# Radiometric Calibration of MVIC

Jessica R. Lovering
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## ABSTRACT

Using the MVIC filter functions, Beam Splitter reflectance, Aluminum mirror reflectance, and the product of quantum efficiency and filter function (product QE), I calculate the final transmission ($\chi$) for each CCD array. $\chi$ is the product of quantum efficiency, filter function, beam splitter reflectance, and the AL mirror reflectance cubed. To calculate the full response, I multiply the final transmission by a spectrum, both from observations of various solar system bodies and a calculated black body.

## 1. Calculating the Quantum Efficiency

### 1.1. Comparing Measured and Calculated Filter Functions

There are two sets of filter functions for each filter, measured and calculated. The calculated transmission data covers the full wavelength scale (350-1100 nm), and the measured transmission data only covers the wavelength range where the filter has a non-zero transmission percentage. Figure 1 compares the two data sets to confirm that they match. Both sets of filter functions are in 1 nm steps.

### 1.2. Calculating the Quantum Efficiency

The product QE is measured on a grossly sampled wavelength scale, 400-1100 nm in 50 nm increments. The filter transmission, beam splitter transmission, and mirror reflectance are measured on a larger wavelength scale in 1 nm increments. To calculate the true Quantum Efficiency we must first down sample the filter functions to the product QE wavelength scale, then divide the product QE by the filter function to get the QE. To downsample the filter functions, I take the average of 50 points centered on the product QE wavelength scale. The results are shown in Figure 2.

The product QE and the downsampled filter function for each filter are provided in Table 1. Where both values are non-zero, I divide the product QE by the filter function. I then interpolate this true QE for each filter to the whole wavelength range. To calculate the endpoints for the color arrays, I fit a polynomial to the Pan1 and Pan2 QE's and use their x-intercept for all other filters. The final QE function is presented in Figure 3

| $\lambda$ *(nm)* | NIR FT | NIR QE | Methane FT | Methane QE | Red FT | Red QE |
|---|---|---|---|---|---|---|
| 400 | 0.0 | 0.00 | 0.0 | 0.00 | **89.0** | **0.0152** |
| 450 | 0.0 | 0.0001 | 0.0 | 0.00 | **96.0** | **0.0518** |
| 500 | 0.0 | 0.0001 | 0.0 | 0.00 | **98.0** | **0.129** |
| 550 | 0.0 | 0.0001 | 0.0 | 0.00 | **42.0** | **0.0296** |
| 600 | 0.0 | 0.0004 | 0.0 | 0.00 | 0.0021 | 0.0007 |
| 650 | 0.0 | 0.001 | 0.0 | 0.0004 | 0.0 | 0.001 |
| 700 | 0.0 | 0.0009 | 0.0 | 0.0003 | 0.0 | 0.0 |
| 750 | 0.098 | 0.0976 | 0.0 | 0.0009 | 0.0 | 0.0 |
| 800 | **84.0** | **0.189** | 0.0055 | 0.00150 | 0.0 | 0.0 |
| 850 | **98.0** | **0.148** | **28.0** | **0.0194** | 0.0 | 0.0 |
| 900 | **98.0** | **0.105** | **66.0** | **0.0849** | 0.0 | 0.0 |
| 950 | **98.0** | **0.0656** | 0.014 | 0.00 | 0.0 | 0.0 |
| 1000 | **83.0** | **0.0223** | 0.0 | 0.00 | 0.0 | 0.0 |
| 1050 | 90.0 | 0.00 | 0.0 | 0.00 | 0.0 | 0.0 |
| $\lambda$ *(nm)* | Blue FT | Blue QE | Pan FT | Pan1 QE | Pan FT | Pan2 QE |
| 400 | 0.0 | 0.0005 | **96.0** | **0.0165** | **96.0** | **0.0163** |
| 450 | 0.0 | 0.0003 | **97.0** | **0.0519** | **97.0** | **0.0516** |
| 500 | 0.0 | 0.0006 | **96.0** | **0.0937** | **96.0** | **0.0926** |
| 550 | **63.0** | **0.138** | **97.0** | **0.141** | **97.0** | **0.140** |
| 600 | **97.0** | **0.17** | **98.0** | **0.173** | **98.0** | **0.172** |
| 650 | **96.0** | **0.199** | **97.0** | **0.202** | **97.0** | **0.199** |
| 700 | **40.0** | **0.0787** | **99.0** | **0.227** | **99.0** | **0.225** |
| 750 | 0.0 | 0.0364 | **98.0** | **0.202** | **98.0** | **0.201** |
| 800 | 0.0 | 0.0005 | **96.0** | **0.184** | **96.0** | **0.183** |
| 850 | 0.0 | 0.00250 | **98.0** | **0.145** | **98.0** | **0.143** |
| 900 | 0.0 | 0.0 | **99.0** | **0.103** | **99.0** | **0.103** |
| 950 | 0.0 | 0.0 | **94.0** | **0.0641** | **94.0** | **0.0641** |
| 1000 | 0.0 | 0.0 | **84.0** | **0.023** | **84.0** | **0.023** |
| 1050 | 0.0 | 0.0 | 71.0 | 0.0 | 71.0 | 0.0 |

Table 1: The downsampled filter function and the product QE for each filter. We can only calculate the QE where both the product QE and the filter function are non-zero (in bold).

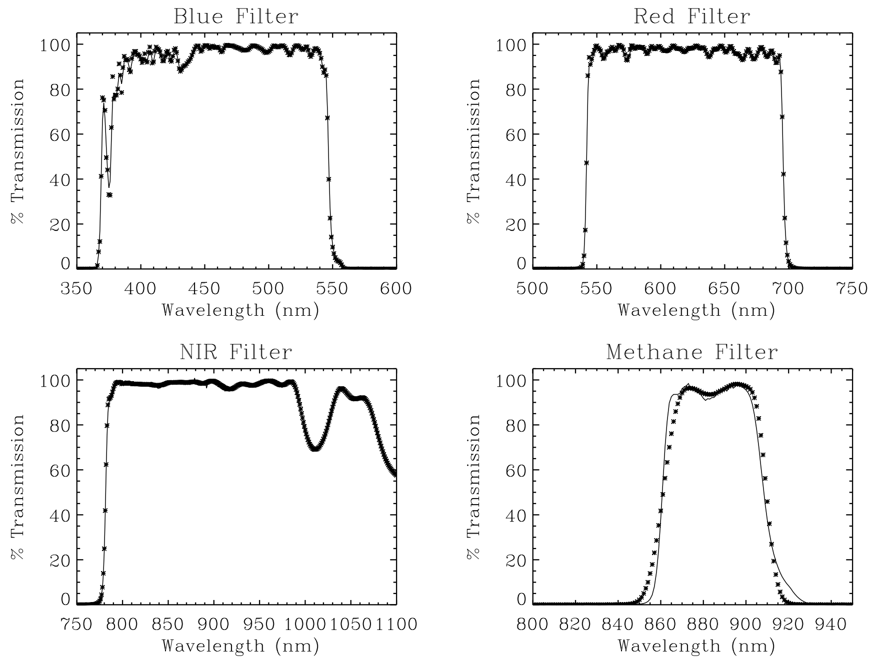


Fig. 1.— Filter Transmission

## 2. Calculating $\chi$

### 2.1. Pan Frame Transmission and Beam Splitter Reflectance

Both the Pan Frame filter function and the Beam Splitter reflectance were measured in 1 nm steps over the full wavelength scale. The Pan Frame transmission data measures the percentage of light that transmits through the clear filter over the two pan frame CCD's. Both functions are shown in Figure 4.

### 2.2. AL Mirror Reflectance

The reflection of the mirror is measured on the product QE wavelength scale. I interpolated the points to the full wavelength scale (400-1100 nm in 1nm steps). The reflectance is cubed since there are three mirrors.

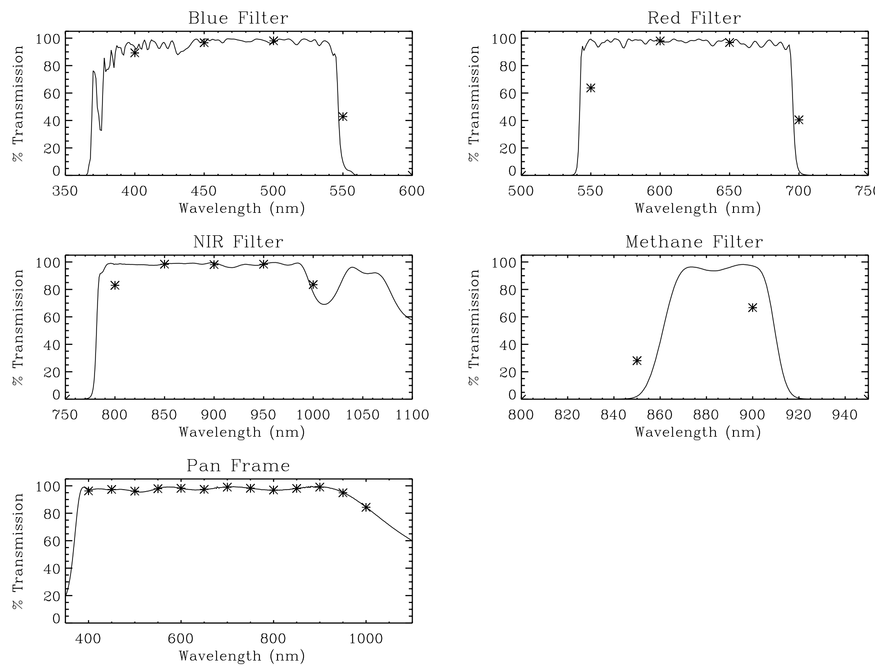


Fig. 2.— The filter transmission data downsampled to the QE wavelength scale is given by asterisks. The original, full scale, filter function is represented by a solid line for comparison.

### 2.3. Putting It All Together

Now that I have every transmission function on the same scale, I can calculate $\chi$ using Equation 1.

$$\chi = QE(\lambda_{fine}) * f(\lambda_{fine}) * BS(\lambda_{fine}) * AL^3(\lambda_{fine}) \tag{1}$$

Every step of the $\chi$ calculation is shown in Figure 5, and the final $\chi$ for each filter is shown in Figure 6. F1 and F2 are the transmissions of Pan1 and Pan2 without the clear filter on top, calculated using a grossly sampled product QE. The $\chi$ calculated from grossly sampled arrays is overplotted with asterisks.

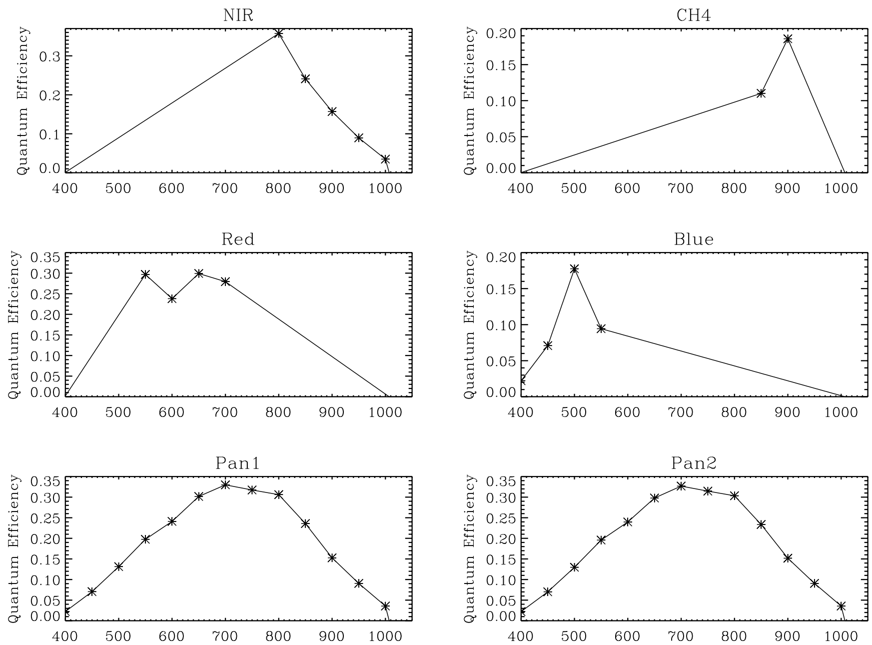


Fig. 3.— Quantum Efficiency of each filter

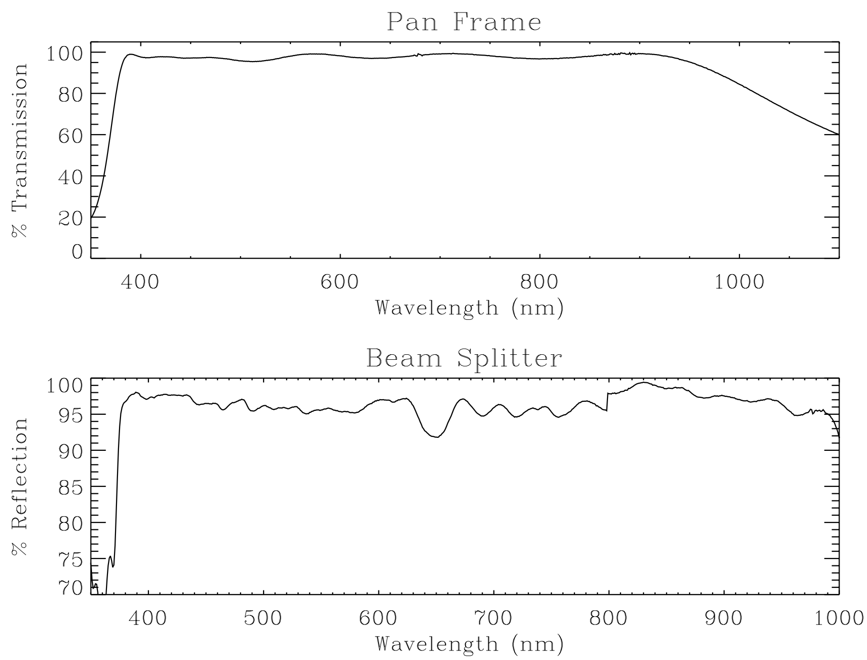


Fig. 4.— The Pan frame transmission, and the Beam Splitter Reflection

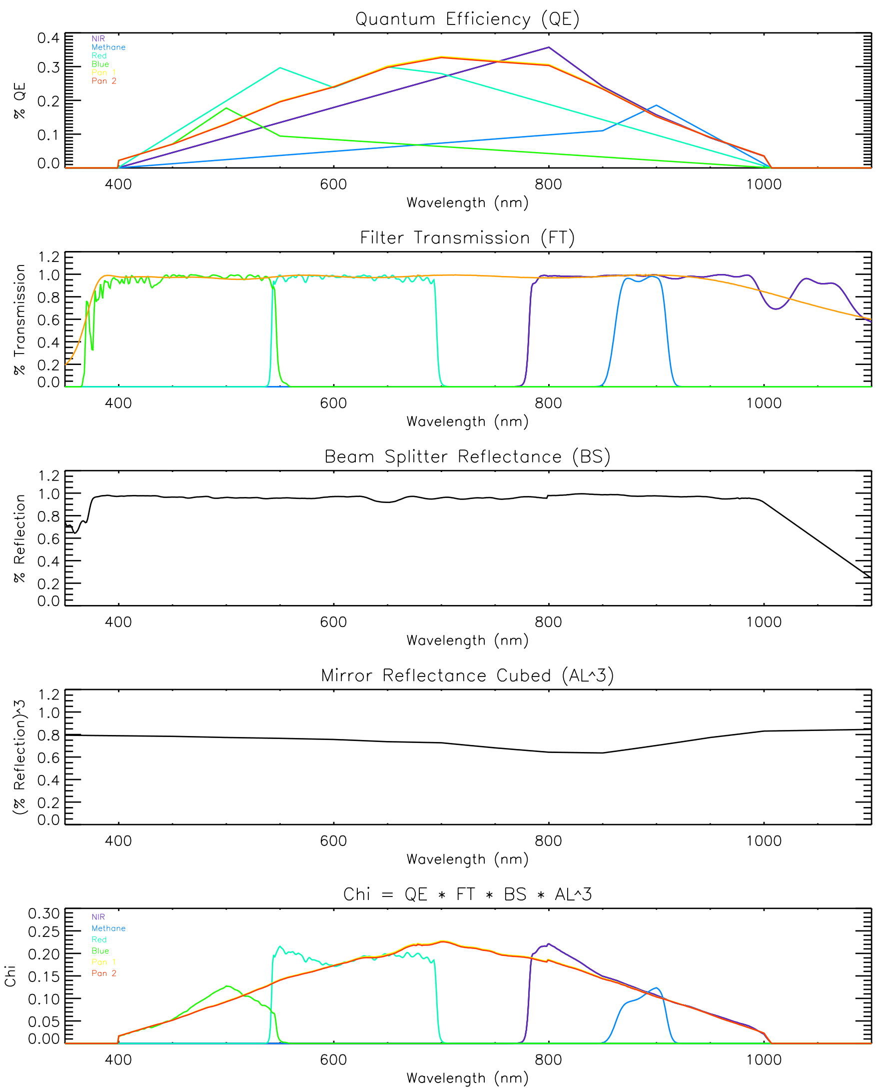


Fig. 5.— The arrays that are multiplied to get $\chi$.

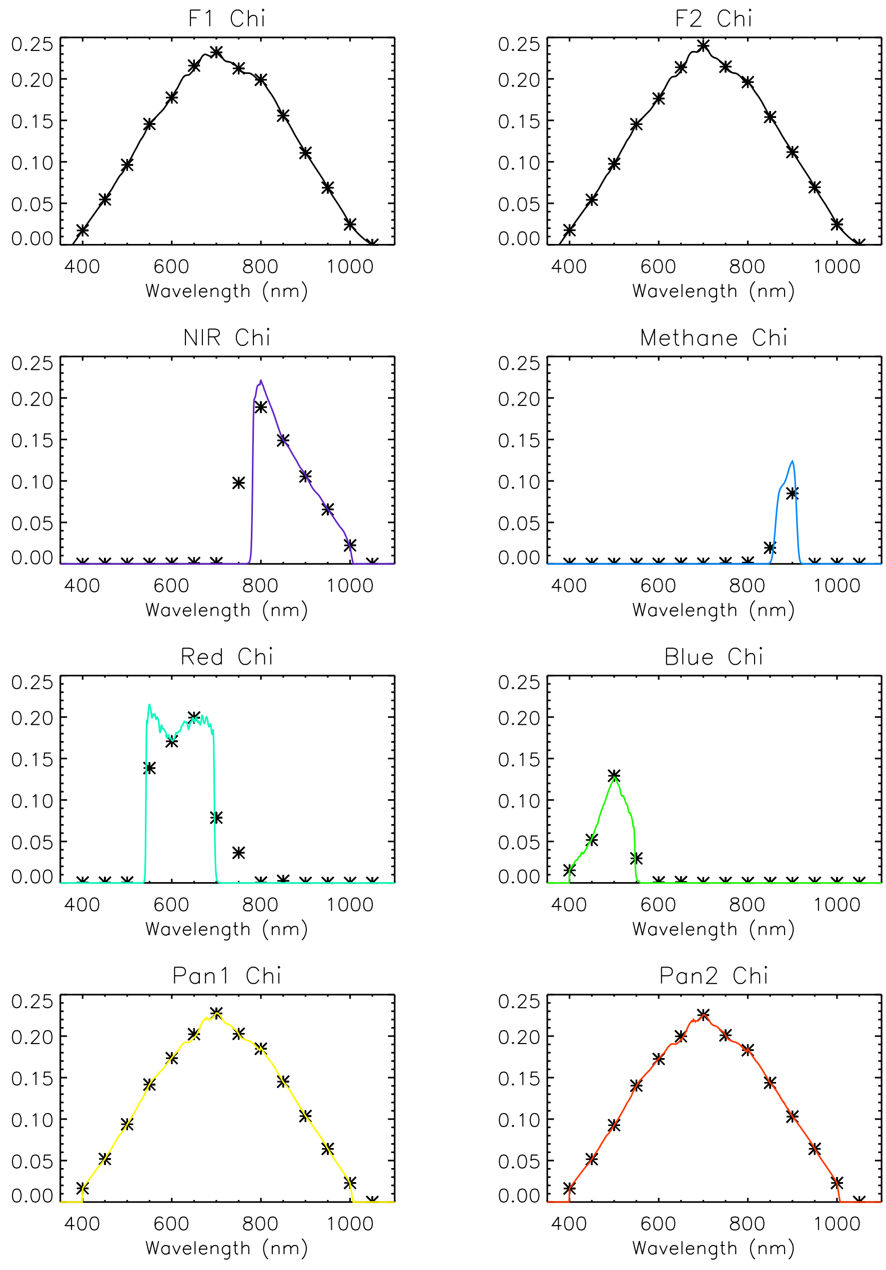


Fig. 6.— $\chi$ for each filter. The lines represent the finely sampled arrays, and the asterisks are grossly sampled arrays.

## 3. Ball Aerospace Response Ratio

Dennis Reuter employs the measured QE from Ball Aerospace to calculate a ratio with his calculated $\chi$. I will calculate the same ratio between the finely sampled $\chi$ for each array with the associated value from Ball Aerospace. The values measured by Ball are provided in Table 2. To calculate the ratio, I sum the finely sampled $\chi$ for each filter over the significant wavelength range (where $\chi > 0$), then I divide this sum by the value given in Table 2. I will refer to this value as the QE ratio.

## 4. Including the Source Spectrum

### 4.1. Black Body Spectrum

Using the planck function, Equation 2, I calculate the black body flux over our wavelength range for 5900 degrees Kelvin. I then multiply the black body flux by $\chi$ to get the full response, which I sum and multiply by the QE ratio to calulate the final values given in Table 3.

| Measurement | NIR | CH4 | Red | Blue | Pan1 |
|---|---|---|---|---|---|
| QE ($\frac{e^-}{\gamma}$) | 0.1540 | 0.2000 | 0.1880 | 0.1250 | 0.1630 |
| QE ($\frac{e^-}{\gamma cm^2 sr}$) | $2.76x10^{-09}$ | $3.59x10^{-09}$ | $3.37x10^{-09}$ | $2.24x10^{-09}$ | $2.93x10^{-09}$ |
| QE ($\frac{DN}{\gamma cm^2 sr}$) | $4.72x10^{-11}$ | $6.13x10^{-11}$ | $5.76x10^{-11}$ | $3.83x10^{-11}$ | $4.99x10^{-11}$ |
| Point Source QE ($\frac{e^-}{\gamma cm^2}$) | 6.8035 | 8.8357 | 8.3056 | 5.5223 | 7.2011 |

Table 2: Measured QE values from Ball Aerospace.

$$I(\lambda, T) = \frac{2hc^2}{\lambda^5} \frac{1}{e^{\frac{hc}{\lambda kT}} - 1} \tag{2}$$

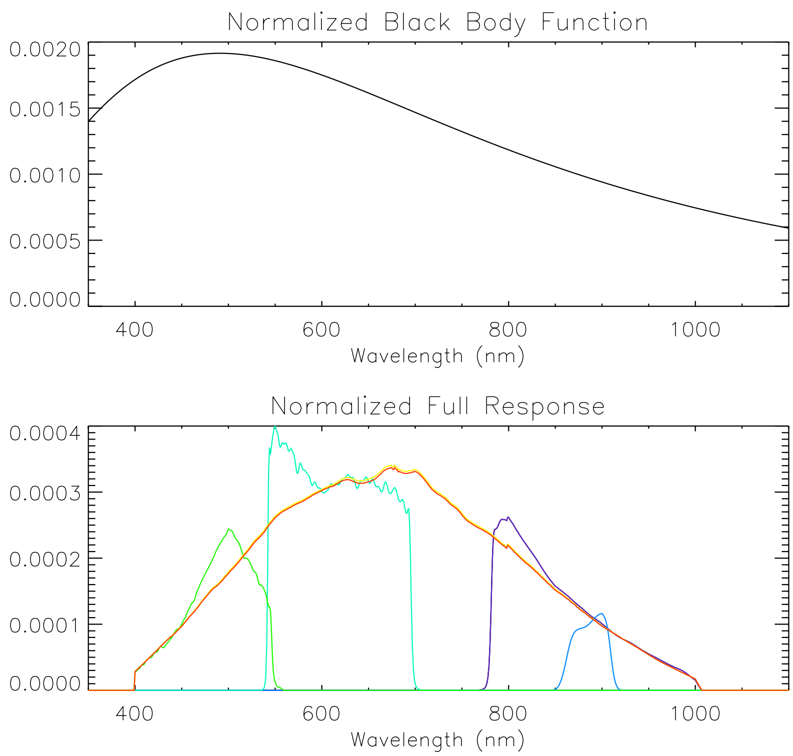


Fig. 7.— The black body function for 5900 K and the full response of the CCD's including the black body function.

### 4.2. Including Spectra of Solar System Bodies

Following the method employed for the black body function, I calculate the final response using observed spectra from Pluto, Charon, the Sun, Pholus, and Jupiter. The spectra used for this calculation I acquired from *****. The summed and scaled values are provided in Tables 4 - 8.

| Measurement | NIR | CH4 | Red | Blue | Pan1 | Pan2 |
|---|---|---|---|---|---|---|
| QE ($\frac{e^-}{\gamma}$) | 0.149 | 0.195 | 0.196 | 0.095 | 0.156 | 0.156 |
| *Dennis* | *0.155* | *0.195* | *0.188* | *0.097* | *0.158* | *0.158* |
| QE ($\frac{e^-}{\gamma cm^2 sr}$) ($10^{-9}$) | 2.66 | 3.49 | 3.51 | 1.70 | 2.81 | 2.81 |
| *Dennis* ($10^{-9}$) | *2.79* | *3.50* | *3.37* | *1.74* | *2.84* | *2.84* |
| QE ($\frac{DN}{\gamma cm^2 sr}$) ($10^{-11}$) | 4.54 | 5.96 | 5.99 | 2.91 | 4.80 | 4.80 |
| *Dennis* ($10^{-11}$) | *4.76* | *5.97* | *5.76* | *2.98* | *4.84* | *4.84* |
| Point Source QE ($\frac{e^-}{\gamma cm^2}$) | 6.56 | 8.59 | 8.65 | 4.20 | 6.91 | 6.91 |
| *Dennis* | *6.86* | *8.61* | *8.31* | *4.30* | *6.98* | *6.98* |

Table 3: Final response including black body function, compared to Dennis Reuter's calculated values.

| Measurement | NIR | CH4 | Red | Blue | Pan1 | Pan2 |
|---|---|---|---|---|---|---|
| QE ($\frac{e^-}{\gamma}$) | 0.147 | 0.190 | 0.198 | 0.100 | 0.158 | 0.158 |
| QE ($\frac{e^-}{\gamma cm^2 sr}$) ($10^{-9}$) | 2.63 | 3.42 | 3.56 | 1.78 | 2.84 | 2.84 |
| QE ($\frac{DN}{\gamma cm^2 sr}$) ($10^{-11}$) | 4.49 | 5.83 | 6.05 | 3.04 | 4.85 | 4.85 |
| Point Source QE ($\frac{e^-}{\gamma cm^2}$) | 6.479 | 8.410 | 8.739 | 4.396 | 6.990 | 6.985 |

Table 4: Final response including Pluto's spectrum.

| Measurement | NIR | CH4 | Red | Blue | Pan1 | Pan2 |
|---|---|---|---|---|---|---|
| QE ($\frac{e^-}{\gamma}$) | 0.15 | 0.19 | 0.20 | 0.09 | 0.15 | 0.15 |
| QE ($\frac{e^-}{\gamma cm^2 sr}$) ($10^{-9}$) | 2.62 | 3.46 | 3.55 | 1.65 | 2.71 | 2.71 |
| QE ($\frac{DN}{\gamma cm^2 sr}$) ($10^{-11}$) | 4.47 | 5.90 | 6.06 | 2.82 | 4.63 | 4.63 |
| Point Source QE ($\frac{e^-}{\gamma cm^2}$) | 6.45 | 8.50 | 8.75 | 4.072 | 6.67 | 6.66 |

Table 5: Final response including Charon's spectrum.

| Measurement | NIR | CH4 | Red | Blue | Pan1 | Pan2 |
|---|---|---|---|---|---|---|
| QE ($\frac{e^-}{\gamma}$) | 0.15 | 0.19 | 0.20 | 0.09 | 0.149 | 0.15 |
| QE ($\frac{e^-}{\gamma cm^2 sr}$) ($10^{-9}$) | 2.62 | 3.45 | 3.55 | 1.62 | 2.68 | 2.68 |
| QE ($\frac{DN}{\gamma cm^2 sr}$) ($10^{-11}$) | 4.47 | 5.89 | 6.06 | 2.77 | 4.58 | 4.57 |
| Point Source QE ($\frac{e^-}{\gamma cm^2}$) | 6.45 | 8.50 | 8.75 | 4.00 | 6.59 | 6.59 |

Table 6: Final response including Solar's spectrum.

| Measurement | NIR | CH4 | Red | Blue | Pan1 | Pan2 |
|---|---|---|---|---|---|---|
| QE ($\frac{e^-}{\gamma}$) | 0.151 | 0.197 | 0.193 | 0.095 | 0.159 | 0.159 |
| QE ($\frac{e^-}{\gamma cm^2 sr}$) ($10^{-9}$) | 2.709 | 3.538 | 3.454 | 1.694 | 2.860 | 2.859 |
| QE ($\frac{DN}{\gamma cm^2 sr}$) ($10^{-11}$) | 4.622 | 6.037 | 5.895 | 2.892 | 4.880 | 4.878 |
| Point Source QE ($\frac{e^-}{\gamma cm^2}$) | 6.677 | 8.707 | 8.516 | 4.177 | 7.028 | 7.026 |

Table 7: Final response including Pholus' spectrum.

| Measurement | NIR | CH4 | Red | Blue | Pan1 | Pan2 |
|---|---|---|---|---|---|---|
| QE ($\frac{e^-}{\gamma}$) | 0.139 | 0.161 | 0.202 | 0.096 | 0.153 | 0.152 |
| QE ($\frac{e^-}{\gamma cm^2 sr}$) ($10^{-9}$) | 2.482 | 2.882 | 3.618 | 1.712 | 2.743 | 2.741 |
| QE ($\frac{DN}{\gamma cm^2 sr}$) ($10^{-11}$) | 4.236 | 4.917 | 6.174 | 2.921 | 4.681 | 4.677 |
| Point Source QE ($\frac{e^-}{\gamma cm^2}$) | 6.119 | 7.092 | 8.917 | 4.220 | 6.742 | 6.737 |

Table 8: Final response including Jupiter's spectrum.