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AUTOMATIC PHOTOELECTRIC TELESCOPE

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I. HISTORICAL INTRODUCTION

Differential photoelectric photometry by its very nature is a repetitious task that seems to have an inherent affinity for digital computers. It was during the 1950's that Stewart Sharpless and others used digital computers to reduce photoelectric data, and the Pierce photometer at the Flower and Cook Observatory logged data in a digital format ready for analysis. While these early efforts are certainly of interest, we will be concerned in this introductory section only with ground-based optical telescopes used to make automatic photoelectric observations. We will limit our concern to those telescopes that were dedicated to photometry and had photometers that were used not only for the measurements per se but also as an aid to acquiring and centering the stars to be observed.

One of the earliest automatic photoelectric telescopes we are aware of was at Kitt Peak National Observatory. The 50-inch telescope project at Kitt Peak was initiated by Aden Meinel as a remotely controlled telescope with the computer located in Tucson (Goldberg 1983). Meinel foresaw the coming importance of remotely-controlled space telescopes and the need to develop remote control and automatic capabilities. The project leadership was later assumed by Stephen Maran who, in a very perceptive paper (Maran 1969), pointed out the principal advantages of automatic photoelectric telescopes. These included observations at a faster rate due both to the faster locating and centering of the stars and to the continuous operation without the breaks and other interruptions introduced by typical human operators. Maran also suggested that the data would be obtained more systematically and that the telescope could be called on to do necessary but boring tasks. He also suggested that the cause of science might be served better by an automatic telescope that could look at many different program stars over a long interval instead of just a few stars over relatively short intervals, as tends to be the case with manually controlled telescopes.

Maran also noted that automatic telescopes posed primarily a control and systems engineering problem rather than an astronomical problem, and that high reliability was a prime requirement. While computers in those days were not noted for their high reliability, the system did become operational and some observational results were published (Hudson et al. 1971). While the project was a success technically, as pointed out by Meinel (1984), few astronomers in those days had an interest in remote control, their preference being hands-on operation at the telescope itself. Of course it is such pioneering work that paves the way for those of us who come later.

Certainly the most interesting of the early automatic photoelectric telescopes is the 8-inch system developed by McNall, Miedaner, and Code (1968). This system was controlled by a PDP-8 minicomputer, and used a permanently mounted photometer to help locate and center the stars in addition to its normal function of measuring the brightnesses. The system was fully automatic, could start itself up in the evening, make measurements on a number of different stars located about the sky, and shut itself off before morning light. While it was used primarily to observe standard stars to determine extinction, it was also used by Millis (1967) to observe suspected delta Scuti variables. This well-designed pioneering system is similar in many ways to the recently developed system described later in this paper. Surprisingly, there were no successful similar developments, to our knowledge, in the 15 years that separated these two projects.

While there were a number of other projects related to automatic photoelectric telescopes, two seem particularly worth mentioning. One was the semi-automatic system at Cloudcroft Observatory. It was used, for example, to observe fixed sequences of solar-type stars in clusters (Worden et al. 1981). Although the Cloudcroft system had reliability problems (Henry 1984), it was dismantled recently due to financial considerations despite having produced a reasonable amount of published results. The other telescope was developed by Skillman (1981, 1982). While it required the operator to set the telescope initially on the variable to be observed, it could then go automatically between variable and comparison star for many hours and thus was useful in observing short-period variable stars. These two telescopes are noteworthy because they both produced useful observational results and both utilized their photometers and computers as an intergal part of the process of finding and centering stars.

In 1979 one of us (Boyd) initiated a project to design, build, and operate a photoelectric telescope that could accomplish fully automatic UBV photometry on a large number of different variable stars every clear night. An earlier description is given by Boyd (1983). With this project now successfully completed, it is the intent of this paper to describe (1) the equipment used to make the observations, (2) the control program that operates the equipment, and (3) the initial observational program and illustrative results. Those interested in the various tradeoffs and considerations in the design and operation of automatic photoelectric telescopes may wish to consult Boyd and Genet (1983).

II. EQUIPMENT

The observations discussed below were made with the 10-inch f/6 telescope located at Fairborn Observatory West in Phoenix, Arizona and shown in Figure 1. The optical system is a conventional Newtonian configuration with a photometer permanently mounted at the focus. A symmetrical fork mount minimizes the moment of inertia of the system.

Telescope drives in right ascension and declination are identical and consist of 32-inch diameter aluminum disks that are each driven by a chain from a sprocket that in turn is driven by a stepper motor through a small anti-backlash worm gear. This drive was chosen because it would be virtually free of backlash without preloading and could accurately execute the many rapid motions commanded by the computer. On a good night as many as 25,000 separate motions are executed, so it is vital that the drive and mount be sufficiently stiff that vibrations induced by the sudden movements die out in a fraction of a second. The telescope mount recently designed by DFM Engineering, which uses 15-inch diameter friction disk drives in both axes, would be ideally suited for use in automatic photoelectric telescopes (Melsheimer and Genet 1984).

The photometer used to make the observations employs a standard side-on 1P21 photomultiplier as the detector. Diaphragm and filter wheels and a microscope flip mirror are all under control of the computer, although it was found subsequently that a fixed-sized diaphragm was entirely adequate and that a flip mirror was unnecessary. Future photometers intended for use on automatic photoelectric telescopes (such as the Optec SSP-4 photometer under development) therefore need have only a filter wheel directly attached to a small stepper motor.

A number of very important simplifications were made in the control electronics after the original electronics became operational. Rather than describe the more complex and now outdated first generation electronics, we will describe only the second generation electronics. The heart of the system is the very capable Motorola 6809E Microprocessor. This advanced 8-bit microprocessor is located on a Peripheral Technology PT-69 single-board computer. In Figure 2 the location of the computer is shown in the overall block diagram of the system. This computer was chosen because it had all the necessary features on a single low-cost (less than $300) board. Besides the processor, it has 56K of RAM (random access memory), 4K of EPROM (erasable programable read-only memory), a floppy disk controller, a clock/calendar with battery backup, two serial RS-232C ports, and two parallel ports. All this is contained on a 3.5-inch by 6.5-inch printed circuit board.

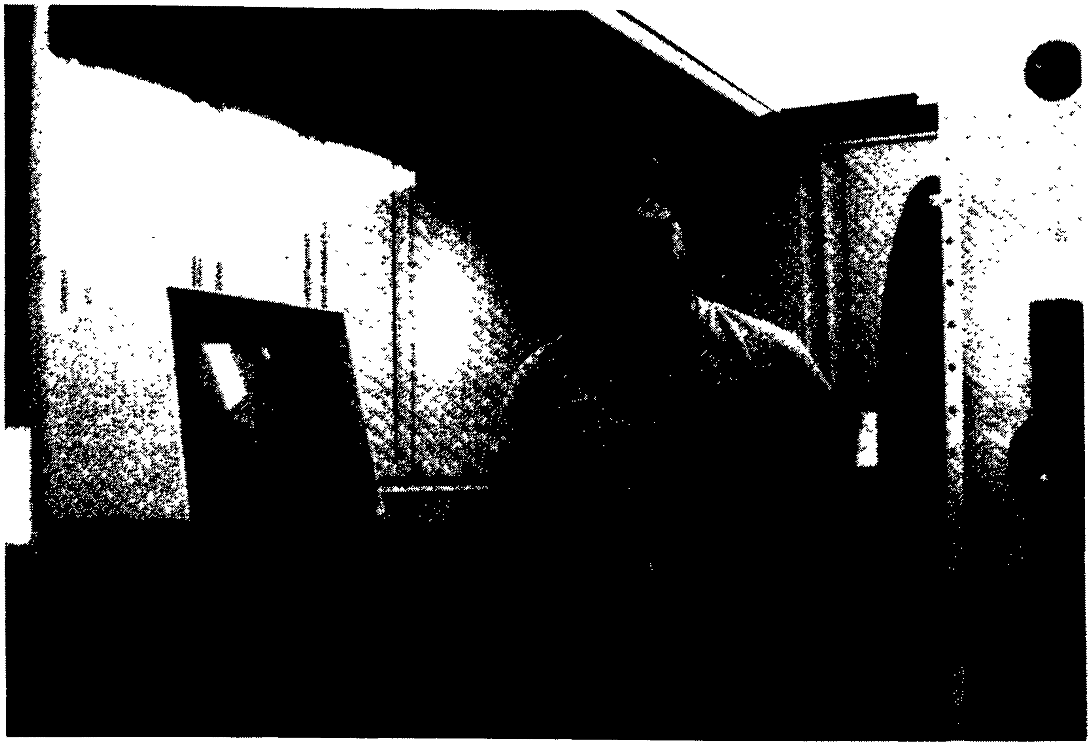

Fig. 1. The Automatic Photoelectric Telescope located at Fairborn Observatory West in Phoenix, Arizona. Louis Boyd is shown beside the 10-inch f/6 Newtonian telescope.

The complete schematic for the electronics control board is shown in Figure 3. The components in the lower left provide an adjustable stellar rate drive that is independent of the PT-69 computer. Thus, from the viewpoint of the PT-69 and control program, the sky is not moving at all; this greatly simplifies the software. When the telescope is just tracking or making slow movements, a normal 6 volts is applied to the stepper motors. When ramping up or down or slewing along at high speed, however, a four-times overvoltage of 24 volts is applied to the steppers to achieve a faster stepping rate, some 5000 half-steps/second. The control board provides the logic for developing the four-phased signal needed to control each of the three steppers and it also provides the logic for combining the constant stellar rate pulses with any pulses in right ascension commanded by the PT-69 computer. The limit switches are inputed directly into the computer and are "anded" in the step generation logic in the machine-language stepper driver program. The "west" limit switch is hardwired to turn off the pulses coming from the stellar rate generator.

The only other electronics needed for telescope control are the three high-speed stepper driver boards. They are identical, and their schematic is shown in Figure 4. The

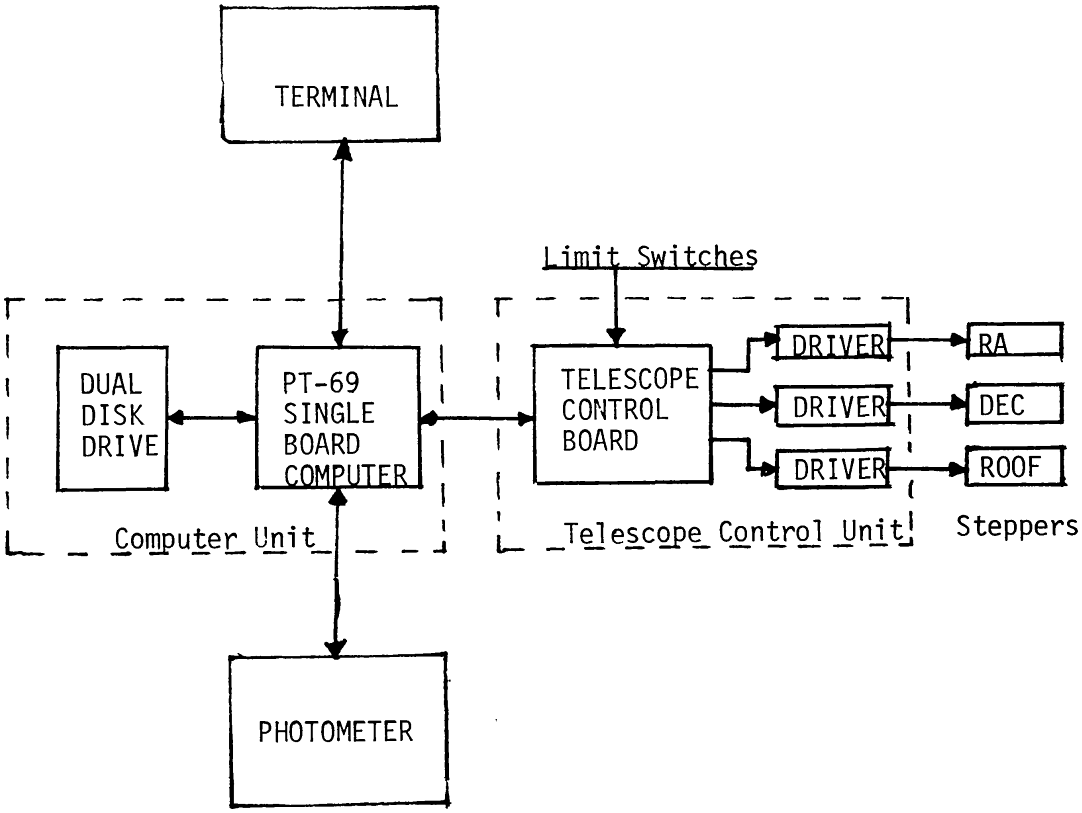

Fig. 2. Block diagram of the second generation electronics.

circuit provides for switching between 6 and 24 volts, driving the steppers, and improving the high-speed performance with diodes.

III. CONTROL PROGRAM

The control program was written in Microware Basic09. This language was chosen because of its ability to handle multiple independent programs (called procedures), its extended control structures such as "while-do-endwhile", and its unusually well-structured Pascal-like format. The operation of the control program can perhaps best be understood by considering the normal sequence of operations. For those interested in more detail, a book on microcomputer control of telescopes (Trueblood and Genet 1984) devotes two chapters to the control program and lists the entire program in an appendix.

The main control program (procedure) is appropriately called MAIN. During the day, procedure TILDARK checks the time and calculates the position of the sun. As soon as astronomical twilight occurs, MAIN calls procedure STARTSCOPE. This procedure places the telescope in a known initial starting position by moving the telescope until it trips optical limit switches in the south-east corner of the telescope's travel range, its "home" position. STARTSCOPE also initializes the filter wheel, etc. and turns on the tracking

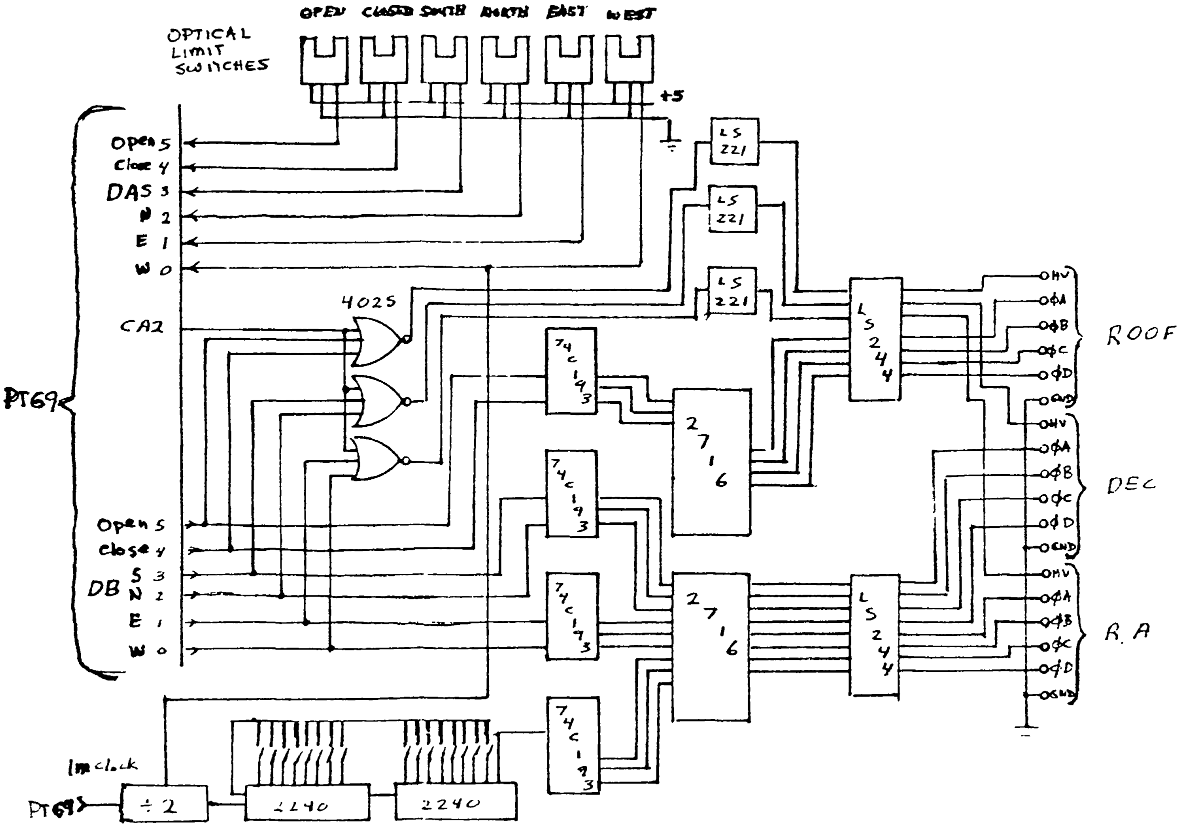

Fig. 3. Schematic diagram of the Telescope Control Board.

rate generator so that the telescope starts moving towards the west.

Procedure MAIN then selects which "group" of stars to observe first. A group consists of variable, comparison, and check stars, and a sky position (usually midway between the variable and comparison). There is a mathematical "observing window" above the telescope within which all observing must be done. The window can be set to avoid trees, go close to the horizon, exceed telescope physical travel limits, etc. The group chosen for observation is the first one that will set on the western edge of the observing window (and which is at least 10 degrees away from the moon). This selection is made from among all the groups in the entire observing program; thus an observing program need be loaded only once and the system will itself choose what stars should be observed and in what sequence. Because the group that will set first on the western edge of the observing window is the first to be observed, groups will be observed from west to east and dawn will find the system working groups just as they rise over the eastern edge of the observing window. This approach maximizes the coverage of groups over the year. Other strategies are possible, such as observing groups closest to the meridian.

Procedure MOVE is then called to move the telescope to the group to be observed. As shown in Figure 5, a move is made from point A to point C in two segments with an inter-

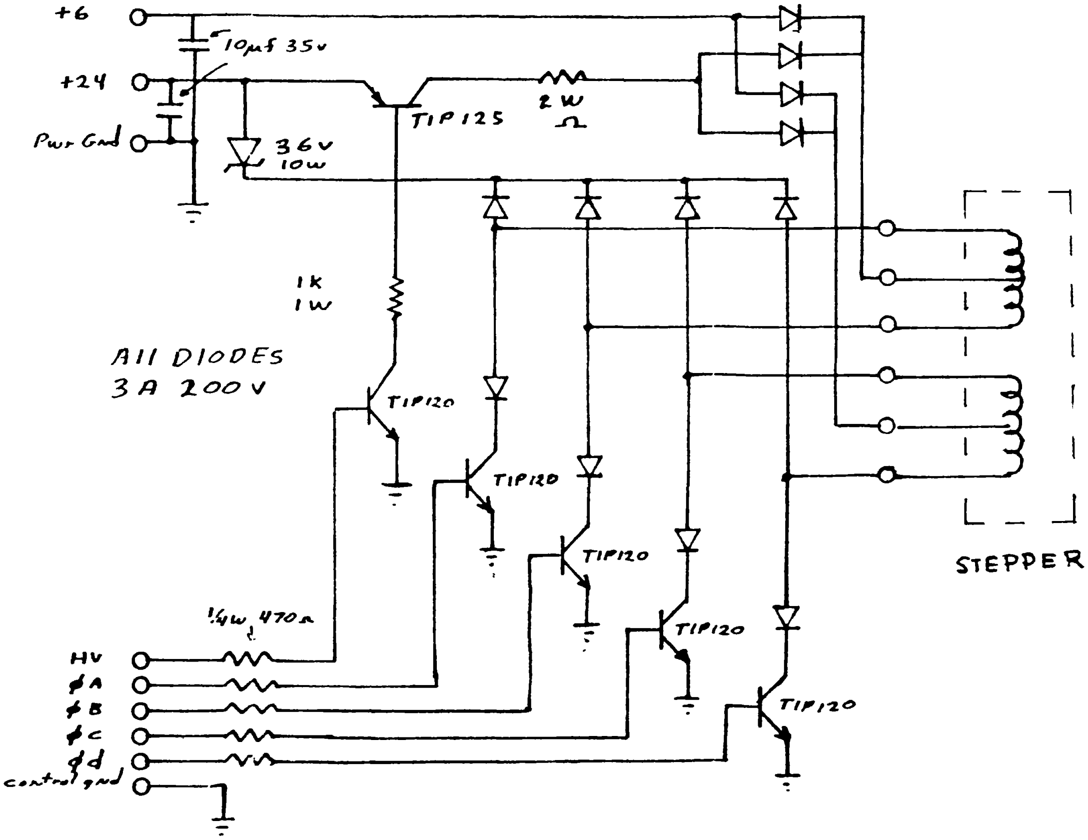

Fig. 4. Schematic diagram of the Stepper Driver Board.

mediate stop at B. This allows a single source of ramped pulses to move the telescope from A to B, with both right ascension and declination steppers operating simultaneously. After a fleeting stop at point B, the declination stepper is operated by itself to bring the telescope to point C.

Experience shows us that, even after traveling clear across the sky with an open-loop stepper system (there are no optical shaft encoders), the telescope is always within 12 arcminutes of the desired position, which is the check star in the group. Before a search can be initiated for the check star, it is necessary to estimate how bright the check star will be, so an appropriate threshold can be set. This estimate is based on the sky brightness, the expected extinction (as a function of zenith angle), and the catalog "V" brightness of the star. The sky brightness is determined by making five measurements in a "square with center" pattern and taking the lowest one.

Procedure HUNT is then called. It executes a "square spiral" search pattern as shown in Figure 6. Starting at position "1" it makes a 0.2-second integration in V and compares the value obtained with the previously set threshold. If it is not exceeded, the telescope is moved to position "2". This continues until the star is found or the 12th spiral has been completed, whichever occurs first. If a star is found, it is centered using procedure LOCK described below. If the star is not found (which experience shows us happens only if the sky has become cloudy), then the telescope is moved back to position "1", the next group is selected, the telescope is moved to it, and another search is initiated. If it, also, is not found, then STOPSCOPE is called and the system shuts itself down automatically.

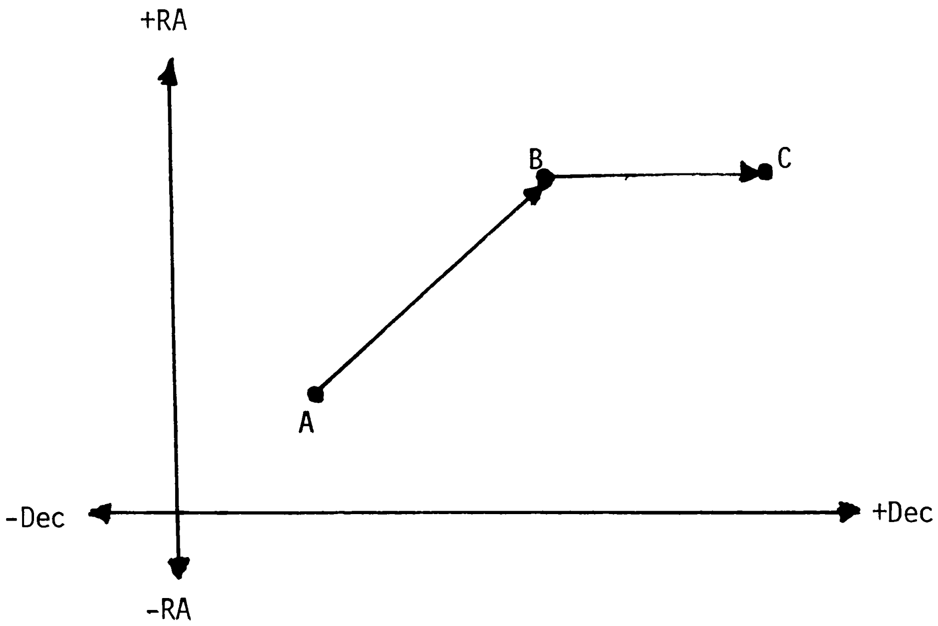

Fig. 5. Sequence of telescope motions made during procedure MOVE.

It might be thought that, with so many stars in the sky, the wrong star might be acquired on occasion. In the five months of operation completed when this paper was written, almost 50,000 stars had been acquired successfully, i.e., always the right star. A crucial factor responsible for this perfect success rate is the selection of the check star, which we sometimes refer to as the navigation star. The check star is chosen to be in an optimal magnitude range for the system and to be clear of any nearby and/or comparably bright stars that might confuse the system. After the long move to a check star and the acquisition of it, the moves to the comparison star and the variable star are over short distances. Here the accuracy of the open-loop telescope positioning is very good, usually better than 1 arcminute.

Once the star is acquired, it is centered in the diaphragm by procedure LOCK. Because single "X" and "Y" scans were found to be slow and inefficient, we use an iterative procedure that requires just four measurements on each iteration. From the initially assumed center position, the telescope is moved to four different positions which allow a slight overlap of the diaphragm edges over the assumed center position. At each of these four positions a check is made for a star that exceeds the threshold. If a star is detected at all four positions, as shown in "a" of Figure 7, then the star must be centered and the job is finished. If the star shows up on both left positions but neither right position, as shown in "b", then the telescope must be moved to the left. Other directions can be deduced from other combinations. Of the 16 combinations possible, two are logically illegal; if either of these is detected, the process is repeated. After each set of four measurements, the telescope is moved to a new assumed center not far from the original one, but in the correct direction. After just a few iterations, our experience shows, the star is always centered.

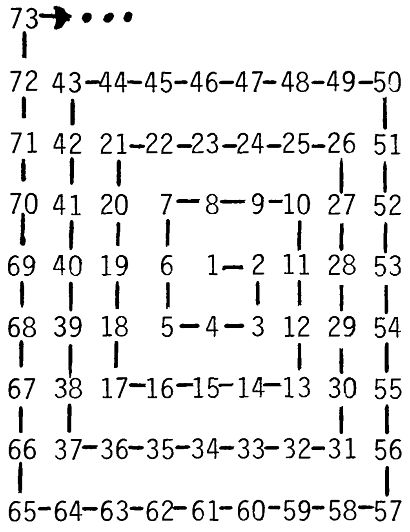

Fig. 6. The square spiral search pattern executed by procedure HUNT.

With the first (check) star centered, measurements of 10 seconds duration each are made in U, B, and V. The telescope is then moved to the comparison star position and that star is acquired, centered, and measured. The complete sequence of moves and measurements made to complete the 33 observations in a group is shown in Table I. This yields three bracketted differential measurements (each in U, B, and V) between variable and comparison and two differential measurements (each in U, B, and V) between comparison and check. These differential measurements are examined in real time for internal consistency. If this examination is failed, then the group is remeasured. If it is passed, then the next group is selected and observed.

This process is repeated until the system fails to find two groups (almost always because of clouds) or until the system determines from the calculated sun position that astronomical dawn has occurred. In either event, the system is returned to its home position and the roof closed.

IV. OBSERVING PROGRAM AND SAMPLE RESULTS

APT Observing Program I consisted of 29 groups of stars. The group names are shown in Table II along with the number of times each group was observed. The name refers to the variable or suspected variable star in the group or, in the case of three groups (5, 16, 23), to the red-blue star pair used for transformation coefficient determinations.

APT Observing Program I began on 12-13 October 1983 and was terminated 30-31 December 1983. After the observations on the program had been completed, data on individual groups

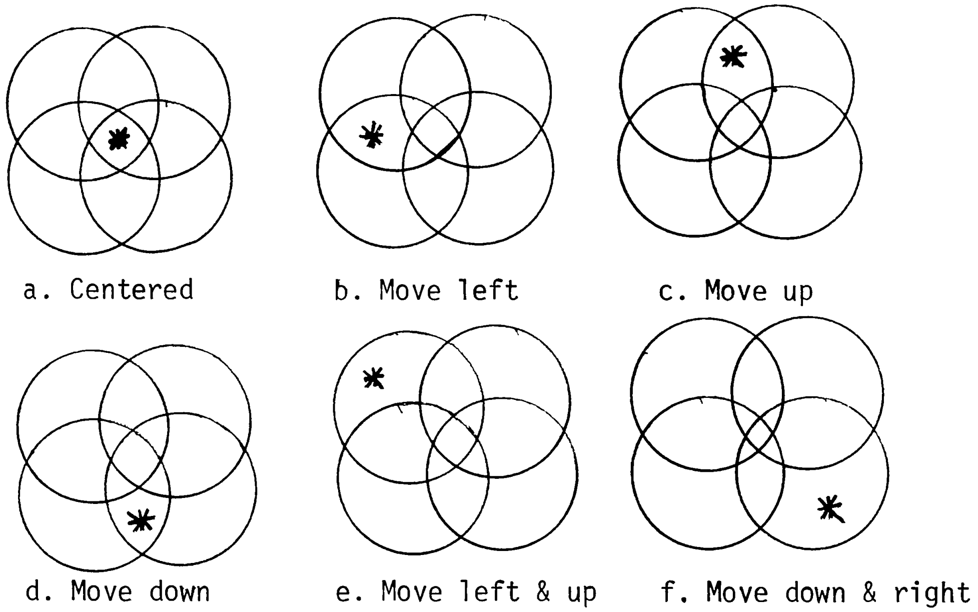

Fig. 7. Some of the 16 possible combinations that can occur during centering with the LOCK procedure.

TABLE I

Sequence of Moves and Measurements

Move	Position	U	B	V
1	Check Star	1	2	3
2	Sky	4	5	6
3	Comparison Star	7	8	9
4	Variable Star	10	11	12
5	Comparison Star	13	14	15
6	Variable Star	16	17	18
7	Comparison Star	19	20	21
8	Variable Star	22	23	24
9	Comparison Star	25	26	27
10	Sky	28	29	30
11	Check Star	31	32	33

TABLE II

APT Observing Program I - Group Names

1. Lambda And	60	11. DK Dra	15	21. 29 Dra	1
2. 39 AY Cet	36	12. R Sct	2	22. 53 UMa	0
3. Sigma Gem	73	13. 12 BM Cam	93	23. 51 & 52 Aur	81
4. V711 Tau	96	14. 33 Psc	63	24. CE Tau	76
5. 27 & 28 LMi	51	15. 5 Cet	40	25. TV Psc	45
6. HR 9024	58	16. HD 210419 & 210434	43	26. RZ Ari	81
7. HR 7428	23	17. 59 d Ser	1	27. Rho Per	108
8. IM Peg	61	18. FS Com	15	28. IN Hya	13
9. HR 7275	34	19. HK Lac	51	29. Epsilon Aur	83
10. HR 6469	4	20. AR Lac	45		

were consolidated across all nights and then reduced in the customary way, including corrections for differential extinction, transformation to the standard UBV system, etc. These data have been deposited in the I.A.U. Commission 27 Archive of Unpublished Observations of Variable Stars where they are available as File No. 131 (Breger 1982). The contents of this file are summarized by Boyd, Genet, and Hall (1984a). Plots and analysis of the RS CVn binary results can be found in Boyd, Genet, and Hall (1984b). During this time some 1,352 group observations were made. As each group observation consisted of 33 individual 10-second observations, a total of 44,616 separate observations were made. Beginning with the first day of 1984, the observing program was expanded to the 69 groups of APT Observing Program II.

Two of the light curves from the first APT program are shown here by way of example. In Figure 8 is the light curve of 5 Ceti. This unusual variable star was discovered by Richard and Helen Lines at their observatory in Mayer, Arizona, not far from Phoenix (Lines and Hall 1981). They were the first to encourage one of us (Boyd) to undertake the development of an automatic photoelectric telescope. The other light curve, shown in Figure 9, is of the semi-regular variable star Rho Persei.

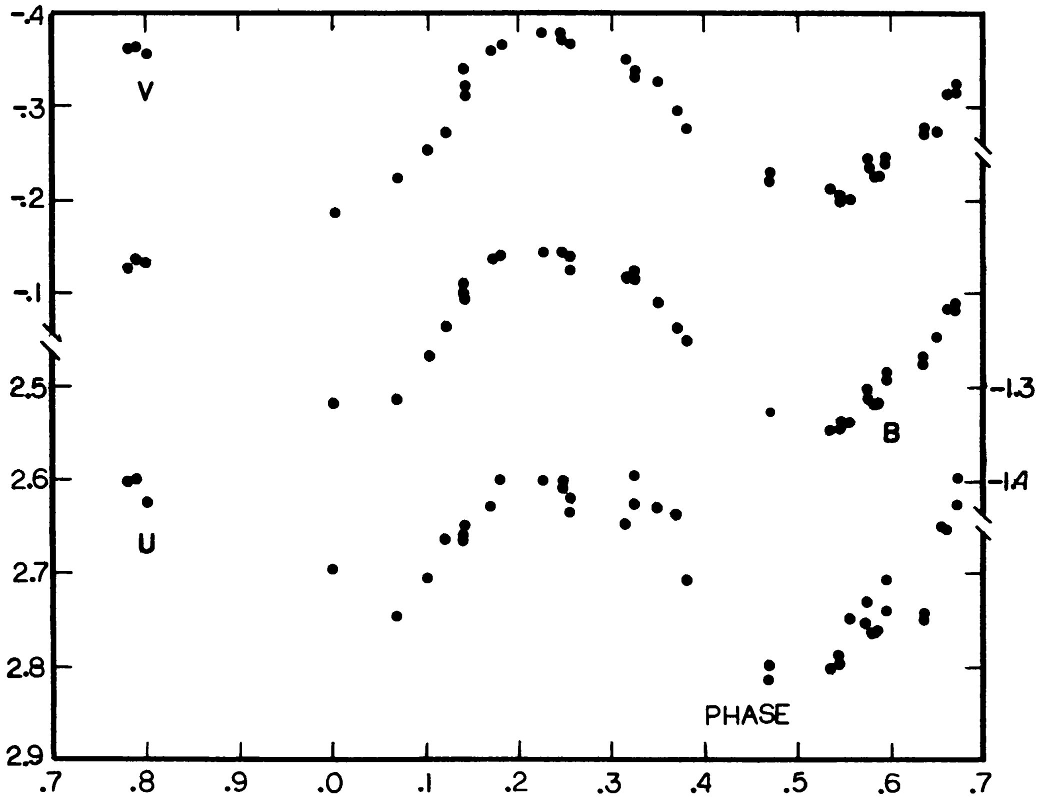

Fig. 8. Light curve of 5 Ceti, the bright eclipsing binary with a 96-day period, discovered by Richard and Helen Lines at their observatory in Mayer, Arizona.

On one exceptional (winter) night the automatic photoelectric telescope observed 93 groups. Some 3049 separate 10-second integrations were made on this night, for an actual observing time of 8 hours and 28 minutes; this excludes non-observing time for moving to, acquiring, and centering stars. Some 837 stars were individually acquired and centered by making approximately 25,000 separate telescope movements. About one-third of the total time was spent moving the telescope, changing filters, and performing computations needed to decide what should be done next. While increases in efficiency are possible, they would be of marginal benefit. Even with 69 groups in the new observing program, the automatic photoelectric telescope still runs out of things to observe towards morning; rather than just sit and wait for new groups to rise above the eastern edge of the observing window, it uses the time to reobserve groups for the second time. Keeping automatic photoelectric telescopes properly and fully occupied may be a task that will keep the next generation of variable star astronomers fully occupied.

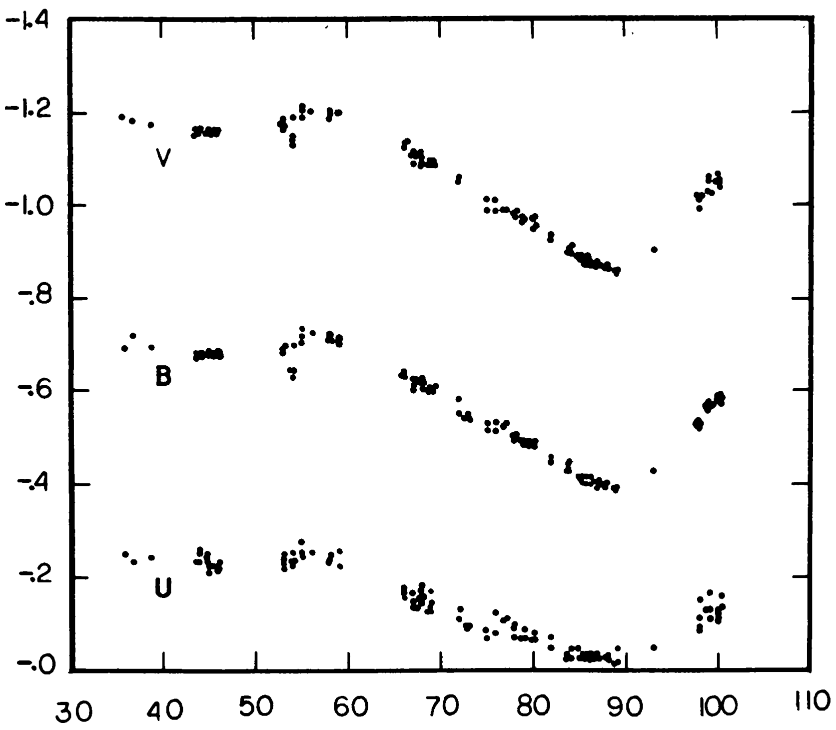

Fig. 9. Light curve of Rho Persei taken with the automatic photoelectric telescope. The ordinate is differential magnitude, while the abcissa is JD 2445620.5 plus the value shown.

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