AN INTENSIFIED CHARGE COUPLED DEVICE
FOR
EXTREMELY LOW LIGHT LEVEL OPERATION

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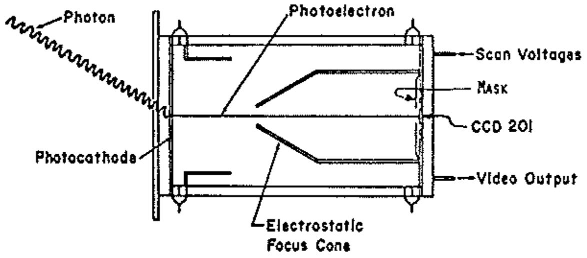
ABSTRACT An internally Intensified Charge Coupled Device (ICCD), using a semi-transparent photocathode and front illuminated Fairchild CCD201 is described. A light detection system incorporating the ICCD should ultimately permit single photoelectron discrimination at a scan rate of about 350 frames a second. This will provide a data rate which is an order of magnitude larger than comparable systems. Such a device, the first of this type, has been fabricated by the Electronic Vision Company and recently tested at the University of Maryland. The tested unit, after being sealed off, had a good photocathode and the CCD operated properly after the bakeout procedure. Successful measurements of video noise, electron gain, penetration of the transfer registers and damage to the CCD were conducted. Before becoming gassy, this tube performed acceptably in the critical areas as an intensified television camera for the low light level detection. Although single photoelectron discrimination was not possible due to excess random noise, the results of the tests indicate that the expected single photoelectron operation is feasible. Another ICCD has been fabricated which has solved some of the problems found in the first device.

INTRODUCTION

An internally Intensified Charge Coupled Device (ICCD) using a semi-transparent photocathode (S-20) and a front illuminated Fairchild CCD201 has been designed, fabricated and tested. This was the first successful test of an imaging ICCD. It is designed ultimately to permit single photoelectron discrimination at a scan rate of about 350 frames per second. For diffraction-limited astronomical observations on large telescopes, a detection system using an ICCD has a data rate which is better, by a factor of ten to thirty, than the best available or projected detection system.

This ICCD, to be operated as a photon counting array, is a sealed off device and has the basic configuration indicated in Figure 1.



Schematic Diagram of Intensified Charge Coupled Device

Figure 1

An incident photon is converted to a photoelectron at the photocathode (an S-20 in this case). This photoelectron is accelerated to an energy of about 15 Kev and electrostatically focused onto the front surface of a Fairchild CCD201. By ionization within the active silicon, the accelerated photoelectron creates a large number of hole-electron pairs at a particular photosite on the CCD. These charges created by the single photoelectron, are collected and form a charge packet which is "scanned" from the CCD by the electrical pulse trains generated from an external clock. After a stage of amplification, which is performed on the chip, the voltage levels which represent the magnitude of the charge packet leave on a single video output line. This data stream is then electronically processed to individually detect the charge packet produced by each photoelectron.

The current status of the work being done at the University of Maryland on the internally Intensified Charge Coupled Device (ICCD) will be discussed. A general description of the theory and method of operation of the ICCD was presented in March 1975 at the Symposium on Charge Coupled Device Technology for Scientific Imaging Applications held at the Jet Propulsion Laboratory[1]. The fabrication of such a tube at the Electronic Vision Co., a division of Science Applications, Inc. has also been described in some detail[2] by John Choisser.

In this paper we shall discuss the results of a series of measurements made on a CCD and on an ICCD. The latter was fabricated at the Electronic Vision Company and was received at the University of Maryland in late June.

PHOTO SENSOR REQUIREMENTS

This development effort with the ICCD is motivated by two different applications being developed at the University of Maryland. These related applications have significantly different requirements.

AMPLITUDE INTERFEROMETER REQUIREMENTS

The primary application of the ICCD will be as the light sensor for a new instrument, the Multi-Aperture Amplitude Interferometer (MAAI), which yields diffraction-limited image information when used on a large telescope. This instrument is a multi-channel version of a similar instrument which has been used in an astronomical observation program over the last few years[3,4,5,6]. Basically, this application requires an array of photosensors, each of which has a high speed response and the ability to discriminate at the single photoelectron level. The requirements are:

1. The ability to discriminate reliably among zero, one, two, or more photoelectrons per pixel per scan.
2. The ability to complete the scan of an entire frame in a few milliseconds.
3. Very low lag, i.e., very little memory from one frame to the next frame.
4. Minimal cross talk between spacial channels (or pixels).

IMAGING CAMERA REQUIREMENTS

The other application in which the ICCD will be used in conjunction with the MAAI consists of an imaging camera in the focal plane of a large telescope. For this application, the first of the above requirements is very important, while the latter three are important but not paramount. The imaging use has the additional requirements of:

1. Very large dynamic range
2. Very low blooming

The electronic operating conditions for the ICCD will be somewhat different for each of the two applications.

METHOD OF CCD OPERATION

THEORY OF OPERATION OF THE CCD

Photons are converted on the photocathode into photoelectrons. These photoelectrons are accelerated to 15 Kev and focused on the front of a Fairchild CCD201. The transfer registers, which carry the charge from the photosensitive sites to the on-chip preamplifier, operate independently of, and at the same time as the photosites which are integrating the electrons produced by ionization due to incident photoelectrons. Thus the transfers or "scanning" take place during the integration period, and the array is sensitive more than 99% of the time.

The transfer registers are protected by a layer of aluminum on the CCD which is about one micron thick. The accelerating voltage is chosen so that the bombarding electrons do not reach the active silicon and produce ionization or "noise" in the transfer registers.

ICCD DESIGN

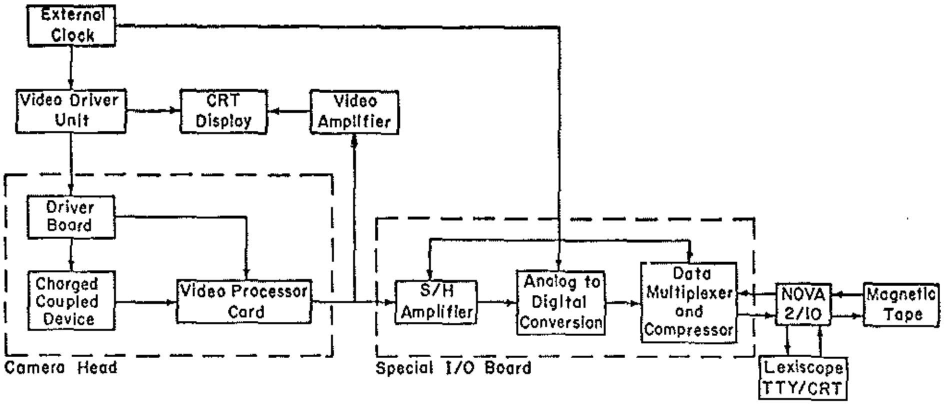
The design of the ICCD incorporates a number of features which enhance the ability to discriminate at the single photoelectron level. A special CCD201, which has the SiO_2 scratch protection layers removed, was mounted by the Fairchild Corporation on a special ceramic header designed by the Electronic Vision Company. The external portion of this header provides the required electrical contacts for the CCD in a circular pattern of pins. Thus it may be socket mounted into the special camera head developed for the ICCD. The header also provides the support for the electrostatic focus cone, and the special mask which exposes the active array and protects the preamplifier and other circuitry at the edge of the chip from damage by accelerated photoelectrons. The chip is bonded directly to the ceramic header so the CCD may be readily cooled using a probe attached to an area which is clear of pins. This cooling may be required to reduce the thermally generated dark current on the chip.

OPERATION OF THE CCD

In order to permit operation of the ICCD on the telescope, most of the electronics must be located a significant distance from the camera head. To handle such long cables, a special camera head has been fabricated which minimizes cross-talk and coherent noise. The pulse trains are transmitted to the camera head or telescope as low current signals and are converted to the required high current pulses by clock drivers within the camera head. The camera head also contains amplifiers, a sample and hold circuit, a video clamping circuit, and a discriminator.

DATA RECORDING SYSTEM

The data recording system which is presently being used to test the CCD's and the ICCD's has the form indicated in the block diagram of Figure 2.



Block Diagram of Single Scan Data Recording System

Figure 2

This "Single Scan Data Recording System" is described in more detail in University of Maryland Technical Report #76-038[7]. This system records a full field of video data onto digital magnetic tape. It also provides amplification, a sample and hold operation, an analog-to-digital conversion, and proper timing and scanning voltage drives. This data recording system will operate at data rates as high as 4 MHz but can record only about a frame per second due to the writing speed of the digital magnetic tape unit.

For the tests described in this paper, the CCD was operated at a data rate of 0.625 MHz (about fifty frames per second) and thus only one frame in fifty can be recorded. In order to reduce the operating time of the tube, at the termination of each recording cycle, the computer provides a signal that indicates that further data may now be accepted. This signal operates a light-emitting diode which illuminates a broad pattern (about 13 pixels across) on the photocathode. The typical length of this light pulse is 0.1 milliseconds and its output power is peaked around 6000Å. The circuitry described in this paragraph does not appear in Figure 2.

The results of these measurements are contained in several thousand digitized arrays stored on magnetic tape. These arrays are processed in the UM Computer Science Center UNIVAC 1108, using a specially developed family of programs, the Image Processing System (IPS)[8]. The IPS may be used to read and transform the arrays, to produce averaged frames and difference frames, and perform pulse height analysis. It can, for later studies also be used for various transform (Fourier, etc.) and for image analysis.

The normal analysis procedure for this data was to average ten frames for which data had been taken under the same set of external parameters. PHD's of this averaged frame and of the difference between a single frame and the averaged frame were used to obtain Figures 4 and 3 respectively. The relative gain as well as the increase of the dark current was determined by printing out selected rows and columns of the averaged arrays, and by studying arrays which were the differences between mean dark arrays and mean "flashed" arrays.

VIDEO NOISE SOURCES

In this section we consider various aspects of the noise which are important when using the CCD both as a photoelectron sensor and as a device for the conversion of the parallel arrangement of the charge packets to the serial arrangement of the data leaving on the video output line. The relevant types of noise are defined, the physical sources of the noise are discussed, and the results of the measurements are presented.

OPERATIONAL DEFINITIONS

We first define our use of the terms "random noise" and "fixed pattern noise".

Fixed Pattern Noise

In order to define the "mean array" which corresponds intuitively to the fixed background pattern, let us consider a very large number of frames of data which are recorded consecutively under the same set of external parameters. The value at a given picture element (or pixel) of the "mean array" is determined by averaging the values of that pixel in each of the successive frames. Thus, the "mean array" is an array of elements each of which is the average of many samples. The variation of this mean array from one pixel to the next pixel is defined as the "fixed pattern noise". This data will be presented in the form of a pulse height distribution (PHD) which is the probability that a given pixel voltage will be found. Most of the discussion of mean arrays which will be considered in this paper will be limited to data taken with no light input. Thus the mean array for those cases will be a study of the thermally generated dark current at each pixel.

Random Noise

The "random noise" at one pixel is the variation from the mean value which one obtains when a particular pixel is repeatedly sampled. This may be presented in the form of a pulse height distribution which describes the random noise at each pixel. For the presently planned system, the discriminator levels are not adjusted to a new value for each pixel. To study such a system, a pulse height distribution in which the data is combined over the entire array is more relevant. In order to obtain this information we shall subtract from a single frame of sampled pixel values the mean frame discussed in the previous paragraph. The pulse height distributions which will now be discussed are obtained by sorting the values of these differences.

More specifically, in this paper we will average ten frames to obtain the "mean frame". The use of a value as small as ten has several implications:

i. the random noise determined from the pulse height distribution (PHD) is somewhat smaller than the value which would be obtained for a very large number of frames.

ii. the standard deviation of the fixed pattern noise is contaminated by the addition of about 30% of the standard deviation of the random noise.

For the present, these corrections will be ignored.

PHYSICAL NOISE SOURCES

In this section, we relate the instrumental effects defined in the previous section to various physical mechanisms.

Thermal Leakage Current

This "dark current" or thermal leakage current is due to thermally generated charge pairs which are created within the active silicon. The leakage current is parameterized by the average number of electrons which collect at a given pixel during the integration interval (the thermal leakage charge). This integration interval is usually the scan or frame time. The value of the thermal leakage charge varies across the frame from pixel to pixel. It also decreases by a factor of two for every 6 or 7° that the temperature of the CCD is reduced and decreases linearly as the integration time is decreased. The average leakage charge across the frame does not significantly affect the ICCD operation but its variation across the frame may create a problem in that the discriminator levels would have to be changed for each pixel. The variation of the thermal leakage charge from frame to frame (Poisson noise) would properly be a component of the random noise, but its value is negligible for the normal ICCD operation.

Thermal Leakage Noise

The thermal leakage noise is the variation of the thermal leakage charge across the array. This will be parameterized by the standard deviation of the thermal leakage charge across the array (i.e., the fixed pattern noise). More precisely, it is the variation of the mean (over many frames) thermal leakage charge across the array. This latter form of the definition removes the random noise as a component of the thermal leakage noise. The temperature and frame rate dependence of the thermal leakage noise is the same as that of the thermal leakage charge. In order to permit single photoelectron discrimination without a change of discriminator level for each pixel, this noise should be reduced to a value of about 100 electrons. This may be accomplished by cooling the CCD to approximately 0°C.

Random Noise

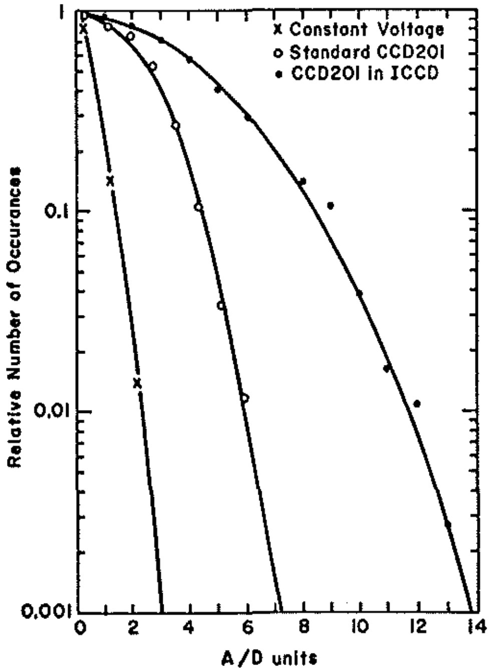
The dominant source of random noise is the input noise of the on-chip preamplifier. This behaves as if dominated by the capacitive input of the preamplifier. It is relatively independent of temperature over the range of interest for ICCD operation. The shot noise due to electrons in the charge packet should also contribute, but for the small charge packets which occur in normal ICCD operation, the preamplifiers noise dominates.

MEASUREMENTS

An important characteristic of the data recording system for this discussion is the level of system noise of the recording system. This noise consists of the contributions due to the analog-to-digital conversion, the data transfer, and the analysis procedure. By injecting a constant voltage as the input of the sample and hold amplifier on the "Special I/O Card" of Figure 2, one may obtain data to characterize the recording system.

Random Noise

Figure 3 is a pulse height distribution (PHD) of the random noise. The units on the abscissa are the least significant bits of the Analog-to-Digital Converter (ADU). These are 10 millivolts, which, with an amplifier gain of 87.5, represent 0.114 millivolts at the CCD. This in turn represents about 570 electrons on the chip. The latter conversion has been made using data obtained from R. H. Dyck of the Fairchild Corporation[9] and has been confirmed by measurements at the University of Maryland. The first curve (denoted by x) is representative of the noise in the data recording system. As might be expected, this has a width of about one quantization unit (one ADU). The second curve (denoted o) consists of data taken on a standard CCD201. The noise level for the CCD is significantly larger than that of the recording system. However, as may be seen in Figure 2, this data also includes the random noise and external pickup contributed by the electronics in the camera head (i.e., the Video Processor Card) and any ground loops which may occur in the overall system. Since direct qualatative measurements of the CCD noise yields values in the range of 300 to 400 e$^-$, it would appear that there are some system contributions to curve 2 and curve 3. The third curve (denoted •) shows the random noise of the CCD in the ICCD. Figure 3 shows that there is a definite excess random noise (about 0.45 mv) in the ICCD. The cause of this is under investigation at the present time.



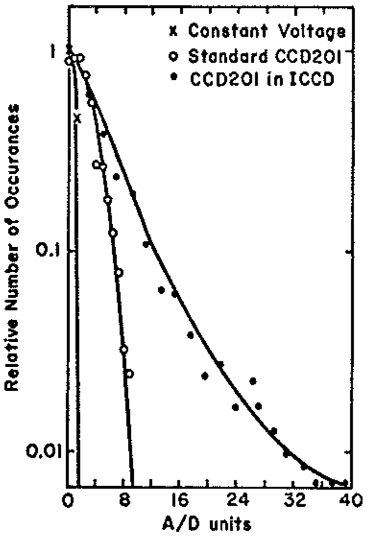
Pulse Height Distribution of Random Noise

Figure 3

An additional stage of amplification is being added and future tests will include data taken with a well shielded discriminator located within the camera head. The latter should eliminate the problem of external interference and ground loops.

Fixed Pattern Noise

Since we do not intend to change the discriminator level for each pixel, an important parameter for single photoelectron discrimination is the variation of the mean array.



Pulse Height Distribution
of Fixed Pattern Noise

Figure 4

The ordinate and abscissa are the same as in Figure 3. The first curve (denoted by x) is the system noise. Most of this width is assumed to be the contamination due to random noise. The second curve (denoted by o) is a standard CCD201. The relative narrowness of this PHD indicates that the variation is relatively small (approximately 3 mv). The third curve (denoted •) is obtained from the CCD201 in the ICCD. The similarity of the upper portions of curve 2 and curve 3 indicates that the background is about as uniform as the previous CCD. The wide skirt indicates that there are regions of increased leakage current. These regions were also visible on the monitor display as relatively broad localized areas. They might have been on the CCD before processing, or they might be nucleation centers formed while processing the ICCD. The CCD's to be used in future ICCD's will have data packages taken before and after processing.

The width of these curves may be made as narrow as required for single photoelectron discrimination by cooling the CCD.

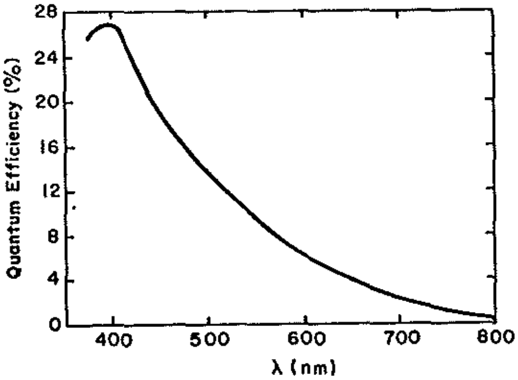
INTENSIFICATION

ROLE OF NOISE SOURCES

As has been discussed by Dyck, the expected r.m.s. random noise is about 300 e^- and this is dominated by the capacitive input of the preamplifier.[10] At the nominal operating voltage of 15 KV, the calculated gain is about 2,000. The pulse height distribution which is then expected will permit single and multiple photoelectron discrimination[1].

PHOTOCATHODE

Since some groups have had significant contamination problems when forming photocathodes with alkali vapors in the presence of silicon devices, the photocathode of the ICCD is processed in a region well removed from the CCD[2]. A very high performance photocathode and elimination of alkali metal "vapors" are achieved by using a molecular beam technique. The response of the photocathode (roughly of S-20 type) of the ICCD used in these measurements is indicated in Figure 5.



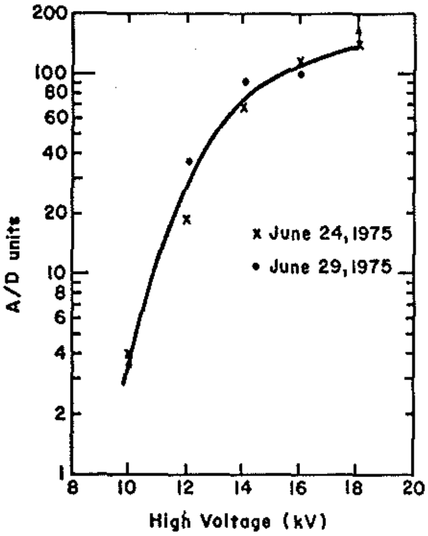
Quantum Efficiency of ICCD Photocathodes

Figure 5

DESCRIPTION OF TEST ICCD

The remaining tests were conducted on an ICCD of slightly different design than indicated in Figure 1. The device tested (denoted as ICCD-1) had no focus cone and relied on proximity focusing. It has about the same dimensions as the device in Figure 1. The measurements on this device were terminated after the second test sequence due to ion bombardment of the photocathode because the tube became gassy. This fabrication problem has apparently now been solved and another ICCD has been fabricated.

The electron gain may be studied by varying the accelerating voltage while maintaining a fixed light input. The tests conducted on 24 June 1975 were run using a light pulse from the LED which has a length of 10 milliseconds and a Neutral Density 2 filter. The tests conducted on 29 June 1975 were run with a 0.1 ms pulse and no filter in front of the LED. This data appears in Figure 6. The 18 KV point is low due to saturation of the A/D converter.



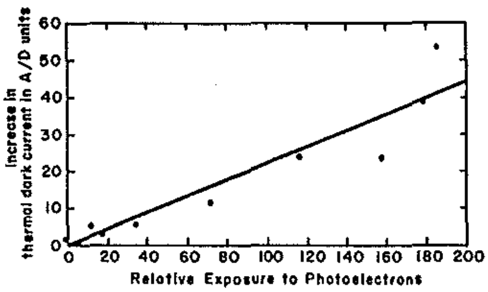
Relative Electron Gain

Figure 6

The nominal operating voltage of 15 KV was determined to prevent a photoelectron which is focused on the transfer registers from either entering the active silicon or the last insulation layer. By sufficiently increasing the accelerating voltage, one expects that the photoelectrons will penetrate the active silicon and produce a signal. However, this has not yet been observed even up to 18 KV.

DAMAGE

A preliminary test of the effect of extended exposure was used to study the operational lifetime. In this test, the light input was increased in one area until there was an observable increase in the dark current. This increase in thermal leakage was measured by a comparison of the magnitude of the dark current before and after the exposure to light. No readjustment of the drive voltages was made. The resultant enhancement of the dark current as a function of the exposure to photoelectrons is shown in Figure 7.



Effect of Electron Damage
on CCD Dark Current

Figure 7

The increase in dark current is expressed in A/D Units, each of which is equivalent to 0.114 millivolts at the CCD output. Thus the increase is about 40 ADU or 5 millivolts. This is somewhat above the fixed pattern noise due to variations in thermally generated dark current, and is less than 5% of CCD saturation. The light input consisted of repeated flashes with a duration of 0.1 ms repeated 1000 times a second. Assuming a gain of 2000, this is equivalent to an input of 0.4×10^6 photoelectrons per pixel in the brighter region.

Measurements on similar devices[11] indicates that this damage mechanism saturates. The effect on single photoelectron operation would be to require additional cooling (perhaps -20°C) in order to assure that the increased dark current will not affect the single photoelectron discrimination operation. More extensive tests are planned on the later ICCD's to explore other damage mechanisms which may occur at higher light doses. In addition, several methods of annealing the damage, which have worked in similar devices, will be tested.

CONCLUSIONS AND PROJECTIONS

An Intensified Charge Coupled Device has been designed and fabricated. The first unit, after being sealed off, had a good photocathode and the CCD operated properly after the bakeout procedure. Successful measurements of video noise, electron gain, penetration of the transfer registers and damage to the CCD were conducted. It performed acceptably as an intensified array for the low light level work. For several reasons, the first device did not meet the performance criteria which are required for reliable single photoelectron discrimination. These problems were a gas leak in the tube and the excess random noise. However, the results of these tests are in general agreement with predictions, which indicate that such a device will be able to do single photoelectron discrimination. In addition, the ICCD showed no transfer noise, even at elevated voltages.

The gas leakage problem seems to have been solved and another ICCD, which is electrostatically focused, has been fabricated.

ACKNOWLEDGEMENTS

A major portion of these tests and subsequent data analysis were performed by Robert Braunstein. John Choisser of the Electronic Vision Company helped in setting up the test equipment and in conducting the 26 June test series. Most of the electronics was designed and debugged by John Giganti, and John Johnson prepared the optical test equipment and helped in the tests. A large portion of the data was run by Larry Bleau.

This work has been supported by several agencies. The fabrication of the ICCD has been supported by Goddard Space Flight Center, and by the Space and Missile Systems Organization through Science Applications, Inc. The specialized electronics for the operation of the CCD at single photoelectron sensitivity has been supported by the National Science Foundation. The data handling and recording electronics, which may be used on any rapid scan photon counting detector, has been supported by the Advanced Research Projects Agency through the Office of Naval Research. The program development and data reduction were largely carried out at the University of Maryland Computer Science Center with the support of NASA grant NSG 398.

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