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Astronomical CCD Imaging at UMR: An Interim Report

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Progress towards the modernization and update of the UMR observatory through the implementation of astronomical CCD technology is detailed. Preliminary image data is presented, specifically: globular cluster M13 and the lunar surface. An evaluation of the Santa Barbara Instrument Group's (SBIG) ST-6 CCD camera is presented; bias frames, dark frames, and flat-fields are all examined. A custom optical assembly for instrument focusing and housing BVRI photometry and RGB colorimetry filters is described. The ST6OPS data acquisition program, provided by SBIG, is reviewed. Additional work towards the development of a custom image processing utility program is mentioned. Finally, optical telescope collimation and polar alignment issues are discussed.

I. INTRODUCTION AND INITIAL DATA

This text details progress towards the modernization and update of the UMR observatory. The implementation of an astronomical CCD camera and the revitalization of the university's sixteen inch Cassegrain reflector were central to this effort. Preliminary image data acquired with the Santa Barbara Instrument Group (SBIG) ST-6 CCD camera is presented.

The first image, represented in Figure 1, is M13 - the Great Globular Cluster in Hercules. This data was recorded during an integration period of ten seconds and includes stars of magnitude 14. It has been radiometrically corrected to insure accurate intensity throughout the image.

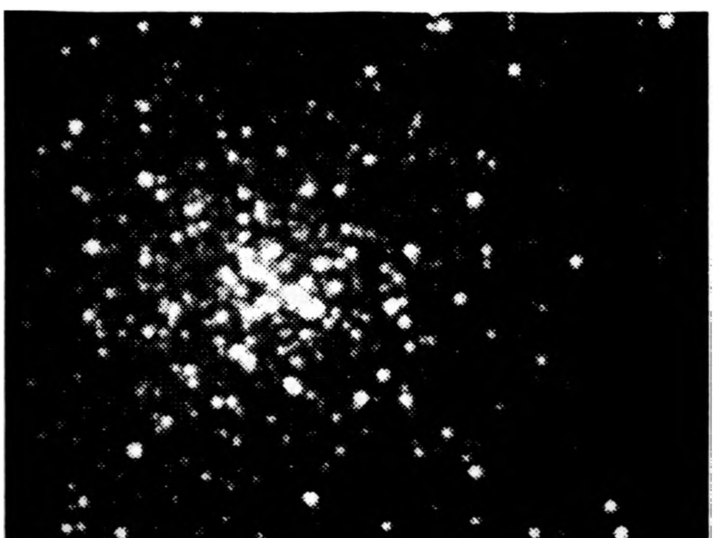

FIG. 1. M13 -- the Great Globular Cluster in Hercules. Ten second exposure during a full moon. The field of view is 6.5 by 4.9 arcminutes.

The southern lunar surface is depicted in our second image. See Figure 2. Most notable in this image the impact crater Clavius (found at top center). The exposure duration for this data was only seventy milliseconds. No filters were needed to reduce CCD saturation and/or readout streaking.

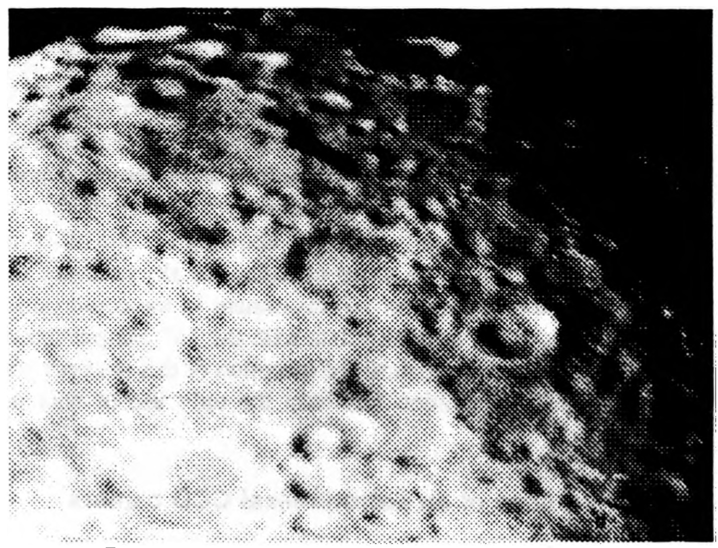

FIG. 2. The southern lunar pole. The crater Clavius is the large crater distinguished by several smaller, overlapping craters.

Also found within the paper are typical bias, dark, and flat-field frames associated with the new ST-6 camera. The custom optical assembly constructed in support of the CCD is then described. Subsequently, the fundamentals of BVRI photometry are examined. Both the SBIG ST6OPS program and advances in UMR image utility software are then reviewed. Finally, optical collimation and polar alignment issues are discussed.

II. BRIEF HISTORY OF ASTRONOMY AT UMR

A. State of affairs before this project

The Physics Department at UMR purchased a 16" research-grade Cassegrain telescope during the 1970's. Specifically, almost $18,000 was invested in the GROUP 128, INC., Model 117 reflecting telescope. This instrument, capable of supporting 68 kg of accessories, was housed in a small-dome observatory located on the campus.

Initially, interest in the science of astronomy was quite high. The new telescope was used often for advanced amateur study of the sky. The UMR "Astronomy Group" was formed to promote such work. Overall, it can be said that photographic results from the 16" instrument were quite good, considering its semi-urban location.

Over time, however, the excitement of a new telescope diminished. Students became involved in other studies and forgot about the telescope. After all, Rolla was not known as a premier school for the investigation of astronomy. In actuality, the Physics Department at UMR focused a large portion of its research on solid-state topics.

For this reason, over a period of years, the 16" telescope fell deeper into a pattern of "recreational" use. Semi-regular visitors to the observatory would point the instrument at Jupiter, Saturn, or the moon, take a long look, and then go home feeling satisfied.

The acquisition of a 10" Schmidt-Cassegrain reflector helped to boost interest in observational astronomy to a moderate level for a few years. This instrument (Celestron Pacific, Model Celestron 10) was easily portable, allowing off-site observations to be made. Within 15 miles of Rolla, the sky becomes significantly darker. Using the 10" instrument in the countryside was nearly equivalent to taking data with the 16" campus-telescope. Unfortunately though, until the inception of this research project, recreational observation has been the only use of both instruments.

B. Purchase of an astronomical CCD camera

The UMR observatory is currently undergoing an intense revitalization process as a result of the our research. As a part of the Advanced Undergraduate Physics Laboratory program, inspired by the chance to modernize the 16" telescope using charge-coupled device technology, we lobbied the department for the purchase of an astronomical CCD camera.

During the early weeks of the Winter 1992 semester, we conducted a thorough investigation of commercially-produced astronomical CCD cameras. This process entailed sending a letter of inquiry to each known camera manufacturer and then waiting for replies.

Among the few replies we received, the information sent by Santa Barbara Instrument Group (SBIG) and SpectraSource, Inc. was the most inviting. SBIG provided us with the specifications concerning their ST-4 and ST-6 products. Additionally, SpectraSource faxed the department a few pages of documentation for their Lynxx PC camera. TABLE I. details the imaging specifications of the ST-6 optical head. TABLE II. contains information about the entire ST-6 system.

TABLE I. ST-6 CCD imaging specifications.

Technical specification	SBIG ST-6
Resolution (CCD chip)	375 x 242 (TC-241)
Pixel size	23μm x 27μm
Anti-blooming	Yes
Maximum integration time	60 min
Frame buffer	Yes
Thermoelectric cooling	Dual stage (-42° C from ambient)
Limiting magnitude (using 20cm telescope)	15th (1 sec) 19th (1 min) 20th (5 min)

By means of feature comparison and cost evaluation, we came to the conclusion that the ST-6 best matched the 16 inch reflector and also gave us "the most camera for the money". A bid request was sent to the UMR purchasing department and indeed, SBIG met the camera specifications at the lowest price. Accordingly, the Physics Department ordered the SBIG ST-6 CCD camera for $3025. We took delivery of the device in late June (approximately 3 months after the order was placed).

TABLE II. ST-6 system specifications

Comparison basis	SBIG ST-6
A/D resolution	**16 bits** (65536 levels)
Readout sampling	**Double correlation**
Image readout baud rate	**Up to 115.2 Khz**
Output signal	RS232 or RS422
Power requirements	+5 Volts, 2.5 Amps 12 Volts AC, 3.3 Amps (wall transformer included)
Shuttering capability	**Yes**
Focus mode	**Yes**
Tracking mode	**Yes** **(also, auto-track- accumulate mode)**

III. CAMERA DIAGNOSTICS

The completion of a series of diagnostic checks was the first task accomplished following the arrival of the new ST-6 camera. Among the diagnostics performed were bias, dark, and flat-field frame acquisition. These cursory tests were used to evaluate the quality of the CCD chip and optical head assembly. Additionally, such measures provided the opportunity to become familiar with the operation of the SBIG data acquisition software.

A. Bias frame check

We began by grabbing a bias frame. The bias frame represents "what you see when you look at nothing for zero time". Bias frames map the variation of the voltage offset level between pixels. Routinely, due to the process of resetting the output amplifier, patterns become apparent in the bias. These patterns could be described as voltage offset spikes at the beginning and end of each pixel column. Furthermore, the bias can be used to spot defective pixels and/or columns on the CCD chip. A few such defects are common in most commercially produced CCDs.

Our ST-6 bias frames appeared normal in all respects. We did, occasionally, observe pronounced voltage spikes at both ends of the CCD. No outwardly defective pixels were spotted. See Figure 3. Having an appreciably higher output than neighboring columns, column 211 appeared somewhat anomalous. Fortunately, elementary methods of data reduction are capable of eliminating such minor defects.

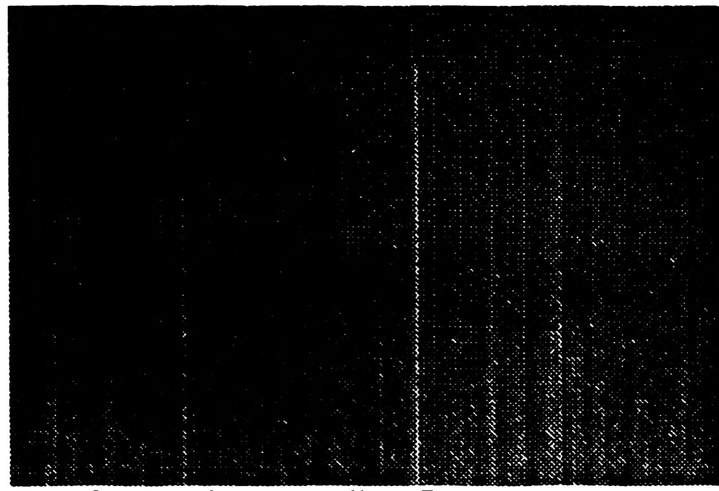

FIG. 3. Sample bias frame from the UMR ST-6 CCD camera. Integration was limited to 10 milliseconds (with a closed shutter).

B. Dark frame analysis

Next, we acquired a representative dark frame associated with an integration period of 30 minutes. This frame was subsequently used to evaluate the effectiveness of the optical head's dual thermoelectric coolers and also to look for extremely "hot" pixels.

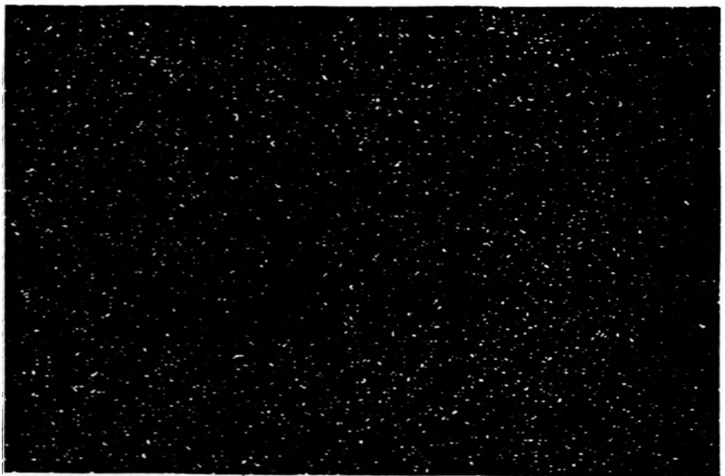

FIG. 4. Linearly scaled image of a typical 30 minute ST-6 dark frame.

The dark frame we recorded is found in Figure 4. The peak value associated with this data represents approximately one fifth the maximum camera output signal. See Figure 5 for a histogram of pixels vs. intensity. During the capture of this particular dark frame, the CCD temperature was maintained at -34.10 degrees Celsius (corresponding to 60 degrees below ambient).

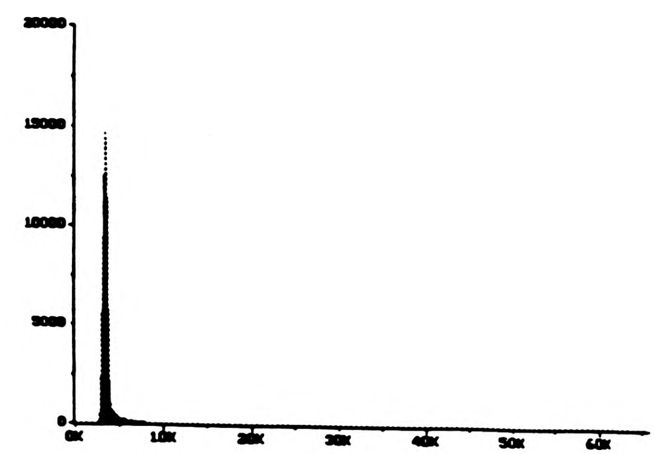

FIG. 5. Histogram of pixels vs. pixel intensity for a 30 minute dark frame.

Such extraordinary performance of the TE coolers was enabled by the simple dissipation of heat with a small six inch fan. The SBIG product specifications indicate standard capability of the TE chips as 42 degrees below ambient. We feel the addition of the fan has facilitated a significant increase in the performance of the camera head. (Recall: reduction of CCD temperature by 7 degrees Celsius results in a 50 percent reduction of dark current carrier production.)

Because the peak pixel value associated with the 30 minute dark frame shown in Figure 4 is minimal compared to the maximum possible (65355) pixel value, we conclude that image integration times of 30 minutes are easily feasible. Such images will still have sufficient dynamic range to record the subtleties of any brightness variation. Extrapolating, we believe integration periods of an hour (or possibly more) will not be inhibited by excessive dark current.

C. Flat-field inspection

Flat-field images need to be recorded at the beginning (or end) of every observing session. These vital images record the current state of sensitivity/gain variation for the entire CCD. They are most easily recorded by pointing the telescope and focused-camera toward a uniformly illuminated portion of the twilight sky and integrating for roughly 30 seconds. Once the flat-field images have been taken, elementary radiometric data reduction techniques may be used in order to equalize the sensitivity of each pixel.

A typical flat field for the ST-6 camera as individually implemented on the 16 inch UMR observatory telescope (without our optical housing) is depicted in Figure 6. The circular "doughnuts" found scattered about the image are due to the unavoidable presence of dust in our optical system. The appearance of these features is completely normal. Some sort of vignetting produced the dark area in the lower-left corner of the image. Finally, the dark feature similar in appearance to a notch at the top-left corner of the image is presently suspected to be either a group of insensitive pixels or a chip location rendered dark by the chance grouping of two particles of dust.

FIG. 6. Flat-field frame for the ST-6.

It should be noted that the use of many filters throughout a night of data acquisition requires extra care when obtaining flats. A flat-field image must be recorded through each filter (in the exact orientation it will later be used). Such unfortunate difficulty is, in part, due to non-uniform spatial response of the CCD to light of varying frequencies. Also, both the amount and position of dust on the individual filters is always different.

IV. PRACTICAL IMPLEMENTATION OF A CCD

We have not yet fully described a few important things to remember when observing the stars with a CCD camera. For instance, it is very important to keep an eye on the temperature of your apparatus. Second and equally important, appropriate radiometric correction of image data is vital.

A. Operating temperature

Constant operating temperature is critical to obtaining quality data because the effects of dark current must be taken into consideration. Neglecting the dark current contribution to signal strength is an unfortunate and incorrect procedure. By keeping temperature constant, the magnitude of this thermal signal may be approximated in terms of a "dark frame" having identical duration.

Dark frames may be defined as those integration runs during which the CCD is not exposed to any light. The signal strength associated with each pixel in such a dark frame ("dark map") is very nearly identical to the partial signal contribution of dark current in a true image frame (if both frames are integration for the same period of time). For this reason, we can artificially reduce the influence of dark current in our final images.

B. Radiometric correction

Variations in dark current production over the area of a CCD often conspire to generate a "raw", unprocessed image which is a great deal different than the true image made by the telescope. We can correct for this problem by carefully processing our data in a radiometric fashion.

The radiometric correction procedure associated with the reduction of dark current is quite simple once we have recorded a dark frame. Merely subtract all the dark map pixel values from the corresponding image pixel values. Application of this method is all it takes to significantly improve an image.

Figures 7, 8, and 9 illustrate the effect of dark frame radiometric correction on the Santa Barbara Instrument Group's ST-4 CCD camera. The image in Figure 7 is an unprocessed representation of Messier Object M51. Figure 8 is a dark map generated at the same time the unprocessed image was acquired. Note the "hot spots" of excessive thermal charge generation and also the corner glow produced by an amplifier in the camera body. These features, especially the glow, can be seen in the unprocessed image. Figure 9 is the radiometrically corrected image (after dark map subtraction).

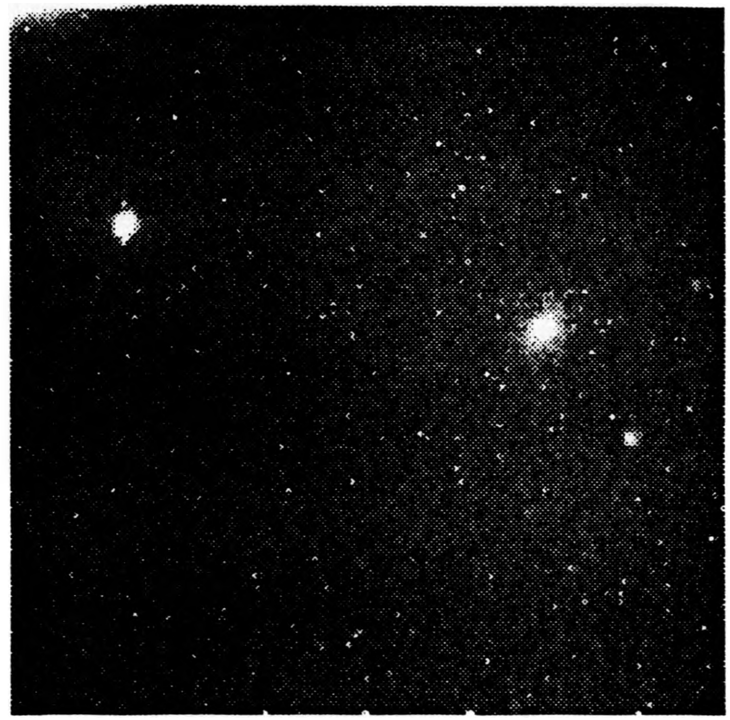

FIG. 7. Image of M51 before dark frame radiometric correction.

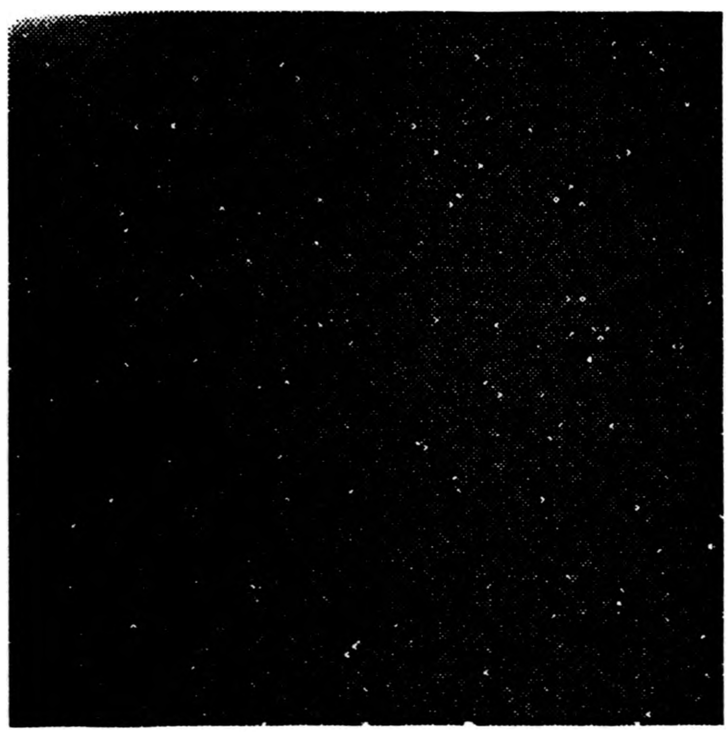

FIG. 8. Dark frame associated with the image of M51.

FIG. 9. Image of M51 after radiometric correction.

However, before starlight can reach the CCD camera, it must first pass through an intermediately-positioned, 5-hole filter wheel. This filter wheel has been designed as an interchangeable portion of the optical assembly. At the present time, we are implementing a set of BVRI filters for standardized astronomical data acquisition. Just as easily, we could place an RGB filter wheel in this position and subsequently take true color images of celestial objects. Such a technique is called tri-color imaging and is the standard in television photography. After passing through the filter assembly, starlight reaches the CCD imaging array.

The entire optical assembly screws securely to the back of the telescope (implementing a flat, circular aluminum plate as a junction base). This aluminum base and the black anodized portion of the optical assembly are joined by an old air-force surplus ring focusing mechanism. The focus is stable under the weight of our entire assembly.

We have had significant preliminary success with the custom optical assembly. Using our device, we reduced the time necessary for achieving proper focus from well over an hour to under a few minutes. Locating objects also appears to be slightly easier. In this respect, we need to try implementing a few other eyepieces having larger exit pupils (so that we gain a wider field of view).

V. EXPERIMENTAL APPARATUS

The present state of our experimental apparatus reflects the need for precision in focus and finding, while displaying the effectiveness of simple innovation. Furthermore, the apparatus facilitates acquisition of standardized data through the use of BVRI filters. Each of these needs has been achieved by the utilization of a custom-built optical assembly (designed as an interface between the telescope and the CCD camera). In addition, we have purchased a cheap six inch clip-on fan to aid in cooling the CCD.

A. The custom optical assembly

The currently operational optical assembly was machined largely from aluminum in the Cloud Physics Laboratory machine shop. See Appendix I, Figures 10-16.

The functionality of our device is based on the presence of a movable 12 mm eyepiece and tube, with a prism placed at the end of the tube. This tube is arranged so as to intercept the light originating from the telescope and direct it to the viewing eyepiece. Furthermore, this illuminated reticle eyepiece, when slid into the assembly, rests parfocal with the CCD chip in order to allow any camera user to focus the camera using his or her eye (and not wasting hours of precious observing time with a hit-or-miss focusing technique).

When the eyepiece tube is not inserted into the body of the optical assembly, light passes to the CCD camera by striking a diagonally positioned, front-coated mirror at the back of the assembly and then exiting through a hole in the housing side opposite the eyepiece.

1. *Fundamentals of BVRI photometry*

The measurement of a star's color and brightness yields important information on stellar temperature, classification, and distance. Periodic measurements of the luminosity associated with certain *variable* stars (variable-brightness) is of significant interest to astrophysical theorists.

The most common system of measuring stellar color and brightness is the UBV photometric system designed in 1965. A multicolor broad-band photometric system, the UBV photometry convention requires the measurement of stellar luminosity at certain regimes of color, specifically (U)ltraviolet, (B)lue and (V)isible (yellow). Differences between the apparent magnitudes of stars help indicate stellar temperature and classification.

With the advent of solid-state CCD detectors (which have low ultraviolet-sensitivity) the UBV system was generalized to cover other spectral bands. This new standard system includes Red and Infrared bands (hence UBVRI) in which the common CCD detector is most sensitive. Since the ST-6 is not sensitive to the ultraviolet, we wish to facilitate the Blue, Visible, Red, and Infrared bands of the UBVRI photometric system (thus we have BVRI). The data obtained through such measurements will be disseminated to professional astronomers through the American Association of Variable Star Observers (AAVSO).

B. The auxiliary cooling fan

We have found, by directing a six inch fan towards the camera's optical head, the manufacturer cooling specifications may be exceeded by roughly 18-20 degrees Celsius. As described in the section on dark frame analysis, we have routinely achieved a temperature reduction of 60 degrees from ambient. Such a reduction corresponds to cutting the dark current carrier production to less than one quarter of SBIG's optimum level. The fan was relatively inexpensive and, accordingly, we feel the investment was well worth the money.

VI. SOFTWARE DEVELOPMENT

After the ST-6 camera was first evaluated, it became apparent that a software program -- capable of performing for camera diagnostics; image acquisition, reduction, and processing; aperture photometric analysis; and RGB (Red-Green-Blue) color imaging -- was needed. An integral piece of the photometric system, the software became a major concern of the researchers. Before completing the project.

A. The SBIG ST6OPS program

The program marketed by SBIG along with the ST-6 camera to run on IBM compatible MS-DOS computers, ST6OPS, has strong features in its data acquisition capabilities and user-friendly interface; yet it is weak in the areas of image reduction and processing, and has little or no application to RGB color image production and aperture photometry.

ST6OPS' user-friendly interface features hot-key menus, dual graphics image display and text menus. Operations are divided into five major menu categories: File (File Operations), Camera (data acquisition), Display (graphics display), Utility (image reduction and processing), and Misc (miscellaneous features). The File menu includes image loading and saving in the SBIG formats, the TIFF image format used by desktop publishing programs, and the FITS format used in astronomical circles; track list saving and loading (track lists are used in track and accumulate modes); image deletion; DOS directory creation; and DOS path changes. The Camera menu includes Grab (grab an image), Focus (iterative image grabs to aid in focusing the ST-6), Track and Accumulate (multiple image grab and add), Setup (temperature regulation and anti-blooming control), Adjust Offset (change the video offset), and Establish Com Link. Display covers image, histogram, parameter, and modification display, as well as color table loading. Utility implements dark subtraction, smoothing, sharpening, flat fielding, scaling, cool pixel removal, warm pixel removal, parameter edit. Miscellaneous features includes pc setup (video modes, COM ports, etc.), telescope setup (parameters for image files), and a loopback com test.

The ST6OPS program is limited in several ways. Most notably, the ST6OPS program has only one memory buffer -- and expanded/extended memory support is not implemented. Therefore, flats and darks are read from disk, rather than from memory. Also there is no way to 'take back' a command, no 'undo' feature. This means that if a function is applied to an image, to get the original image back, it must be re-read from disk.

Also missing is adequate image browsing for simply looking at image parameters. To see comments, exposure times, etc. the entire image must be loaded into memory. Also, during image taking, the ST6OPS program does not continue to regulate camera temperature. Finally, the ST-6 software has no capability to measure a star's luminosity compared to a reference star or a sky background level nor does it support BVRI photometry (aperture photometry).

B. Development of imaging software

Because of the inadequacies inherent in the ST6OPS program, the researchers decided to dabble in PC systems programming to create an image manipulation utility. Progress was slow, since neither researcher was an expert on high-resolution color computer displays or large array programming. Most work focused on taking image data and developing the camera mount and BVRI photometry filter housing. While the knowledge gained was great, designing a user-friendly, multi-purpose, display adaptive program was deemed to great an investment in researcher time. In fact, the necessity of writing such a program is quickly abating -- since the initiation of this project, new programs have come upon the market at reasonable rates that should satisfy the UMR observatory's needs.

1. Eight bit (256) and fifteen bit (32768) color images

An imaging system needs an effective video output system, as closely matched as feasible to the hardware as possible. IBM computers have traditionally utilized one four of standard video modes: Hercules, CGA, EGA, and VGA graphics, each characterized by their resolution and color levels. Only VGA graphic cards implement 256 colors simultaneously, making them the minimum usable graphics mode. Other modes look like childish crayon drawings -- many pixels to color, but only a few colors available for use. The base VGA 256 color display is called MCGA (same 320x200 resolution as CGA but with 256 colors rather than 4). Super-VGA modes available on many video cards allow 640x480x256 and 800x600x256 video modes (available using the Orchid cards in the Physics CLC). Also, a new generation of 32768 color VGA display systems are slowly becoming affordable.

Unfortunately, the Borland TurboPascal product (used to develop the utility software) does not directly utilize these video modes. However a shareware product available through Jordan Hargraphix Software of Pittsburg, PA for $20 implements the high-resolution video modes. A display program has been written to implement the SVGA256.BGI video driver. The 32K video driver is currently superfluous, since no Physics Department video monitors are capable of such resolution.

2. The problem of large arrays

Images are fundamentally very large arrays of 16 bit integers. This creates a computer memory storage problem -- usually programs are limited to 64 kilobytes of static storage. This limitation fundamentally constrains standard compile-time arrays to small values. However, *dynamic* arrays have no 64K limitation, since they are allocated to heap space (DOS machines generally have 400 kilobytes of heap space free). These dynamic arrays are challenging to create and define, and this side of programming has slowed progress tremendously.

Even after concepts in dynamic array programming were mastered, memory was still an issue. The heap space allocated must be shared by the control program. Since the images take up more than 100 kilobytes (on average), memory is still cramped. Much effort and research was allocated to making the images storable in *extended memory*, memory unused by DOS programs, and currently become the additional memory of choice.

3. Camera Communications

Since the ST6OPS program has adequately performed most image acquisition functions, only preliminary work has been developed toward the goal of camera communications. Information has been obtained from the SBIG company on the protocol for camera communication; however, this data cannot be incorporated until greater knowledge of the IBM communications chip -- the UART. IBMS BIOS (Basic Input/Output System) communicates with the UART via software interrupts (specifically interrupt $14). However, the BIOS only has parameters to tell the UART to communicate up to 19.2 kilobaud, although the UART on most 286/386/486 computers allow 115 kilobaud or greater communication rates (the rate the ST6OPS program utilizes). Until more pressing functions are implemented, camera communication and image acquisition will be set aside.

VII. TELESCOPE REVITALIZATION

A. Optical collimation

In late June, we successfully collimated the 16 inch UMR observatory telescope. This procedure, normally considered to be part of the routine upkeep for any telescope, was performed over the course of one afternoon and evening. Satisfactory results were subsequently noted.

Collimation is the process of aligning the optical elements within a telescope. In our case, the elements (mirrors and lenses) must each be concentric along a central axis and also lie in parallel optical planes. That is, they must not be skew with respect to each other. Successful collimation often yields sharper, more detailed images.

We collimated the 16 inch Cassegrain telescope following a procedure found in a series of Sky and Telescope articles[1,2].

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[1] P. Valleli, "Collimating Your Telescope - I," Sky & Telescope (3),259-263 (1988).

[2] P. Valleli, "Collimating Your Telescope - II," Sky & Telescope (3),363-365 (1988).

B. Polar alignment

Plans have been made for the polar alignment of the UMR observatory telescope. Currently, we are awaiting a clear night.

The polar alignment will proceed via the method of successive approximation. Two group of several stars will be selected which lie near the celestial equator (zero declination) and near the meridian (on both sides of the celestial pole), respectively. After obtaining the 1992.5 celestial coordinates of the selected stars (from the library's Astronomical Almanac) and accurately setting the observatory sidereal clock, the researchers will record the amount and direction by which each stellar coordinate is off from the tabulated values.

Subsequently, the telescope mount will be tilted so as to force agreement with the coordinates for a single star. After this first approximation to perfect alignment has been completed, the telescope will be directed to a second star in the selected group. Once again the giant bolts holding the telescope in polar alignment will be tweaked to remove any remaining discrepancy. This successive process will continue until the coordinate errors are negligible. (Each coordinate direction is aligned separately - first right ascension and then declination.)

VIII. CONCLUSION

The information just presented within the confines of this text details the progress we have already made towards converting the UMR observatory from a recreational to research-capable facility. Pending good weather, the BVRI system will soon be used for a first data gathering session. Initial multicolor broad-band luminosity measurements of common, reference objects will provide a gateway to scientifically valuable variable star information.

The telescopic experimental apparatus is complete. It will support standard BVRI photometric data acquisition and reduction. Tri-color imaging can be made possible through the use of red, blue, and green filters or by simulating true color with the blue, visible, and red bands of BVRI system. In this manner, scientifically significant data and full color images might then inspire a new generation of student to continue our work.

IX. ACKNOWLEDGEMENTS

We would like to heartily thank the following individuals:

Dr. John Schmitt -	for all of his time and assistance in the design and construction of the optical housing - also for all the advice.
Dr. Edward Hale -	for continuing encouragement and support.
Dr. Ralph Alexander -	for aiding us in the acquisition of the camera and for other necessary items.
Dr. Laird Schearer -	for encouraging our research through the means of financial support.

APPENDIX I. Photographic figures

FIG. 10. The UMR Observatory. Pictured is the 16 inch Cassegrain telescope and a preliminary version of the optical assembly. Note the six-inch fan to facilitate CCD camera head cooling.

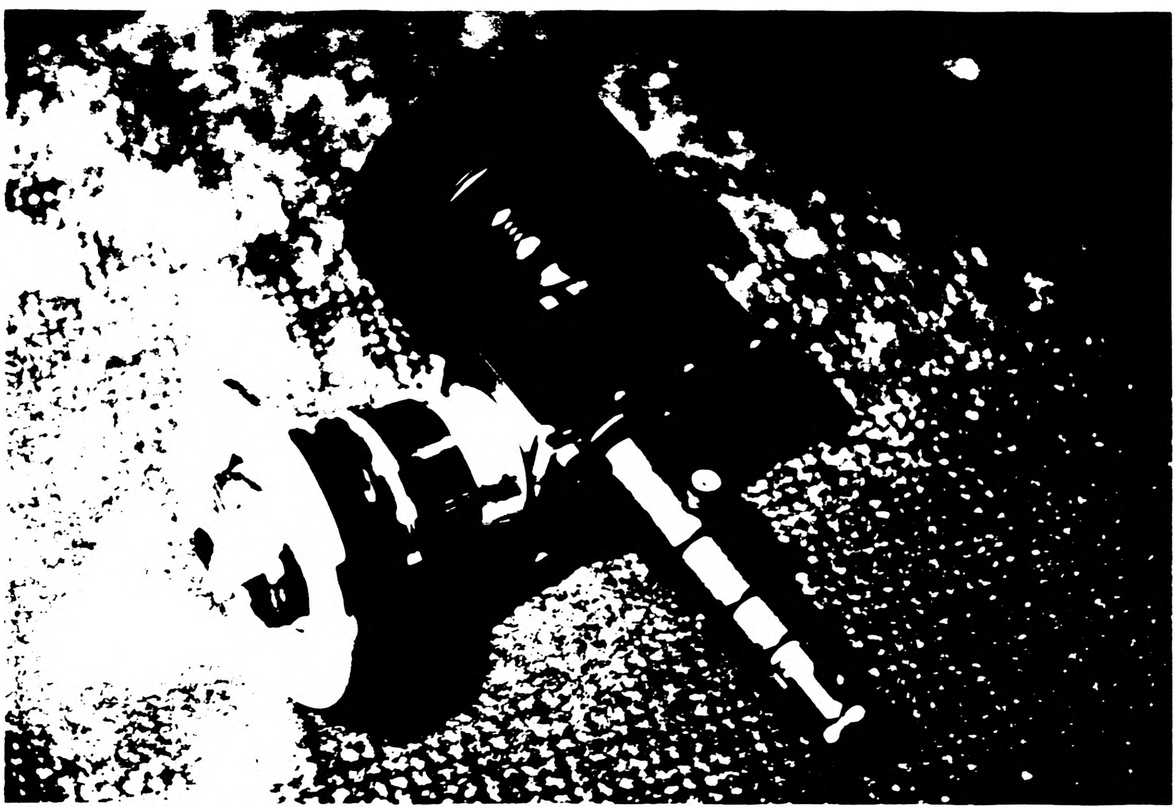

FIG. 11. The custom optical assembly (focusing aid and BVRI filter wheel) and the SBIG ST-6 CCD camera.

FIG. 12. The interior of the optical assembly. At the right in a black anodized Aluminum housing is the front coated mirror. At the left is the fine focus and telescope mount.

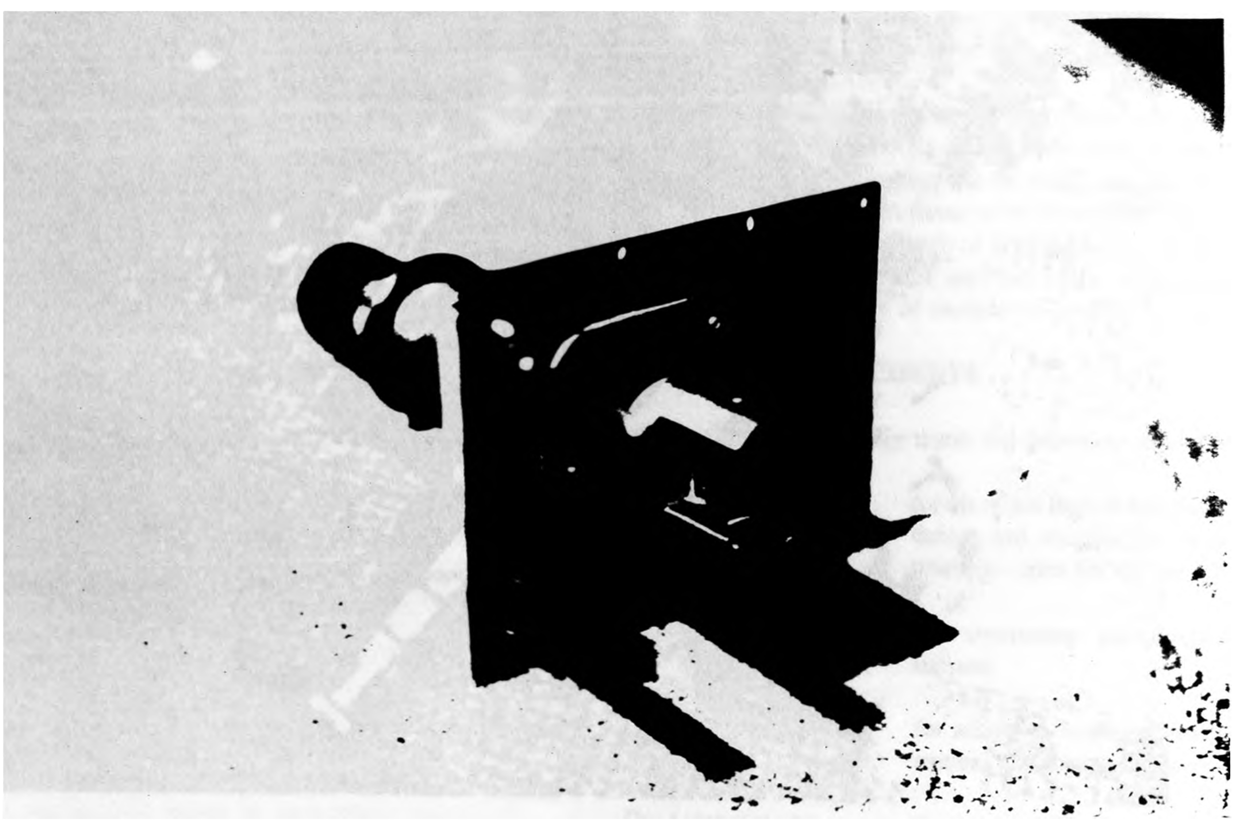

FIG. 13. The 12mm illuminated reticle eyepiece, sliding focus tube, and prism.

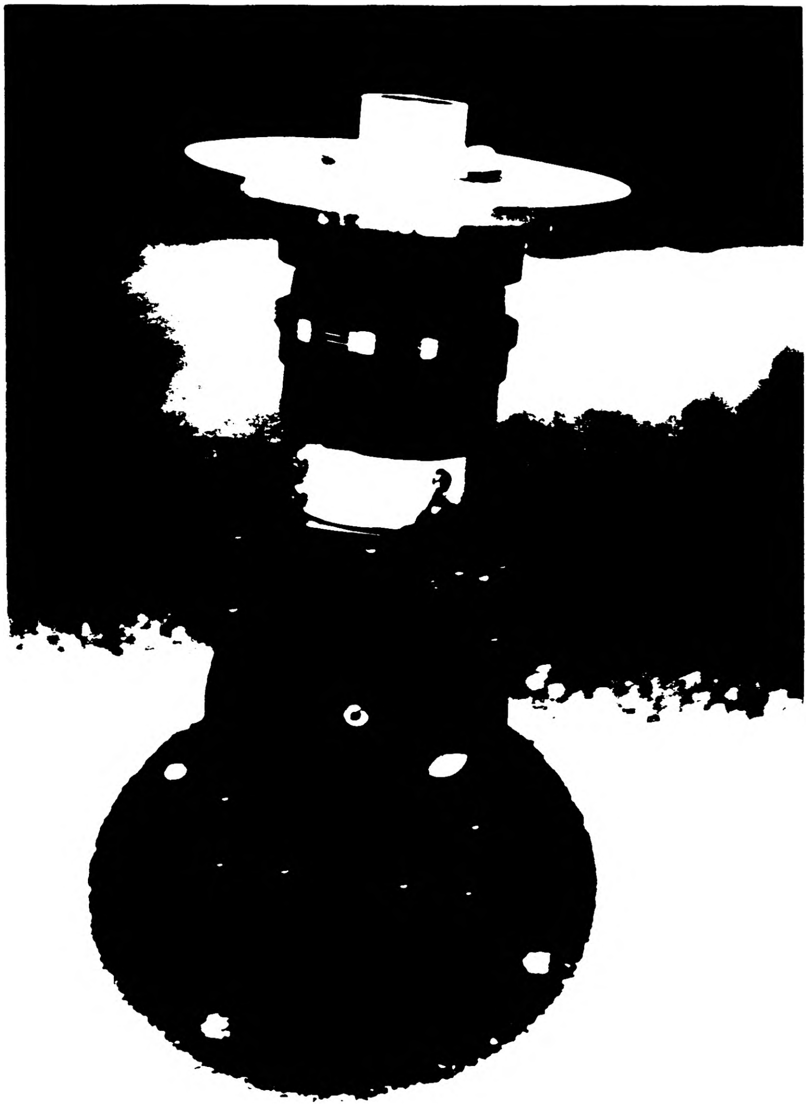

FIG. 14. The other side of the anodized aluminum housing showing the filter wheel. Clockwise from the bottom: Blue, Visible, Red, Infrared, and Clear (with anti-reflection coating) filters.

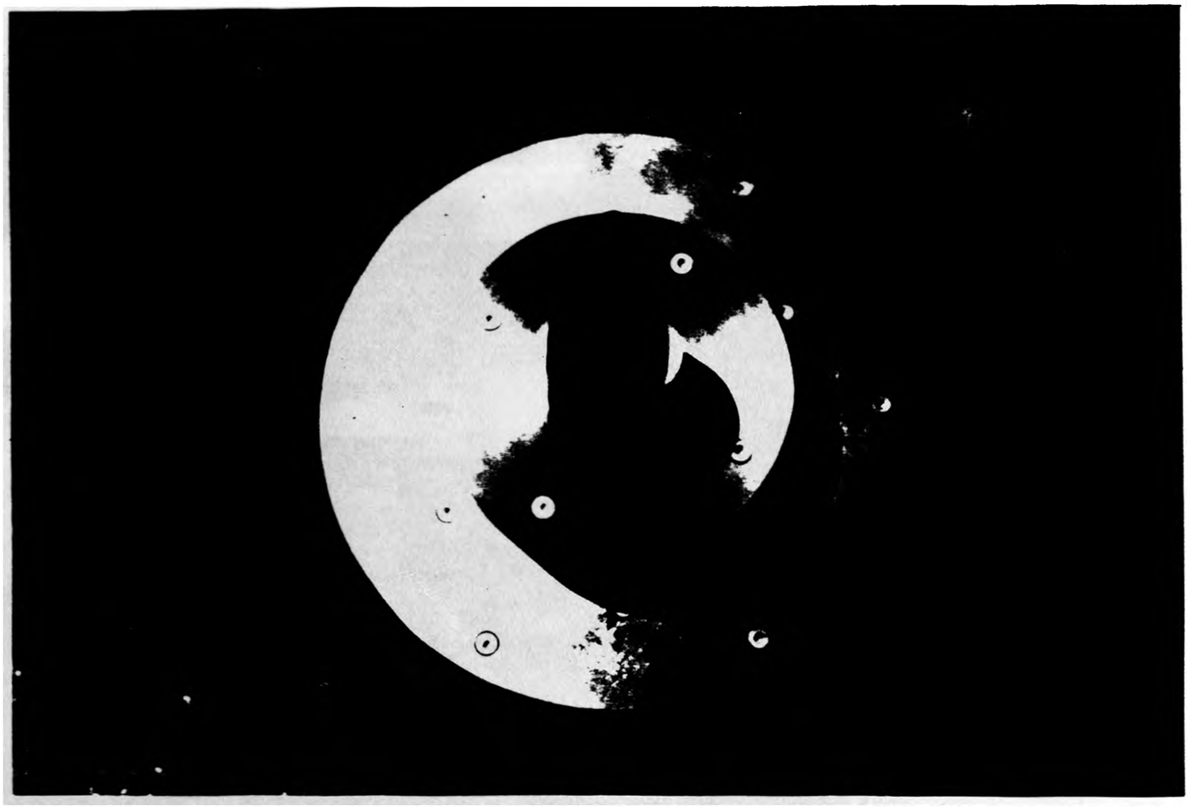

FIG. 15. The front face of the Santa Barbara Instrument Group ST-6 CCD camera. The imaging surface, the CCD chip, is plainly visible in the optical tube.

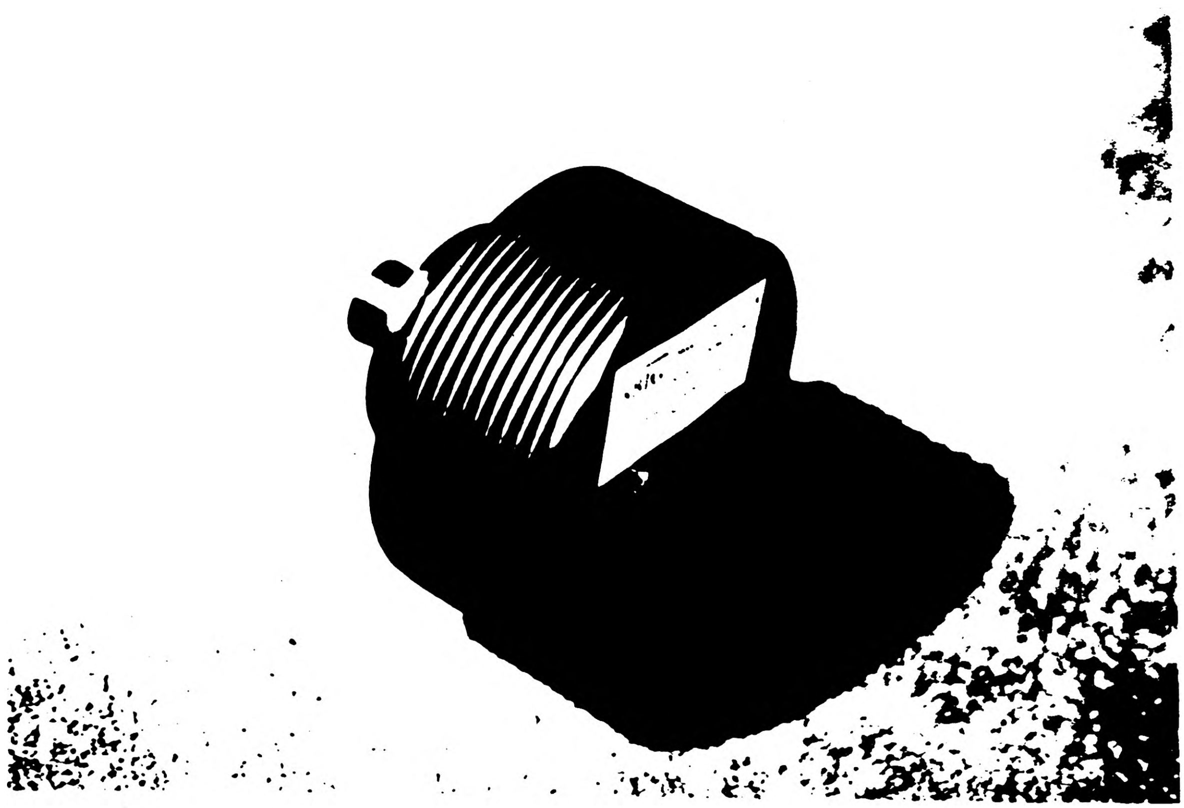

FIG. 16. A side view of the SBIG ST-6 CCD camera. Noticeable are the heat-dissipative fins. The RS232 interface connecting the camera head to the computer interface and memory frame buffer is also visible.