CMOS DETECTORS FOR BRITE

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ABSTRACT

By reviewing the properties of the best CMOS detector systems available today, it is clear that the detector is not the limiting factor in BRITE's potential. Current CMOS detectors have less dark current at room temperature than the best CCDs. I show that BRITE can be a photometric system capable of 1% photometry in 10 second integrations of 8th magnitude stars, over fields of view between 10 to 30 degrees. Millimagnitude precision in 10 seconds is predicted for stars at 4th magnitude. It is imperative that parasitic and scattered light be kept to a minimum.

Subject headings: instrumentation-detectors

1. INTRODUCTION

The proposed BRITE nanosatellite has a detector power budget allowance of only 500 milliwatts. This means that a CCD cannot be used, but CMOS detectors generally consume below 500mW, and at low frequencies well below that. However, an initial survey by our Dynacon colleagues showed that all the commonly-available standard OEM chips had excessive dark current, read-out noise and insufficient bits of digitization, as well as a rather small number of pixels. Typically, such CMOS chips have about 1000-5000 e/s/pix dark current at 20C (close to our expected working temperature). Even with integrations of a few seconds, the dark current becomes the dominant limitation. Readout noise of a few tens of electrons is less than the dark current noise. An excellent review of CCD and CMOS principles and the state of the art is to be found in Janesick and Putnam (2003).

While searching the Web, I found that many amateur astronomers have been using digital still cameras on telescopes. By far the best imaging of this type was being done using the Canon EOS 10D, 300D and 20D cameras, and astonishingly, these high-end cameras, with 6 to 8 megapixels, use CMOS detectors. All other high-end "Digital Single Lens Reflex" (DSLR) cameras use CCD's (as of mid-2004). I set out to investigate the performance of the Canon DSLR cameras, which can be bought for as little as CDN $1000.

2. CHARACTERISTICS OF DSLR CAMERAS

There are numerous accounts in the photographic press regarding DSLR cameras; the standards for the past couple of years have been set by the Canon 10D and the Nikon D70. While each has just over 6 megapixels in a 3K x 2 K with square pixels of 7-8 microns size, the Canon camera uses a proprietary Canon CMOS sensor, while the Nikon camera uses a Sony ICX413AQ CCD. These are colour cameras employing Bayer matrix filters: of every group of 4 pixels, two have a G filter, one has a B and the other an R. An IR-blocking filter is mounted in front of the whole sensor, since these cameras are designed to reproduce the colour balance of the human eye.

More recently, Canon have produced a less expensive version of the 10D, called the EOS Digital Rebel or 300D, with the same detector and performance as the 10D, and an updated 8 Megapixel successor to the 10D called the 20D, while Nikon are rumoured to be producing a top-end camera with CMOS detector. There are also much more expensive and larger cameras produced by both these and other companies, but they don't appear to offer superior performance for astronomy (e.g. Canon 1D Mk. II, see Lovejoy (2004b)).

Two amateurs have done the sort of tests needed by astronomers, Christian Buil in France and Terry Lovejoy in Australia. They publish their results on the Web. These are the tests one performs on any CCD-type detector. Buil is well known for his development of the Audine camera, equivalent to the SBIG ST-7, both using Kodak CCD's Buil (2004a), and Lovejoy (2004a) is a knowledgeable contributor to the "digital_astro" list on Yahoo Groups.

2.1. Sensitivity, or Quantum Efficiency

Unlike the full-frame charge transfer, often back-illuminated, "science grade" CCD's, the sensors in digital cameras generally have dead spaces between photosensitive pixels, leading to a fill factor less than 100%. In the case of CCD's in digital cameras, it is due to the use of inter-line transfer of charge (ILT), while in the case of CMOS detectors, there is a lot of circuitry laid down over the surface. This loss of sensitive area can be partially recovered using a matrix of microlenses bonded to the front surface.

There is another important limitation: many sensors are colour detectors with the Bayer matrix filters mentioned above. This reduces effective quantum efficiency, and introduces geometric sampling differences between images in R, G and B, which are reduced if the image is significantly over-sampled.

2.2. Absolute QE

Lovejoy (2004a) reports crudely determined efficiencies of 0.2, 0.4 and 0.4 in the *peaks* of the R, G and B bands, respectively. Buil (2004b) measures the quantum efficiency of the Canon CMOS camera to be between 0.16-0.25 that of the Kodak KAF-402ME CCD (which at these wavelengths averages about 0.6). Thus we can expect a QE of about 0.1-0.15 for the colour CMOS chip in the Canon DSLR's. Of course, without the Bayer matrix filters, the effective quantum efficiency would be much higher, perhaps 0.5. I believe that the Canon chips have microlenses.

2.3. Relative QE

This is better established, and depends also on whether the overall IR blocking filter is removed or replaced. Blocking filter transmission curves are shown.

Buil (2004b) has obtained relative transmission curves for the RGB filters (Fig. 2), and a relative overall quantum efficiency plot (Fig. 3). The Bayer matrix is shown in Fig. 4.

2.4. Read-Out Noise and Gain

The read-out noise and gain of the Canon EOS cameras and of the Nikon D70 CCD-based DSLR have been measured by Buil (2004b) and by Lovejoy (2004a), and Lovejoy (2004b) has further tested the more expensive Canon 1D Mk.II. Their results are thoroughly professional and highly consistent. Table 1 is a summary of their combined results, to which I have added numbers from the datasheet of the Electrim EDC-300D monochrome camera (see below). The Nikon D70 is included for comparison with a high-end CCD based camera.

The DSLR cameras have various gain settings, identified by ISO numbers by analogy with film. Most commonly with the Canon DSLR's, ASA 400 is used.

Table 1. Advanced CMOS Parameters

Chip	Format Nx x Ny	Pix Size microns	Typ.Gain e-/ADU	Read-Out noise e-	Dk.Curr. e-/s/pix	Temp. C
10D/300D	3072x2048	7.4	2.41	15	1	22
20D	3504x2336	6.4	3.14	7.5	0.5	22
1D-II	3504x2336	8.2	2.51	7.0	0.3	22
D70 CCD	3040x2014	7.8	2.98	19.0	24	22
EDC-3000D	1280x1024	5.2	···	10	20	25

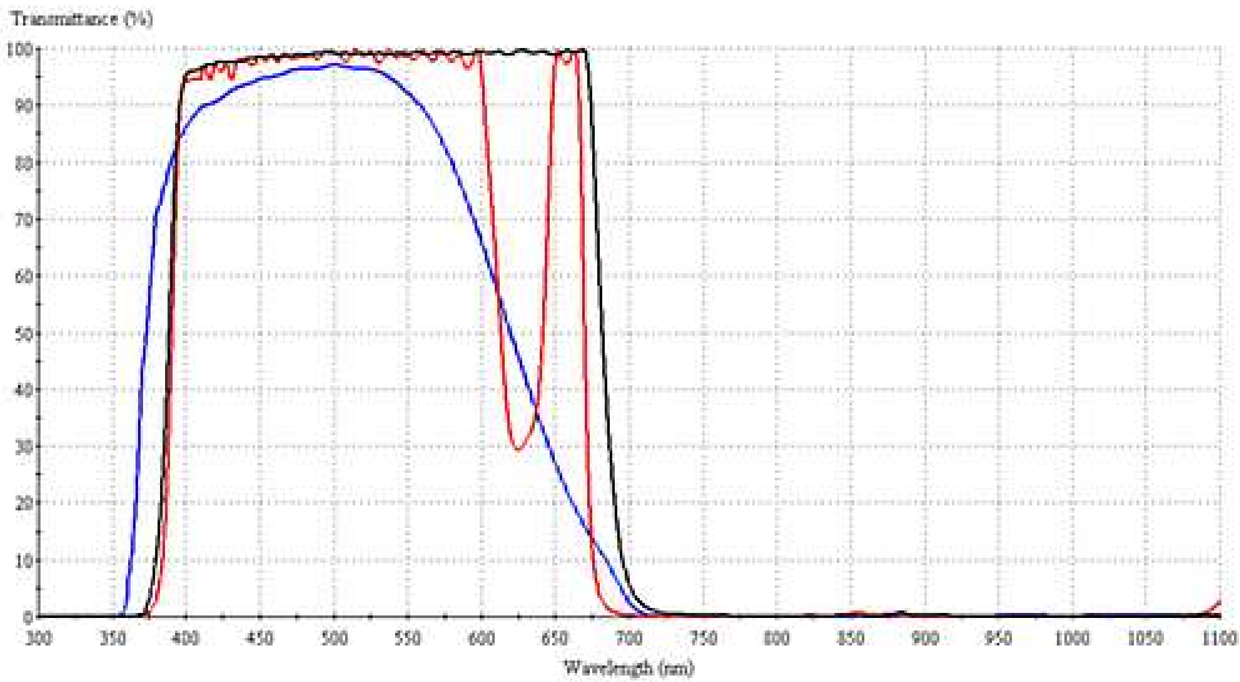

Fig. 1.— Canon IR Blocking Filter Spectral Responses

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* Blue:  Original Canon IR blocker filter
* Black: Hutech Type I  (used in EOS011 camera)
* Red:   Hutech Type II (used in EOS012, EOS021 cameras)
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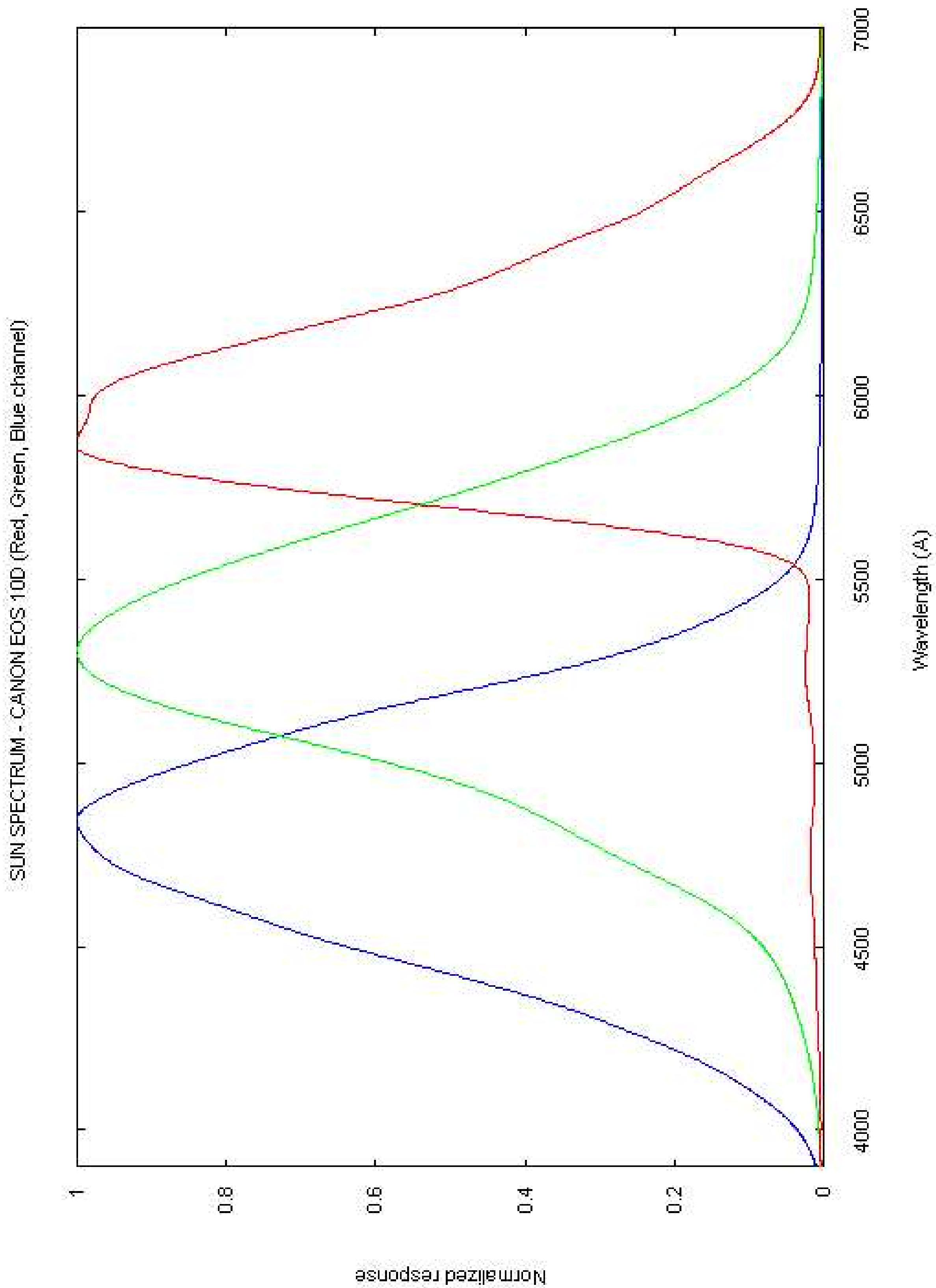

Fig. 2.— RGB relative transmission curves.

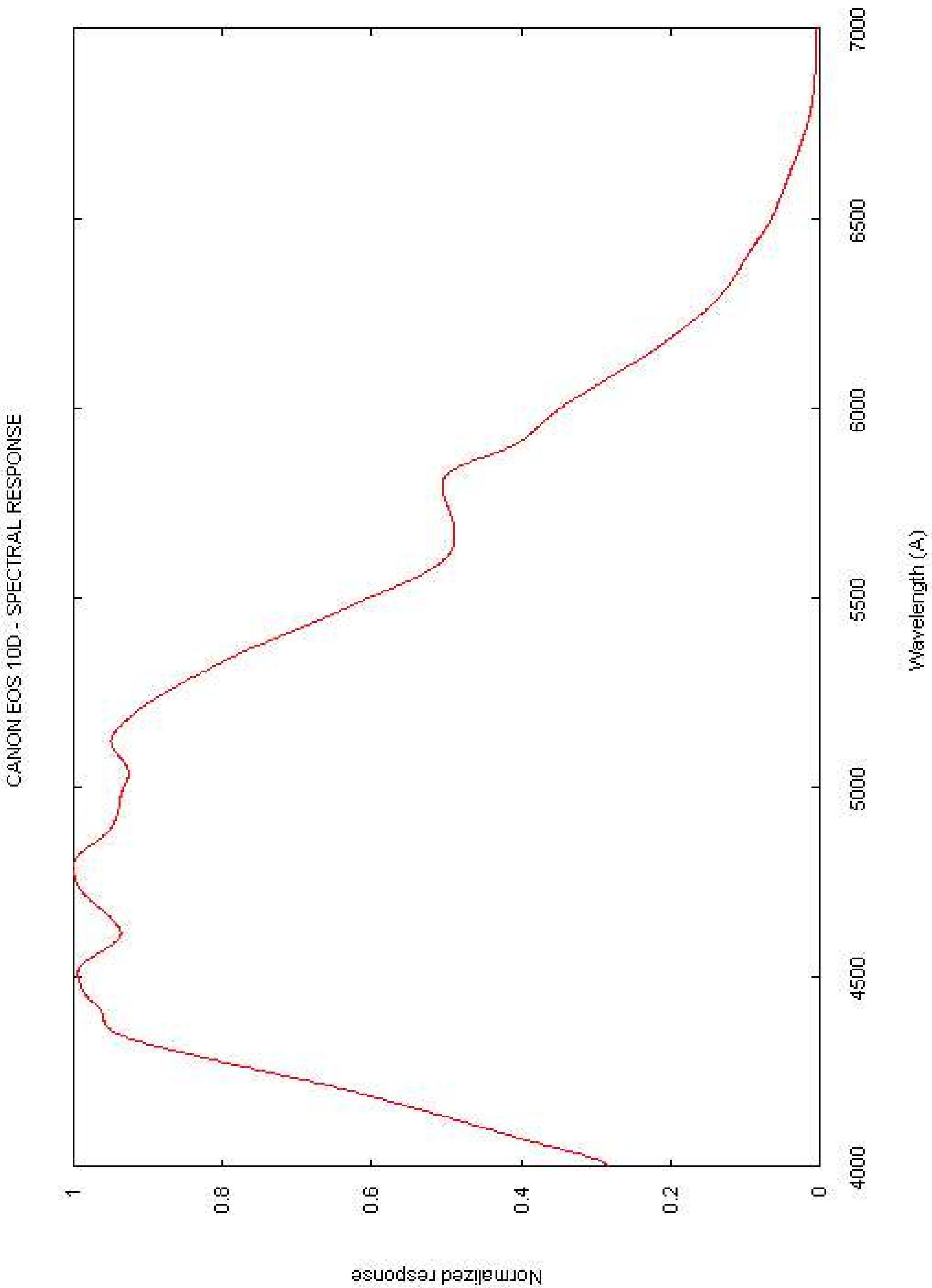

Fig. 3.— Relative quantum efficiency curve.

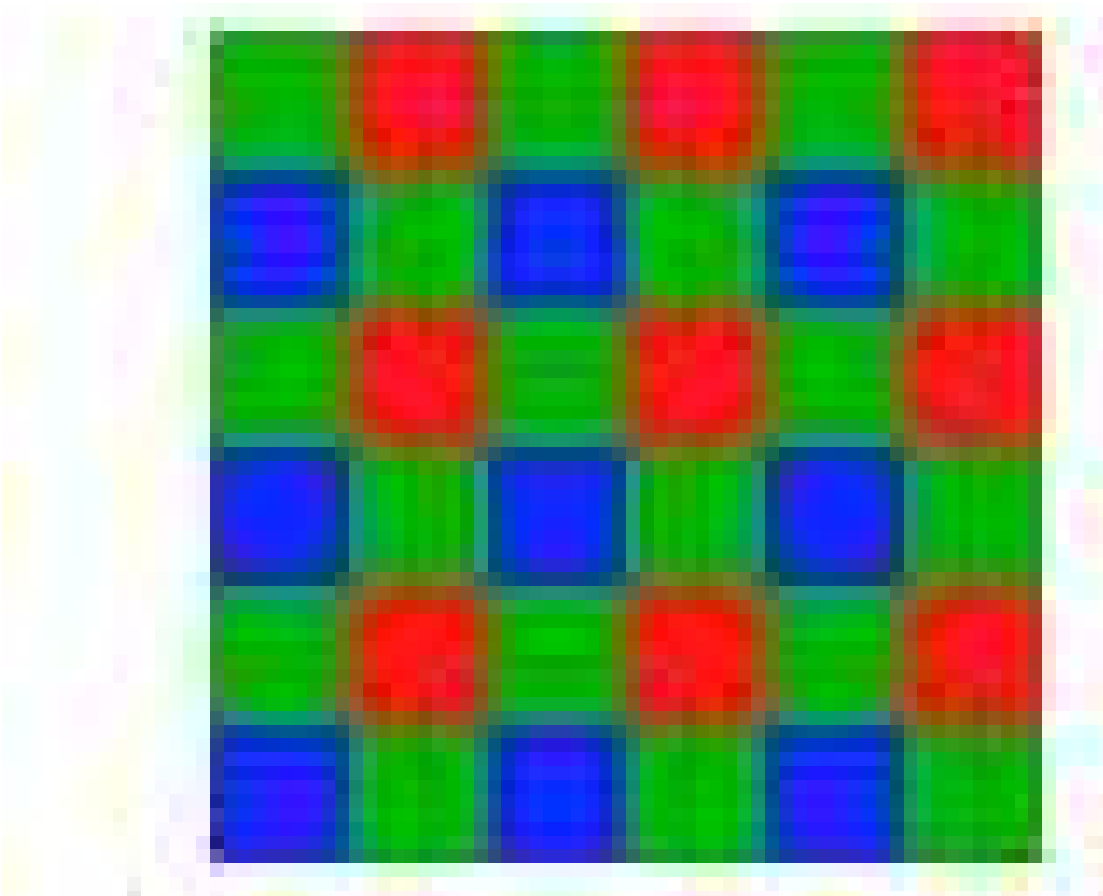

Fig. 4.— Bayer matrix of filters over pixels.

Table 1 shows that the readout noise of the best DSLR cameras is now as good as or below that of the commonly available TE-cooled CCD cameras (SBIG, Apogee, FLI etc.), but somewhat higher than the 5 electrons typical of "science grade" cryogenically-cooled CCD cameras. However, the smaller pixels and Bayer color matrix reduces their quantum efficiency compared with monochromatic full-frame CCD's.

2.5. Dark Current

In the uncooled BRITE environment, we can expect 20 C as a typical working temperature. With older-style CMOS detectors, dark currents of 1000 e-/sec/pixel are not uncommon, which severely restricts the usefulness of such devices. However, the work of Buil and Lovejoy, quantifying what dozens of amateurs have found qualitatively (see the digital_astro Yahoo group, for example), proves that the Canon CMOS cameras have extremely low dark current at room temperature. In fact, Lovejoy has posted usable exposures as long as **28 minutes** at 10 C. The dark current rate of 1 e-/s/pixel at room temperature is less than that of the dark current of the Kodak KAF series CCDs (1 e-/s/pix at 0 C), which are themselves very good. The evidence is that Canon have reduced the dark current of CMOS detectors to below that of CCD's.

In Fig.5, I have computed the dark current per pixel using equations 7.44 and 7.46 of Janesick (2001), with a figure-of-merit dark current of 1 pA cm^{-2} at 300 K. This is at the very lowest value expected for CCD's.

Furthermore, the Canon chips are extremely clean, with few hot pixels. This is seen clearly in Fig. 6 from one of Buil's comparison of the 10D with the Nikon D70 CCD-based camera:

3. SMALLER SCIENTIFIC CMOS CAMERAS

I searched the Web for other new CMOS cameras, and found a number of compact cameras in the 1-2 Mpixel range, by such manufacturers as Altasens, Electrim, Basler and Aries. Only the new Electrim EDC-3000D monochromatic camera is relevant. It is a 1.3 Mpixel CMOS camera, with 5.2 micron pixels (rather small), progressive scan, full-well capacity 40Ke-, dark current 20 e-/s/pix (very good), quantum efficiency 56%, exposure time 8 μs to 10 sec, 10 bits ADC, readout noise 10 e- (very good). It can read out at 30 full frames per second, or up to 100 frames per second over a selected smaller region of interest. The entire camera in its container weighs 145g, with all power supplied from the USB 2.0 bus, and costs less than US $1000. I have sent an e-mail requesting more information than is in the data sheet. This is an interesting camera, but its pixels are rather small, and it has only 10 bit digitization. If the other electronics are efficient, the whole camera could be suitable for BRITE. Electrim has a long history of supplying scientific CCD cameras.

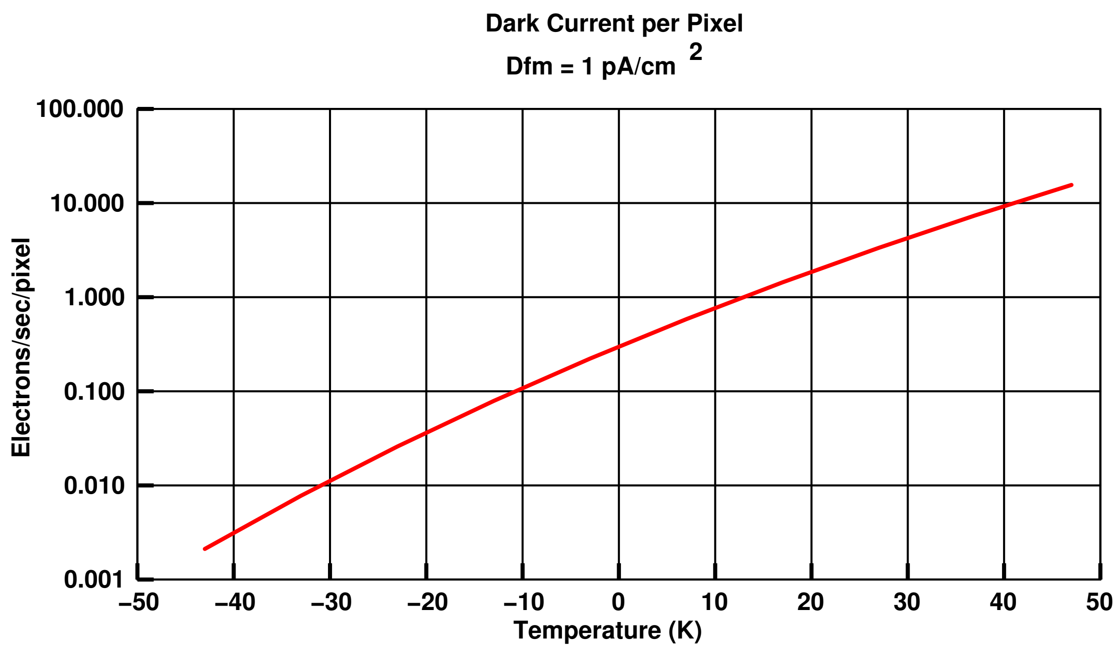

Fig. 5.— Dark current from Janesick's Formula

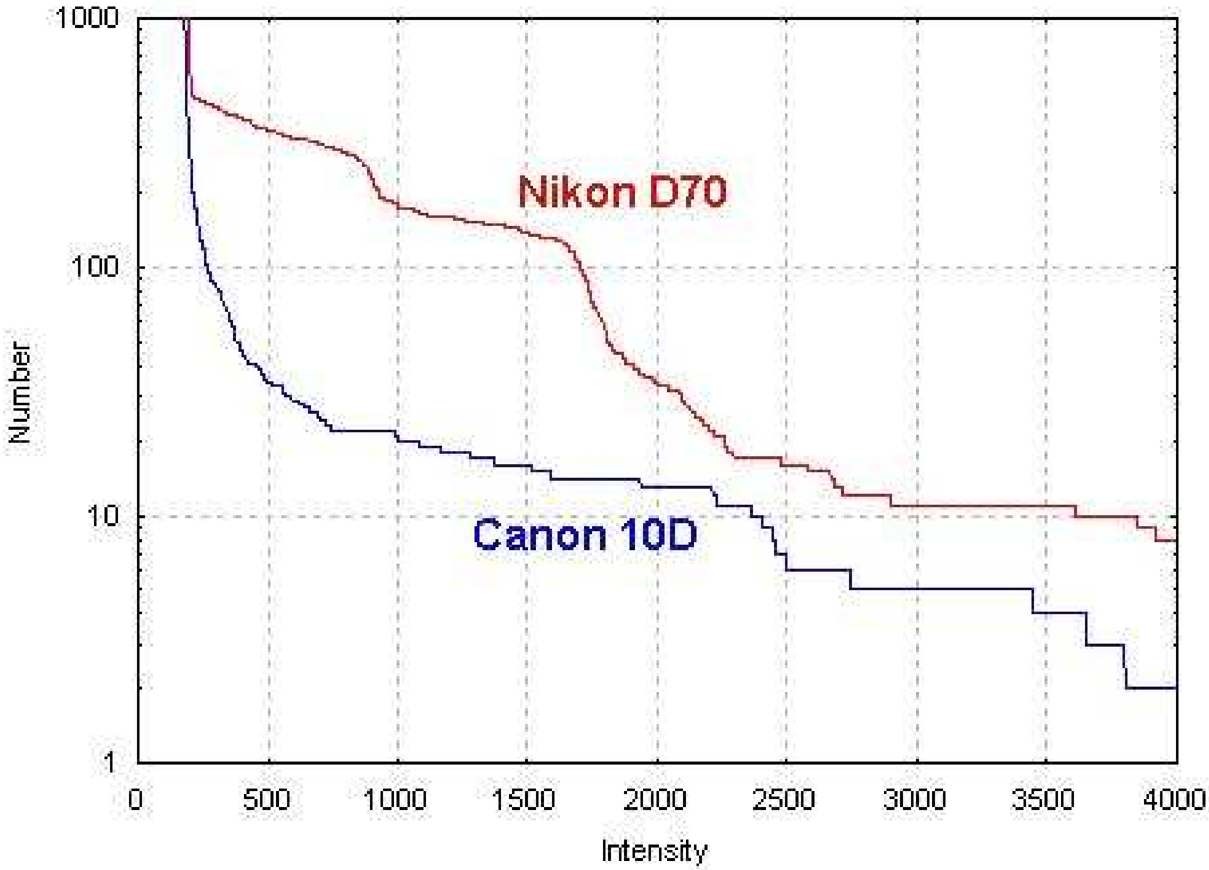

Fig. 6.— (From Buil 2004a). Inverse cumulated histogram of the thermal signal (from RAW data). Dark exposure of 120 seconds with ISO 400 and 21C. Note that the vertical scale is logarithmic. In the Canon 10D image there are 20 hot pixels which have an intensity higher than 1000 ADU. For the same exposure time, in the case the of Nikon D70 there are 200 pixels which have an intensity higher than 1000 ADU (mode 3). Before correction, the dark signal of the D70 is typically 10 times higher than that of the 10D. In both cases several families of hot pixels are identified.

4. PERFORMANCE SIMULATIONS

I have developed a spreadsheet to very crudely model the imaging by BRITE. I compute the signal-to-noise of a star spread over an aperture of 2 arcminutes diamter, integrated over an aperture of 2 arcminutes radius. I assume a telescope aperture of 25mm. I compare a Canon 10D/300D type of chip with the Electrim EDC-3000D detector. The calculation is completely standard, including source photon noise, readout noise, sky background photon noise, dark current quantum noise, optical efficiency factors, quantum efficiency. At this stage I am not considering digitization limits, saturation or flattening limitations.

The observing strategy with multi-megapixel detectors with limited dynamic range is to spread the stellar images over a fairly large number of pixels. I am assuming a 2 arc minute aperture. Now, given that the diffraction limit of a one-inch telescope is 5 arc seconds, this requires quite a bit of apodization. We need to determine what the maximum integrating aperture size can be to avoid source confusion (contamination by other stars).

A large point-spread function with unmodified Bayer matrix colour sensors makes sense, since the oversampling reduces the errors due to the geometrical mismatch of the three colour channels. There may be benefit in having three-passband measurements, but there is a serious penalty due to the rejection of light by filters of relatively narrow passband.

Optically, the Electrim chip allows a 12.7 degree extent along the longer axis of the chip at f/1.2 (41"/pixel), whereas the bigger Canon 10D/300D chip covers 35 degrees along the longer axis at f/1.5 (36"/pixel). The calculation is presented in Fig. 7. The lower S/N of the Canon chip is due to the lower effective quantum efficiency due to the Bayer matrix filtering.

5. FURTHER INFORMATION REQUIREMENTS

What these results show is that the best CMOS detectors are fully capable of supporting the BRITE mission. The question to be answered now is whether they can be obtained and configured in appropriate form, with sufficiently low power consumption.

It would be highly desirable to obtain stand-alone Canon CMOS detectors WITHOUT Bayer matrix filters. An approach to Canon may be highly desirable. It may be possible to gut a standard Canon digital camera of unneded hardware, but clearly Canon's involvement or assistance would be most desirable. The Canon chips would give us the desired field of view, at a more relaxed f/1.5.

The Electrim camera would also work well, as is if the power requirements are low enough, though its field of view is not as good as the Canon chips allow. Its dark current is essentially negligible for our purposes, despite being 20 times higher than the Canons; this shows just how good the Canon chips are.

I have not made any effort to estimate the on-board computing power needed to support these

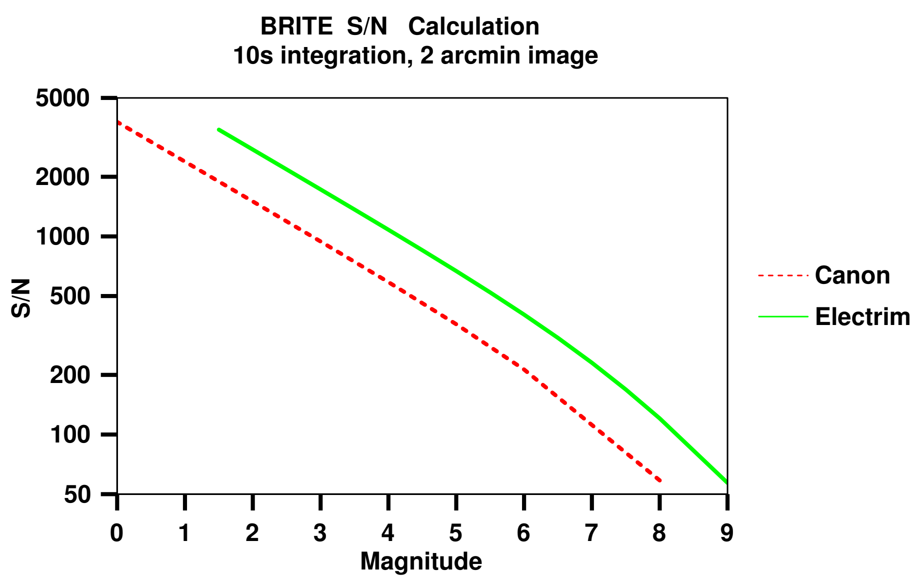

Fig. 7.— Signal to noise ratios for 10 second BRITE integrations.

detectors. Clearly, an integrated engineering analysis is required.

It is essential that scattered light be eliminated. I would propose sacrificing some optical transmission efficiency to have a low-scattering optical design.

6. CONCLUSIONS

I have shown that measurements by expert amateurs indicate that the best large CMOS detectors are extremely effective, and that the performance of CMOS detectors is not a limitation. In fact, BRITE could be a more general-purpose photometric instrument than we had assumed, since it could get 1% photometry in 10 seconds down to 8th magnitude.

It is highly desirable that a communications channel to Canon be opened.

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