
<td>Max. External Trigger Freq.</td>
<td>8</td>
<td></td>
<td></td>
<td>MHz</td>
</tr>
<tr>
<td>Max. Trigger Freq. (afterpulse probability &lt;1%)</td>
<td>100</td>
<td></td>
<td></td>
<td>kHz</td>
</tr>
<tr>
<td>Gate Duration</td>
<td>2.5, 5, 20, 50, 100, user defined</td>
<td></td>
<td>ns</td>
<td></td>
</tr>
<tr>
<td>Adjust. Delay Range</td>
<td>25</td>
<td></td>
<td></td>
<td>ns</td>
</tr>
<tr>
<td>Adjust. Delay Step</td>
<td>0.1</td>
<td></td>
<td></td>
<td>ns</td>
</tr>
<tr>
<td>Adjust. Deadtime</td>
<td>0, 1, 2, 5, 10, 20, 40, 60, 80, 100</td>
<td></td>
<td>ms</td>
<td></td>
</tr>
<tr>
<td>Internal Trig. Gen.</td>
<td>1,10,100,1000</td>
<td></td>
<td>kHz</td>
<td></td>
</tr>
<tr>
<td>Trig. &amp; aux counter inputs</td>
<td>NIM, TTL, Var</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Clock &amp; Gates Output</td>
<td>NIM</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Detection Output</td>
<td>NIM (10 ns wide)</td>
<td>TTL (100 ns wide)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Oper. Temp.</td>
<td>10</td>
<td></td>
<td>30</td>
<td>°C</td>
</tr>
<tr>
<td>Cooling Time</td>
<td>5</td>
<td></td>
<td></td>
<td>minutes</td>
</tr>
<tr>
<td>Noise – SPDE = 10%</td>
<td>1.5x10^4</td>
<td></td>
<td>counts / ns of gate</td>
<td></td>
</tr>
<tr>
<td>Noise – SPDE = 25%</td>
<td>1.2x10^5</td>
<td></td>
<td>counts / ns of gate</td>
<td></td>
</tr>
</tbody>
</table>
4. INTEGRATION OF SOLUTION

The selected solution did not pose a problem for integration into the electrical or physical environment of the Nasymth port platform. The required 110 volts was readily available. The space to mount the instrument was available. The instrument outputs were compliant to the TTL required of the existing instrumentation. But, as previously noted, the input signal to the detector was via a MMF cable. The integration issue becomes getting the 25.4 mm collimated free space beam into the 50 micron MMF.

Several options were investigated to accomplish the free space beam to MMF integration. The selected solution was an optical system that takes a free space collimated beam and focuses it into MMF. The supplier of the optics was Schäfter + Kirchhoff of Hamburg, Germany. The device part number was 60FC-L-0-M60L-37 which is a fiber collimator, focusable, focal length of 60 mm, 34.5 mm diameter, 24 mm clear aperture, FC-PC connector, numerical aperture of 0.2, with an AR 750 to 1550 nm optical coating. Figure 8 shows the optics adapter and retaining ring.

The selected system had a limit of 24 mm clear aperture so that some signal is lost from the 25.4 mm free space beam. There is the possibility of removing or modifying a retaining ring to increase the clear aperture to 25 mm.
Figure 8. Optics Adapter for Integration of HSP collimated Free Space Beam to MMF cable.

The numerical aperture is the arcsine of the critical angle or the maximum angle (off axis) light can enter a fiber and be reflected down the fiber, and not out the side. By having a smaller numerical aperture on the optics than the fiber, the angle of light entering the fiber from the optics should be smaller than the fiber’s critical angle and therefore be transmitted down the fiber. The numerical aperture of the MMF was 0.22. The numerical aperture of the optical system was 0.20. Operationally the optical device is aligned with the collimated free space beam of the HSP and delivers the light to the MMF cable that is the input to the id201 instrument.

4.1 Engineering

The primary considerations / constraints for the engineering of the installation are: 1) remove the interference to the J-channel installation caused by the
existing I-channel installation, 2) provide a mounting for the J-channel optical integration solution, 3) the design must use the existing holes, cutouts and attach points of the HSP (no machining / drilling allowed), 4) installation will not require removal of the HSP from the telescope, 5) the stages for both the J and I channel must move freely a minimum of ± 4 mm, and 6) light tightness and non-reflective interior of the box will be preserved.

Installation of new, smaller, XY stages at the I-channel port and arranging them so that their adjustment screws did not protrude into the J-channel space addressed the interference from the I-channel. New mounting brackets were required and designed to fit the new stages of the I-channel. The new mount includes a light shield to keep external light out of the HSP, which was black anodized to prevent internal reflections. The light shield is designed to allow free movement of the detector. The mount holds the I-channel detector in the beam and allows a minimum of ± 4 mm travel for centering the detector on the beam with the XY stages for alignment. Only existing holes in the HSP are used to attach the new mount. Figure 9 is an exploded view of the final I-band mount and detector.
The mounting for the J-channel optical integration solution required design of a new mounting bracket that attaches to the XY stages. The bracket was designed to keep the optical integration solution orthogonal to the beam. A light shield is
included and has identical function as the light shield of the I-channel. Again, only existing holes are used to attach the mount. The design allows for a minimum of $\pm 4$ mm travel of the XY stages for centering the optics on the beam. The final design is shown in Figure 10. Identical stages were used for all mounts at the I and J channels. Figure 11 shows the aft end of the HSP where I and J assemblies are mounted with the I-band detector and the J-band optics.

**Figure 10.** Exploded view of J-channel mounting.
4.2 Manufacturing

Manufacturability changes were incorporated into the design to improve stability of the mounting. The I-channel bracket material was changed from two flat plates to a single “L” extrusion. This change improved stability and assure that the mounting surfaces are orthogonal between the two webs of the bracket. Minor adjustments to the light shields mounting was incorporated to assure free movement as the stages are moved. The light shields were also black anodized to avoid internal light reflection.
5. INSTALLATION, TESTING, AND RESULTS

The following paragraphs describe the installation on the HSP, integration testing, and results for the J-channel.

5.1 Installation

The completed J-channel assembly was mounted onto the HSP and is shown in figure 12 below. Prior to mounting the J-channel the existing I-channel was removed to eliminate the interference with the J-channel.

Figure 12. J-channel mounted on HSP with the optics adapter and X&Y stages. Note that the I-channel has been removed for eventual replacement.
Figure 13. id201 position on top of the GPS clock of the HSP for integration testing to the data collection system of the HSP.

Figure 13 shows the id201 on top of the HSP with the TTL cable that integrates it to the data collection system of the HSP. The J-channel assembly on the HSP is also visible along with the R-channel.

No difficulties were encountered during the installation. All fasteners from the assembly matched the existing HSP mounting holes, all cables were of sufficient length to attach the instruments, and proper power was available.

One issue with the data collection software was encountered as no J-channel had been anticipated in the software and the I-channel was substituted for testing.
Figure 14. View showing 1-meter telescope mirror, Nasmyth port #2 with the HSP attached and id201. The Nasmyth port #2 instrumentation platform with the HSP data collection and control instrumentation is also visible.

Figure 14 provides a view of the NMSU 1-meter telescope, Nasmyth port #2, Nasmyth port #2 instrumentation platform, HSP, HSP data collection system, and id201 showing their relative positions

5.2 Testing

The objective of the testing is to demonstrate that the id201 instrument has been successfully integrated into the HSP and does detect J-band light.
In order to demonstrate that the objective was accomplished the following test plan was developed:

**Baseline test:** Power on id201 and allow detector to cool. Set up the instrument to reproduce the dark count given by the manufacturer as part of the calibration of the instrument. The ranges will be the extremes of Single Photon Detection Probabilities (10 and 25%), gate width (2.5 and 100 ns), dead time (none and 10 µs), at 10 and 100 kHz trigger frequency. With no external connections to the instrument but power, start counting and stop at 10 minutes. The counter displayed dark count will be recorded and compared to the calibration data.

The expected results are that there will be some counts recorded that were the result of dark counts. This should demonstrate that the instrument itself is working. The test dark count per ns of gate is calculated by dividing the counts per 10 minutes by the product of trigger frequency, gate width, and 600 (10 minutes in seconds). By comparing the results to the calibration values it should show that the instrument is working correctly.

Test 1 thru 8 of table 4 show the results of the baseline test compared to the manufactures calibration data for this particular device.

**Extended Baseline test:** The extend test is a repeat of the baseline test except the frequency of the trigger is raised to 1 MHz. Again measurements are taken at 10 and 25% Single Photon Detection Probabilities with 2.5 and 100 ns gates and dead time of 10 µs.
The expected results are that there will be more dark count at this higher frequency. Test 9 thru 12 of table 4 are the result of the extended baseline test.

**Counter integration test:** Connect the existing data collection system of the HSP to the TTL output of the id 201. Set up the counter consistent with test 12. Run a brief test and record the results. Repeat the test process for consistency. The expected results are that the id201 counter values are same as the HSP counter values. Results are reported in the next section.

### 5.3 Results

During the testing it was determined that external NIR photons were entering the test device through the plug on the MMF cable connection on the front panel of the device. A cap of aluminum foil was placed over the optical input connector to help eliminate the external photons. In addition, the tests were run with the lights off and the tester to one side of the device.

Tests 1 through 8 are described in Table 4. The final column on the right gives the deviation from the factory calibration and the test results. Two items contribute to this deviation. The first is that the manufacturer supplied calibration data is a “dark count probability”. It would require statistically significant number of test runs to determine if the values are consistent. There was not sufficient time to under take such a test. The second is that the manufacturer uses a full width half max value for the gate timing signal in determining dark count probability per ns of
gate. Table 4 calculates the dark count probability by using the nominal gate width. This difference in calculation methods would have to be addressed to achieve statistically similar results.

What this test did demonstrate is that the id201 is functioning and that the dark count levels are at the same order of magnitude as the factory calibration probabilities.

The discovery that the ambient lighting was not fully blocked by the opaque cap over the optics connector further indicated the sensitivity of the instrument. For reference, the difference with just the cap on and lights on was about 3 times higher than the count with the cap and aluminum shield in place with the lights off.

Tests 9 through 12 were run to establish a baseline for a trigger frequency of 1 MHz. As shown in table 4 the dark counts at 1 MHz are significantly higher than the lower frequency test at the same detection probability and gate width. This is expected and is the result of increased after pulsing at the higher frequency.

Integration into the HSP data collection system was demonstrated by starting the id201 counting and the HSP data collection system counting over a 10 second period. This was repeated several times and the counts were the same.
### Table 4. Id201 Testing Result

<table>
<thead>
<tr>
<th>Test #</th>
<th>Trigger Frequency (kHz)</th>
<th>Gate Width (ns)</th>
<th>Detection Probability (%)</th>
<th>Dead Time (μs)</th>
<th>Counts per Test (10 minutes)</th>
<th>Calculated Dark Count (ns⁻¹ gate time)</th>
<th>Manufacturer Dark Count probability (ns⁻¹ gate time)</th>
<th>Difference Manufacturer to Calculated (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>10</td>
<td>2.5</td>
<td>none</td>
<td>10</td>
<td>121</td>
<td>8.07E-06</td>
<td>9.20E-06</td>
<td>12.32%</td>
</tr>
<tr>
<td>2</td>
<td>10</td>
<td>100.0</td>
<td>none</td>
<td>10</td>
<td>26,361</td>
<td>4.39E-05</td>
<td>4.50E-05</td>
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6. CONCLUSIONS

As stated in the introduction, the objective of this project was to attain a working sixth data channel for the NMSU HSP that collected data in the J-band. As the results of the testing show this objective has been achieved.

To reach the objective of this project, photometry in general and high-speed photometry were described to provide context. Included in the descriptions where the current detector technologies of CCDs and PMTs as well as the emerging avalanche photodiode technology. The existing NMSU HSP was described in detail including the potential for inclusion of a sixth data channel for the NIR J-band.

Next the requirements for the sixth data channel solution were presented. These requirements were developed to assure that the chosen solution would meet the needs of the HSP and expected data collection activities. The requirements were grouped into three categories of detector, instrument, and project. Analyses of selected requirements were presented to provide detail and context.

Based on the requirements, solution options and sub options were developed and analyzed. The ranges of options were from single chip solutions to complete instruments to “home brew” solutions. None of the options fully met the requirements. They all failed the budget requirement.

Budgeting was increased and the options revisited with the result that the most viable solution was the complete instrument option. From the four sub-options one solution was selected that met the new budgetary limitations. The selected
solution was the id201 Single-Photon Detector Module from manufacturer id Quantique of Switzerland. This solution was purchased.

The id201 required integration into the HSP light path via MMF cable. The solution chosen for this integration was an optics adapter that took a 25.4 mm collimated free space beam from the HSP as source and focused it into the MMF. This device was purchased from Schäfter + Kirchhoff of Hamburg, Germany.

After selection of the solution components was complete, engineering of the required mountings to the HSP was conducted and a design finalized that met the requirements for this project.

Manufacturing of the mounting solutions was completed and the components were assembled with no problems.

The HSP mounting assemblies were installed on the HSP with no difficulties encountered.

Testing was performed on the instrumentation and its integration into the HSP, which was successful. This testing completed this project and the objective of a functioning J-band data collection channel for the NMSU HSP has been realized.
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