TUESDAY 21 APRIL, MORNING SESSION
Horace W. Babcock presiding

THE LUYTEN - CONTROL DATA STELLAR PROPER MOTION MEASURING MACHINE*

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The discovery and measurement of stellar proper motions has always been associated with machines: for proper motion measurements involve four activities: observation, recording, comparison and measurement. Participation by the astronomer in these activities has step by step been replaced partically or wholly by machines. First the observation and recording functions changed from visual to photographic - with the fine guiding done by the astronomer; then the comparison by the blink microscope and the measurement by visually operated measuring machines. On a comparative time scale, the next step - automation of the comparison and measurement function - has been much money, time, and effort away from the previous steps, but as this presentation and other presentations at this conference will show, machines of varying degrees of automation and astronomer participation are now in operation.

That these machines are in operation does not mean, however, that the astronomer need only to push a button to publish stellar proper motion measurements. On the contrary, during the design, fabrication, and testing stages, the methods used in the part for comparing and measuring must constantly be reviewed and translated into system compatible hardware or machine instructions. Then, as the system begins to turn out measurements, the astronomer soon finds that the system has measured all the easy and obvious motions, and brought to his attention all of the comparisons which are difficult to evaluate. Thus, the system does as any good automation should do, accomplishes all the routine and tedious tasks, leaving the tasks on which the experience, knowledge, and skill of the astronomer are still vitally necessary.

The degree and nature of the automation of the stellar proper motion measurement vary a great deal between measuring systems. In the Luyten-Control Data system one machine scans the pair of star plates; both the discovery and the measurement of proper motion are performed from the data from the single scan. It should be noted, however, that the measurement of stellar proper motion from the data from the scanned plates is the result of the data reduction system in the computer software; significant astronomical information can be obtained from the same data with a change

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in the software, not in the hardware. Thus the Luyten-Control Data system is classed as a general purpose star plate scanner with software for the extraction of stellar proper motions from pairs of star plates.

A summary of the information path from sky to publication is shown in Figure 1. The observation and recording functions are performed by the exposure of 14" square photographic plates in the 48" Schmidt telescope at the Hale Observatories. The extent of the survey is indicated by the number of plates - 936 - each covering 6 1/2 x 6 1/2 degrees of the sky. In all, they cover all of the sky visible from the Observatory; this amounts to 77 percent of the celestial sphere. The number of stars on each plate vary widely, but a rough estimate is 100,000 for the sparse plates and at least 1,000 times that for the dense plates! The first set of plates which are used in the form of duplicates, was taken as the National Geographic-Mount Palomar Sky Survey between 1949 and 1958, the second set, taken between 1962 and 1970 by Luyten, is in process of completion.

The plate pairs are mounted in the scanning microdensitometer and the measurements recorded on computer compatible magnetic tape. The tape is brought to the large scale high speed computer for data reduction, where the stellar proper motions are discovered, measured, and documented. The information output can be in printout, punch card, or tape form. The proper motions will be described in terms of motion, direction, and area and diameter of images. In addition, the motions will be described in right ascension and declination. Missing from this illustration but not from the measuring system is the astronomer, whose judgment is essential to the selection and verification of proper motions.

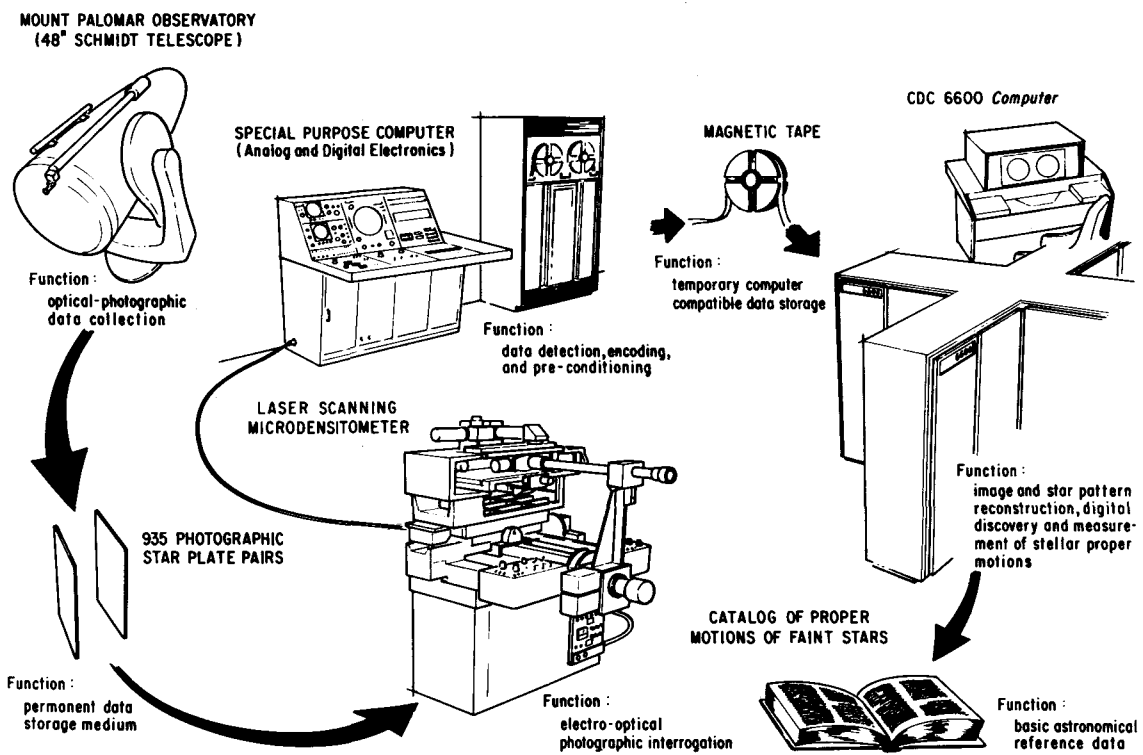
On the basis of his extensive experience with visual blinking of many pairs of these star plates, Luyten estimates a yield of about 400 proper motions per plate pair. Our experience with plate measuring with the scanner indicates that an average of about four plate pairs measured per day is reasonable; since the computer processing is a separate operation, the processing for the previous day's run can be run at the same time as the scanning of new plate pairs. This means that four million or so star images of the "fixed" stars can be scanned and aligned, and 1600 proper motions can be documented; per normal working day!

A more detailed look at the system is shown in functional block diagram form in Figure 2. The basic data obtained from the scanner and recorded on the magnetic tape is the position and width of each image whose density exceeds a preset value. To accomplish this transfer, the position of the star plate holders as measured by the lead screws must be continuously monitored; in addition, the instantaneous position of the scanning spot must be known, like the other two positions, to the nearest micron. The encounter of the scanning spot with a dense image triggers the transfer of all three dimensions - X position of the plate holders, Y position of the plate holders, and the instantaneous position of the scanning spot - to the high speed buffer for grouping into tape compatible records. The width of the image being scanned is obtained as the spot emerges from the dense image.

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AUTOMATED STELLAR PROPER MOTION STUDY



THE OPTICAL SCANNING SYSTEM:

The interrogation of the star plates is accomplished by a moving spot of light scanning each plate; the amount of light passing through each plate is measured by a special light collection system terminating in a photomultiplier. The light source is a helium neon laser emitting light of .6328 microns wavelength. Light from the laser is concentrated on a small spot on each star plate by a converging lens. The scanning action of the spot is provided by the rotation of an octagonal prism placed between the converging lens and the star plates. The displacement of the spot by the rotation of the prism is in one direction only - there is no "flyback" in the spot motion.

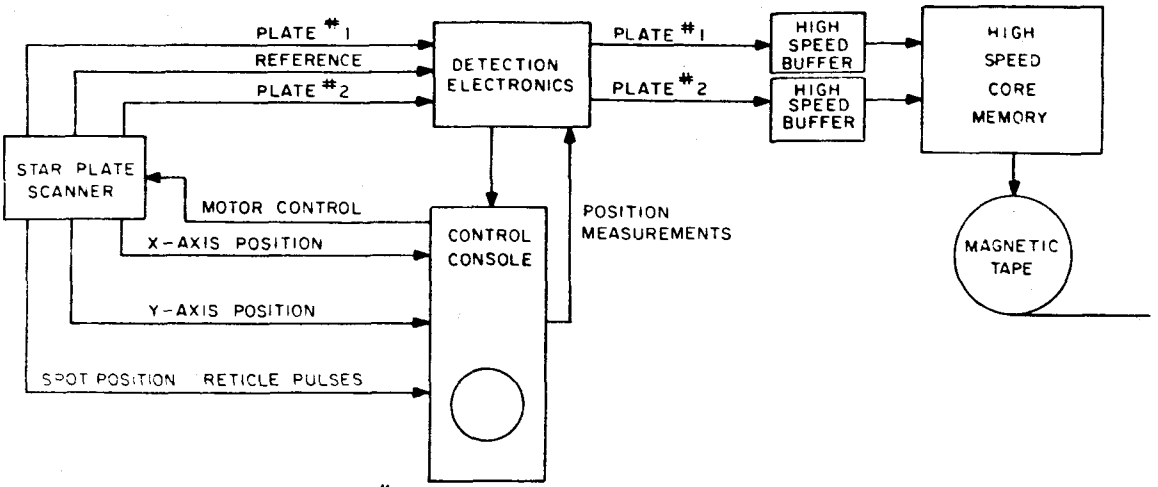
THE LIGHT COLLECTION SYSTEM:

The purpose of the light collection system is to provide the optical means of detecting the passage of the spot of light over star images regardless of the relative size of spot and image; in particular, to provide adequate information for the detection of the passage of the spot over star images considerably smaller than the spot itself. A schematic diagram of the light collection system is shown in Figure 3. In this diagram the star plate and star image being scanned by the downward moving spot are shown on the right. A convex lens is placed close to the plate to collect the light from the interaction of the spot of light with the images on the photographic plate. An opaque screen with a square aperture is placed at the focus of the convex lens. The diffraction pattern of the photographic image sharply formed in the monochromatic partially coherent light of the laser beam moves across the opaque screen and aperture as the spot moves across the star plate with a velocity approximately ten times that of the spot. Light entering the aperture is focused on the photocathode of the box dynode 1P21 photomultiplier by the plane-cylindrical lens mounted directly behind the aperture. The cylindrical axis of the lens is parallel to the direction of the scan, as is the long axis of the photomultiplier photocathode. The diffraction shown in Figure 3 is moving upward out of the aperture as spot moves downward on the star plate.

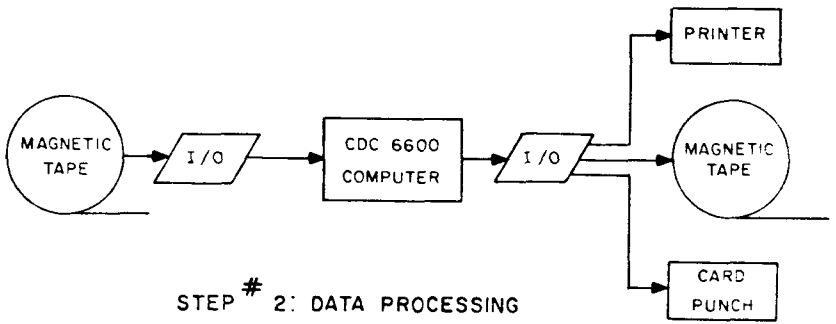
The relationship between the size and shape of the diffraction patterns formed from the star images and the size and shape of the aperture determine the relative sensitivity of the detection system to the images forming the diffraction patterns. The critical relationship between image size and detection sensitivity occurs at the low end of the image size scale, and is most important in the scanning of the newer original plates. The photographic and sky brightness fog level on the newer original plates produces large numbers of images or grain collections whose size approaches that of valid star images near the plate limit. On most original plates, the smallest valid star image diameter is in the 35 to 40 micron range; detection of images smaller than this does not produce useful information but can require important quantities of computer time. It should be noted that the older plates which are scanned as duplicates have had the background suppressed by suitable choice of high contrast photographic emulsions for

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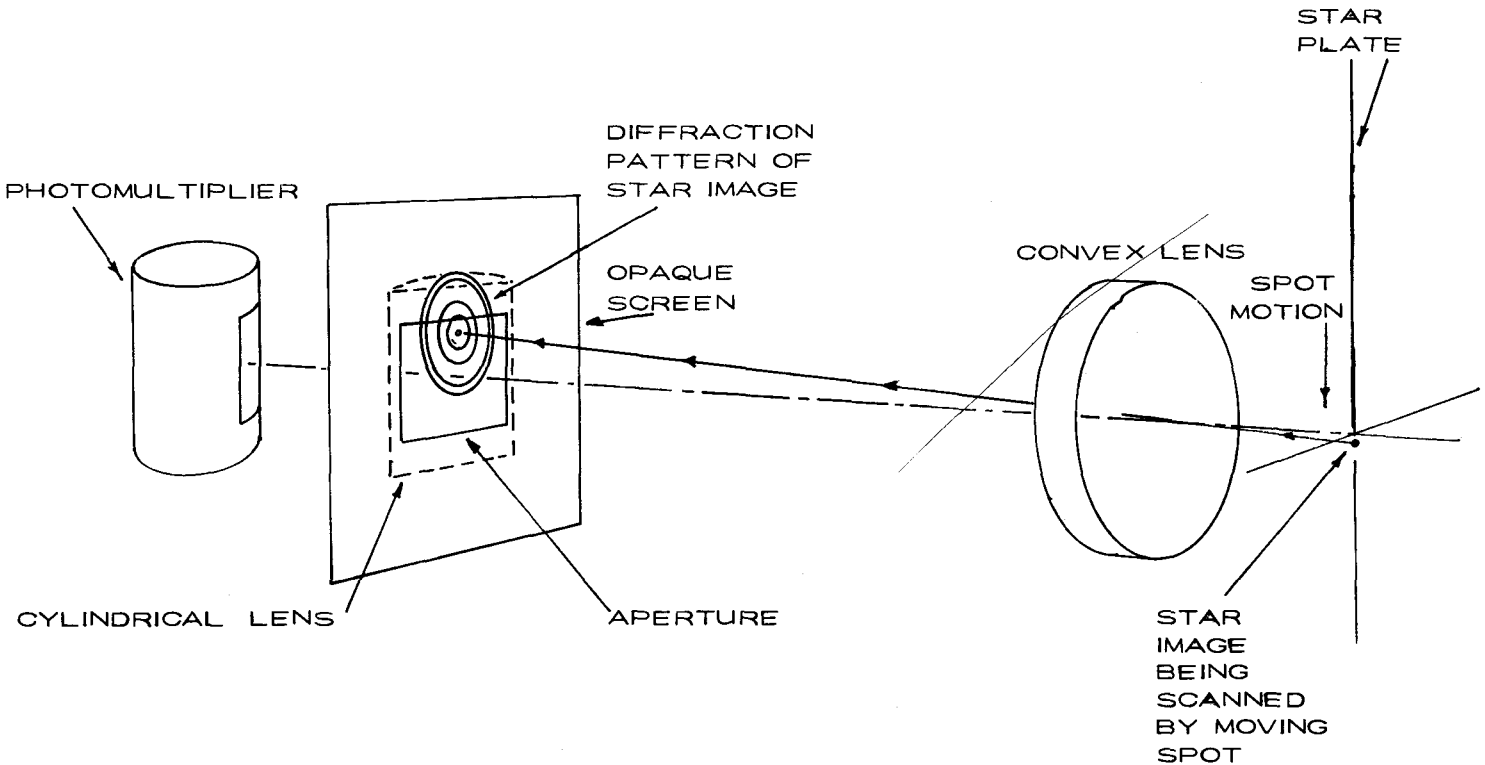


STEP #1: DATA STORAGE ON TAPE



STEP #2: DATA PROCESSING

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LIGHT COLLECTION SYSTEM OF STAR PLATE SCANNER

the intermediate positives and the duplicate negatives so that the fog level problem does not exist compared to the fog level problem for the originals.

The diffraction patterns produced by the star images are like the familiar "Airy disc" patterns associated with the images of stars formed by high quality optical systems, except that the light and dark areas of the image are interchanged. As in the case of the "Airy disc", the smaller the image on the star plate, the larger the diffraction pattern. The basic detection mechanism depends for its action on a decrease of light intensity collected by the aperture when the star image is being scanned by the spot. The effect of aperture configuration was estimated by evaluating the reduction in intensity occurring when the diffraction pattern was centered in the aperture. The reduction in intensity compared to the intensity when no spot was being scanned was defined as the modulation index of the image for the aperture selected.

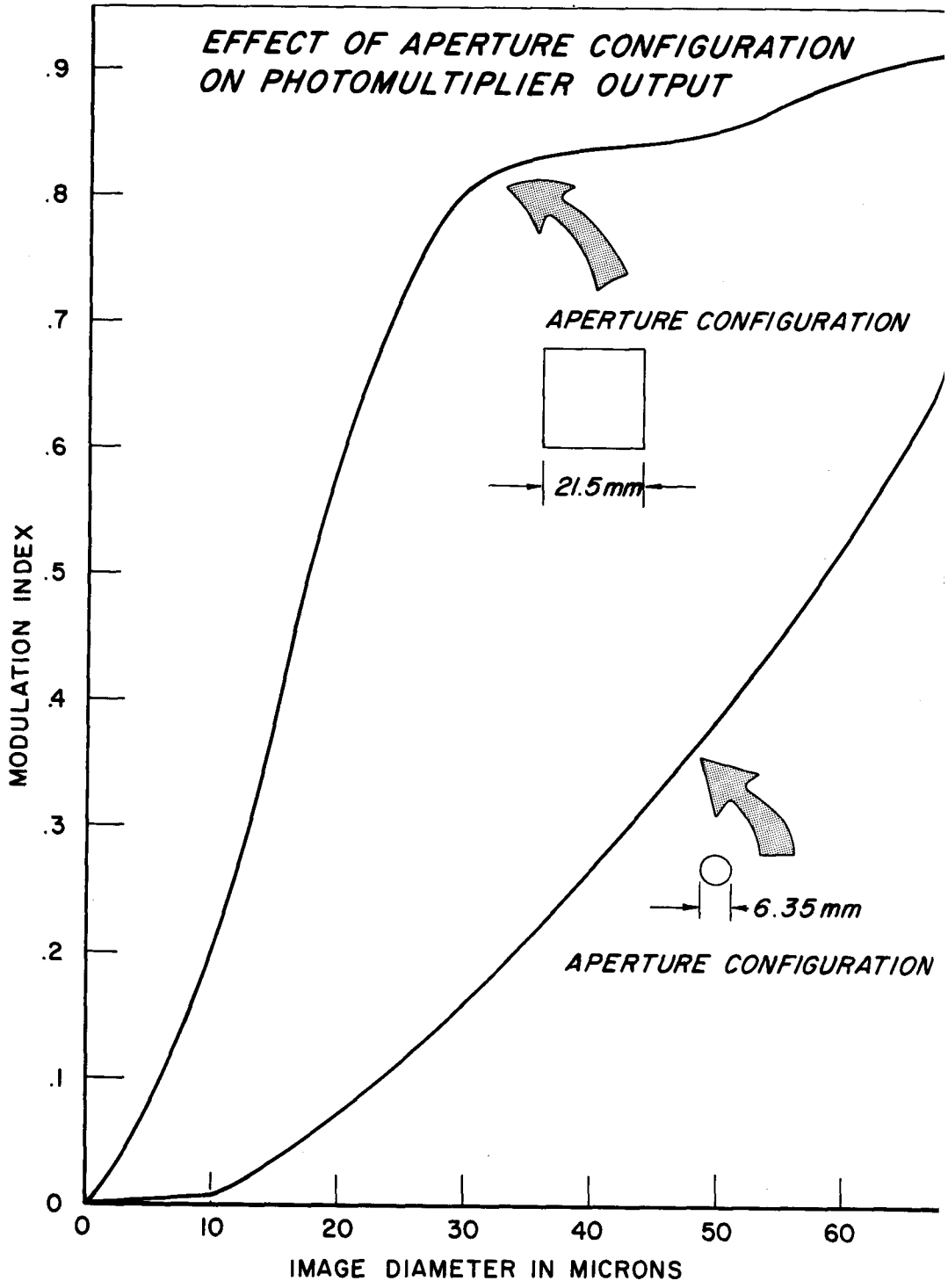
The modulation indices for circular image diameters ranging from 4 to 70 microns were computed for two aperture configurations. The modulation index - image diameter curves for the two aperture curves are shown in Figure 4. The circular aperture configuration represents the maximum effective diameter circular aperature that could be placed in front of the photocathode without additional collecting optics. The square aperture is the one presently in use with the plane-cylindrical collecting lens immediately behind it. Note that the modulation index decreases for both systems as the image diameter decreases; however, if, for the circular aperture the detection system is adjusted to detect 35 micron diameter images, the decrease in detection sensitivity between 35 micron and 15 micron diameter images is relatively small, while if the detection system is adjusted to detect 35 micron diameter images with the present system, not only is the change in sensitivity larger as the image size is reduced to 15 microns diameter, but the sensitivity changes very little as the image size increases.

In addition to the light collection systems for the two star plates, a light collection system for the reticle is provided. This system collects the light produced when a spot of light scans alternate light and dark bars 32 microns wide placed at right angles to the scan. The optical system is essentially the same except that the plane-cylindrical lens at the aperture has its cylindrical axis parallel to the bars rather than to the direction of the scan.

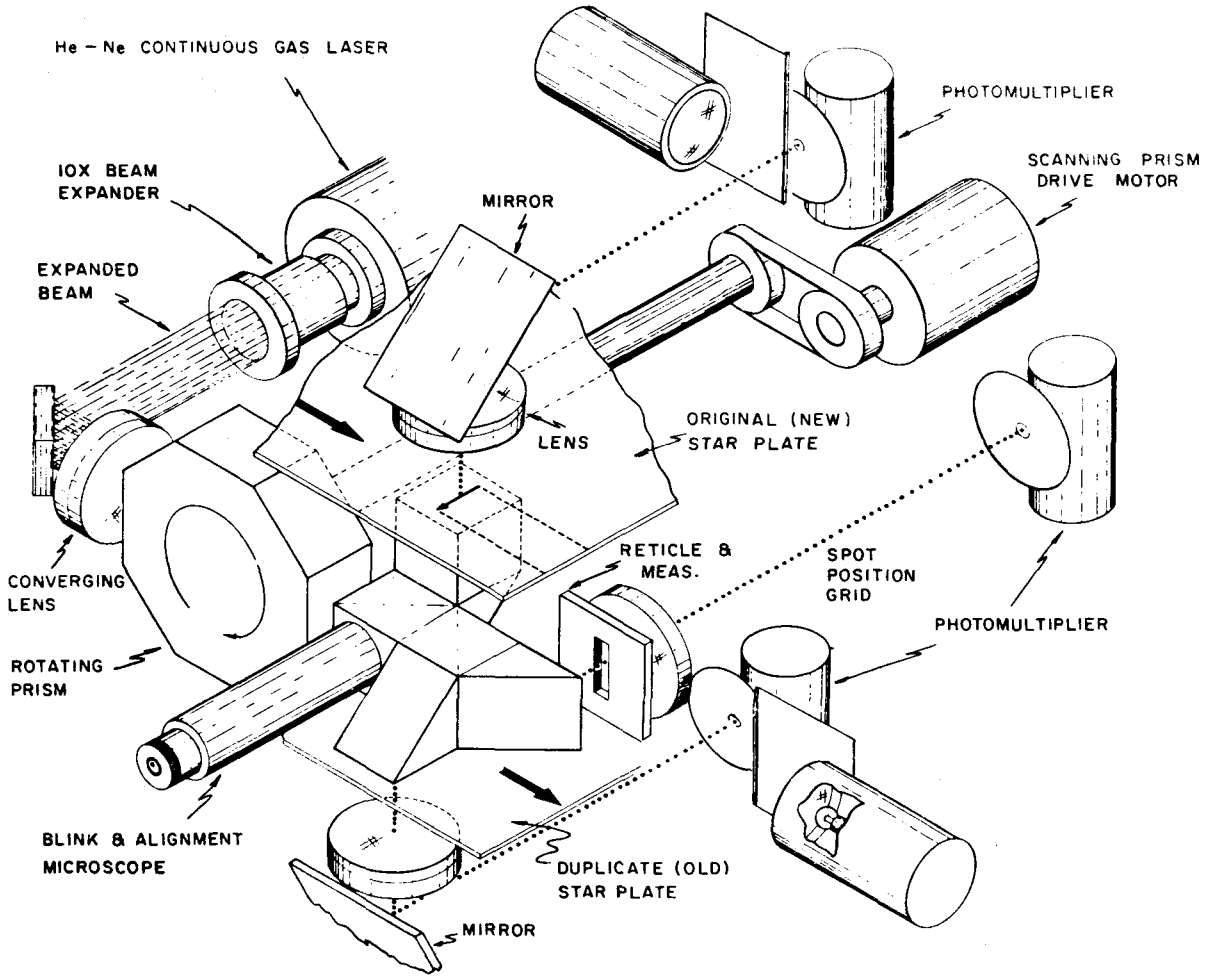
THE COMPLETE OPTICAL SYSTEM:

The complete optical system serves two very different functions: (1) it provides the scanning spot and light collection systems for the two star plates and the reticle, and (2) it provides the illumination and optics for a special blink for plate alignment and observation of the star plates. A schematic of the system is shown in Figure 5. The star plates are mounted horizontally parallel to each other with the scanning spot apparatus between them. The light collection system for the upper plate is mounted above it, and the light collection system for the lower plate mounted below it. The

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light collection system for the reticle is mounted between the plates. Light from the laser first passes through a ten power beam expander, then is deflected at right angles by a mirror into the converging lens and rotating prism cluster. This complex optical assembly consists of two beam splitting cubes, two 45° - 90° - 45° prisms, a 45° - 90° - 45° roof prism, a path equalizer, and a plane-cylindrical lens.

The assembly performs the following functions:

(1) separates approximately 50 percent of the beam and deflects it upward to the original plate,

(2) separates approximately 25 percent of the main beam and deflects it doanward to the duplicate plate,

(3) shapes the remaining 25 percent of the main beam into a short intense line at right angles to the direction of the scan and parallel to the reticle bars,

(4) provides the light path for observation of the two star plates through the blink microscope.

The light collection systems for the two star plates are optically identical to the schematic shown in Figure 3; a front surface mirror folds the system at right angles for mechanical convenience.

The illuminators for the blink microscope system are housed near the photomultiplier ends of the star plate light collection systems. A mirror pivoted to swing into and out of the tube of the light collection assembly turns into the tube by a small motor to reflect the illumination to the star plate in the blink microscope observation mode. Optical filters of the visually contrasting colors red and cyan are placed over the illuminators to provide chromatic identification of the images of the two plates. Electromechanically operated shutters between the illuminators and the mirrors provide the blinking action for the microscope observation.

Focusing of the optical elements is accomplished remotely by small motor actuators with large gear reductions. The focusing can be controlled either at the scanner or at the remote console. Three focusing adjustments are provided; they are (1) the converging lens between the laser and the rotating prism, (2) the reticle and its associated light collecting lens, and (3) the path length equalizer which changes the position of the scanning optics between the two plates. The converging lens and the path length equalizer focusing mechanisms are both provided with arbitrary numerical position readouts which are visible only from the scanner.

THE MECHANICAL CONFIGURATION OF THE SCANNER:

A general view of the mechanical configuration of the scanner is shown in Figure 6 with an engineer observing the star plates through the blink microscope. The plates are mounted in plateholders which provide rotational and translational motion between the two plates. The plate holders are mounted on the carriage of a Moore Measuring Machine 2 modified to accomodate a 14-inch lead screw in the Y direction, which is parallel to the blink microscope. The X and Y axis motions are provided by motor driven lead screws which provide both motion and measurement. Electro-optical

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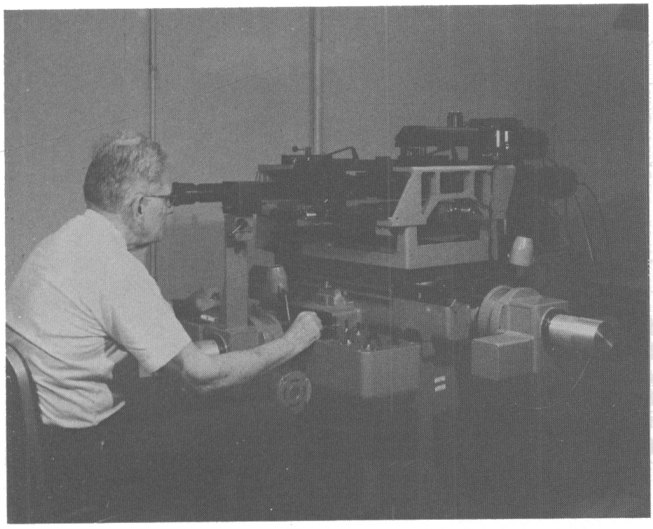


Figure 6. General View of Star Plate Scanner with Luyten observing the Star Plates through the Blink Microscope.

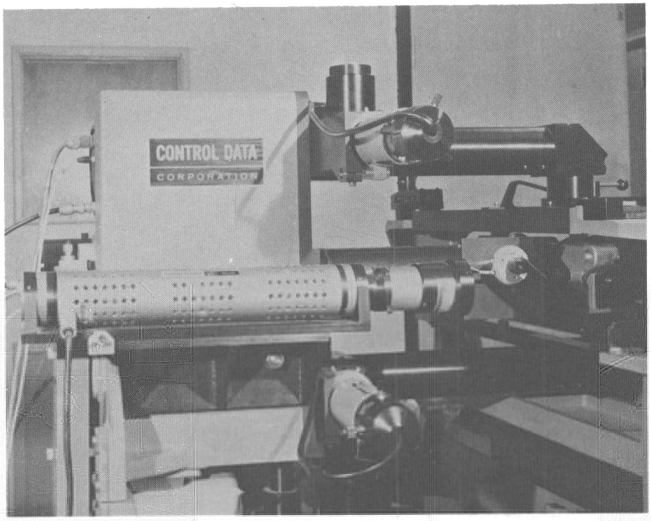


Figure 7. The Laser Side of the Scanner.

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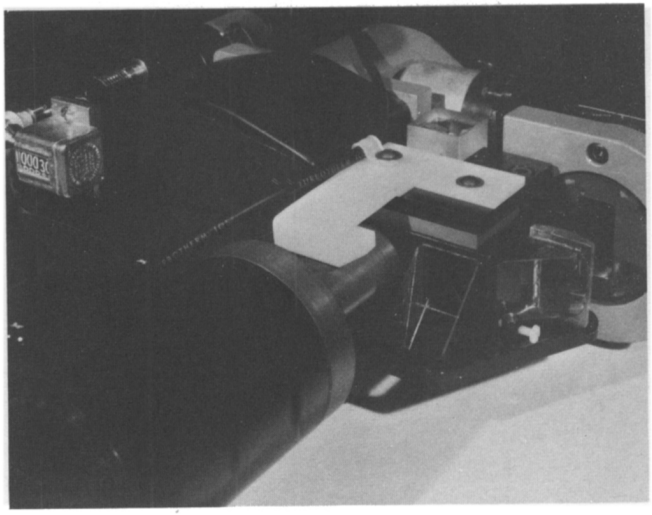


Figure 8. Prism Cluster Assembly.

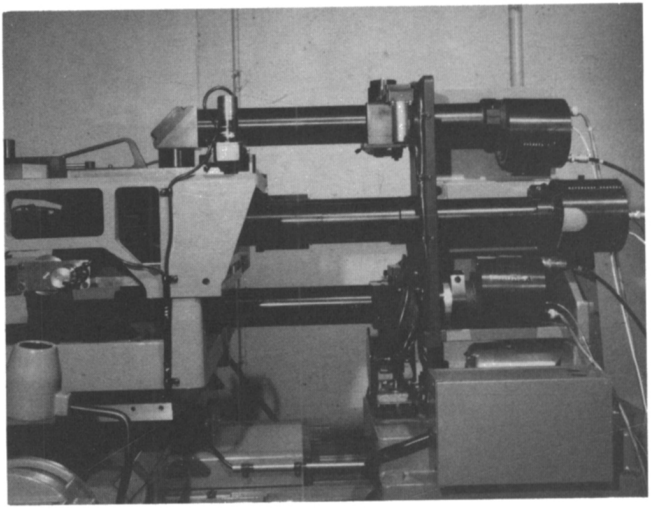


Figure 9. Light Collection Tubes on the Side of the Scanner.

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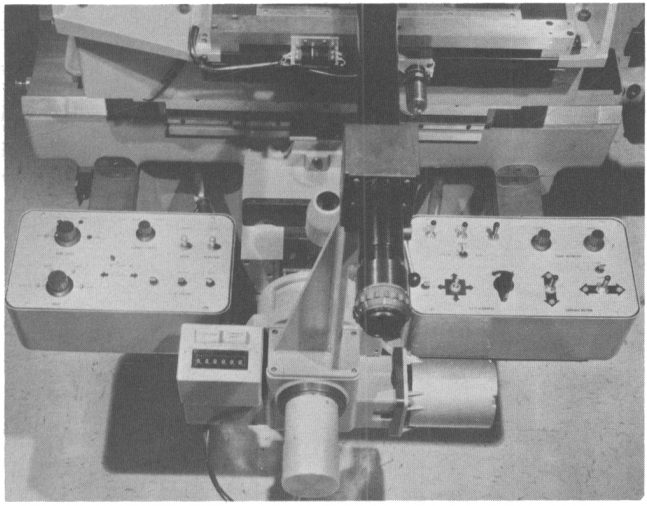


Figure 10. View of Scanner from Operating Position, showing Controls.

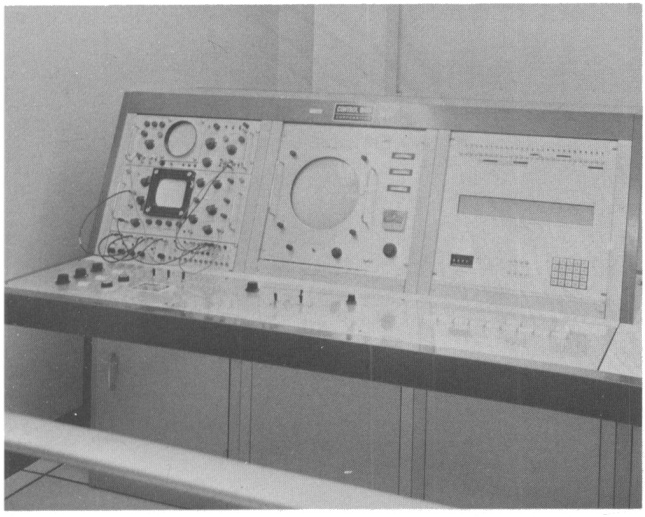


Figure 11. General View of Control Console.

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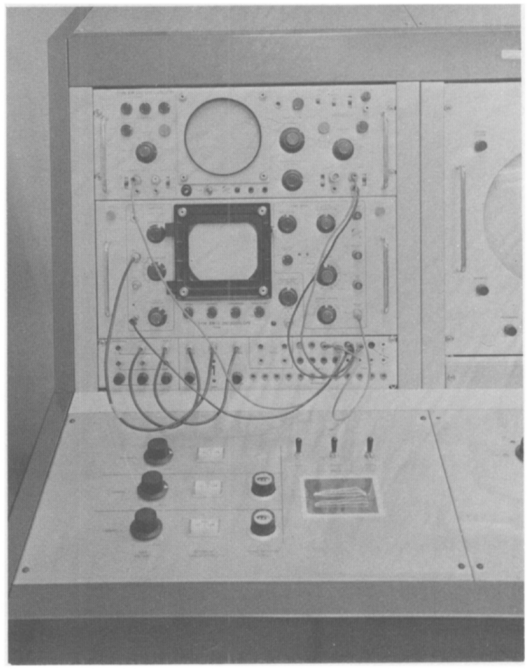


Figure 12. Left Bay of Console containing Analog Control and Display Equipment.

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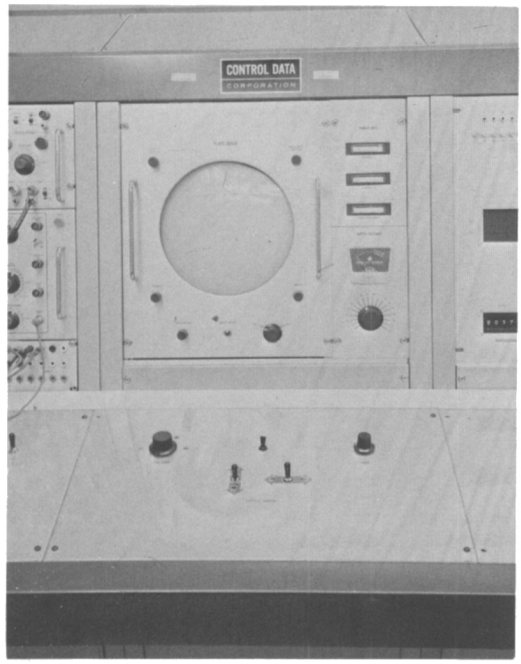


Figure 13. Central Bay of Console showing Scan Display and Motion Control Areas.

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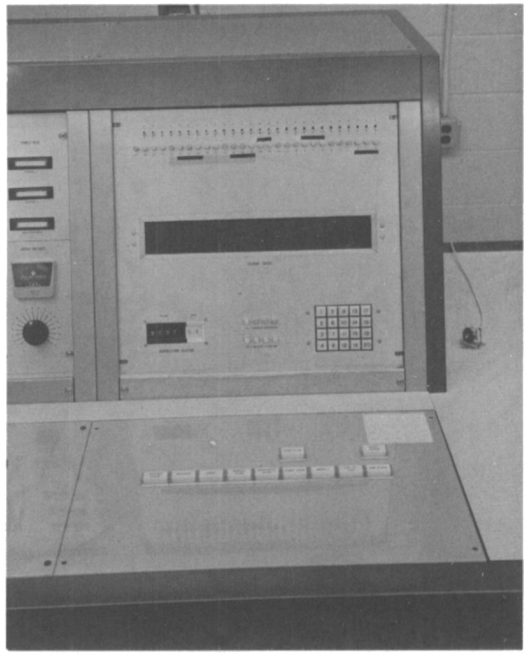


Figure 14. Right Bay of Console, showing Digital Data Acquisition and Control Areas.

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angle encoders directly coupled to the lead screws provide 3000 pulses per revolution of the lead screw; since the pitch of the lead screw is 3 millimeters per revolution, this provides a count of one pulse per micron of lead screw advance. The X axis encoder can be seen in the lower right of the picture projecting from the motor mount driving the lead screw.

Figure 7 shows the laser side of the scanner, with the laser in the center and the microscope illuminators above and below it.

Figure 8 shows the rotating prism with its protective cover removed, the beam separator prism cluster and the mounting channels for the blink microscope. Figure 9 shows the three light collection tubes and the associated photomultiplier assemblies with the power and signal cables attached.

Figure 10 shows the controls for plate alignment, focusing, carriage motion, and scanning located in the front of the scanner. Immediately to the left of the blink microscope support is the control assembly at which the identification of the reference stars is made. This identification makes possible the conversion of star plate coordinates to right ascension and declination.

THE CONTROL CONSOLE:

The signals coming from the photomultipliers are normalized by automatic gain control circuits and passed into a threshold detecting system. In this system all signals whose voltage falls below a preset threshold value trigger the counters which keep track of the X and Y positions of the plate holders to send their instantaneous position information to the buffer memory, in addition, the reticle bar counter and the associated interpolation counter are similarly triggered. This position information is the spot ingress information. When the spot emerges from the star image, the length of the scan between ingress and egress is also sent to the buffer memory from the counters. These pairs of position information constitute the basic data recorded on the magnetic tape. This data control and handling, as well as the control of the scanner itself, is accomplished at the control console which is located in a room adjacent to the scanner, since the scanner must be operated in a dark, clean, constant temperature and humidity room. The signals from the scanner are transmitted directly to the console for processing. Figure 11 shows a general view of the console with an engineer seated in front of the analog control and display section. The controls and displays are grouped in three bays.

Figure 12 shows the left bay of the console in which the region of the plate being scanned is displayed as a bright spot in a coordinate grid of the face of a cathode ray tube in the upper center of the picture. Below the scan location grid is a complete oscilloscope which can display the output of any two of the three channels with the threshold level at which that channel is operating super-imposed on the signal trace. This information is very important in the operation of the machine, as it gives a direct visual display of the effect of changing the threshold level. The photomultiplier, threshold, and focusing controls are on the horizontal surface immediately in front of the oscilloscope.

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Figure 13 is the central bay of the console. It is dominated by the star plate image display in which an enlarged view of a 12 x 16 millimeter area of the star plate peing scanned is shown; on the long persistence tube face all images which crossed the trigger level are shown as bright spots on the tube face; any image appearing on this tube face will be analyzed by the computer. Data rate meters are on the upper right of the panel beside the the tube. Motor speed and function controls are on the horizontal area.

Figure 14 is the right bay of the console. This bay and an additional lower right projection on the console constitute the digital data acquisition and control section. In this section a special purpose computer of over 800 circuit cards designed and built especially for this project are located. In addition, in the lower right member there is a 4096 word high speed core memory which is the buffer between the scanner and the magnetic tape unit. The panel of the bay contains at the top an array of binary test lights which can indicate the value of data in selected regions of the digital system for tests and measurement. The row of switches above the lights can be used to insert known values of data into the system for test purposes. Below the binary lights is the rectangular illuminated signal region which reports on the status of the functioning parts of the data acquistion system. In general, an amber illuminated message reports a normal functioning; a red illuminated message reports a danger condition. The box of numbers at the lower right are the actuating surfaces of push buttons used for test purposes or for the selection of the region which the binary lights read out. When any of the lights in the lower center of the panel are lit, it means that an excessive data flow has occurred. The switch at lower left is for the insertion of housekeeping data on the tape. The push button switches on the horizontal panel actuate the functions of all data acquistion and control as well as certain special modes of operation.

DATA PROCESSING:

The data reduction operation starts by the reconstruction of the scanned images from the data on tape giving position and width information. Much of the basic operating data of this part of the program is obtained from the results of a "pilot scan" of a typical small region of the plate before the complete scan proceeds. Analysis of the results of the pilot scan indicate the best setting for the threshold controls and the most probable values of differences in the diameters of images of the same star on two plates. These and other values from the pilot scan are used to reject obviously non-stellar images early in the processing. A very important value obtained by correlation between pilot scan values and experience with other star plates is the minimum acceptable number of transits which an image will be formed. If the image reconstruction for a given image produces less than the required number of transits, the image is rejected, and no further operations are performed on it. Reconstructed images surviving all rejection tests are assembled in groups occupying 12 x 12 mm square areas of the star plates. The computer then performs an alignment of the images of one plate with

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the corresponding images on the other plate using translational, rotational and stretch terms in the transformations. After obtaining optimum alignment of the "fixed" stars in the region, matches are sought for the images which did not fit in the alignment procedure. Matches are sought within a radius of 250 microns of each image candidate. An intermediate stage of the processing prints out the candidates for matching together with the data on the relative size, image shape, and resulting motion for the inspection of the astronomer. Information accumulated from the inspection about the astronomical or photographic significance of the image parameters will be used to refect more and more non-stellar matches.

The final processing step is the transformation of the plate coordinates and the proper motions to celestial coordinates.

The ouput of the system is then the stellar proper motions in celestial coordinates with image diameter, magnitude, and area available to the scientific community.

DISCUSSION

Strand: Are those individual fields 12 x 60 mm or are they put one into another?

Newcomb: You go down the scan. The actual scan of a plate consists of a spot moving repeatedly along a 12 mm line, and the plate moving slowly. So, essentially we scan a stripe as we call it. The matching then occurs down one of the stripes. We match one 12 mm square and go on to the next one. We take care of overlap between two areas so essentially the data goes down a stripe, and so we do the matching down a stripe.

Question: How many plates could you scan per day?

Newcomb: Eight plates, but really four plate pairs.

Question: Are they scanned or processed through the computer?

Newcomb: Both, actually, since the two can go on simultaneously.

Strand: When you say they are 12 x 12 mm this actually means 1/25 of a square degree, doesn't it?

Newcomb: Yes, the plates are 6°.5 x 6°.5, and a 12 x 12 mm area is almost exactly 1/20 of a square degree.

Question: Do you expect to find a star in there with a known position every time, or are you combining it with another area?

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Newcomb: To get right ascension and declination? For that purpose we pick about twenty-five reference stars per plate, on the average.

La Bonte: Insofar as determination of right ascension and declination are concerned, basically, what we do is enter a few stars at the beginning just to solve the pattern matching problem to identify a much more detailed catalogue of stars for that plate. We get that detailed catalogue from the SAO tapes which we processed prior to that, and take out all the candidates that are listed, and match those up with the images that we find in the scan. But we do not expect to find a reference star in the vicinity of every proper motion star. We use essentially the same transformation for right ascension and declination as Herget.

Dieckvoss: But you do combine similar areas?

La Bonte: Yes, we do right ascension and declination over the whole plate.

Dieckvoss: Together with the stripes you have the coordinates from the tape?

La Bonte: Yes, and fortunately about half of the SAO reference stars are in the eighth to ninth magnitude range. Small enough to give a reasonably well-formed image - on the Schmidt plate there are not too many optical problems.

Strand: How often do you make a visual inspection? Obviously you cannot look at every image you scan because this would mean about thirty images per second.

La Bonte: Correct. Basically I will get into that in a little more detail in the next paper.

Eichhorn: How accurate are the right ascensions and declinations?

Newcomb: We do not really have any numbers on that. We anticipate that we shall be able to get the coordinates of the individual proper motion stars to about 15 microns - about one second of arc. Every indication we have is that right now.

La Bonte: With the reference stars we will probably be a little less accurate because the images present more problems - the bright ones are poorly formed.

Luyten: May I add something to this? The coordinates of the ultimate proper motion stars are going to be as inaccurate as we can get away with.

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Because, unfortunately, this involves a great deal of money, time, and everything else. And it does not really help in the identification. You simply cannot identify uniquely a 20th magnitude star from its coordinates alone. For very faint stars you have to have a chart. On the other hand, most of the smaller motions are of statistical value only. As far as I am concerned we are going to spend as little time, energy, money, anything we can think of on the positions.

Dieckvoss: Couldn't you plot a number of faint stars surrounding the proper motion star? It should be possible as you must have the data on the tape.

Newcomb: I suppose it could be done, but for an expected 400,000 proper motion stars it is quite a job.

Question: There are an awful lot of things on the plates that are not stars. What happens when you come across an H-2 region, or a large galaxy, or something like a ghost image of a bright star?

Newcomb: Oh, we have been through the ghost image of Arcturus.

La Bonte: We have had some experience with both Arcturus and its ghost. When we hit such a region, the scanner is basically turned off by the presure of this image. But what we do there is to sense the density of the transit information that we are getting, particularly as we are coming into, say, an image like that of Arcturus where there is a lot of bloom around the image. We sense that density, and if it exceeds a certain value we basically turn off that portion of the scan in the computer and so one of our little boxes, for example, might be off-centered on one corner of the star image. We would just cut out the part of Arcturus and work with the stars that are in the reasonably clean part of the scan. Actually we have picked up stars from the middle of the hole in the ghost, and we have actually even recorded the bands that make up the ghost. This is one of those hard problems that Jim was referring to where the astronomer would probably have to go in and look explicitly in that region.

Dieckvoss: Is this a question of diffraction?

La Bonte: Yes, the ghost makes rings and all sorts of things. Arcturus' ghost is enough to scare you. Actually we have detected proper motions in the middle of the vacant space of that ghost. But the first time we hit it, man, it was a gem!

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