Sensors for the high resolution astronomical imaging

Swapan K. Saha
Indian Institute of Astrophysics, Bangalore - 560 034, India

Abstract

Optical interferometry with single aperture, as well as with multi-aperture require high quality sensor that enables to obtain snap shots with a very fast time resolution of the order of (i) frame integration of 50 Hz, or (ii) photon recording rates of a few MHz. Although advancement of real time compensation of atmospheric turbulence using adaptive optics (AO) system has made inroad in obtaining diffraction-limited astronomical imaging (mostly in infrared wavelength), it needs 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. Until recently, micro channel plate based intensifier is added before a CCD to gather the speckles or fringes of faint objects. Recent development of the solid state based non-intensified low light level CCD (L3CCD), which effectively reduces readout noise to less than one electron RMS has enabled substantial internal gain within the CCD before the signal reaches the output amplifier. After a brief presentation on the interferometry and adaptive optics system, the current trend and future progress in developing new generation optical/IR sensors will be discussed.

1 Introduction

Ever since the invention of telescope, the phenomena of atmospheric turbulence, which distort the phase and amplitude of an incoming wavefront of starlight causing the degradation of image of stars, has frustrated the astronomers who need to look into deep space to unravel the secrets of the universe. The turbulence is because the various layers of the atmosphere have different refractive indices depending on the temperature and pressure at that height. A small temperature fluctuation of one tenth of a degree can generate strong wavefront perturbations over a propagation distance of a few hundred meters. Naturally occurring variations in temperature cause random changes in the wind velocity (eddies), which one views as turbulent motion in the atmosphere. Light reaching the entrance pupil of an imaging system is coherent only within patches of diameters of the atmospheric coherence length, called Fried's parameter [1]. This limited coherence causes blurring of the image, blurring that is modeled by a convolution with the point-spread function (PSF).

The image of a star obtained through a large telescope looks 'speckled' or grainy because different parts of the image are blurred by small areas of turbulence in the Earth's atmosphere. Labeyrie [2] proposed speckle interferometry (SI), a process that deciphers the diffraction-limited Fourier spectrum and image features of stellar objects by taking a large number of very-short-exposure images of the same field. Computer assistance is then used to reconstruct from these many images a single image that is free of turbulent areas-in essence, an image of the object as it might appear from space.

Recent advancement of hardware technology made astronomers to develop a technique, called adaptive optics (AO) system, which removes turbulence induced wavefront distortions in real time. In recent years, the technology and practice of such a system has become, if not commonplace, at least well known in the defence and astronomical communities. 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 [3, 4].

All these afore-mentioned techniques require a high quality sensor so as to enable one to obtain snap shots with a very high time resolution of the order of (i) frame integration of 50 Hz, or (ii) photon recording rates of several MHz. In what follows, a few sensors that are used for the high resolution image are enumerated in brief.

2 Conventional sensors

Till a few decades ago, astronomers used photographic technique to record images or spectra of celestial objects. Owing to low quantum efficiency of the photographic emulsion, usage of the modern cooled charge coupled device (CCD) camera system became necessary 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.

2.1 Charge-coupled device (CCD)

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. A polysilicon gate is applied on the Silicon substrate separated by a thin insulating layer made of Silicon-Silicon dioxide.

The operating principle of CCD is photoelectric effect. When a positive potential is applied to the electrode, the holes are repelled from the region beneath the Silicon-Silicon-dioxide layer and a depletion region is formed. This depletion region is an electrostatic potential well whose depth is proportional to the applied voltage. The free electrons are generated by the incident photons, as well as by the thermal energy, and are attracted by the electrode and thus get collected in the potential well. The holes, that are generated, are repelled out of the depletion region and are lost in the substrate. The electrons and the holes that are generated outside the depletion region, recombine before they could be attracted towards the depletion region.

Figure 1: Left panel: Preamplifier board is mounted which will be coordinating output signal of CCD to its controller that is connected to a PC; Right panel: CCD Dewar is filled with LN_2 (Liquid Nitrogen) to cool the CCD.

The whole CCD chip is a two dimensional array of such pixels. The electrons, that are collected, should be shifted along the columns. The whole CCD array can be conceived as shift registers arranged in the form of columns close to each other. Highly doped p-regions, called channel stops, are deposited between these columns so that the charges do not move across the columns. Every third electrode in these shift registers are connected to the same potential. The electrodes of each pixel in a column are connected to the corresponding electrodes in other columns also. By manipulating the voltages on these electrodes, the charges can be shifted along the columns. This array is the imaging area and is referred as the parallel register.

The CCD is exposed to the incident light for a specified time generally called the exposure time. During this time the central electrode in each pixel is kept at a more positive potential than the other two (3-phase CCD). The charge collected under this electrode should be measured. First the charges should be shifted vertically along the parallel register (the columns) onto the output register. After each parallel shift, the charges should be shifted along the output register horizontally onto the output amplifier. Hence there should be n serial shifts after each parallel shift, where n is the number of columns.

The main advantage of CCD is its good quantum efficiency (back-illuminated CCD responses as high as 90%). The other notable qualities are large dynamical range and linearity of response (see Table 1). The limitation comes from the heterogeneities of response. This is due to unidentical elements. There are a few hot pixels which is abnormally receptive and a few do not work. In order to identify such elements, calibration may be made by analyzing flat fields with various intensities and spectral distributions. In general, a scientific grade CCD has more than 99% operative pixels. The exceptional pixels are either dead, producing no signal, or hot that are abnormally receptive, while a few do not work. The pixels have a Gaussian distribution of read noises, but with a tail extending to high values. There are several sources of nonuniformities, which pose limitation on the performance of the device, should be removed in a series of processing steps. These are (i) zero variations, (ii) bias variations, (iii) thermal agitation, (iv) dark current, and (v) Pixel-to-pixel variations. The processing steps work better if the operating conditions of the array are kept as constant as possible throughout acquisition of the science data and calibration images.

Table 1
Typical Performance of CCD

Characteristics	Range
Quantum efficiency	90 %
Charge transfer efficiency	99.995%
Spectral range	350 - 1000 nm
Peak signal	200 ke/pixel
Output amplifier sensitivity	6.0 microvolt/e
Linearity	0.1%
Readout noise at 20 KHz	4-6 e RMS
Uniformity of response	5 %

2.2 Frame-transfer camera system

A frame-transfer CCD is composed of two parallel registers and a single serial register. The parallel register next to the serial register is opaque to light and is referred to as the storage array while the other parallel register having the same format as the storage array is called image array. After the integration cycle, the charge is transferred quickly from the light sensitive pixels to the covered portion for data storage and the image is read from the storage area when the next integration starts. This kind of detectors are usually operated without shutter at television frame rates.

The frame-transfer intensified CCD (ICCD) detector consists of an image intensifier coupled to a CCD camera [6]. This system employs micro-channel plate (MCP) as an intensifier. In the MCP image intensifier, the photo-electron is accelerated into a channel of the MCP releasing secondaries and producing an output charge cloud of about $10^3 - 10^4$ electrons with 5 - 10 kilovolt (KV) potential. With further applied potential of $\sim$ 5 - 7 KV, these electrons are accelerated to impact a phosphor, thus producing an output pulse of $\sim\ 10^5$ photons. These photons are directed to the CCD by fibre optic coupling and operate at commercial video rate with an exposure of 20 ms per frame [7]. The video frame grabber cards digitize and store the images in the memory buffer of the card. Depending on the buffer size, the number of interlaced frames stored in the personal computer (PC) can vary from 2 to 32 [8, 9].

3 Photon counting camera system

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. In such a situation, photon counting camera system is ideally suited. The marked advantage of such a scheme is that of reading 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 10 micron to 10 cm, (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.

The frame integrated photon counting camera was developed by Blazit [10]. His subsequent development in this direction was CP40 that consists of a set of four Thomson 288×384 CCDs image sensors with a common stack of a 40 mm diameter Varo image tube and a MCP. However, the major short-comings of such a system based on frame integration [11], arise from the (i) calculations of the coordinates which are hardware-limited and (ii) limited dynamic range of the detector.

Several photon-counting sensors that allow recording of the position and time of arrival of each detected photons have also been developed such as, (i) Precision analog photon address (PAPA; [12], (ii) resistive anode position detector [13], (iii) multi anode micro-channel array (MAMA; [14], (iv) wedge-and-strip anodes [15], and (v) delay-line anodes [16]. PAPA detector allows recording of the address (position) and time of arrival of each detected photon. The front end of the camera is a high gain image intensifier which produces a bright spot on its output phosphor for events detected by the photocathod. The back face (phosphor) of the intensifier is then re-imaged by an optical system which is made up of a large collimating lens and array of smaller lenses. Each of the small lenses produces a separate image of the phosphor on a binary mask.

Behind each mask is a field lens which relays the pupil of the small lens onto a small photo-multiplier (PMT). The remaining sensors detect the charge cloud from a high gain MCP. They provide spatial event information by means of the position sensitive readout set-up; the encoding systems identify each event's location.

4 Low light level CCD (L3CCD)

All the afore-mentioned devices have several problems [17, 18]. They suffer from (i) low quantum efficiency and (ii) false counting due to thermoionic emission. Alternative resolutions for the detection of photons cameras with photon counting rest on the principle of a multiplication of photo-electrons.

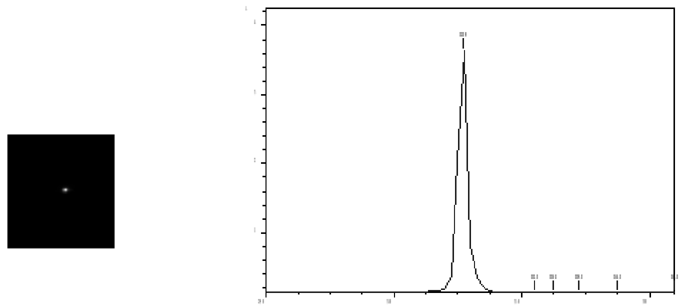

Figure 2: Left panel: Corrected image with a tip-tilt mirror for tilt error correction and other high frequency errors with a MMDM; Right panel: its cross section; images are twice magnified for better visibility (Courtesy: V. Chinnappan).

The low light level CCD (L3CCD; [19] is developed using both front- and back-illuminated CCD and is provided with Peltier cooling system that is comparable with liquid nitrogen cooled cryostats. It is a frame transfer device where the image store and readout register are of conventional design that operates 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. Adjustment of gain is possible with fine control of the voltage. All the output signals above a threshold may be counted as photon events provided the incoming photon flux is of a sufficiently low intensity that no more than one electron is generated in any pixel during the integration period, and the dark noise is zero, and gain is set at suitable level with respect to the amplifier read noise.

An important factor influencing electron multiplication gain is that of cooling the CCD; the more cooler the CCD, a primary electron generates a secondary electron in the silicon, which gives rise to higher on-chip multiplication gain. The system is provided with Peltier cooling that operates to - 65°C with air-cooling and with further additional water circulation, it reaches -80°C. The performance of this cooling system is comparable with a liquid nitrogen cooled cryostats. Saha and Chinnappan [20] reported that their L3CCD has the provision to change gain from 1 to 1000 by software. The noise at 1 MHz read rate is 0.1 e. Each pixel data is digitized to 16 bit resolution; the data can be archieved to a Pentium PC. Figure (2) depicts a corrected image with a tip-tilt mirror for tilt error correction and other high frequency errors with a membrane deformable mirror (MMDM), and (d) its cross section.

5 Infrared sensors

Use of IR detectors as a regular instrument in astronomy began a couple of decades ago, although sensitive IR detectors were in place by the mid 1960's. The first infrared survey of the sky was made at the Mt. Wilson Observatory employing a liquid nitrogen cooled lead-sulphide (PbS) detectors, which revealed as many as 20,000 IR sources.

In the infrared band, no photon-counting is possible with the current technology. Nevertheless, a near-IR focal-plane array, NICMOS, has been developed. It consists of 256 X 256 integrating detectors organized in four independent 128 X 128 quadrants and is fabricated in HgCdTe grown on a saphire substrate that is very rugged and provides a good thermal contraction match to silicon multiplexer [21]. The typical NICMOS3 FPAs have read noise less than 35 e- with less than 1 e-/sec detector dark current at 77 K and broadband quantum efficiency is better than 50% in the range of 0.8 to 2.5 μm.

6 Summary

Optical interferometry using diluted apertures, though a relatively new field, has several new findings to its credit [22, 23]. This technique, in addition to the short-exposure speckle imaging as well as the adaptive optics system, require a 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 reproduction of interferometric visibilities to high precision.

Frame transfer photon counting detectors have limited use since they are prone produce Centreur hole resulting in the degradation of the power spectra or bispectra (Fourier transform of triple correlation) of speckle images. A photon counting system has an advantage, since it detects photons individually, as well as measures the photon positions in an (x,y) focal plane. In the field of optical interferometry, the time resolution of these cameras should reach 1 msec.

For experiments like speckle imaging and adaptive optics where the integration time is dictated by the atmospheric coherence time, which is normally of the order of a few milliseconds, this L3CCD may be more suitable than the MCP-based detectors. For the selective image reconstruction technique [24], where a few sharpest images are selected from a large data set of short-exposures images, such a detector provides important advantages [25].

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 [26].

References

1. Fried D. L., 1966, J. Opt. Soc. Am., 56, 1380.
2. Labeyrie A., 1970, Astron. Astrophys., 6, 85.
3. Roggemann M C, Welsh B M, Fugate R Q, 1997, Rev. Modern Phys., 69, 437.
4. Roddier F, 1999, Adaptive Optics in Astronomy, Cambridge Univ. Press.
5. Boyle W. S. Smith G. E., 1970, Bell System Tech. J., 49, 587.
6. Lemonier M., Richard J. -C., Riou D., Fouassier M, 1988, SPIE., 980, 27.
7. Chinnappan V., Saha S. K., Faseehana, 1991, Kod. Obs. Bull., 11, 87.
8. Saha S. K., Jayarajan A. P., Sudheendra G., Umesh Chandra A., 1997a, Bull. Astron. Soc. Ind., 25, 379.
9. Saha S. K., Sudheendra G., Umesh Chandra A., Chinnappan V., 1999, Experimental Astronomy. 9, 39.
10. Blazit A., 1976, Thesis, University of Paris.
11. Blazit A., 1986, SPIE, 702, 259.
12. Papaliolios C., Mertz L., 1982, SPIE, 331, 360.
13. Clampin M., Crocker J., Paresce F., Rafal M., 1988, Rev. Sci. Instr., 59, 1269.
14. Timothy J. G., 1993, Proc. SPIE., 1982, 4.
15. Siegmund O. H. W., Lampton M., Bixler J., Chakrabarti S., Vallaga J., Bowyer S., Malina R. F., 1986, J. Opt. Soc. Am., 3, 2139.
16. Lampton M., Siegmund O., Raffanti R., 1987, Rev. Sci. Instrum., 58, 2298.
17. Morel S., Saha S. K., 2005, '21st Century Astrophysics', Eds. S. K. Saha, and V. K. Rastogi, Anita Publications, New Delhi, 237.
18. Saha S. K., 2007, Diffraction limited imaging with large and moderate telescopes, World-Scientific, New Jersey.
19. Jerram P., Pool P., Bell R., Burt D., Bowring S., Spencer S., Hazelwood M., Moody L., Carlett N., Heyes P., 2001, Marconi Appl. Techn.
20. Saha S. K., Chinnappan V., 1999, Bull. Astron. Soc. Ind., 27, 327.
21. Cooper D., Bui D., Bailey R., Kozlowski L., Vural K., 1993, SPIE, 1946, 170.
22. Labeyrie A., 1975, Astrophys. J., 196, L71.
23. Saha S. K., 2002, Rev. Mod. Phys., 74, 551.
24. Dantowitz R. F., Teare S., Kozubal M., 2000, A J, 119, 2455.
25. Baldwin J. E., Tubbs R. N., Cox G. C., Mackay C. D., Wilson R. W., Anderson M. I., 2001, A & A., 368, L1.
26. Reike G. H., 2007, Ann. Rev. Astron. Astrophys., 45, 77.