

CCD-Based Instrumentation for Radiometric Measurements, for the Space Qualified Optics

Shamanth N¹, H.R. Ramesh², Sathya Narayan Raju K³, Bijoy Raha⁴,
Krishnamprasad B⁵, Elumalai S⁶,

¹M.E. Student (Control and Instrumentation), Department of Electrical Engineering, UVCE, Bangalore-01

²Associate Professors, Department of Electrical Engineering, UVCE, Bangalore-01

³OEND, Scientist/Engineer-SC, LEOS-ISRO, Bengaluru-58

⁴OEND, Scientist/Engineer-SD, LEOS-ISRO, Bengaluru-58

⁵Scientist/Engineer 'SF' section head (LLIS, SDA), LEOS-ISRO, Bengaluru-58

⁶Scientist/Engineer 'SG' (OPD) LEOS-ISRO, Bengaluru-58

Abstract: The use of CCD detectors for radiometric measurements has more advantages and time saving compared to the use of single element detectors. This research work presents realization of hardware, development of software and testing. This work also presents the method to measure intensity of light and calibrating space borne optics.

Key words: Charge Coupled Devices (CCD), Photons, Radiance, Illuminance, Transmission, Effective Focal Length (EFL).

I. INTRODUCTION

Light is just one portion of the various electromagnetic waves flying through space. The electromagnetic spectrum covers an extremely broad range, from radio waves with wavelengths of a meter or more, down to x-rays with wavelengths of less than a billionth of a meter. Optical radiation lies between radio waves and x-rays on the spectrum, exhibiting a unique mix of ray, wave, and quantum properties. In optics radiometry is a set of techniques for measuring electromagnetic radiation including visible light. A radiometric technique which characterizes the distribution of radiation power in space. Generally electromagnetic radiation or EMR is classified by wave length into radio, microwave, infrared, visible region (light), ultraviolet, x-rays and gamma rays all Electromagnetic radiation is a form of energy. The spectrum of such radiation provides information on its energy composition. The entire spectrum of electromagnetic radiation ranges from X-ray radiation at the high-energy, short-wave end to radio waves at the low-energy, long-wave end. Radiometry is the measurement of optical radiation, which is electromagnetic radiation within the frequency range between 3×10^{11} and 3×10^{16} Hz.

This range corresponds to wavelengths between 0.01 and 1000 micrometers (mm), and includes the regions commonly called the ultraviolet (UV), the visible (VIS), and the infrared (IR). Like all electromagnetic waves, light waves can interfere with each other, become directionally polarized, and bend slightly when passing an edge. These properties allow light to be filtered by wavelength or amplified coherently as in a laser. In radiometry, light's propagating wavefront is modelled as a ray travelling in a straight line. Lenses and mirrors redirect these rays along predictable paths. Wave effects are insignificant in an incoherent, large scale optical system because the light waves are randomly distributed and there are plenty of photons. The use of single element silicon detector has several disadvantages, they are 1. Most of the instrumentation and human errors are reduced compare to older methods. 2. All the readouts can be stored in the PC and can be used at any time. 3. The lenses which undergo radiometric measurements remain undisturbed till the completion of measurements. 4 Time saving and helps in decision making process this paper gives the details of designing of an hardware, software, implementation of the system for calibration of the lenses, calculation of relative-illumination, result and discursion and final conclusion.

II. DISCRPTION AND OPERATION OF CCD BASED INSTRUMENT

The CCD line sensor contains a photoactive region which is a linear array of Individual pixels. These pixels are sensitive to light and accumulate electric charges which are proportional to the light intensity and the light exposure time. Those charges are converted to digital light intensity values through the analog-to-digital converter (ADC). As soon as an acquisition has been initiated by the host PC, the acquired data is stored in onboard RAM and finally sent to the PC through USB.

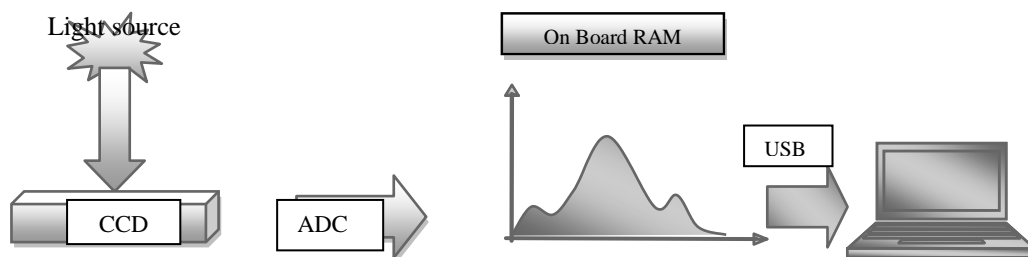


Fig 2.1 Operations of CCD based system

III. CCD ARRAYS

3.1 Principle of operation:

CCDs are array detectors with metal oxide capacitors (photo gates). During the illumination by the spectrum focal line a charge (electron – hole pairs) is produced under the gate. A potential well is created by applying a voltage to the gate electrode. The charge is confined in the well associated with each pixel by the surrounding zones of higher potential. The read out of the array is preceded by a charge transfer by means of varying gate potentials according to sequential clock schemes. The charges of the pixels are transferred simultaneously to the shift register(s), followed by a sequential transfer to the output section, where the charge is converted into a proportional voltage. The node doing this is first set to a reference level (clamp level) and afterwards to the signal level. The difference is used as the final signal. This technique is called Correlated Double Sampling (CDS) and allows a significant reduction of the system noise. The signals of each pixel row in the direction perpendicular to the spectrum are additionally combined to create a greater pixel height.

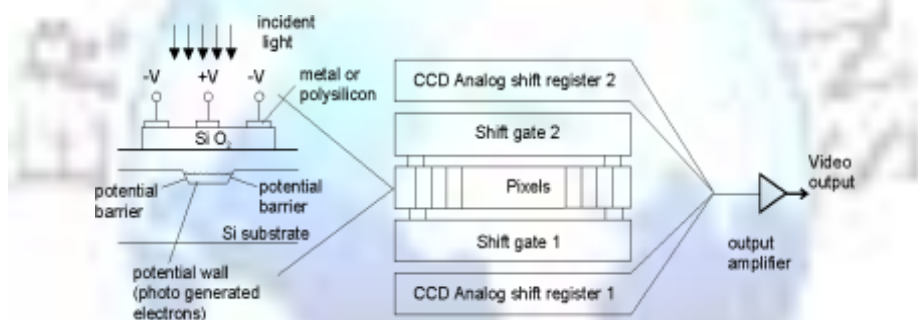


Fig: 3.1 Operation principle of a CCD array detector

3.2. Line Arrays for Radiometer

Line arrays are detectors with several individual readable sensitive areas, so-called pixels (picture elements), arranged in one straight line. They can be seen as “black boxes” transforming a spatially light distribution, in case of radiometers the spectrum focus line, into a signal voltage or current distributed in time. This sequential output signal, the video signal, is further preceded, mainly with an analog digital conversion as the first step.

3.3. The main parameters of line detectors

- Pixel number – the number of pixels arranged in the line
- Pixel dimensions – the pixel width and height [μm]
- Pixel pitch – the distance between the centers of two pixels [μm]
- Sensitivity – the wavelength dependent ratio of electrical signal output to the optical signal input [e.g. $\text{V}/\text{lx}\cdot\text{s}$]
- Wavelength range – the range of wavelengths where the detector can “see” radiation [nm]
- Dark signal – the output signal without illumination of the detector [e.g. mV]
- Saturation exposure – the illumination level, at which the output signal stays constant with increasing illuminance [e.g. $\text{mlx}\cdot\text{s}$]
- Linearity range – the illuminance range where the electrical signal output is proportional to the impinging energy [e.g. $\text{mlx}\cdot\text{s}$]

- Dynamic range – the range in which the detector is capable of accurately measuring the input signal [10^x]
- Pixel non-uniformity – the output signal difference of the pixels under same illumination conditions [%]
- The scheme of the operation pulses (every line detector needs several clocks for the read out operation)
- The thermal behaviour of the array.
- The image lag – a property of line detectors to “remember” the illumination of previous read out’s.

3.4. Criteria of Selection for a Specific Application

There are many parameters to consider for a proper selection of a line array for a specific application. Furthermore, it is necessary to weight the significance of the parameters because there is often no ideal choice possible.

Wavelength Range and Sensitivity: The detectable wavelength range of silicon-based arrays extends from 200 to 1100nm; above this limit the photon energy is lower than the band gap energy.

Pixel Dimensions (pitch and height): The pixel dimensions are an essential criterion for the selection of an array. The pixel width and pitch influence the digital resolution of a CCD and stand in relation to its optical resolution. If the pixel height is too low, a part of the signal is lost and the efficiency of the system is low. On the other side a pixel height much larger than the spectrum height ends in an unwanted increased stray light influence.

Dark Output: The dark output is a small electrical output of the line array without incident light. It is caused by thermal generation of carriers in the light sensitive elements, mainly due to Si – SiO₂ interface states. It has a strong correlation with the operation temperature. The dark output doubles for every temperature increase of 6 ... 10 K. Therefore, line arrays are cooled in low light level applications, e.g. in astronomic measurements.

Saturation and Linearity Range: Saturation exposure is that level of photon intensity where the photon signal of the detector is no more dependent on the incident light flux. The value depends on the doping of the detector material. A rule of thumb is that a good linearity is achieved with photodiode and CCD arrays modulated between 0 and approximately 75 % of the saturation charge (exposure). Above this value the non-linearity raises significantly.

3.5 Types of Video Signals

The classical video signal originates from the TV technologies. The defined voltages are 1 V for the synchronization level, 0.75 V for black and 0 V for white. This video signal is called negative. Furthermore, all video signals have a positive offset voltage shifting the levels to higher values

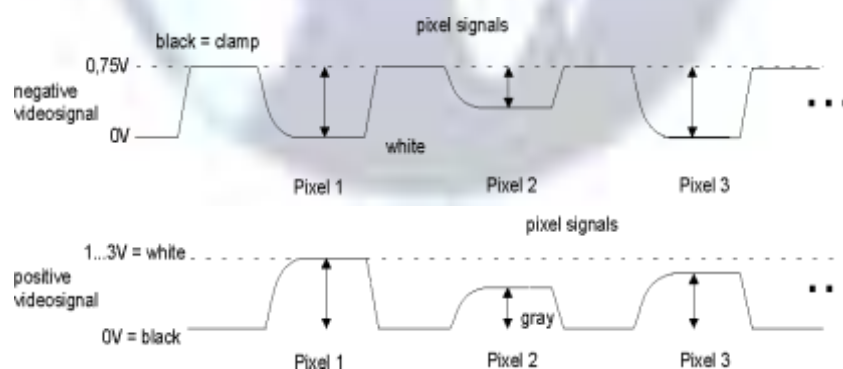


Fig 3.2: Scheme of the image lag

Negative video signals often offer a so-called clamp level, which allows to set back the integrator to a defined offset voltage. So it is possible to use the clamp signal for a technique called correlated double sampling (CDS). One capacitor is loaded with the black level, the other one with the active video signal. The combination of both capacitors subtracts the charges. The result is a positive video signal for the ADC. Another solution uses two conversions of the black level and the active video signal and a following difference operation. This solution is much slower than the first one. The AD conversion is mainly based on a positive ADC related to 0 V. Therefore, a positive video signal offers the advantage of a much simpler subsequent AD converter. Furthermore, an additional noise due to further amplifiers is avoided

IV. READ OUT ELECTRONICS AND HARDWEARE

4.1 Components of Line Array Read Out Electronics and Algorithm



Fig: 4.1 Block diagram of a simplified CCD based instrumentation for radiometric measurement

A read out electronics for line arrays consists of the following main parts:

- **Timing:** The electronics needs to generate the necessary clock pulses for the array. These pulses differ from array type to type.
- **Drive circuit:** It serves for the operation of the shift registers.
- **Signal processing circuit:** It serves for the CDS and the amplification.
- **AD converter:** It transforms the analog signal to a digital level.
- **Processor:** It controls all processes and can be used for a precalculation of raw data
- **RAM memory:** There can be stored system data (e.g. the pixel – wavelength fit and measured data (e.g. dark signal or reference signal).
- **Interface driver circuits:** They manage the data transfer via different interfaces (e.g. USB, RS 232, parallel, CAN).

4.2 Schematic of the system: The schematic view of the entire circuit diagram is shown in fig:4.2 which consists of FCCD143A,ADC0804,OP27,LM117,LM136, MAX

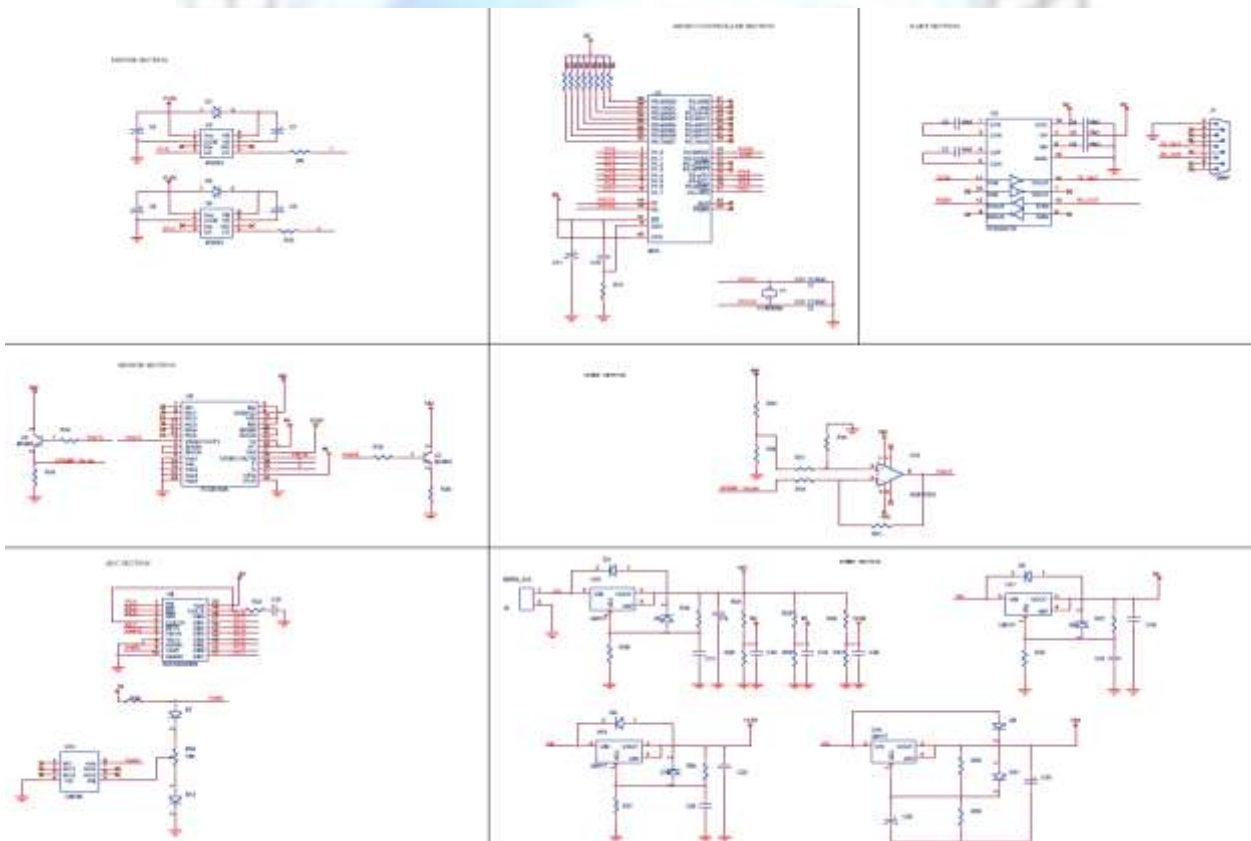


Fig 4.2: Schematic of the system

VI. RELATIVE ILLUMINATION CALCULATIONS

4.1 Relative illumination:

Relative illumination in an optical system is a function of many variables including distortion, vignetting, and pupil aberration. It can be obtained by determining the size of the exit pupil in direction cosine space, using the appropriate coordinate system. In general, the calculation is done by tracing bundles of rays through the system. In many cases of interest, it is possible to calculate relative illumination accurately by tracing one on-axis ray and three off-axis rays. We assume a uniform light intensity over the object and that it behaves like a plane lambertian source. If we plot the exit pupil shape, as defined by the limiting rays, as a function of (l, m) we get a figure whose area is proportional to the illumination on the image surface. This is illustrated in Figure 4.1. Thus, the relative illumination is obtained by dividing the off-axis pupil area by the on-axis pupil area. It should be noted that this approach automatically takes into account any variation of pupil size as a function of field, including the effects of vignetting and image distortion. It is valid for any general optical system and is not limited to rotationally symmetric systems.

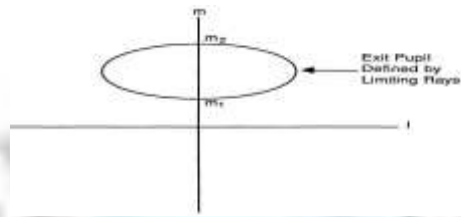


Figure 4.1: Exit pupil in direction cosine space

The effective F-number can also be obtained from Figure 4.1. If we denote the points where the exit pupil periphery crosses the m -axis in the figure by m_1 and m_2 , the effective F-number in the m -direction is $l/(m_2 - m_1)$. A corresponding number can be obtained in the l -direction.

4.2 The cosine 4 law:

Figure 6.1 depicts the exit space of a thin lens with stop in contact and shows the limiting rays for the on-axis beam and for an off-axis beam where the chief ray makes an angle, U , with the optical axis. R is the radius of the pupil, D is the distance from the pupil to the image, and H is the image height. We can algebraically define the direction cosines of the limiting rays in the meridional and sagittal directions and, assuming the pupil can be represented by an ellipse, generate an expression for the relative illumination. If we now take this expression and let R go to zero (the paraxial limit), we will find that the relative illumination, RI , is

$$RI = \cos^4 U$$

This is the well known cosine⁴ law and agrees with the simpler notion that one cosine arises from the obliquity of the beam with the image, one from the obliquity with the pupil, and two from the square of the reciprocal distance. This law more generally applies to a flat-field system whose exit pupil is constant in size and position with respect to field. The angle, U , is measured in image space. If, in addition, the pupils of the system are at the nodal points, the angle in object space is also U .

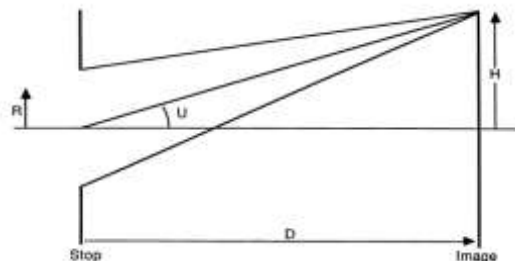


Figure 4.2: Thin lens with stop in contact

4.3 A simplified calculation

The extensive ray tracing described above is not required in many cases. If we assume a rotationally symmetric lens with no obstructions, then in most cases the pupil can be approximated by an ellipse sufficiently accurately. The ellipse, in turn, can be defined by two meridional rays and one sagittal ray. On-axis, of course, only one ray is needed since the pupil is circular. Figure 5.3 shows on-axis and off-axis exit pupils and gives the directions cosines for the defining rays. The relative illumination is then $RI = (m_2 - m_1) / (2m_0^2)$.

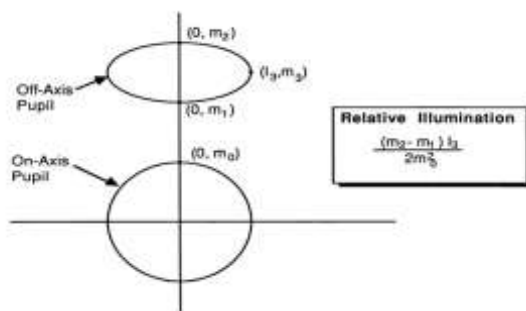


Fig 5.3 Simplified Calculations

V. IMPLIMENTATION OF THE SYSTEM AND EXPERIMENTAL METHOD

5.1 Experiment Setup:

The experiment setup consist of a CCD based Instrumentation, Integration sphere, Microcontroller based stepper motor, Optics bench which consist of a lens which has to be calibrated and a Personnel computer. The setup for the calibration of flight lenses is as shown in below.

5.2 Procedure to carry out the Experiments

1. Place the lens in a optical bench in front of integration sphere as shown in the setup diagram.
2. Switch on the integration sphere and adjust the light intensity such that CCD should not saturate.
- 3 Adjust the focal length of the lens such that the exact focal point should fall on the CCD.
4. Interface the CCD to a PC using USB and open a Front Panel of the Lab view.
5. Select the communication link from VISA box of the front panel and adjust the integration time. Integration time must be greater than the CCD.
6. Click the run continues button from the front panel to start the data acquisition. The data i.e. intensity with respect to pixels can be stored in the array.
7. Take the 20 pixel values from 20 off-axis side and 20 pixel values from on axis side and calculate the sum of average of these pixels after this divide the off-axis value to the on-axis value the resultant value should follow the \cos^4 of the total angle subtend from off-axis to on-axis.

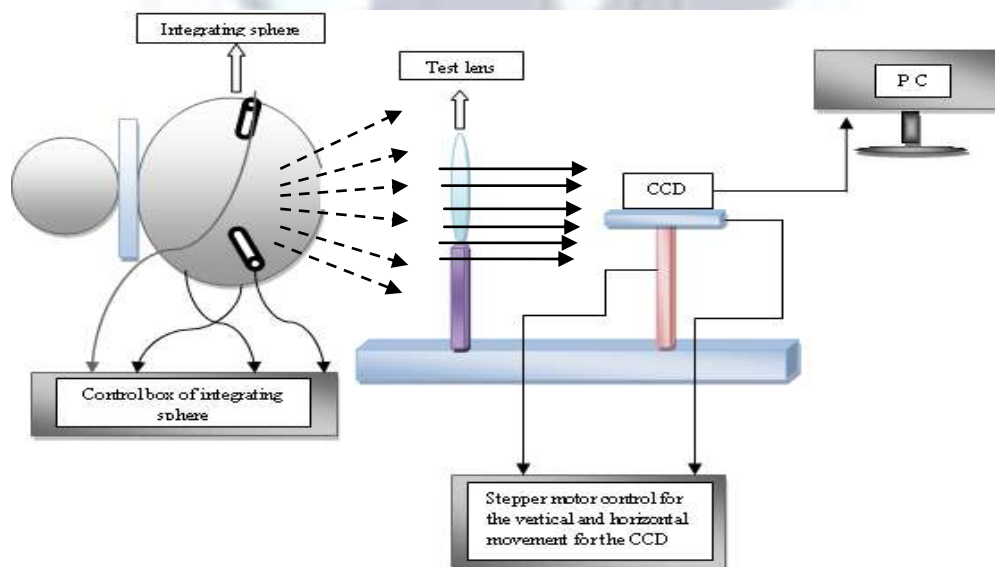


Fig 5.1: Block diagram of Experiment setup

5.3 GUI using Lab View.

The GUI consists of a user interfaces, in that a user can use the CCD based Instruments according to the required form. The GUI consists of a VISA which provides standardized software interface permitting the use of instruments under VXI, GPIB, RS232C,PXI or any other hardware protocol. Graphs are used to display the acquired data, control boxes are used to give a command to the interfaced instruments and an array to store the readout data.

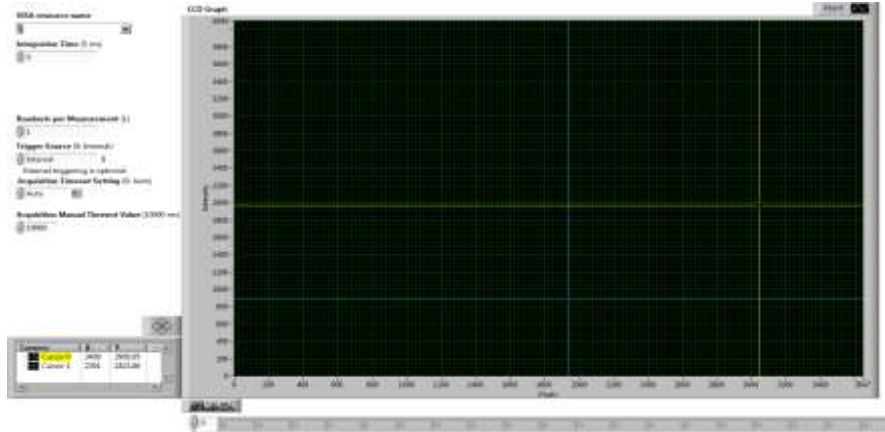


Fig: 5.6 Graphical user interface using LabView

5.4 Experiment Results

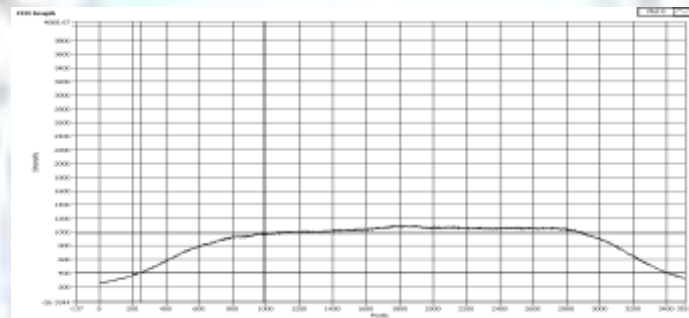


Fig:5.7 80% of the pixels are exposed to the light

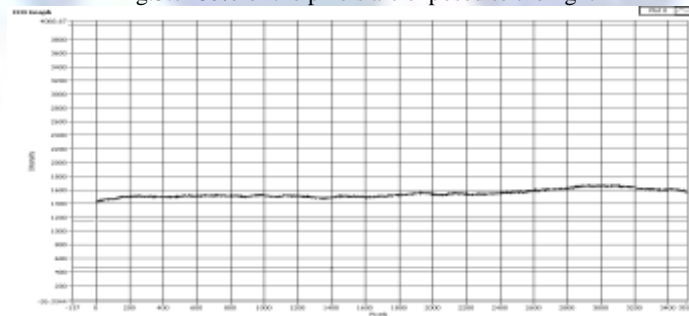


Fig: 5.8 All pixels are exposed to light



Fig: 5.9 Graph of light intensity w.r.t pixels when CCD is moved towards the right extreme end of the field of view

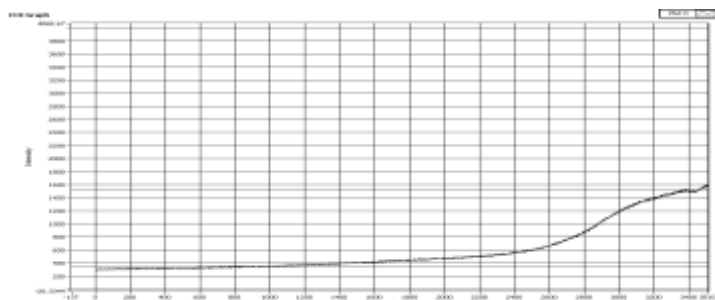


Fig: 5.10 Graph of light intensity w.r.t pixels when CCD is moved towards the left extreme end of the field of view

7.4 Example:

Using Figure 4.2, we can arbitrarily assign the values, $R = 1$, $D = 10$ and $H = 10$. This corresponds to a $F/5$ lens at a 45 degree obliquity. The values of the limiting direction cosines are $m_0 = 0.0995$, $m_1 = 0.7399$, $m_2 = 0.6690$ and $m_3 = 0.0705$. Evaluating equation $RI = (m_2 - m_1) / (2m_0^2)$ gives a relative illumination of 25.2 percent which is very close to the 25.0 percent predicted by the cosine law.

VI. CONCLUSION

The CCD based instrumentation for radiometric measurements is implemented. Use of CCD based instrument in radiometry have produced more accurate values compared to a single element detector. CCD based instrument satisfy the cosine⁴ law more accurately. The instrument showed excellent performance. Few lenses are tested from this instrument using the above discussed method and the test results are compared with the theoretical values.

ACKNOWLEDGEMENT

The present work was carried out at Optics Development Area, Laboratory for Electro-Optics Systems, Indian Space Research Organization, Bangalore. The authors are grateful to Shri J. A. Kamalakar, Director, LEOS-ISRO for his support during this work.

REFERENCES

- [1]. W. Boyle and G. Smith, "Charge coupled devices," Bell Syst. Tech. J., 49, pp. 587-593 (1970).
- [2]. J. R. Janesick, "History, Operation, Performance, Design, Fabrication and Theory," Scientific Charge-Coupled Devices, ed. (SPIE Press, Bellingham, Washington, USA, 2001), pp. 3-94.
- [3]. R. Gentile, P. Allebach and E. Wallowood, "Quantization of Colour Images Based on Uniform Colour Spaces," J. of Imag. Techn.,
- [4]. JETI Technische Instrument GmbH Jena, May 2005.
- [5]. Stimson, A. (1974). Photometry and Radiometry for Engineers. New York: John Wiley & Sons.
- [6]. Data sheets of FCCD143A, 89V51RD2, AD0804, IR2110, LM136, LM137, LM117, OP027 and MAX232.
- [7]. Hopkins, H. H., Optical Design Calculations Using Canonical Coordinates, Lecture Notes, Univ. of Reading.
- [8]. Hopkins, H. H., Image Formation by a General Optical System, Lecture Notes, Univ. of Reading.
- [9].

AUTHORS

First Author: SHAMANTH. N, IV Sem, M.E (Control and Instrumentation), Department Of Electrical Engineering, University Visvesvaraya College of Engineering, Bengaluru-560001, Karnataka, India. E-mail: shamanthcpl@gmail.com, Mob: +91-8088035087.

Second Author: Mr. H. R. RAMESH, Associate. Professor, Department Of Electrical Engineering, University Visvesvaraya College of Engineering, Bengaluru-560001, Karnataka, India. E-mail: nayaka.ramesh@yahoo.com

Third Author: Mr. SATHYA NARAYAN RAJU.K Scientist/Engineer-Sc, LEOS-ISRO, I Phase, Peenya Industrial Area, Bengaluru-560058, Karnataka,

Fourth Author: Mr. BIJOY RAHA, OEND, OPG, Scientist/Engineer-SD, LEOS-ISRO, I Phase, Peenya Industrial Area, Bengaluru-560058, Karnataka, India. E-mail: bijoy_raha@leos.gov.in

Fifth Author: Mr. KRISHNAM PRASAD B Scientist/Engineer 'SF', section head (LLIS,SDA), LEOS-ISRO, I Phase, Peenya Industrial Area, Bengaluru-560058, Karnataka, India.

Sixth Author: Mr. ELUMALAI. S Scientist/Engineer 'SG'(OPD), LEOS-ISRO, I Phase, Peenya Industrial Area, Bengaluru-560058, Karnataka, India. E-mail: elumalai@leos.gov.in