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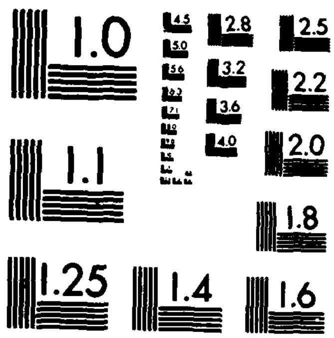

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Project Report
ETS-72

AD A 137214

A CCD Photometric Camera for Satellite Observation

G.J. Mayer
M.J. MacDonald
N.G.S. Pong

29 November 1983

Lincoln Laboratory

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

Lexington, Massachusetts

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This technical report has been reviewed and is approved for publication.

FOR THE COMMANDER

Thomas J. Alpert, Major, USAF
Chief, ESD Lincoln Laboratory Project Office

MASSACHUSETTS INSTITUTE OF TECHNOLOGY
LINCOLN LABORATORY

A CCD PHOTOMETRIC CAMERA FOR SATELLITE OBSERVATION

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Group 94

PROJECT REPORT ETS-72

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LEXINGTON MASSACHUSETTS

Abstract

A CCD camera for photometric measurement of satellites has been built, tested, and has been integrated into the Experimental Test System (ETS). This report describes the camera, the computer system and programs used to collect data, the camera's sensitivity parameters, the sensitivity of the camera on the ETS 31-inch Telescope, and its projected sensitivity on Ground-Based Electro-Optical Deep Space Surveillance System (GEODSS) main telescope.

CONTENTS

I. INTRODUCTION

Presently satellite optical signatures (intensity vs. time) are measured by GaAs photo-multiplier tubes in the ETS and GEODSS systems. These area photometers generate a voltage that is proportional to the light striking the entire tube. In order to reduce the unwanted light from stars and the night sky background, field stops are inserted in the optical path to reduce the field of view. Typically the field of view is 30 to 60 arc-seconds. This large field of view, relative to the satellite image, is due to the variability in seeing conditions, pointing and tracking limitations, and uncertainty as to whether the satellite is always within the field of view. The field stop selection is a compromise and cannot be changed as rapidly as the seeing conditions change.

The photo-multiplier tube cannot image the sky it is looking at, so a beam splitter or pellicle optical system is used to divert most of the light to the photo-multiplier tube and a small amount of light to an imaging camera. This allows the operator to see when the satellite light that is being measured is contaminated by star light or bright cloud light, and when the satellite is no longer in the field of view. This arrangement is another compromise between wanting to get the maximum amount of satellite light to the photo-multiplier and providing enough light to enable the operator to see the satellite and stars.

The sky background light measurement is subtracted from the combined satellite and sky measurement, which results in the satellite light intensity. The photo-multiplier system makes a sky background measurement either before or after the satellite measurement. A good background measurement should be made near the satellite and not contain a star. The operator must view the background field of view, reject those that contain a star, and accept one that doesn't. The procedure to take a background measurement (including moving the beamsplitter or pellicle in and out of the optical path) can take longer than the satellite measurement.

A CCD array used as the sensor in a satellite photometer system inherently removes the limitations described for the photo-multiplier tube. A 30 x 30 pixel CCD will have a field of view of 48 x 48 arc-seconds when a pixel size is 1.6 x 1.6 arc-seconds. This field of view is large enough to keep a satellite in the field of view despite seeing and tracking limitations. The light striking each pixel is maintained in that location and then read-out one pixel at a time. The pixels that contain a satellite image can be separated from the pixels that contain only the background. This feature allows the CCD photometer to be used without a field stop and at the same time allows only the pixels containing the satellite image to be summed, which gives the maximum satellite signal and the minimum background contamination. This can be done continously for each 30 x 30 image frame despite seeing and tracking perturbations.

The CCD array is a self-scanning imager that can be displayed while it is also being used for photometry. This eliminates the need for beamsplitting, and therefore the total amount of light is seen by the CCD, which is the photometer and imager that views the photometry field of view. A significant amount of operating time is saved because there is no beamsplitter to move in and out of the optical path.

The CCD pixels that contain the satellite image are electrically separated from the remainder of the pixels which contain background light. These background pixels can be used to measure the background sky light. This is an ideal measurement source because it is in the same field of view as the satellite, and many samples of the background are available. The background pixels can be electrically checked for stars in the field of view, and any pixels containing star images can be removed from the background measurement. This also eliminates the need for the operator to search for a field of view free from stars before taking background measurements.

While the CCD photometer is measuring light from the satellite and background, the pixels can be electrically monitored to determine if a star is intersecting the pixels that contain the satellite image. This frees the operator from continually monitoring the satellite light measurement. The incidence of a star interfering with the satellite pixels of the CCD array is much lower than the incidence of a star interfering with the 30-60 arc-second field of view of the photo-multiplier tube. This results in the satellite signatures being less contaminated by star light.

The imaging capability of the CCD also allows the calculation of pointing system error signals that can be used for closed-loop tracking of the satellite. This is important when satellites that have not been tracked before are encountered.

The potential of a CCD photometer system provides impressive system capabilities. The first step towards this system is the development of a CCD camera. This report describes the CCD camera built for this application, the computer system used to analyze the camera performance and a demonstration of the photometric capabilities of a CCD camera. The sensitivity of the camera has been measured on three telescopes using solar spectrum calibration stars.

The sensitivity parameters of the camera are given along with a plot of the visual magnitude-sensitivity of this camera as mounted at the photometric focal plane of the ETS 31-inch telescope as a function of integration time. A projected sensitivity plot is also given for this camera mounted on the GEODSS main telescope. This camera has been operating since July 1982 without any electrical or mechanical problems and was integrated into the ETS system in March, 1983.

II. CAMERA DESCRIPTION

The camera is described by grouping the various subsystems under four major headings; sensor, analog circuits, digital circuits, and mechanical configurations. The entire camera system is contained in the two boxes shown in Figure 1. The camera is on the left, and the power supply box on the right, which contains all the power supplies, the thermo-electric cooler controller, the X-Y monitor driver, and the computer interface. All other systems are in the camera housing. The two boxes are connected by a fifty conductor ribbon cable and two multi-conductor power cables. These are all fifty feet long. All connections from the camera system to the outside world are through the power supply box. The video is digitized in the camera housing (12 bits) to eliminate the pick-up of external signals. There are no external adjustments required for camera operation, and the three gain settings and 4096 different integration time settings are selected digitally. Figure 2 shows the camera and power supply box with covers removed. Figure 3 shows another view of the camera with cover removed and the rear view of the power supply box.

Sensor subsystem: A 30 x 30 pixel CCD built by Group 87 is used as the imager. The CCD is mounted in a 24-pin dual-in-line package which is inserted into a socket mounted on a printed circuit board. The CCD is cooled by a thermo-electric cooler and cold finger assembly. All of the above are mounted in a vacuum dewar. The dewar has a quartz window on one end and a heat sink to remove heat from the thermo-electric cooler on the other end. Electrical connections are made using 42 vacuum feedthroughs in the dewar body. The thermo-electric cooler and cold finger, the dewar and heat sink, and the thermo-electric power supply controller were manufactured by

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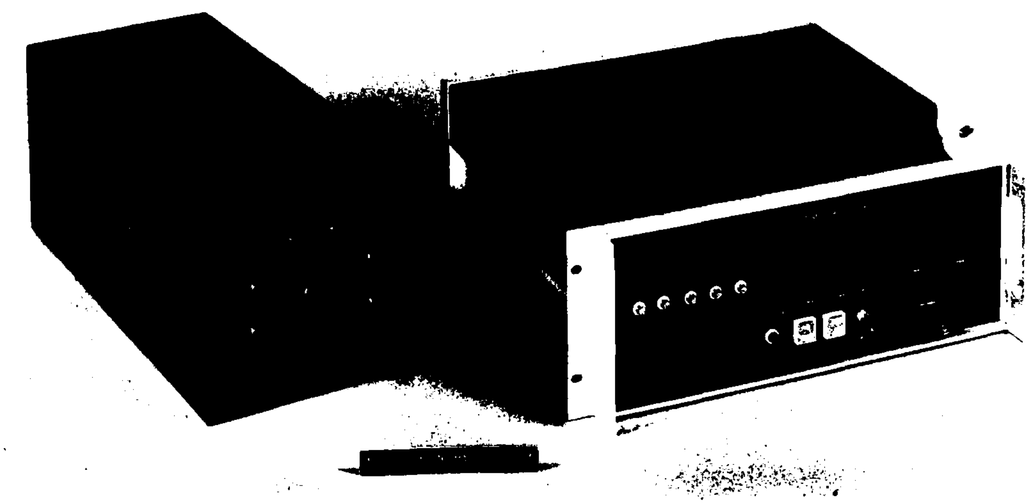

Fig. 1. CCD photometric camera and power supply box.

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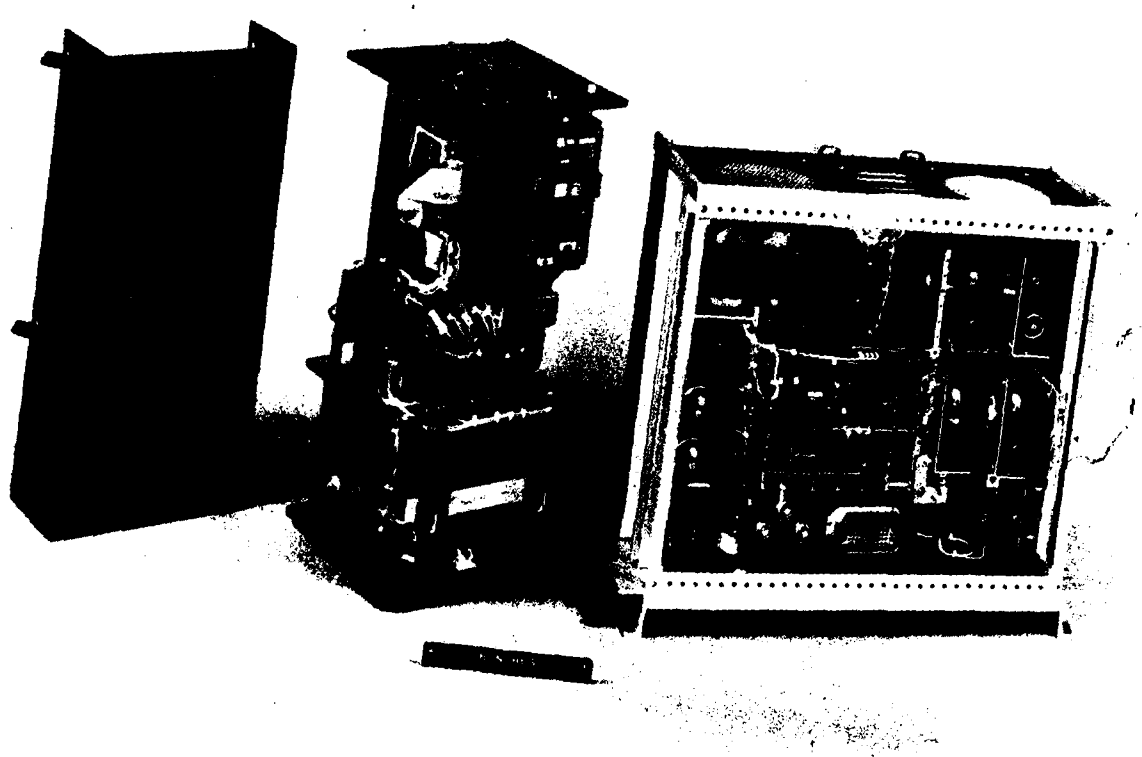

Fig. 2. CCD photometric camera and power supply box (cover off).

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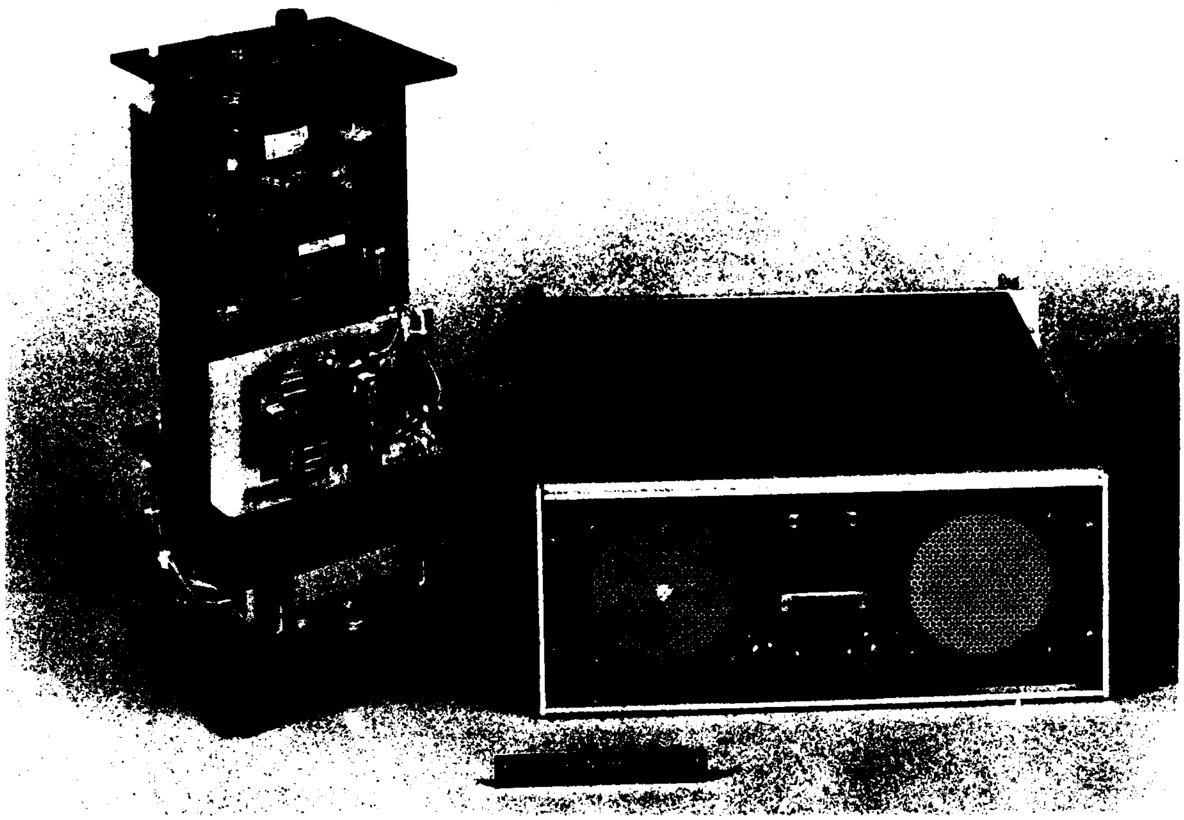

Fig. 3. CCD photometric camera (cover off) and power supply box (rear view).

Marlow Industries. The dewar assembly is mounted in the camera mainframe and can be moved in three-dimensions, independent of the camera mainframe. The single stage thermo-electric cooler lowers the CCD temperature 47°C below ambient.

Analog circuits: The CCD clock drivers (National DS3642) are mounted on a double-sided ground-plane printed circuit board with on-board adjustable voltage regulators to control the clock voltage levels. The CCD output signal is input to a three-gain (4, 40, 400) amplifier specifically designed to amplify the signal and reset levels of the CCD output, and to not saturate with the feedthrough of the reset pulse. The gain setting desired can be selected remotely by a digital signal. A circuit is included in the amplifier to maintain the reset output level at the lower end of the input range of the A/D that follows the amplifier. The amplifier was designed to achieve a noise level below the noise of the CCD (30 electrons rms) and has surpassed that goal with a noise of nine electrons rms at the 400 gain setting, seven electrons rms at the 40 gain setting, and four electrons rms at the 4 gain setting.

A 12 bit, 5 MHz A/D board manufactured by Analog Devices is used to digitize the CCD signal after the amplifier. This board is plugged into a double-sided ground-plane mother board that has DC decoupling for power supply voltages and connectors for input and output signals. A separate decoupling printed circuit board is used to minimize EMI effects on all the power supply lines and additional decoupling is incorporated on the clock driver board, the amplifier board, and the CCD socket board in the dewar.

A temperature sensing circuit consisting of a current source, a thermister, and an 8 bit A/D are used to monitor the CCD temperature.

Digital circuits: All timing for the camera is generated from a 20 MHz crystal. The timing for all camera circuits including the CCD is fixed except for the integration time of the CCD which can be digitally selected from 1 mS to 4.095 S in 1 mS steps using switches in the camera, and from 10 mS to 1.27 S in 10 mS steps using a Motorola 6801 microprocessor in the camera which is remotely controlled over a serial communication link. The 6801 is also used to communicate the CCD temperature, and which gain setting to select for the amplifier. The 6801 was chosen for the application because it replaces eight separate ICs, and because speed and computing are not required in this application.

The reset and signal levels are both sampled, A/D converted, and then are digitally subtracted to result in a digital CDS (correlated double sampling) which is used to remove the reset noise inherent in all CCDs. The digitized video of the CCD is sent to the power supply box where it is available for distribution to various systems. One digital circuit in the power supply box converts the CCD video to analog and provides appropriate ramps to drive an X-Y monitor to display the CCD video in real time. Another digital circuit in the power supply box provides a one frame cache memory and computer interface.

Mechanical Configurations: All camera components are supported in a welded aluminum frame whose covers have twist-lock fasteners. The camera is mounted on a telescope by bolts through the end of frame, therefore the covers were designed for easy access to the camera components while it is mounted on the telescope. A fan in the camera, coupled with an air plenum (not shown in Figures 1, 2, and 3), and air ducts in the mainframe and covers provide cooling for the electrical components and for the thermo-electric cooler heat sink.

III. COMPUTER DATA COLLECTION

The computer interface circuit mentioned in the previous section allows the 12-bit camera video to be stored, displayed, and analyzed using the HP9845 and HP9836 computers. The computers' 16-bit parallel interface and DMA transfer are used to store frames of camera video in a 30 x 30 pixel format in the mainframe RAM memory for temporary use, or on floppy disc for long-term storage. The computer programs written for this project are described and example output of the display programs are given. The performance of the camera is measured using these programs and is presented in the following section.

<u>30 x 30</u>: Stores 1 frame of 30 x 30 pixel video in the camera cache memory, transfers this to the computer RAM memory, computes the frame parameters (mean, standard deviation, minimum, and maximum amplitude values), and then stores on disc a frame of pixels, the frame parameters, and the date and time of video acquisition. Each disc holds 126 frames and the frames can be uniquely identified by their file label.

<u>REDAT</u>: Retrieve 1 frame of pixels and associated information from disc. Displays in a 2-D format the pixels that exceed a user selected threshold and marks the pixel of highest amplitude with an asterisk. Figure 4 is an example of a REDAT 2-D plot showing binary star component images separated by 14 arc s on the ETS telescope. REDAT then will display a 3-D plot of the frame as illustrated by Figure 5. Hard copies of the 2-D and 3-D plots are easily generated on a thermal or pen plotter and a display or hard copy of all the pixel amplitudes is another option of REDAT. The features of REDAT allow for exhaustive study of a frame of pixels.

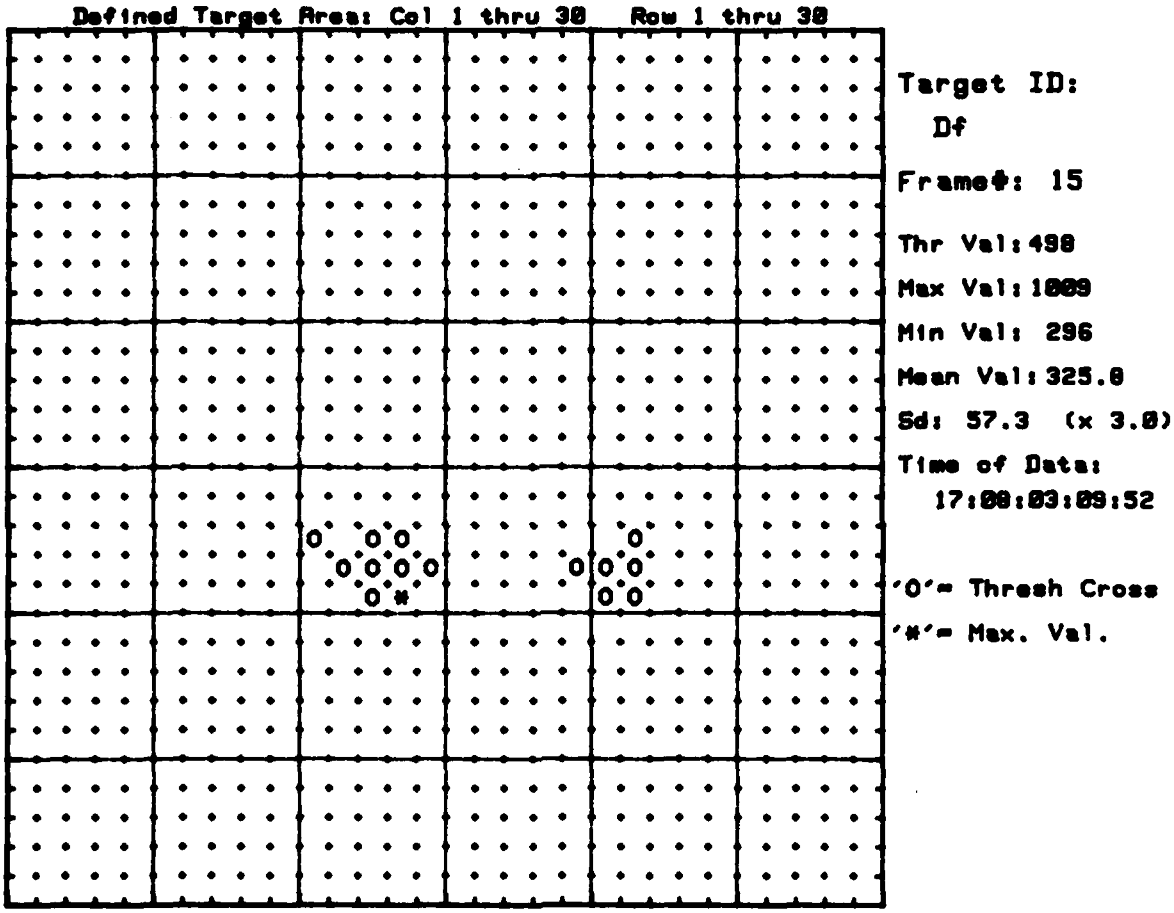

Fig. 4. REDAT 2-D plot of binary star.

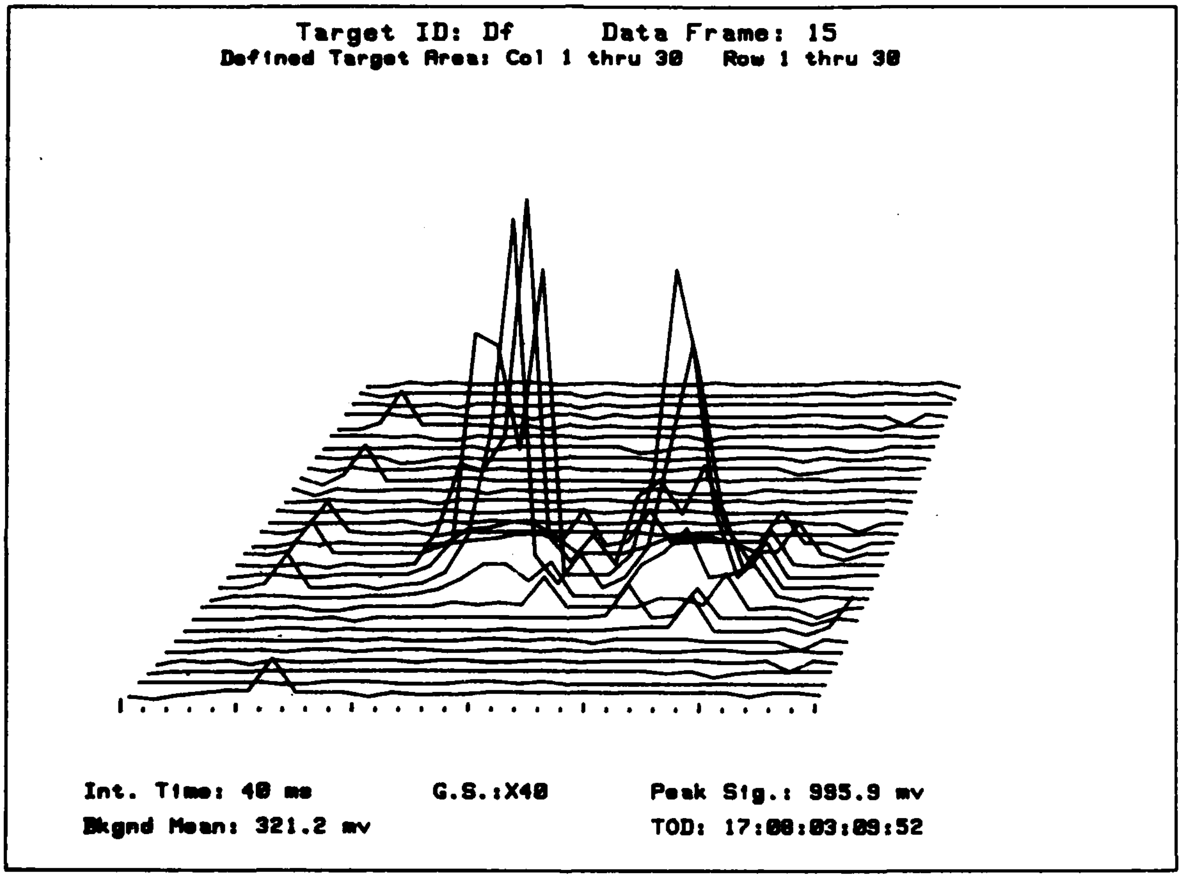

Fig. 5. REDAT 3-D plot of binary star.

REDAT 1: Performs the same operations as REDAT except that five background frames stored on disc (with no image) are averaged and then subtracted from the frame of interest containing an image. This removes pattern noise in the image frame.

CAMDIS: Stores 1 frame in the camera cache memory, transfers this to the computer RAM memory, and then displays 2-D or 3-D plots. CAMDIS doesn't store any data on disc, and is used as a real-time display for focus, alignment, and target acquisition.

CONSEC: Controls the storage of 5 consecutive background frame and 120 consecutive image frames in computer RAM and then with frame parameters and labels on disc. The background and image frames are automatically labelled so that other programs can easily retrieve the frames. This program allows a continuous time history of a spinning satellite's reflected light to be recorded and analyzed at a later time.

DATDIS: Provides a 120 frame sequential 2-D or 3-D display with background frame subtraction of the frames stored by CONSEC.

SOI: Using the image and background frames stored by CONSEC the average background is subtracted from each image frame. A subset of pixels from each resultant frame is chosen by defining a rectangular window which contains the satellite image and excludes as much of the night sky background as possible. The amplitude of these pixels are summed to provide a measure of the satellite's reflected light for that frame. The reflected light is plotted for each frame stored by CONSEC. An example of this is shown in Figure 6 using light reflected from a satellite taken from the ETS.

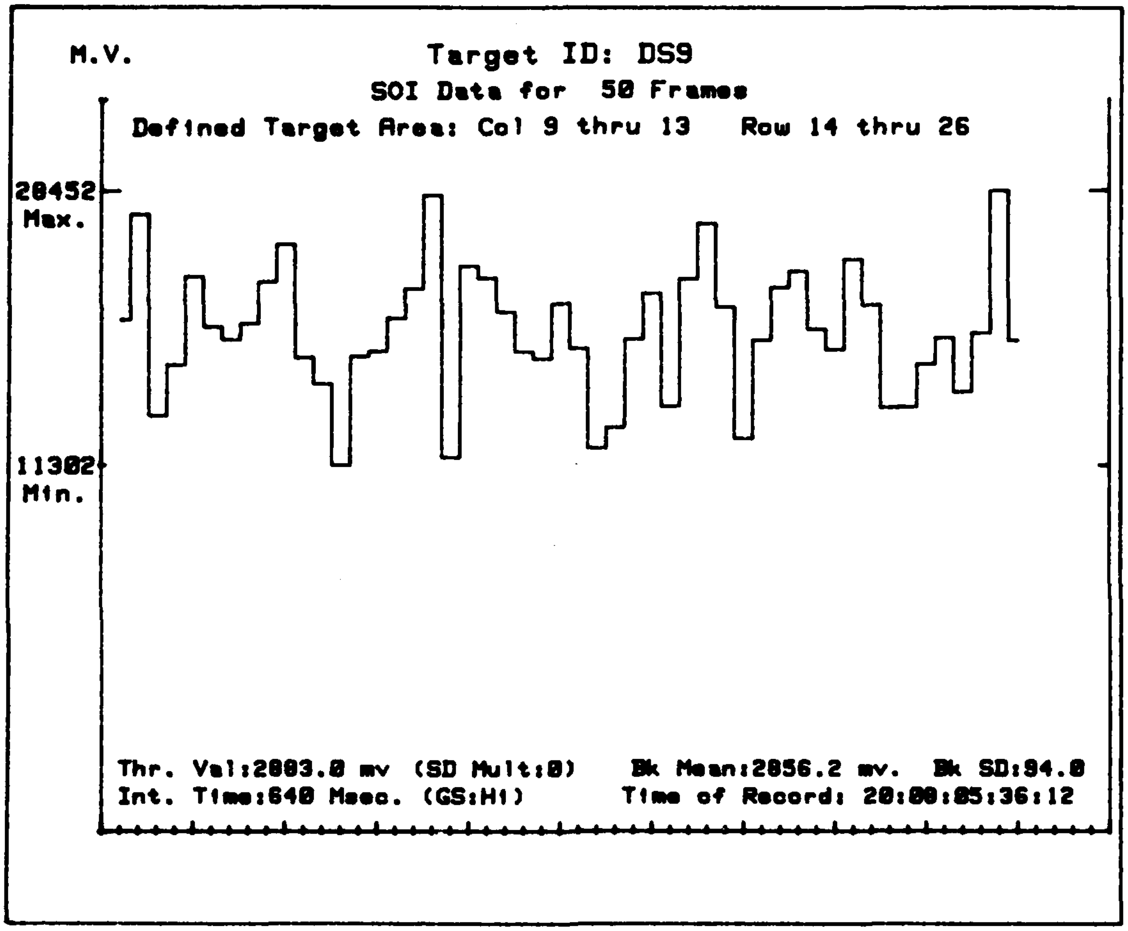

Fig. 6. SOI plot of light intensity as a function of time from a satellite.

<u>NOISE</u>: For any one pixel location specified by the user, this program measures the mean and standard deviation (RMS noise) of the pixel amplitude for any number of frames. Typically 1000 to 5000 frames are used which take from 2 to 10 minutes.

These programs have been used for photometric measurement of calibration stars to determine the sensitivity parameters of the CCD camera. They have also been used to measure the photometric signatures of several satellites using programs CONSEC and SOI. The programs are continually used to monitor the camera characteristics including noise, amplifier gain and linearity, pixel to pixel uniformity, and total camera linearity.

IV. CAMERA SENSITIVITY

The 900 pixels that comprise each frame are read-out in 900 μs, and the minimum frame integration time is 1 ms. This results in a maximum frame rate of 526 frames/s. The read-out time is fixed, but the integration time can be varied from 1 ms to 4.096 s in 1 ms steps. This wide range of integration time and the large dynamic range of the camera (72 dB) enables the camera to image satellites and astronomical sources over a large range of light intensities.

The sensitivity of the camera can be expressed as a SNR in electrons according to the formula:

$$SNR = \frac{P_s Q\ A\ T_t\ T_c\ I}{(P_b Q\ A\ T_t\ T_c\ I\ A_p + N^2)^{1/2}} \qquad (1)$$

where:

- P_s = photons per second, per unit area, from a satellite or solar-type star at the telescope aperture
- Q = average quantum efficiency for a solar spectrum
- A = effective aperture of the telescope
- T_t = optical transmission of the telescope
- T_c = optical transmission of the camera frontplate
- I = integration time
- P_b = photons per second, per unit area, per angular area of sky background at the telescope aperture
- A_p = angular area for each CCD pixel
- N = camera noise (predominantly CCD noise)

The following parameters characterize the camera and are independent of the telescope used. These values have been measured in the laboratory using calibrated light sources and in field measurements using solar-type stars of known magnitude. The linearity of the camera has been verified with calibrated neutral density filters and a constant light source.

$Q = 0.35$

$T_c = 0.92$

N = 40 ELECTRONS

The camera has been tested on three telescopes. $A = 0.003m^2$, $T_t = 0.79$, $A_p = 2343$ arc-second squared for one telescope; $A = 0.007m^2$, $T_t = 0.79$, and $A_p = 246$ arc-sec squared for the second telescope at Lexington; and $A = 0.34m^2$, $T_t = 0.23$, and $A_p = 2.6$ arc-sec squared for the ETS 31-inch f/5 telescope in the Cassegrain configuration at the photometric focal plane. Based on testing at Lexington using Polaris and at the ETS using several solar spectrum calibration stars[4], the camera parameters Q, T_c, N have been determined. While Q and T_c are constant, N varies depending on the ambient temperature. N = 40 was measured when the ambient temperature was 28°F, and N = 55 when the ambient temperature was 75°F. Since the night time temperatures at the ETS range from 0°F to 68°F, N = 40 @ 28°F could be considered a typical value.

Since P_s and P_b are a function of the satellite or star intensity and the sky background intensity, respectively, passing through the varying atmosphere, the only variable in equation (1) that is controlled by the operator is the integration time. Figure 7 shows the satellite or star magnitude that has a SNR = 6 on the ETS telescope using this camera as the integration time is

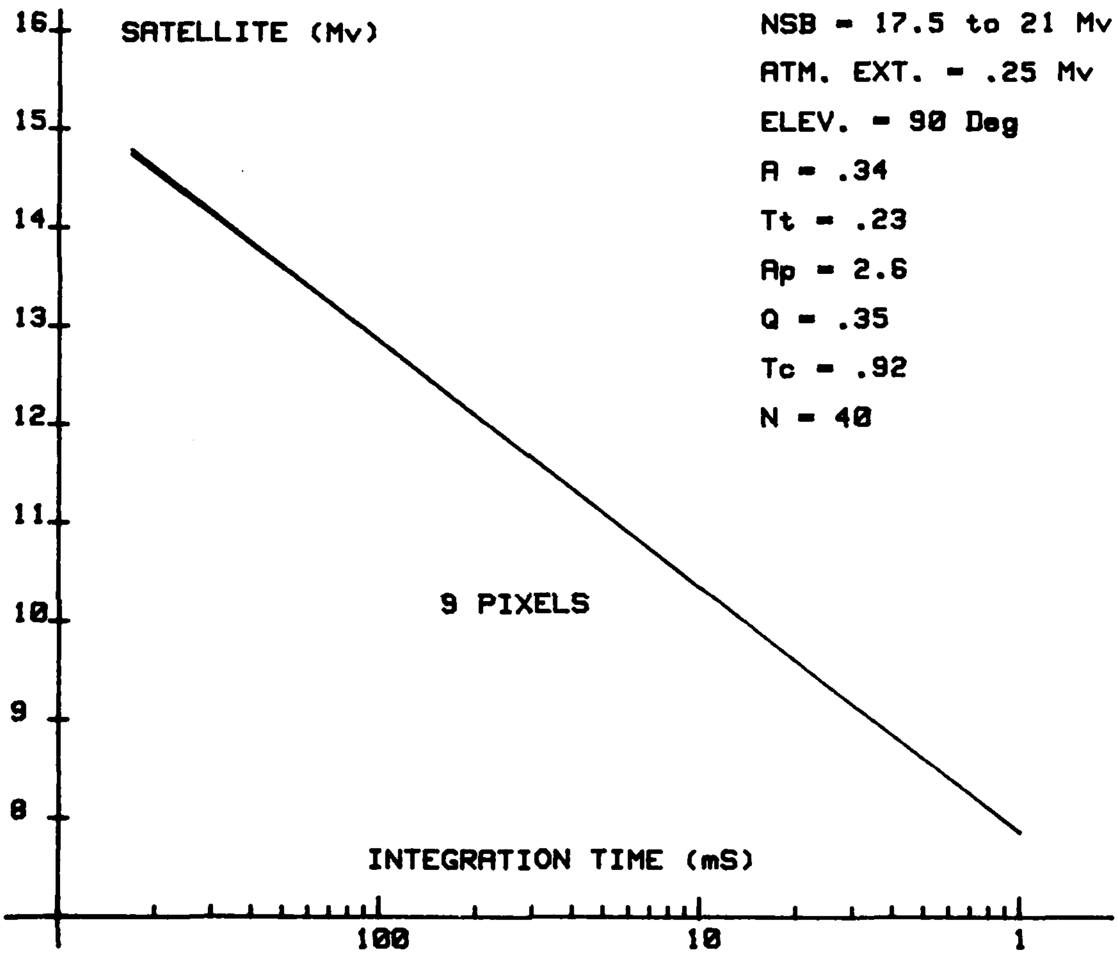

Fig. 7. Sensitivity of camera on ETS for SNR = 6.

varied. This curve was verified using the calibrated stars listed in reference 4. The satellite or star image is assumed to occupy 9 pixels, and when the signal from these pixels is added together, the noise from the pixels adds as the square-root of the number of pixels. This number of pixels for an image is reasonable[1] for a photometric system that is to measure all the light from a star or satellite. The SNR = 6 was chosen because it can be seen by a human observer[2] and because a well designed electronic photometry system should be able to operate with this input level. The satellite or star was assumed to be at zenith and the atmospheric extinction was assumed to be 0.25 $M\nu$, which would be a good night at the ETS. The P_s and P_b values were determined as described in reference 3.

The GEODSS main telescope has $A = 0.46\ m^2$, $T_t = 0.78$, and $A_p = 8.4$ arc-second square if the beamsplitter is replaced with a mirror. As mentioned in the introduction, this would provide photometry and a visual display to the operator using only the CCD as a photometer and imager. Figure 8 gives the satellite or star magnitude that has a SNR = 6 on the GEODSS main telescope using this camera as the integration time is varied. The image is assumed to occupy 9 pixels, and the noise from these pixels adds as the square-root of the number of pixels. The vertical scale of Fig. 8 is higher than the scale of Fig. 7. This demonstrates the effect of larger aperture (A) and the higher transmission (T_t) of the GEODSS telescope. Figure 7 shows no dependence on the night sky background (NSB) and Fig. 8 is only affected at integration times longer than 100 ms. The lower curve of Fig. 8 is for a NSB of $17^{m}.5$ per square arc s, while the upper curve is for a NSB of $21^{m}.0$ per square arc s.

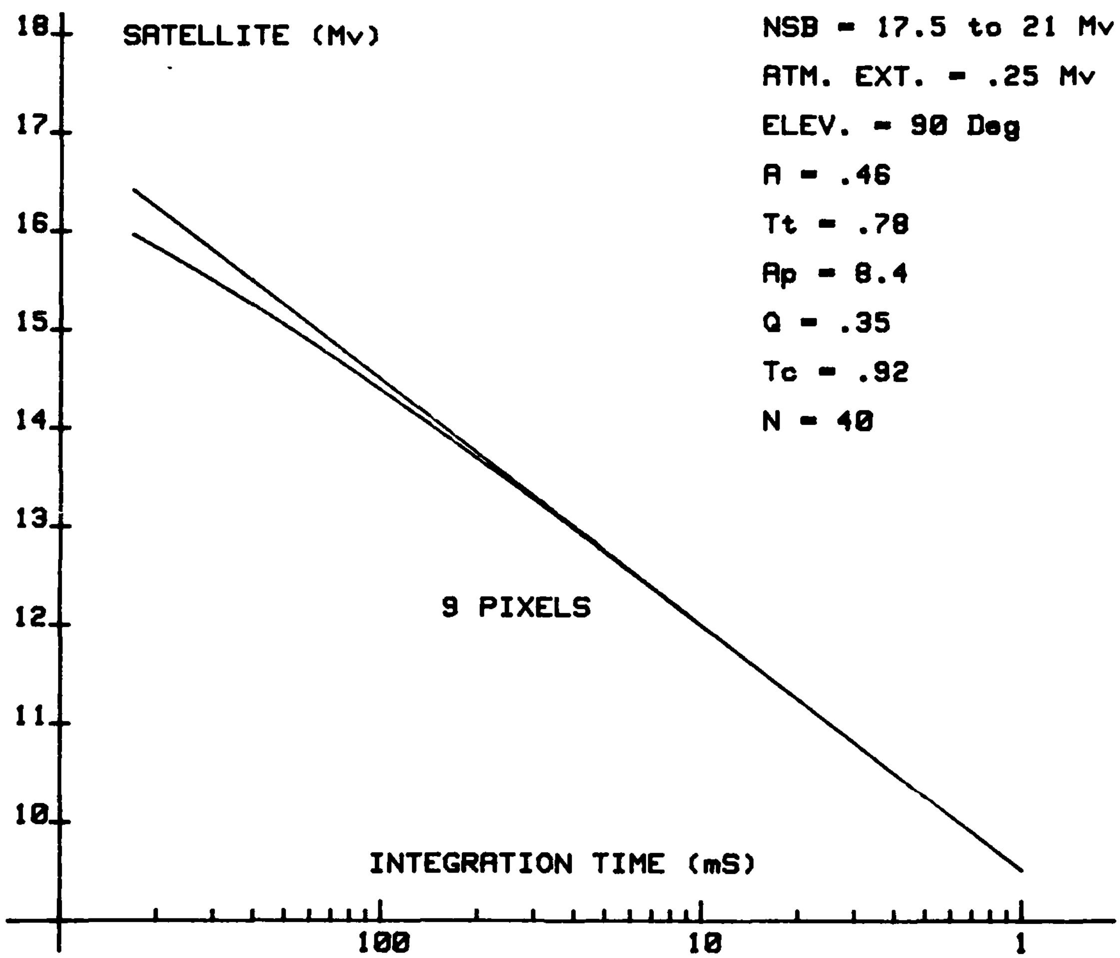

Fig. 8. Projected sensitivity of camera on GEODSS for SNR = 6 for NSB values of $17^{m}.5$ per square arc s (lower curve), and $21^{m}.0$ per square arc s (upper curve).

V. CONCLUSIONS

The inherent advantages of a photometer system based on a CCD imager have been discussed with reference to the photo-multiplier photometer system employed at the ETS and the GEODSS sites. The major component of such a CCD photometer system (the camera) has been described, built, the performance measured, and is operational at the ETS. The computer data collection system developed for this project has been used to analyze the performance of the camera and to demonstrate the photometric capabilities and potential of a CCD photometer system.

The CCD photometer-camera performance has met the theoretical predictions projected for it. The one advantage that the photo-multiplier photometers have over the CCD camera is at short integration time (1-10 ms) for dark sky (19 - 21 M_v); the photo-multiplier tube is more sensitive due to the intensification stages. In order to eliminate this disadvantage the CCD will be coupled to an intensified stage, and then integrated into the present camera. A new CCD has been built for this application by Group 87 that will allow a 1 ms integration time and a 1 kHz frame rate, due to it's frame transfer architecture, and may also result in lower noise. The intensifier stage with fiber optic coupler has been specified to mount on either the 30 x 30 pixel CCD or the new frame transfer CCD. The sensitivity of the camera with these additions will be measured using the same computer system.

Acknowledgement

The authors wish to thank John DeCaprio for the care and diligence he used in the construction of the camera and power supply box and the interest he expressed in the project. We would also like to thank the ETS personnel, in particular R. Ramsey and R. Irelan for assistance in camera testing and D. Beatty and R. Irelan for integrating the camera mechanically, optically, and electrically into the ETS system. Thank you, to Lynne Perry for her quick and accurate typing of this report.

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(αuμi)	308	8890	2.02	0.60
	45348	133484	6.65	0.46
	111488	112339	8.73	0.50

II. A. U. Landolt, "UBV Photoelectric Sequences in the Celestial Equatorial Selected Areas 92-115", ATJ 78, 959, (1973).

#651 in SA-114: $V = 10^{m}.3$,

$B-V = 0.59$

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- radiometric measurement
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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

A CCD camera for photometric measurement of satellites has been built, tested, and has been integrated into the Experimental Test System (ETS). This report describes the camera, the computer system and programs used to collect data, the camera's sensitivity parameters, the sensitivity of the camera on the ETS 31-inch Telescope, and its projected sensitivity on Ground-Based Electro-Optical Deep Space Surveillance System (GEODSS) main telescope.

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