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Detectors for the astronomical applications

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Abstract

Astronomical observations are dependent on focal-plane instruments, and detectors continue to play a key role. The detector technology is evolving rather fast with the large-format CMOS and CCD array mosaics, electron-multiplying CCDs, electron-avalanche photodiode arrays, quantum-well IR photon detectors etc. However, the requirements of artifact-free photon shot noise limited images are the higher sensitivity, higher quantum efficiency, reduced noise that includes dark current, read-out and amplifier noise, smaller point-spread functions and higher spectral bandwidth, etc. One of the fastest growing applications is signal sensing, particularly wavefront sensing for adaptive optics and fringe tracking for interferometry. A few detectors that are being used in astronomical imaging are discussed in this talk.

I. Introduction

Optical telescopes collect the radiation from the faint stellar sources. As the source is normally faint and the photons received from these distant objects are feeble, more collecting area is often required and the time of observation is increased. However, it is indeed a difficult task to get diffraction-limited image from the telescope. This is mainly due to the problems related to the surface accuracy of the mirrors (both primary and secondary) and alignment, mechanical structure and atmospheric turbulence. Variation in refractive index in the atmosphere above the telescopes lead to severe distortion of the wavefronts coming from the stars. The resultant images are shifted and broadened to sizes many times larger than the diffraction limit. This broadening process is referred as the atmospheric seeing. The image degradation produced by atmospheric turbulence is characterized by the size of the atmospheric coherence length, called Fried's parameter [1].

Optical interferometry fitted with an adaptive optics (AO) system has made inroad in obtaining diffraction-limited astronomical imaging (mostly in infra-red wavelength). AO systems introduce controllable counter wavefront distortion which both spatially and temporally follows that of the atmosphere. The purpose of this system is to (i) sense the wavefront perturbations, and (ii) compensate for them in real time [2, 3]. This new technology improves the throughput of telescopes and it will enable new exciting programs like finding planetary system around stars and high resolution imaging [4]. However, both interferometry and AO system need high time resolution cameras. The performance relies on the characteristics of such sensors, e.g., (i) the spectral bandwidth, (ii) the quantum efficiency, (iii) the detector noise that includes dark current, read-out and amplifier noise, (iv) the time lag due to the read-out of the detector, and (v) the array size and the spatial resolution. In what follows, a few detectors that are being used in astronomical imaging are enumerated in brief.

II. Charge coupled device (CCD)

The charge coupled device (CCD) camera system became useful an imaging device in the fields of astronomy. It is being used as an imaging device in other scientific fields like biomedical science and in commercial applications like digital cameras as well. The CCD [5] is a light sensitive electronic chip made up of p-type silicon. The chip consists of a two dimensional array of sensors, called pixels, with each sensor having a set of simple parallel plate metal oxide semiconductor (MOS) capacitor like structures. Every pixel's charge is transferred through a very limited number of output nodes to be converted to voltage, buffered, and sent off-chip as an analog signal. All of the pixel can be devoted to light capture, and the output's uniformity is high. In general, the CCD controller is based on a Digital Signal Processor (DSP), which comprises of (i) Dewar housing the CCD, in a cryogenic environment, (ii) DSP CPU board, (iii) Bias and Clocks Board, (iv) Analog Signal Processing Board, (v) Pre-amplifier Board, and (vi) Host interface Board. The DSP CPU board is the heart of the controller unit, whose functions are: (i) to receive and execute the program, from the host, (ii) to load all the DACs in the Bias and Clocks board, (iii) to generate the timing sequences for readout of the CCD, (iv) to send the digitized data to the host, with a strobe signal, and (v) to generate handshaking signals with the host computer. The recent approach of using a Field Programmable Gate Array (FPGA), would enhance the image processing strategies [6]. It consists of an array of logic elements together with an interconnect network which can be configured by the user at the point of application. Such a system reduces hardware, reconfigurability and multiplicity of operations. Most of astronomical observations are being carried out using conventional CCD. In order to cool the CCD, the Dewar is filled with liquid nitrogen.

III. Complementary metal oxide semiconductor (CMOS)

Like CCD sensor, the operating principle of a CMOS sensor is photoelectric effect, in which it converts light into electric charge and process it into electronic signals. In this, each pixel has its own charge-to-voltage conversion. The sensor often also includes amplifiers, noise-correction, and digitization circuits, so that the chip outputs digital bits. The responsivity, which is defined as the amount of signal sensor delivers per unit of optical energy, the CMOS is marginally superior to CCDs. Of course, CCD has a better dynamic range, i.e., the ratio of a pixel's saturation level to the signal threshold. CMOS sensor requires more uniformity, the consistency of

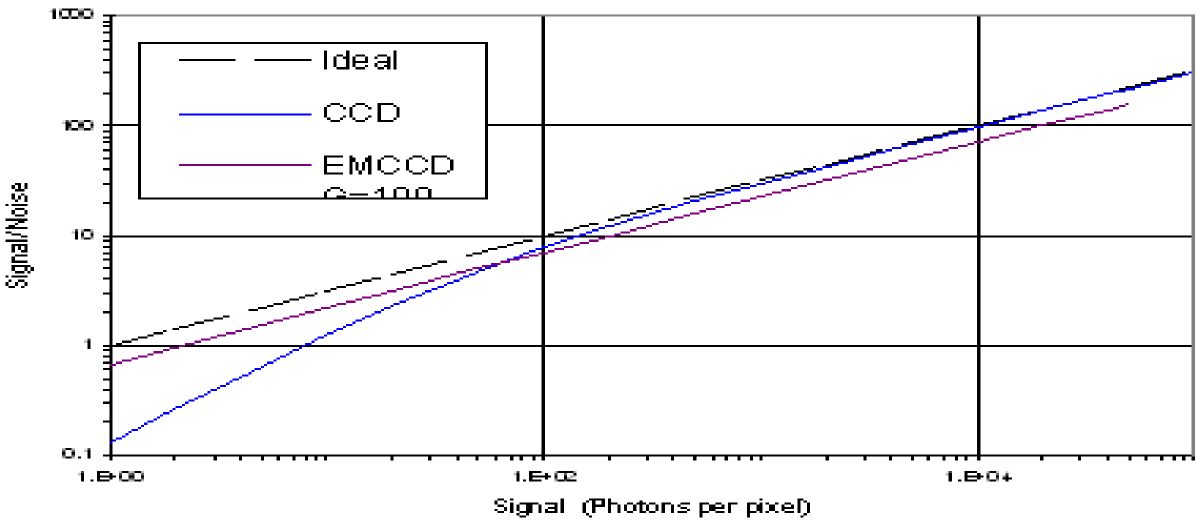

Figure 1a: Performance of an EMCCD against a CCD and ideal detector.

response for different pixels under identical illumination. However, it has the advantage over CCD in the case of the speed that is required for wavefront sensing, as well as the ability to read out a portion of the image sensor. The notable other characteristics of CMOS devices are high noise immunity and low power consumption. Intensified based CMOS camera [7] can also be used for recording images of the photon-starved astronomical sources.

IV. Electron Multiplying charge coupled device (EMCCD)

Development of the solid state based Electron Multiplying charge coupled device (EMCCD), which can allow a signal to be detected above the noisy readout, has enabled substantial internal gain within the CCD before the signal reaches the output amplifier [8]. The EMCCD is developed using both front- and back-illuminated CCD and is provided with Peltier cooling system that is comparable with liquid nitrogen cooled cryostats. The image store and readout register are of conventional design operating typically at 10 volts. But there is an extended section of gain register between the normal serial register and the final detection mode which operates at much higher amplitude (typically at 40-50 volts). This large voltage creates an avalanche multiplication with thereby increases the number of electrons in the charge packets, thus producing gain.

The operation of multiplication register is similar to the readout register but the clocking voltages that are much higher (typically at >20 volts as opposed to the ~10 volts). At this higher voltage there is an increased probability that electrons being shifted through the Multiplication register have sufficient energy to create more free electrons by impact ionization. Although the probability of secondary generation in each pixel of the multiplication register is low; typically it ranges from 0.01 to 0.016. By designing a Multiplication register with many pixels the effective gain of the register can be more than 1000x. The gain (M) is multiplicative. The probability (p) of generating a secondary and hence the gain is dependant on the voltage levels of the serial clock and the temperature of the CCD. The EMCCD gain amplifies the signal by M but also adds additional noise to that of the incoming photons. The excess noise known, as the Noise Factor (F) needs to be taken into consideration. Note the dark signal is also amplified by EMCCD gain and the resultant noise from the dark signal is also further increased by the noise factor. In an ideal amplifier the Noise factor would be unity. However, the EMCCD gain originates from a stochastic process, and theory [9] shows that for a stochastic gain process using infinite number of pixels in the gain register the Noise Factor should tend to 20.5.

From the graph above comparing the performance of an EMCCD against a CCD and ideal detector one can see these effects. At low photon flux levels the readout noise of CCD dominates the signal to noise and the EMCCD wins out. At higher photon flux levels the noise factor of the EMCCD reduces the Signal to noise ratio below that of the CCD. The apparent reduction in detector quantum efficiency can be eliminated by using a true photon-counting system in which an event is recognised as a single photon. All the output signals above a threshold generally are counted as photon events provided (i) the incoming photon flux which is of a sufficiently low intensity, (ii) no more than one electron is generated in any pixel during the integration period, (iii) the dark noise is zero and (iv) gain is set at suitable level with respect to the amplifier read noise.

With photon counting an important consideration is the level of clock-induced charges. The clock-induced charges arise from spurious electrons, which do not arise from photons but either from spurious charges created by clocking potential over the surface of the CCD or charges that are thermally generated. Cooling the sensor can significantly reduce the spurious charges. One spurious electron is generated for the transfer of every 10 pixels at -30 ºC. The spurious count rate can drop to one spurious electron every 10,000 pixels at -90 ºC.

Saha and Chinnappan [10] reported EMCCD system having 576x288 pixels of size 20x30 micron in the image area, procured from Andor Technology for the speckle interferometric programs [11] at the 2.34 meter Vainu Bappu Telescope (VBT), Vainu Bappu Observatory (VBO), Kavalur, India. This EMCCD camera is a front-illuminated type with 45% efficiency and is provided with Peltier cooling system that operates at -60 ºC with air-cooling. With additional water circulation, it reaches to -75 ºC. The performance of this cooling system is comparable with liquid nitrogen cooled cryostats. This EMCCD has the provision to change gain from 1 to 1000 by software. The noise at 1 MHz read rate is 2 e rms. Each pixel data is digitized to 16 bit resolution and the data can be archived to a Pentium PC.

V. Avalanche photo-diode (APD)

Avalanche photo-diodes (APD) [12] are the most common solid state photon-counting sensors. They are based on the ionization of a high-voltage pn^+ junction, triggered by a single photo-electron. The avalanche effect in the high-field region of an APD multiplies the number of photo-excited carriers by the avalanche gain. This raises the signal level, which may be useful for raising low signal levels above the amplifier noise. Another consideration is the amount by which the noise is increased through the avalanche process. APDs must have low dark currents, since the latter might be multiplied in the device along with any photo-current. Recent development of solid state photo-detectors with quantum efficiencies reaching over 70% seems very attractive. APDs are being considered for atmospheric Cerenkov telescope (ACT) high energy imaging cameras [13].

VI. Near infrared camera and multi-object spectrometer (NICMOS)

Unlike a CCD, the individual pixels of the near infrared camera and multi-object spectrometer (NICMOS) arrays are strictly independent and can be read non-destructively. NICMOS provides (i) imaging capabilities in broad, medium, and narrow band filters, (ii) broad-band imaging polarimetry, (iii) coronagraphic imaging and (iv)slitless grism spectroscopy, in the wavelength range 0.8-2.5 microns. This camera consists of 256x256 integrating detectors organized in four independent 128x128 quadrants and is fabricated in HgCdTe grown on a saphire substrate which is very rugged and provides a good thermal contraction match to silicon multiplexer [14]. The typical NICMOS3 FPAs have read noise less than 35 e with less than 1 e/sec detector dark current at 77 ºK and broadband quantum efficiency is better than 50% in the range of 0.8 to 2.5 micron. Built by Ball Aerospace, a similar system in the range of 1 to 5 micron has been installed for use in the Hubble space telescope (HST). High performance near- and mid-IR arrays are available for astronomy over the past two decades. From 1 to 5 micron, the arrays use photodiodes in InSb or HgCdTe, whereas detectors operating from 5 to 40 micron are based on extrinsic photoconductivity in silicon [15].

VII. Summary

The coherence time of the atmosphere is a highly variable parameter. Depending upon the high velocity wind, it varies from less than 1 msec to about 0.1 second. The exposure times are to be selected accordingly, to maximize the signal-to-noise ratio, as well as to freeze the speckle pattern [16]. In such a situation, photon counting high speed camera system is ideally suited. The marked advantage of such a scheme is the ability to read the signal a posteriori to optimize the correlation time of short exposures in order to overcome the loss of fringe visibility due to the speckle lifetime. The other notable features are, (i) capability of determining the position of a detected photon to 10micron to 10cm, (ii) ability to register individual photons with equal statistical weight and produces signal pulse (with dead time of ns), and (iii) low dark noise typically of the order of 0.2 counts per square centimeter per second [17].

Optical interferometry using diluted apertures, though a relatively new field, has several new findings to its credit [18, 19]. This technique, in addition to the short-exposure speckle imaging as well as the adaptive optics system, require a high speed intensified sensor. However, in spite of the high sophistication of modern photon counting cameras that are engineered to address the challenges of ultra-low light level imaging applications, they are unable to detect very faint signals and reproduce of interferometric visibilities to high precision.

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