A NEW ASTROMETRIC SYSTEM

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The 30-inch Thaw Refractor of the University of Pittsburgh's Allegheny Observatory has been completely rebuilt. Changes include a new objective lens, a new detector system, and computer control and data acquisition. With an observational accuracy exceeding one-thousandth of an arc second, the new system will greatly expand the domain of astrometric research.

INTRODUCTION

For one-hundred-and-twenty years, the detector of choice for astrometry has been the photographic plate. The introduction of that detector brought a new level of precision and with it a need for a new generation of telescopes, instruments with sufficient imaging precision to allow the photographic plate to reach its full potential. Today, this century-old story is being repeated. Groups in the astrometric community are once again experimenting with a new class of detectors, and once again a need for a new series of telescopes has arisen. It is the purpose of this paper to describe briefly the first of these astrometric telescopes, an instrument built upon the frame of the University of Pittsburgh's 30-inch Thaw photographic refractor.

Electronic astrometric detectors have been under development by various groups for more than a decade. Some of the earliest work, with photomultiplier tubes, was that of van Altena (1974) and Frederick et al. (1975). More recently, several groups have been working in the application of charged-coupled devices (CCDs) as astrometric detectors (Baum 1982, Bangert et al. 1983). While these devices have much greater quantum efficiency

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than the photographic plate, they have not been shown to have a greater metric stability. They also suffer from the limited dynamic range inherent in any analog device. At the high count rates, this takes the form of "well overflow," which contaminates the count in neighboring pixels. At very low count rates, the confusion occurs because of a minimum readout noise that places a large uncertainty on small counts. Thus, over wide magnitude ranges (greater than six or seven), they have a problem with brightness linearity and can be confused by magnitude-dependent optical aberrations. Nevertheless, there are a wide range of uses for area detectors. Hence, the long-range promise for the eventual development of highly linear devices with excellent metric stability is good.

Several other groups have been working with various versions of a new detector known as the Multichannel Astrometric Photometer (MAP) (Gatewood et al. 1980), Gatewood (1983), Gatewood and Stein (1983), Bandermann et al. (1983), Buffington (1984), Beckwith (1984), and Jones (1984). In its most common form, this device combines the brightness linearity and quantum efficiency of the photomultiplier tube with the metric stability and redundancy of a Ronchi ruling (a type of transmission grating). Unlike the others, this detector is a self-improving measuring device capable, under controlled conditions, of attaining Angstrom level accuracies (Gatewood 1983). Thus, in the presence of excellent optics and reasonably bright reference stars, the ground-based, MAP-equipped telescope is limited primarily by the atmospheric conditions of the site.

THE TELESCOPE

The telescope to be described, built on the frame of the Thaw 30-inch photographic refractor, is probably the last of the large refractors. As with those that preceded it, its designers struggled with the harassments of surrounding city lights and were restricted by the availability of glass types in large disks. Nevertheless, the result has been a new high-precision instrument with easy access to the University of Pittsburgh, where students can learn a discipline that is now once again breaking onto new horizons and where astrometrists can tackle, with new precision, both classical and excitingly new, observational problems.

We did not originally intend that our efforts with this telescope should go as far as they have. Our decision to build and test a new detector has been detailed in several places, e.g. Gatewood et al. (1980), Stein (1978), and in particular Gatewood (1983). At first, our plans to reconstruct the telescope's drives and electronic systems included the usual modernization, but did not include such items as our new control room or the control computer. However, when we realized that we would have to replace the objective lens itself, it became clear that by the time we were done, little of the original system would be left. From that point on, the planned revisions were viewed as a whole, and as the creation of a new system.

The realization that the objective lens was a source of some error began with a study by Kamper (1972) and, somewhat later, in several plate-overlap studies by Gatewood and Russell (e.g. Russell 1976). The first results suggested a weak, time-variable color dependence, while later results suggested that there was a minimum value, associated with each night, below which repeated observation could not push the standard error of the mean positions obtained using wide-spectral-band photography. The latter is a direct indication of an unresolved, slowly changing systematic error. This conclusion was strengthened by a series of tests conducted, in 1975, by Gatewood and Russell (unpub.) that showed that stellar images obtained during periods of exceptional seeing had a small flare. The latter is probably related to a line of inhomogeneity in the objective glass shown clearly in Foucault grams taken by Kamper. More recently, the effect of the flare was noted in the electronic scans of the MAP, where it directly affected the image profile and, therefore, the standard error of the measurements.

Of course, the detection of a problem, its theoretical resolution, and its actual physical resolution are all too often not successive steps. The desire to replace the objective lens was a result of the realization that that objective would severely limit the accuracy of future astrometric studies. Another technical consideration was the central wavelength of that system. The choice of a blue bandpass (an advantage in the early days of photography) now placed the limiting magnitude totally at the mercy of modern city lighting. However, no matter how compelling the technical reasons, the desire to modernize is often quelled quickly and mercilessly by the realities of finance. Our salvation came in the form of a federation of private sources (noted below).

Table 1 lists some of the differences between the old system and its revision. As noted above, a major change involves wavelength. For the glass types we could obtain in the sizes and homogeneity sought (Schott's BK7 and F2), the bandpass which can be brought into focus broadens as the central wavelength is increased. For 4400 Angstroms, the central wavelength of the old photographic lens, the bandpass (defined in this manner) is less than 240 Angstroms. But at 6400 Angstroms, the value chosen for the new objective, it is almost 700 Angstroms. Thus, by changing the central wavelength of the objective lens, we have increased the white-light photon-gathering power of the Thaw Refractor by a factor of nearly 3.

Another factor arguing for the chosen wavelength has to do with the nature of the targets that the instrument will be used to study. Blue stars are usually intrinsically bright and can, thus, be observed at the relatively great distances of the planned program. The intrinsically fainter stars are usually red. The chosen bandpass contains the peak of Planck's curve (expressed in photons emitted) for K stars.

Finally, the night skies over cities have recently become line sources. Currently favored lighting includes mercury arc, high-pressure sodium, and metal halide sources. Mercury arc lamps produce a strong line at the center of the bandpass of a violet-light photographic lens. However, none of these sources produce strong emissions between 6150 and 6850 Angstroms. Several photographs of the spectrum of the Pittsburgh night sky indicated that this part of the reflected spectrum was indeed quite dark.

Working against the chosen wavelength was the lower energy of the longer wavelength photons and the consequent lower sensitivity of the materials currently available for the cathodes of the photomultiplier tubes used in the present configuration of the MAP. Nevertheless, operating at the central wavelength chosen in the compromise imposed by these several factors, the new system is several times more sensitive to the intrinsically faint stars which are so often the favored subjects of modern stellar astronomy.

TABLE 1

ALLEGHENY OBSERVATORY REFRACTOR OBJECTIVES

Characteristic	Photographic	New Lens
Aperture	30 inches	30 inches
Central Wavelength	4400 A	6400 A
Bandpass (with MAP)	160 A	650 A
Focal Length	556 inches	560 inches
F Ratio	18.53	18.67
Focal Plane Scale	14.60 arcsec/mm	14.51 arcsec/mm
Glass:		
element 1	Flint	F2 Flint
element 2	Crown	BK7 Crown
Lens Design	Aplanat (photographic)	Aplanat (red light)
Field Size (design)	0.8 x 1.0 degree	0.6 x 0.6 degree
Cell:		
material	cast iron	stainless steel
lens positioning:		
a) horizontal	2-point definition	4/2 point
b) vertical	3 pads	3 pads, 3 springs
c) separation	3 sets of push-pull	6 nylon spacers

TABLE 2

OPTICAL DESIGN OF NEW ALLEGHENY OBSERVATORY OBJECTIVE LENS

Surface	Radius (inches)	Central Thickness (inches)	Medium	Index of Refraction	DF
0	0.0000	infinite	air		
1	247.5254	1.5000	F2	1.615690	0.941
2	119.0529	.3572	air		
3	117.8908	3.0000	BK7	1.514972	0.315
4	-7965.2321	567.3156	air		

EFL (inches)	BFL (inches)	F Ratio	Length (inches)	GIH
570.00	567.32	19.00	4.857	2.985

SA3	PACY	PLCY	CMA3	COL
0.000004	-0.000231	-0.000006	0.000002	0.000233

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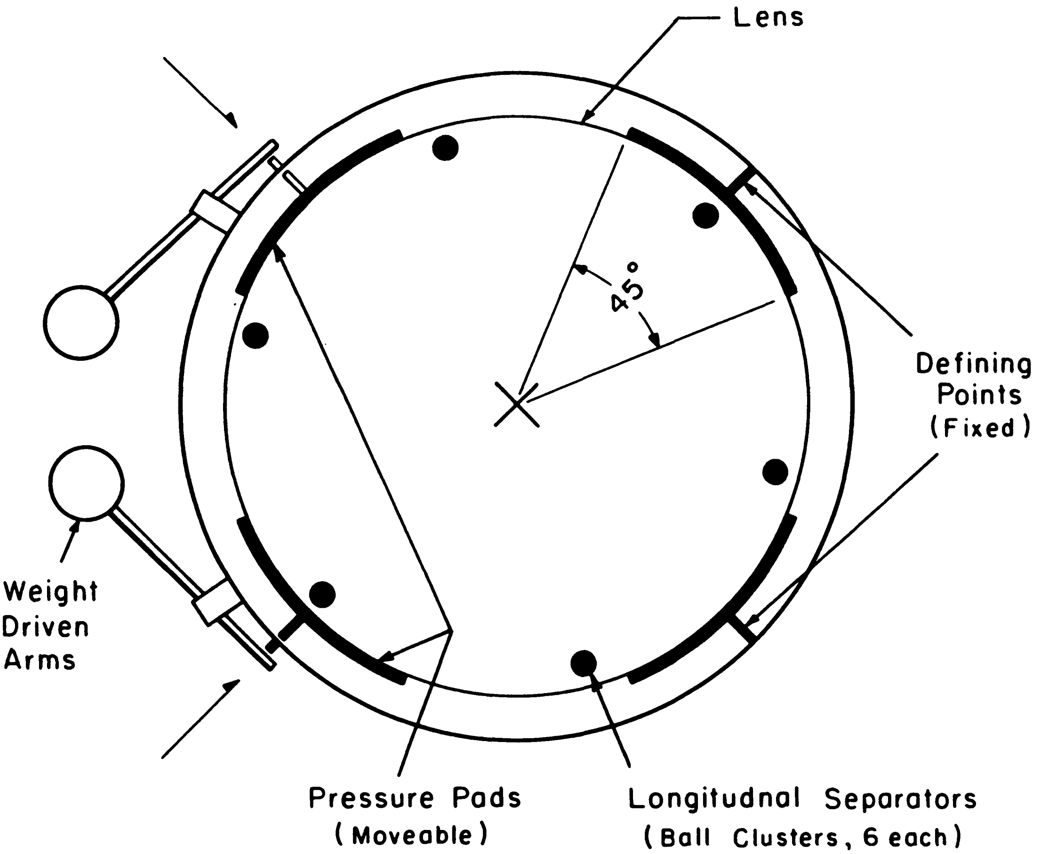

FIGURE 1 CELL ASSEMBLY FOR SYSTEM I

Shown here is one of the two very similar cells that hold the flint and crown elements of the new objective lens. Lateral position is defined by a pair of rocker arms located in the south and west. These pivot on supports attached to the cell wall. In the north and east are similar arms attached to weight-driven arms. Surrounded by springs, these arms each exert a minimum force equal to 15 % of the weight of the lens. When the lens is resting directly over the arms, a maximum of 115 % of the lens weight is exerted. The separation of the lenses, when their cells are joined, is maintained with six 0.375-inch-diameter curved nylon rods lying in the plane of the Figure. The lower (crown) element rests on three soft metal defining points and three springs. These six evenly spaced points give equal support at a zenith distance of 22 degrees, the expected average value during use.

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Table 2 contains the specific design characteristics of the new objective lens as derived by Steve Lang of the University of Arizona Optical Sciences Center (now with the WYKO Optical Company of Tucson, Arizona). The design was subjected to a second set of programs by James G. Baker of Harvard and checked further by one of us (J. K.de J.). Both lateral color and coma conditions are met to very high tolerances and the design yields near-gnomonic projection over a field 0.6 degrees in diameter.

The contract for grinding and figuring the lenses was awarded to the Optical Sciences Center. The senior optician is Richard E. Sumner, who was assisted by Brian Lizotte.

It may be noted that the values listed in Tables 1 and 2 differ slightly. This is due to slight variations from the the design curves. The original design included an error budget, the amount that each surface could vary from the design and still conform to the quality criteria sought. The actual curves are all within that budget and first tests indicate a diffraction-limited lens of the correct astrometric design.

A feature hopefully to be incorporated, at a later date, is the addition of a ribbed, light-weight optical flat that can be mounted on the front of the objective cell and utilized for tests of the optics while the telescope is pointed into various observing positions. This would allow regular high-precision checks of the performance of the telescope's optics, helping to insure the long-term stability of the system of the observations.

The cell shown in Figure 1 is a variant of the system designed by Frank Schlesinger (1936) and used successfully on the Thaw refractor for over 70 years. We have doubled the number of points of edge contact with the glass and modified the design to allow the elements to be mounted closer together. As in the original system, the lens elements are essentially mounted in separate cells. Radially, around the optical axis, there are eight points of contact. These points are arranged in pairs, each pair resting on a pivot. Two of the pivots, in the south and west when the cell is mounted on the vertical tube, are built directly on the stainless-steel wall of the cell. The other two, one in the north and the other in the east, are supported on pivots that are pushed towards the optical axis by a spring and a weight-driven arm. The spring is mounted inside the cell (with the arm passing through it) so that it always develops a force of 15 percent of the 200-lb weight of a single element (the elements are very similar in weight), thus insuring that the lens is always pushed towards the opposite defining position. As the orientation of the cell shifts the weight of an element towards one of the movable arms, the weight on the end of the arm causes the supports attached to it to push upward against the glass with a force that can become equal to the weight of the glass. As a result the elements are always held gently but firmly against the positions defined by the south and west pivots. As the slight differences in the coefficients of expansions of the stainless steel and glass react to the changing temperatures, the north and east arms adjust their positions. The slight offset of the flint and crown at the center of the lens system that will result at extreme temperatures is well within the lens design tolerances.

Support along the optical axis comes from 6 nylon cylinders placed between the glass elements and 6 metal supports placed below (closer to the focal plane) the lower (crown) element. The cylinders are located 60 degrees apart radially and have a diameter of 0.3750 inches, each with a uniformity of 0.0002 inches. With the telescope pointed to the zenith, the cylinders transmit the weight of the flint element onto the crown element. The weight of the flint element causes the cylinders to be compressed by 0.001 inches each, 5 times their variation in thickness. Thus, the weight of the glass is distributed over 6 broad points. The change in element separation is well within the error budget of the lens design, while the tilt between the elements is guaranteed by the uniformity of the cylinders and their tendency to increase their resistance rapidly with compression. The cell was designed in cooperation with, and built by, Ronald Hilliard of the Optomechanics Research Company of Tucson. This is the same firm that built, and helped design, the mechanical portions of the MAP.

Delivery of the lens was made in April of 1985 and the instrument is now involved in testing, calibration, and the beginnings of a new astrometric program. With its accuracy and limiting magnitude, the new system is ideally suited to complete the tasks it inherits from the photographic program. However, the capabilities of the system also suggest a number of previously impossible

TABLE 3

SOME QUANTITIES THAT CAN BE OBSERVED WITH INDICATED PERCENT ERROR

TARGET PARAMETER	ASSUMED VALUES	DISTANCE (parsecs)	PERCENT ERROR
stellar parallax	very distant reference points	250	10
IR dwarf detection	binary with a primary of 1, and a companion of 0.02, solar masses in orbit of 2 AU	20	10
jovian planet detection	mass=0.001 suns in a 5-AU orbit about a star of 1 solar mass	8	33
internal motion in star clusters	10-year proper motion study	1000	10

The above values are approximations meant only to suggest the potential of the new instrument.

tasks (Table 3). Even after its characteristics have been exceeded by later systems, they will continue to make it a viable research and educational system for decades to come.

CONCLUSION

Once again, astrometry is entering a period of substantially improved accuracy. And once again, the change has been brought on by a new class of detectors. Detectors that can, within a few minutes of observation, in most cases, reach the positional accuracy limitations of previous astrometric telescopes, telescopes that were designed around the the now venerable photographic plate. However, with proper attention to the design of future telescopes, or to the refurbishment of existing instruments, the new detectors can approach their innate potential in any given environment. Combined, these improved instruments and their detectors will eventually have sufficient accuracy to push the horizons of astrometry to the edges of our galaxy and well beyond

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(Gatewood et al. 1980). The domain of astrometric research has begun an expansion that will, within our lifetimes, spread past the confines of the solar neighborhood to add two new dimensions to the study of cosmology.

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However, there are times when that which needs to be done requires unusual financial resources. Such was the circumstance that surrounded the decision to upgrade the Allegheny Observatory's main telescope. Our ongoing support does not provide for major upgrades of the optical components of the telescope. Yet, we had arrived at the conclusion that the meaningful continuation of the fundamental program required a new objective lens for the refractor. It is at times of unusual need when individuals, and the institutions that they form for such purposes, can make a very large difference. Dr. Bernard Oliver, retired Vice President of Research for Hewlett Packard, was the first to make a matching gift toward our seemingly distant goal. This offer was met by the Helen Clay Frick Foundation of Pittsburgh with an additional matching gift. Additional contributions were made by the Extrasolar Planetary Foundation, the Planetary Society, the Foundation for SETI, the National Science Foundation, the Office of Research of the University of Pittsburgh, the Department of Physics and Astronomy of the University of Pittsburgh and the Allegheny Observatory Endowment. Altogether, more than one-hundred-and-thirty-thousand dollars were raised for the new lens and its objective cell.

As one experienced in these matters will undoubtedly surmise from the quoted price, we also owe a note of gratitude to the organizations that cooperated to make the new objective lens and its cell possible: the Schott Glass Company of Mainz, Germany and Duryea, Pennsylvania, the Optical Sciences Center of the University of Arizona, and the Optomechanics Research Company of Tucson, Arizona.

To this diverse group of individuals, foundations and corporations, in no small part, should go much of the credit for the science that the improved telescope will produce.

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Discussion:

JEFFERYS: I may have missed this, but did you say anything about pointing stability? I'm sorry to mention this, but I am very sensitive to this issue!

GATEWOOD: When you realize that the ruling is moved simply to avoid moving the telescope, you see that a slow drift is similar to a slight error in the rate of motion of the ruling and this is not a problem. The pointing need only be sufficient to bring the field on to a rather large area detector.

STRAND: Lockheed made a study and came up with a proposal for a super-achromat. If you cannot get glass for a ground based telescope, how would you get it for one to go into space?

GATEWOOD: In space, in free fall, the glass can be relatively thin and thus the blanks may have a larger diameter. One meter is obviously possible.

van ALTENA: Have you considered the problems of resonance and jitter in such a long flexible telescope, especially when microarcsecond accuracy is desired?

GATEWOOD: Vibrations can of course be a serious problem. However, most of them are easy to remove. Rapid vibrations are unlikely in a structure of this size. If present they cause an increase in the accidental error and are removed by averaging. Long period vibrations are removed directly as the field is modeled every 1/10th of a second. Vibrations near the frequency of measurement would seem to be removable by system design. Given all of this we are OK. Of course full engineering remains to be done.

THORNBURG: What is the aperture for your third system (on the ground), how much will it cost and how soon can it be manufactured? For "system 3 on the ground" what aperature, costs and time frame?

GATEWOOD: Much of the final cost will depend upon the design of the building. Our current estimate, based on the building suggested here, is 4 or 5 million dollars. We expect an engineering study to be conducted in 1985/6.