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Acquisition Cameras

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ABSTRACT: The expected V magnitude limit for main sequence stars has been estimated for a set of monochrome CCD cameras in order to select one for image acquisition. Prices for the considered cameras range from under \$70.00 to \$12,000.00.

1. INTRODUCTION

Every telescope in the Array will be equipped with an image acquisition system. The acquisition system will be used not only for identifying objects during observations but for finding the point in the field of each telescope where the observed object should be placed to speed up and simplify the alignment of the Array. The acquisition system will consist of a small 6- or 8-inch telescope, a B&W video camera, and the necessary hardware to display the images on a computer screen. The telescope will be fed by reflecting ~10% of light from the science beam by an uncoated pellicle beam splitter. The whole system most likely will be mounted on the side of the fork between mirrors M4 and M5. This arrangement allows us to view an image of a star during the alignment of the telescope and requires a smaller aperture for the acquisition telescope.

In order to select the best possible camera for our purposes we estimated the limiting visual magnitude for several different cameras. The comparison between different cameras is not trivial, because the "sensitivity" is defined slightly differently by different manufacturers. The sensitivity of commercial video cameras is usually given as a minimum illumination level on the detector, for example 0.5 lux. It is usually not specified what 0.5 lux is sufficient for in terms of picture quality. Even when a manufacturer specifies that "0.5 lux means half full-well at the nominal exposure but the camera needs only 0.02 lux for 80% video", the translation of these terms to "What are we going to see on the screen?" is difficult.

Another important point is the pixel size of the camera. The required image scale is ~0.3 arcsec/pixel, which matches the expected speckle size in the optical range of the spectrum of a 1-m telescope. The image scale and the actual pixel size of a detector determine the effective focal length f of the acquisition system. Since the main telescope has an angular magnification of eight, the required focal length of the acquisition telescope itself is $f/8$. The aperture of the acquisition telescope is 6 inches. If the pixel size of the detector is small then the acquisition telescope turns out to be very fast, which makes the construction more difficult and expensive. Unfortunately, CCD video cameras and in

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general all fast cameras tend to utilize small ($6\,\mu$m – $10\,\mu$m) pixels because of the smaller capacitance and higher yield.

In the next sections we estimate the illumination on detectors behind an acquisition telescope as a function of effective temperature T_e and visual magnitude V_0 of stars, as well as seeing s and effective focal length f of the acquisition system. We then estimate the limiting visual magnitude as a function of sensitivity.

2. THE POWER RECEIVED FROM A STAR

We assume that stars can be treated as blackbodies and therefore as Lambertian sources. The spectrum can then be characterized by a single parameter, namely the effective temperature T_e. The spectral radiance of a star, i.e., the power leaving a unit projected area of the surface (in square meters) into a solid angle (in steradians) and unit wavelength interval (in meters) is

$$L_\lambda = \frac{2hc^2}{\lambda^5(e^{\frac{hc}{\lambda k T_e}} - 1)}. \tag{1}$$

The total power emitted per unit surface area per unit wavelength interval is the integral of the spectral radiance over solid angle and is called the spectral radiant exitance M_λ:

$$M_\lambda = \int L_\lambda \cos\Theta \, d\Omega = 2\pi L_\lambda \int_0^{\pi/2} \sin\Theta \cos\Theta \, d\Theta = \pi L_\lambda. \tag{2}$$

We are interested in the spectral irradiance, E_λ, which is the power per unit surface area per wavelength interval received from a star. E_λ is obtained by first multiplying the spectral radiant exitance by the total projected surface area A of the star to get the flux, which is $A\pi L_\lambda$. The flux is then divided by the area of a sphere of radius r centered on the source to give

$$E_\lambda = \frac{AL_\lambda}{4r^2} = \frac{\pi}{4}\phi^2 L_\lambda, \tag{3}$$

where we introduced the angular size ϕ of the star.

In order to evaluate Equation 3 for a star at a given T_e we need ϕ. A good estimate to the angular size can be obtained from the Barnes-Evans relation (Barnes, Evans & Moffet 1978) which states a tight relationship between the surface brightness parameter F_V,

$$F_V \equiv 4.2207 - 0.1V_0 - 0.5\log\phi, \tag{4}$$

and color indices. The best relationship was found for the index $(V-R)_0$ and is well defined for the entire range of stellar temperatures without any dependence on luminosity class. In order to apply the relation, we need the unreddened color index $(V-R)_0$ of the star as well as its visual magnitude V_0. $(V-R)_0$ at the given T_e can be obtained, for example, from the tables presented by Johnson (1966). The tabulated $F_V - (V-R)_0$ relation (Barnes, Evans & Moffet 1978) can then be used to determine the surface brightness parameter. Finally, ϕ can be found from Equation 4 after substituting the given V_0 (see Figure 1).

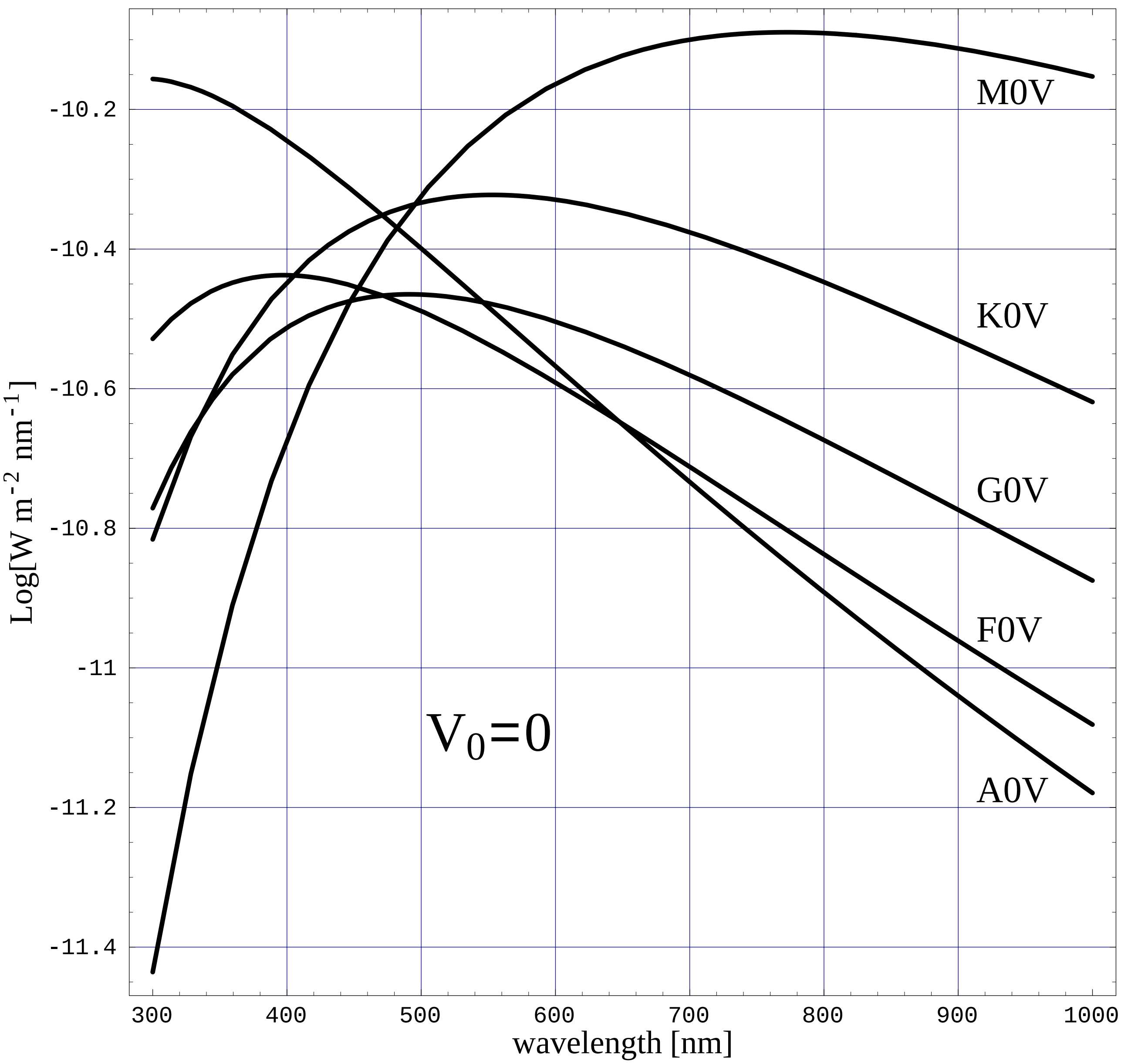

FIGURE 1. The spectral irradiance E_λ at the top of the Earth's atmosphere due to different main sequence stars. The visual magnitude of the stars is assumed to be zero.

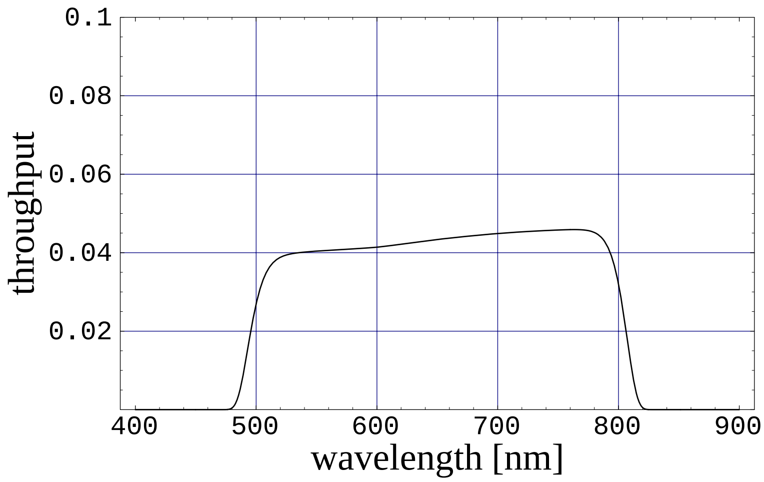

FIGURE 2. The assumed total throughput of the optical system including the atmosphere.

Only a fraction of E_λ reaches the surface of a ground-based detector, due to a series of optical elements in front of the detector, including the Earth's atmosphere, mirrors, and windows.

3. IRRADIANCE ON THE DETECTOR

In order to estimate E_λ on the detector a number of factors have to be taken into account. All these factors are wavelength dependent and not very well known. Therefore, some "guesstimation" is involved in the following calculation.

We assumed normal atmosphere and airmass=1 to estimate the continuous atmospheric absorption (Allen, 1972). We also assumed that the reflectance of all mirrors is better than 95% in the 500 – 800 nm range and is zero outside this range. With this assumption we obtain a lower limit for the irradiance because the CCD is sensitive outside this range and the reflectance is not likely to be zero but unknown. The pellicle which feeds the acquisition telescope is assumed to be spectrally flat with reflectance of 10% in the 500 – 800 nm range. The throughput of the acquisition telescope is estimated at 90%. The window in front of the detector is going to be uncoated for cheap cameras which results in approximately 8% loss. For more expensive cameras we assumed 2% loss. All transmissions and reflections are included in a single quantity $S(\lambda)$ (see Figure 2).

The total power in a stellar image on a detector can be written as

$$P_{\text{tot}} = a \int_{\lambda_1}^{\lambda_2} S(\lambda) E(\lambda)\, d\lambda, \tag{5}$$

where a is the light collecting area of the telescope, which is $0.76\,\mathrm{m}^2$ in our case. The spatial distribution of this power in the focal plane of the acquisition telescope can be approximated by a Gaussian function,

$$i(r, f, s) = \frac{4\ln(2)}{\pi f^2 s^2} e^{-4\ln(2)\frac{r^2}{s^2}}, \tag{6}$$

where r is the distance from the center of the image, s is the seeing in radians and f is the effective focal length of the acquisition telescope[2]. The term $i(r, f, s)$ is normalized in such a way that

$$\int_0^\infty 2\pi r\, i(r, f, s)\, dr = 1. \tag{7}$$

The peak illumination on a detector in lux is

$$L_{\text{peak}} = 683 \times i(0, f, s) P_{\text{tot}} = 683 \times \frac{4\ln(2)}{\pi f^2 s^2} P_{\text{tot}}. \tag{8}$$

If L_{peak} is greater then the sensitivity given for a camera, then we assume that the star is visible on the screen[3]. This formula is used to estimate the performance of commercial video and intensified video cameras.

For those cameras (for example, DALSA) where the frame rate is variable, the noise-equivalent-exposure (NEE) is given in $\mathrm{J\,cm^{-2}}$ rather than the minimum illumination. We can convert from $\mathrm{J\,cm^{-2}}$ to lux at a given frame rate $1/\tau$ by multiplying by $6.83 \times 10^6/\tau$. Thus, $100\,\mathrm{pJ\,cm^{-2}} = 2.05 \times 10^{-2}$ lux at the standard 30 frames/sec.

Having these formulas we can estimate the limiting visual magnitude for different cameras as a function of the effective temperature of stars at a given magnitude, seeing and effective focal length (see Figures 3 and 4).

4. ESTIMATED PERFORMANCE OF CAMERAS

4.1. VV5430 Camera Module

This is a single chip camera by VLSI Vision, Ltd., which requires only a few external components. It was not particularly designed for astronomy (fill factor = 50%) but it is extremely cheap ($62.97/module) and this is why it is included. The device incorporates a 388×295 pixel photodiode array with $12\,\mu\mathrm{m} \times 12\mu\mathrm{m}$ pixels. The sensitivity is specified as 1 lux (see Figure 4) at standard 30 frames/s. The focal length of the acquisition telescope would be 1.03 m to give a 0.3 arcsec/pixel image scale. The limiting magnitude can be as high as $V = 9$ under excellent ($0\farcs3$) seeing or as low as $V = 4$. The module is capable of integrating. This camera would not be adequate for acquisition but may be a good choice for security and alignment purposes.

4.2. Edmund Scientific P53,309

This is a single-board monochrome camera with a 1/3″ interline transfer CCD with 768×494 pixels. The fill factor is assumed to be 50%. The required illumination is 0.5 lux at standard 30 frames/sec. The frame rate is fixed. The operating temperature range is -10°C to

[2]The main telescope is afocal and has an angular magnification of 8. Therefore, the effective focal length of the acquisition telescope is 8 times its actual focal length.

[3]Note that in case of CCDs, even if L_{peak} was slightly greater on a single pixel than the required sensitivity, a star would be indistinguishable from the background noise if the pixel scale is too large.

50°C and the price is \$270.00. We tested this camera under a clear sky but quite poor seeing conditions ($\sim 3''$) at HLCO. The limiting magnitude we found was $V = 4.2$. This corresponds to $\sim$0.5 lux illumination on the CCD which is in very good agreement with the sensitivity quoted by the manufacturer. As with the VV5430, this camera is not adequate for acquisition but operates nicely on the theodolite, for example.

4.3. Cohu 4910

This is a high quality $1/2''$ monochrome camera which utilizes micro lenses in front of the pixels. This camera is also capable of integrating to boost the sensitivity. The manufacturer-quoted sensitivity is 1.3 lux full video (AGC off) and 0.02 lux at 80% video (AGC on) and 0.008 lux at 30% video at standard video rate. The fill factor is 50%. The price is \$895.00. It is not clear what the picture quality is at 80% and 30% video but supposedly it is still quite good or tolerable. The limiting magnitude is $V = 8$ under poor seeing but can be as high as $V = 13$ with excellent seeing and at f=6 m. The pixel size is $\sim 8\,\mu$m and the focal length of the acquisition telescope would be 0.7 m. Because of the integrating capability and price, this camera is a candidate for acquisition.

4.4. DALSA CA-D1

The fill factor is 100% for these cameras and the noise equivalent exposure NEE=20 pJ cm^{-2}, which corresponds to 4.1×10^{-3} lux at standard video rate. The limiting magnitude would be close to $V = 10$ even at $3''$ seeing and f=12 m and can be fainter by lowering the frame rate. This is a fast, fully programmable 8- or 12- bit industrial camera with optional 64×64, 128×128, or 256×256 CCDs and binning capability. This camera has the largest pixel size $16\,\mu$m among those we have considered. The resultant focal length of the acquisition telescope is 1.4 m. The price is \$3185.00, which makes it a candidate.

4.5. Pulnix TM-7

We have also considered an intensified CCD cameras, the Pulnix 007 series. This small camera incorporates a $1/2''$ CCD and an optional Gen III intensifier which is coupled to the CCD by a fiber optic minifier. The output is standard RS-170 and remote control was not available. The life time of the tube is 2,500 hours or 312 eight-hour nights. The minimum illumination is 10^{-6} lux, which means that this camera would not have any problem to meet or magnitude requirement even at f=12 m. Actually, the limiting magnitude would be determined by the sky brightness rather than the camera. The effective pixel size is about $2.25\times$ the actual pixel size due to the minifier. The focal length of the acquisition telescope can be as long as 1.54 m. The quoted price is \$12K.

4.6. Princeton Instruments Model V/ICCD

This is a professional ICCD camera with optional fiber optic link, remote operation, single photon sensitivity and integrating capability. The price is \$18K.

Since we will observe bright stars $V < 10$, the last two cameras seem to be overkill. Also bright stars or the alignment laser beam can be dangerous to the intensifier. Nevertheless, these cameras are definite candidates.

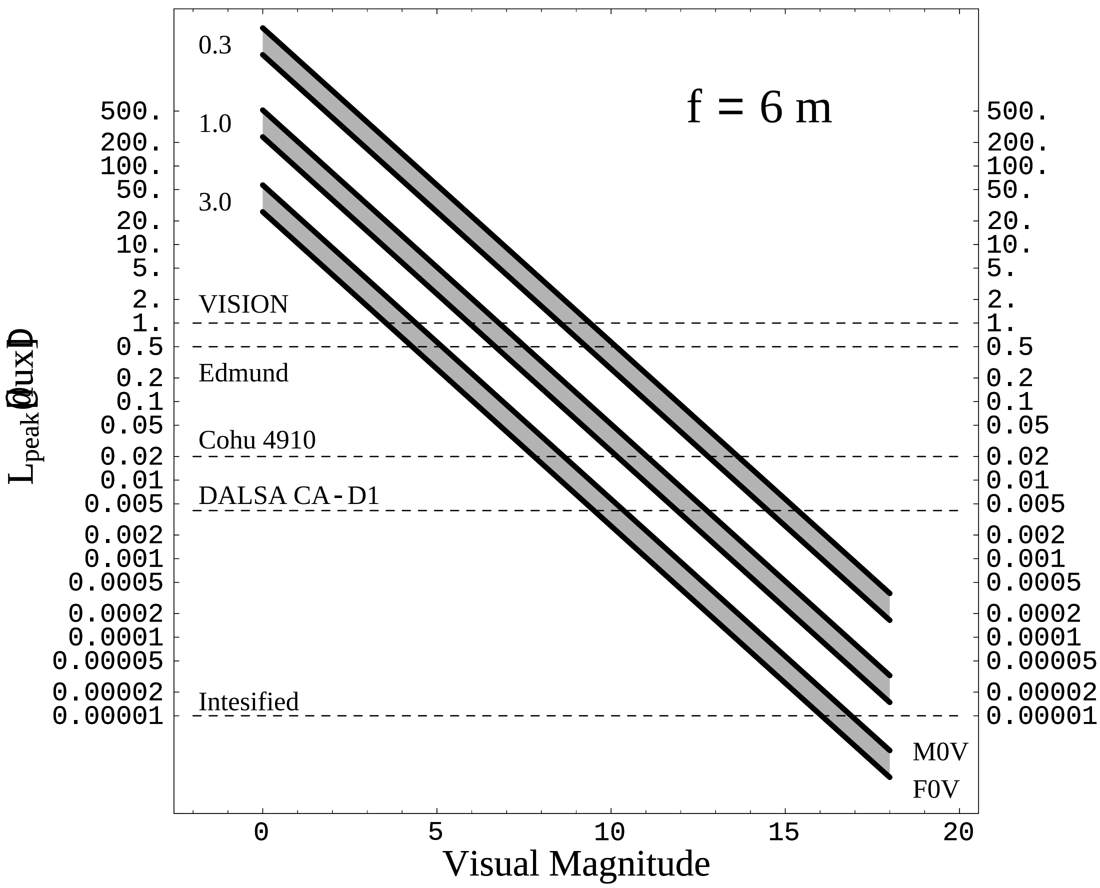

FIGURE 3. The peak illumination in the image of main sequence stars as a function of visual magnitude. The different diagonal bands correspond to different seeing from 0″.3 (top) to 3″ (bottom). The bands themselves represent the different spectral types from B0 to M0. The dashed lines shows the sensitivity of different cameras. The effective focal length of the acquisition system is f=6 m.

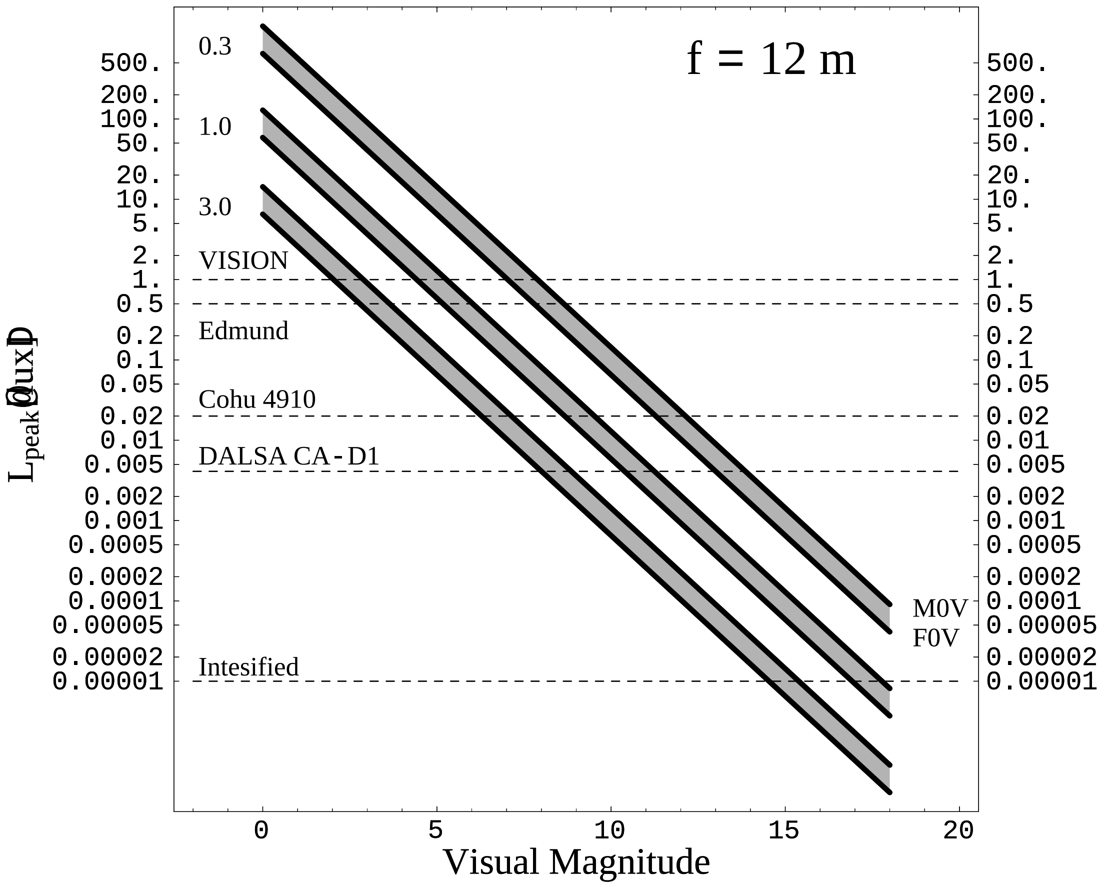

FIGURE 4. The same as Figure 3 except f=12 m.

5. CONCLUSION

We found four candidates for acquisition camera, the most affordable of which are the Cohu 4910 and the DALSA CA-D1. The Cohu 4910 is the cheapest and probably still meets our $V = 10$ limiting magnitude requirement. The DALSA CA-D1 is more sensitive than the Cohu 4910 and still affordable. It has larger pixels than the others which likely to make the acquisition telescope cheaper and simpler. However, it also has fewer pixels which would result in a field of 1.3 arcmin at 0.3 arcsec/pixel. It is flexible and digital. Frame grabbers are readily available from several vendors.

The intensified cameras have considerable reserve in terms of sensitivity, but at a steep price. We could use smaller pixel scale without compromising the $V = 10$ limit, but at the expense of field of view. Another concern is the vulnerability and relatively short life time of the tube.

6. REFERENCES

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